An Adaptive Conceptual Framework for Smart Management of Recyclable Construction Materials by Leveraging the Salvage Value through Blockchain and Building Information Modelling-Compliant Material Banks

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Abstract:

As the global economy moves towards a sustainable and circular trajectory, the immense role of the construction industry is becoming increasingly apparent as one of the most waste-intensive sectors. Urban mining and subsequent material reuse or recycling are the recommended remedies to lower resource extraction and waste generation in the upcoming decades.

This article looks at the recycling practices and offers a solution to revalorise construction recyclables, regulate the isolated recycling activities and incentivise construction material manufacturers to take responsibility for recycling their own products after their lifecycle is over. Consequently, the future volumes of recyclables will become calculable and transparent, which balances the supply and demand of secondary materials. To this end, this study goes beyond manufacturing traceability and investigates manufacturer traceability. Material banks, Building Information Models, blockchain technology and smart contracts are used to conceptualise a novel business model for highly recyclable construction materials.

On the one hand, the value of recyclables is captured through salvage value based on accounting methods. Smart contracts administer the physical material transfer for recycling while automating the monetary value transactions between stakeholders. On the other hand, a financial instrument is proposed to link the on-chain captured value to the off-chain financial practices through the Recycling Requirement Rights. The right holders are responsible for recycling; they could be the material manufacturers or not. The discussions on the threats and opportunities as well as weaknesses and strengths of the proposed framework together with its potential to integrate with existing solutions conclude this study.

Keywords: Circular Economy, Recycling, Blockchain, Smart Contracts, Construction and Demolition Waste, Digital Deconstruction

Highlights:

- A digital take-back system for tracking the status and recycling responsibility of recyclable construction materials is proposed in support of introducing Extended Producer Responsibility principles in the construction sector.
- Blockchain technology is used as an infrastructure together with Building Information Modelling and Material Banks to create transferable value for construction and demolition waste in a circular economy.
- Recycling responsibilities of construction stakeholders and producers are clear, recorded, and communicated in due time.
- The proposed system is applicable to other sectors and has the potential to create cross-sector circular business models and stabilises the market prices of materials through increased transparency.

1. Introduction

The global waste sector, with an annual value of $410 billion, is to some degree unregulated with occasional informal businesses. As a consequence, organised environmental crimes such as unreported recycling, illegal waste and the trafficking of chemicals happens in various parts of the world. These environmental crimes are usually accompanied by white-collar crimes such as money laundering, fraud, tax evasion or falsely claimed carbon credits (Nellemann et al., 2016). According to Schmelz et al. (2019), the waste flow does not stop at the border of a state or a region. This hampers waste tracking from the source, stops reuse and increases illegal dumps. Lack of transparency regarding the volume and location of waste, inability to track the impact of environmental counter-actions (e.g., recycling) and not having an accountability mechanism for waste treatment inspired this study to look into ways through which all the mentioned shortcomings are resolved. This is done by looking at the current bookkeeping norms and environmental policies, as well as secure digital infrastructure (e.g., blockchain), to build a transparent and orderly waste treatment ecosystem. Therefore, a conceptual framework is proposed for not only tracking but, more importantly, for revalorising the recyclable construction waste and Construction and Demolition Waste (CDW) in order to reintroduce them to the value chain and close the material loop. Closed-loop cycles are championed by the Circular Economy (CE) concept in which the importance of keeping the value of resources in the market for as long as possible in multiple lifecycles is highlighted (Kirchherr et al., 2017). A combination of Building Information Modelling (BIM), blockchain and material databases and accounting concepts are proposed for a novel closed-loop cycle. Through this framework, we would like to make a case for the need for updated economic policies to catch up with the new revenue streams coming from the synergies of disruptive technologies, such as blockchain, in the uncharted phase of the building lifecycle, i.e., End-of-Lifecycle (EoL).

This study aims to give value to the CDW and enhance the recycling efficiency and transparency in the construction sector by defining clear lines of EoL responsibility for the project's participants. This aim is achieved through a synergy of digital technologies to create a foundation for further financial and take-back systems. As a result, this paper seeks to answer three research questions:

1. How to increase the transparency of materials and roles in the EoL phase of construction projects?

2. How to revalorise CDW and provide financial benefits for producers and consumers?

3. How is EoL treatment accountability enhanced and tracked through digital technologies within the construction supply chain?

A framework is suggested to address these questions. The proposed framework is a digital, sustainable and circular solution that offers manifold benefits that are in line with the other advantages of CE, such as higher optimisation, eco-efficiency, eco-effectiveness, and waste reduction, as well as more reuse and recycling (Kalmykova et al., 2018). Moreover, this solution follows the existing policies such as Extended Producer Responsibility (EPR) that is actively implemented in different waste categories.

The rest of this paper is organised as follows. Section 2 presents the theoretical background concerning the key terms, concepts, and technologies used in developing this study, and looks at other blockchain-based models in the literature. Section 3 describes the proposed Blockchain-based model. Section 4 discusses further points regarding the suggested framework and explains some limitations or future research avenues. Finally, Section 5 concludes the paper.

2. Background: key terms and concepts

In this section, key features of the different concepts that are mentioned in the framework are explained. The background explanations provide the required cross-disciplinary knowledge for understanding the framework. Furthermore, previous use cases and similar studies in the relevant literature are delivered here.

2.1. Blockchain Technology

Satoshi Nakamoto first introduced blockchain technology in a white paper published through a mailing list (Nakamoto, 2009). Blockchain is an ongoing digital distributed log of economic transactions, which can be programmed for the recording of not only financial operations, but literally anything that is valuable including bargains, agreements and contracts (Ablyazov and

Petrov, 2019; Tapscott and Tapscott, 2016). How blockchain works as a network is shown in Figure 1.a.

Blockchain is a special case of the Distributed Ledger Technology (DLT) and is built upon three other technologies: a) blockchain's protocol, b) private key cryptography, and c) Peer-to-Peer (P2P) network (Ari Sivula et al., 2018; Tapscott and Tapscott, 2016). DLT is a distributed, peer-to-peer network of value transactions where peers in the network have equal rights. Each network node (i.e., peers, users or miners) have a copy of the transactions. In essence, blockchain is a decentralised and distributed database, unlike a central database such as an Excel file. This difference is shown in Figure 1.b.

Different blockchain architectures have been developed to meet different needs and use-cases. Their point of differentiation is the access rights to transaction processing, they could be "permissioned" or "permissionless," as well as "public" or "private." Anyone can connect a computer and become part of the network in a permissionless blockchain ledger, for example, Bitcoin. A permissioned ledger system, on the other hand, has a limited number of contributors, which makes it suitable for a group of independent organisations that need a common trustable record-keeping system, such as a manufacturer and its suppliers (Tapscott and Tapscott, 2016). Further explanations are visually illustrated and shown in Figure 1.c. Within the context of the construction industry, Yang et al. (2020) investigated the application of public and private blockchains. They concluded that both types could be useful depending on the digital skills and infrastructure of businesses, their initial capital, desired scalability, level of confidentiality and complexity of the project.

DLT has several attributes. It is immutable, meaning that once a transaction is added, it cannot be modified. DLT is non-repudiable, meaning that each transaction is added to the chain only once. DLT has integrity; the network nodes verify data before being added to the ledger (Tapscott and Tapscott, 2016). These characteristics of DLT have resulted in the development of the Consensus Protocol. What keeps a blockchain network running is the creation of a new block of transactions and its addition to the previous log of blocks. When new transactions are requested in a network, a new block of information is created. The consensus in a blockchain is the agreement between nodes to accept a new block in the ongoing chain of blocks. In addition, it is not possible to go backwards in the chain in order to correct or to rewrite the information of a certain block without having the consensus of the network peers. Different mechanisms to reach consensus within a blockchain network include Proof of Work (PoW) and Proof of Stake (PoS). Different consensus mechanisms have their benefits and drawbacks, all of which have been summarised previously (Bodkhe et al., 2020; Nawari and Ravindran, 2019a).

A more comprehensive description of blockchain can be found in the existing academic literature reviews (Casino et al., 2019; Kitsantas et al., 2019; Liu et al., 2020; Xu et al., 2019). Blockchain technology is studied in terms of cryptography, consensus mechanisms, tokens, smart contracts, financial instruments, individual identity, marketplaces and supply chain potentials. The experimental applications of blockchain technology are investigated in various contexts, from money laundering (Moser et al., 2013), to human resource information management (Wang et al., 2017), within the aerospace and automobile industries (Kar et al., 2019; Zhao et al., 2018) and with respect to different supply chains (Boison and Antwi-Boampong, 2019; Saberi et al., 2019; Wang, 2019). Furthermore, blockchain technology's impact on business models is studied by Weking et al. (2019).

2.2. Smart Contracts

A popular application of blockchain technology is "Smart Contracts". However, this concept was first introduced and coined by Nick Szabo in 1996, long before blockchain was born (Szabo, 1996). Clack et al. (2016) described smart contracts as a contract that is automatable by a computer and enforceable either by legal enforcement of rights and obligations or via tamper-proof execution of computer code. However, human input and control could also be required.

Smart contracts are not the digital version of real contracts. They are small blockchain-based programs that automatically execute an if-then or condition-action protocol that is previously agreed upon between two users in the network. Not all blockchain networks have architectures capable of writing and invoking smart contracts. Ethereum and Hyperledger (Ethereum, 2021; Hyperledger, 2021) are the major platforms that support smart contracts, which are public and private, respectively.

Smart contracts add a layer of computational logic to the blockchain network, where other conditions can be coded into a block in tangent to the financial transactions. Once the code is executed, it is deployed and invoked on the network and, finally, it is validated by users in the consensus process. Figure 1.d depicts how smart contracts are linked to the blocks in a blockchain. According to Clack et al. (2016), smart contracts can also be linked with semantic web technologies, which could be an essential feature for the future of Linked Building Data.

Over time, there has been an extensive literature developed around smart contracts (Zheng et al., 2020). This topic is comprehensively reviewed by Ante (2020), where future directions of this technology are delineated that include disruption of existing processes through decentralised business models, ecosystems and markets. Within the construction industry, Li et al. (2019) reviewed blockchain and smart contract's chances and challenges. Many multidisciplinary studies concerning the digital construction processes and products, including the present work, have relied on the benefits of smart contracts more than other blockchain characteristics. Li et al. (2020) proposed a smart contract-based framework for the semi-automated maintenance and repairs of built assets for increased traceability of materials throughout the lifecycle. Likewise, Wang et al. (2020) developed the blockchain-based information management framework for a precast supply chain (BIMF-PSC), in which smart contracts (chaincodes) auto-regulate the information traceability and sharing between project participants for real-time control of pre-case scheduling. Fitriawijaya et al. (2019) conceptualised a supply chain model with a decentralised blockchain-based Common Data Environment (CDE) in which smart contracts trace and authenticate the movement of objects from suppliers, to contractors, to clients. A similar study was conducted by Shojaei et al. (2019), where smart contracts track the purchase, shipment, on-site reception and construction steps in the steel supply chain.

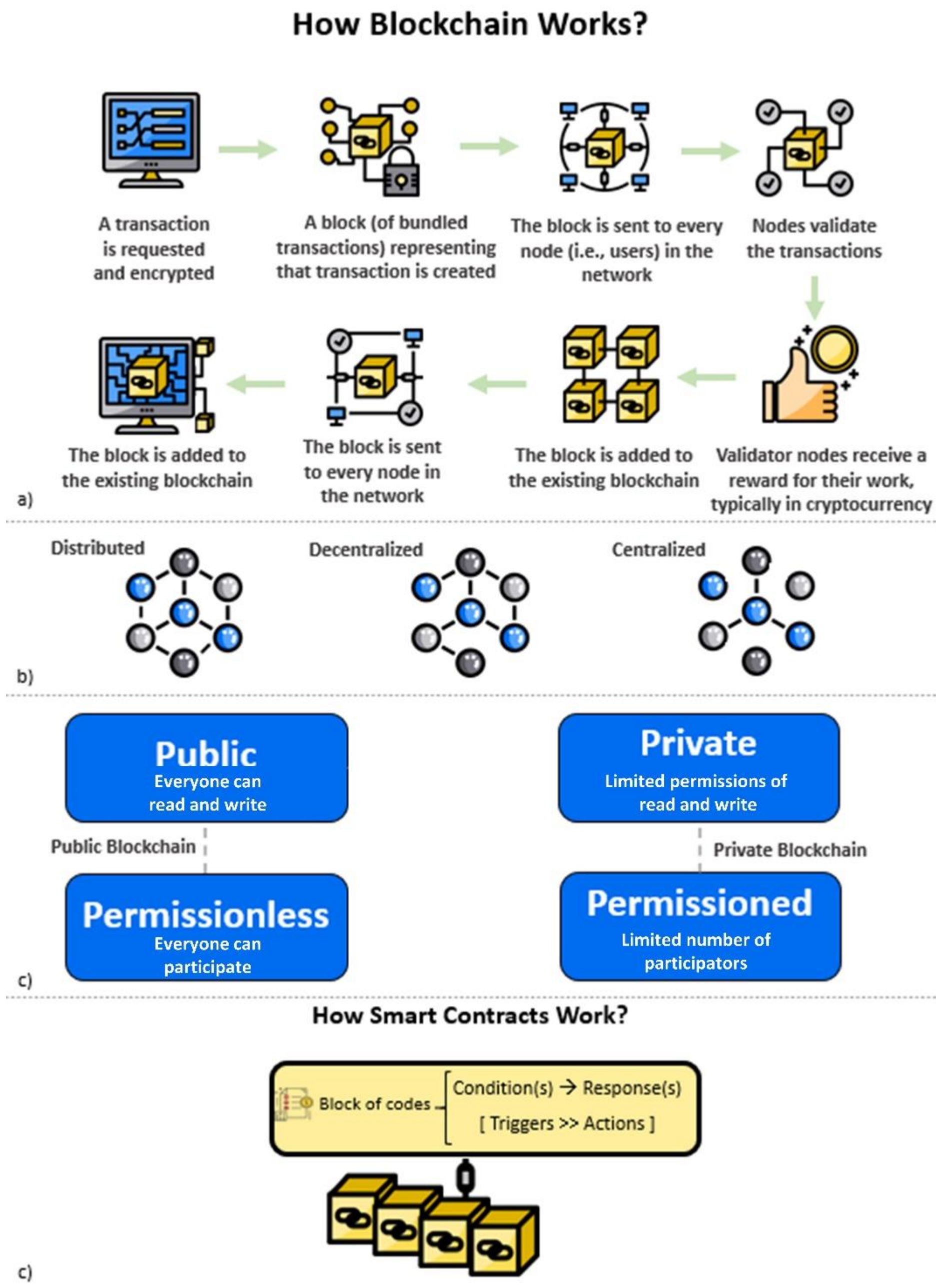

Figure 1 The different aspects of blockchain technology. a) A schemata of how a blockchain network functions. b) the comparison between different types of networks. c) The difference between network trust and anonymity levels that lead to the public, private, permission and permissionless networks. d) The mechanism of the smart contracts in a blockchain network

2.3. Building Information Modelling (BIM)

BIM is a methodology to create a digital and object-oriented representation of a built asset where three-dimensional measurements, as well as other building information, are modelled together as illustrated by Figure 2.a. The output model of this methodology is called BIM or BIModel. All the information related to a building can be modelled, stored, and queried through a BIM. Therefore, this model provides a data platform for which other technologies can plug in and reuse the building information (Sacks et al., 2018).

BIM has brought many benefits to the construction industry through creating new digital workflows. However, there are still areas where digitalisation through BIM is not solving the existing problems in the construction industry. Issues regarding the data governance, provenance, security and ownership of construction objects have still firmly remained unchanged. This is because BIM only model, manage, and store the data, but the authenticity of the data cannot be confirmed via BIM. It is widely accepted that Blockchain-enabled features for the Architecture, Engineering and Construction (AEC) industry include transparency, traceability and collaboration (Howson, 2019), although a large number of existing studies in the literature have examined the integration of BIM and blockchain to offer a secure way for data authentication, ownership and tracking. Hijazi et al. (2019) examined the possibility of BIM acting as the "Single Source of Truth (SSoT)" in existing blockchain frameworks in the construction literature. A similar concept was also investigated in Li et al. (2019). Additionally, Nawari and Ravindran (2019b), and Perera et al. (2020) reviewed and analysed the interaction and capabilities of Blockchain and BIM within the AEC industry.

Ye et al. (2018) suggested the "Cup-of-Water" theory in which BIM is the bottom of the cup for lifecycle information management. Blockchain is the cup's wall that stores and authenticates high-value data in a transparent fashion. Lastly, data is the water inside the cup in this theory. This analogy emphasises the impracticality of any digital solution in the construction industry without BIM since BIM is the only existing methodology to digitalise construction information. BIM acts as a "Data Lake" for other digital technologies such as the blockchain or Artificial Intelligence (AI) as illustrated in Figure 2.a. BIM is an ideal candidate for the role of the foundation technology, into which other technical means are integrated and is the gateway to the digital economy in the construction industry (Aleksandrova et al., 2019; Bukunova and Bukunov, 2019; Ganter and Lützkendorf, 2019). An increasing number of studies are using BIM to create novel and efficient workflows in which on-site and off-site data are connected and work progress is tracked simultaneously (Hamledari and Fischer, 2021).

Furthermore, the bcBIM framework is proposed to trace and authenticate BIM data history as well as positioning BIM as a base to integrate digital technologies, including big data, blockchain, and mobile cloud architecture (Zheng et al., 2019). The BIM+BC conceptual framework for sustainable building design information management is suggested by Liu et al. (2019). BIM+BC supports project stakeholders in information management through smart contracts for tracking and resolving BIM documentation issues in different lifecycle stages. Turk and Klinc (2017) suggested different scenarios for "blockchaining building information," i.e., to manage building information with blockchain. They studied other BIM and Blockchain integration aspects such as the size of the data to be managed, the number of transactions and participants in decentralised networks. Only a few works in the literature examine BIM-blockchain integration case-studies, although Hunhevicz and Hall (2020) reviewed and summarised all the use cases.

2.4. The Material and Component Bank (M/C Bank)

The concept of Material and Component Bank (M/C Bank) was introduced by several authors, including Cai and Waldmann (2019). An M/C bank helps to close the material loop and contribute to a circular built environment. After a building is deconstructed, materials and components are tested by the M/C bank with respect to their structural, environmental and chemical performance. They will be either suited for further reuse or recycling after the assessment. The information about the reusable materials and their performance is recorded in the M/C Bank. Material bank, therefore, is a) responsible for assessment of the materials and components, b) recertifying them as structurally robust as well as environmentally safe for reuse and c) guaranteeing the material's reliability throughout their second lifecycle. This information would be available for the designers to use the available reusable materials in a new building and through BIM-authoring tools or BIM-compliant material banks as shown in Figure 2.b (Akbarieh et al., 2020b; Jayasinghe and Waldmann, 2020). Reusing materials and components would extend their lifecycle and lower their negative environmental impacts (Akbarnezhad et al., 2014). Figure 2.c. demonstrates a simple mechanism of BIM and M/C Bank interaction.

Kouhizadeh et al. (2019b) is among the earliest works that reviewed the advantages and disadvantages of blockchain technology for civil engineering. Many studies that investigate the blockchain's potential in CE, look at the supply chain of materials in order to create new inner cycles or to help with closing the material loop. Few studies scrutinised the nexus of blockchain, CE and the construction materials supply chain (Saberi et al., 2019; Shojaei, 2019). Succar and Poirier (2020) suggested the integration of blockchain with the Lifecycle Information Transformation and Exchange (LITE) framework to store the "audit trail", which is the history of a product. Based on this audit, the real-time value of the asset can be tokenised and exchanged on a blockchain platform. Furthermore, the concepts of Lifecycle agent and Refurbish-agents were introduced by Van Moergestel et al. (2018) to create a blockchain-enabled marketplace with autonomous agents that have access to all the information about the parts and subparts of a particular product for a hassle-free spare parts trade. A BIM and blockchain-enabled lifecycle repository concept is developed by Aleksandrova et al. (2019) and A. Sivula et al. (2018) looked into the research opportunities of blockchain and digital ledgers in the construction industry's supply chain logistics.

In the scientific literature, blockchain and BIM are discussed from the design phase to the construction and then operation phases. However, among studies that have been conducted by many authors, an EoL phase-specific solution that interoperates with all these digital technologies is still insufficiently explored. Ganter and Lützkendorf (2019) briefly mentioned the potentials of blockchain for lifecycle management, deconstruction and reconstruction. While Cao and Fang (2019) suggested future research on the collation of suppliers and assemblers in a supply chain to reduce the supply chain risk due to supply uncertainty. Wang (2019) studied the reaction of construction actors to smart contract-based supply chain models and the subsequent business impacts. Furthermore, Yadav and Singh (2020) identified major causes of a successful integration of blockchain information technology with sustainable supply chains operations, namely data safety and decentralisation, accessibility, laws and policy, documentation, data management, and quality.

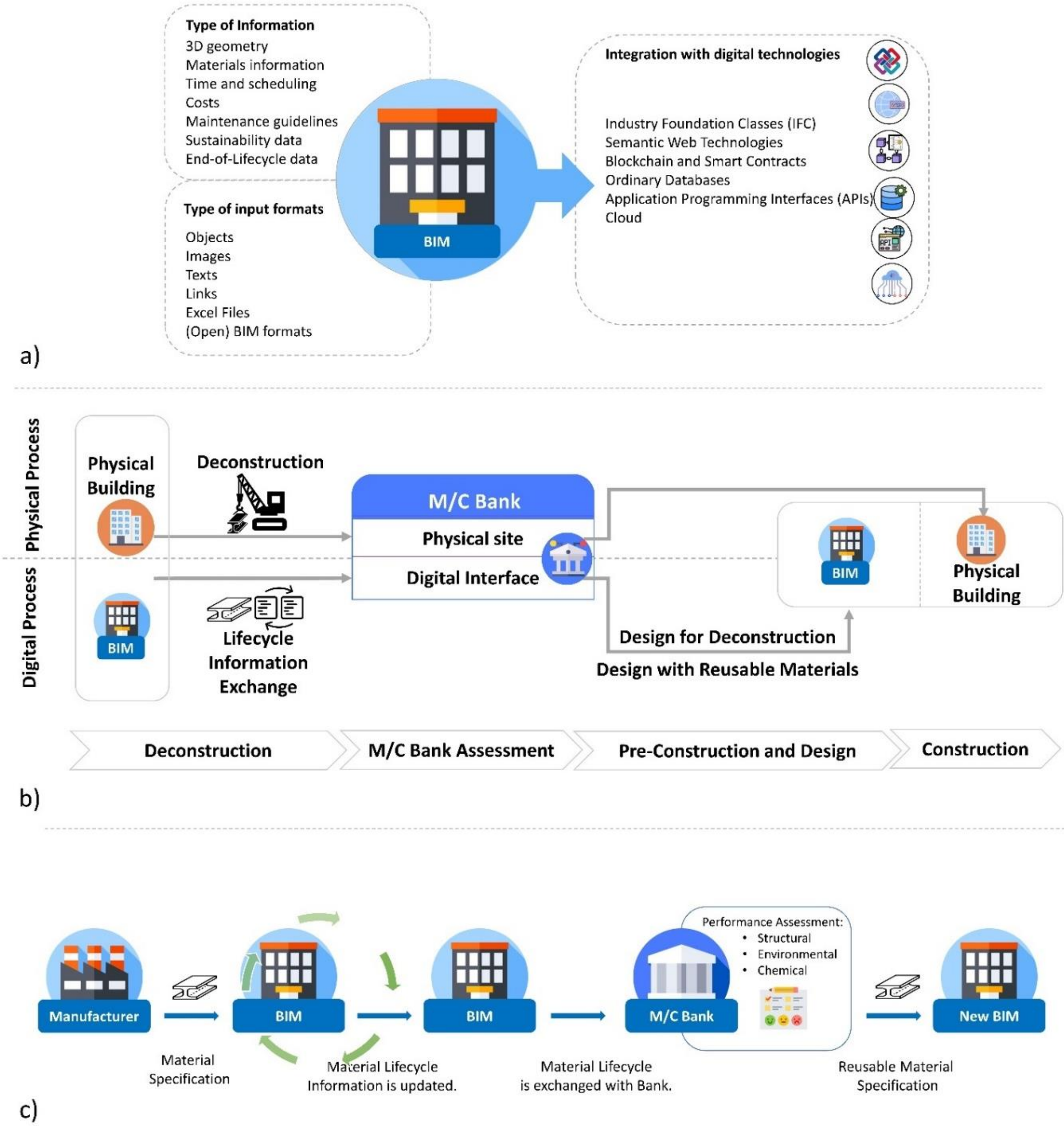

Figure 2 BIM and Material Bank. a) BIM as a Data Lake to prepare construction information interoperable with other digital technologies to construction data, b) Detailed material and lifecycle information flow in two parallel processes involving BIM and M/C Bank, c) 3 The mechanism of BIM and M/C Bank interaction for circular reuse of materials and components.

2.5. Recycling, Reuse, Waste and Blockchain

The application of blockchain for natural resources, conservation, recycling and waste management that has been explored and categorized in prior studies (Gopalakrishnan and Ramaguru, 2019; Saberi et al., 2018). An automated Blockchain and IoT-based waste management model to track, categorise and transfer waste for making smart decisions about the recycling process was proposed by Latif et al. (2019). Gupta and Bedi (2018) suggested similar concepts for e-waste. In order to create information symmetry and transparency between regulators, consumers, producers, transportation and treatment companies for the management of hazardous wastes, a framework is suggested (Song, 2021). Researchers in the project "Recycling 4.0" studied the possible integration of recycling materials with databases and blockchain (Kreutzmann et al., 2019). Schmelz et al. (2019) suggested a blockchain-enabled schema for trans-border waste tracking followed by an audit. Subsequently, the audit-critical information is stored on the blockchain to be accessible, transparent and simultaneously immutable. With this architecture, it is possible to audit waste flows without compromising data privacy. Other studies inspected the data quality in blockchain-based recycling marketplaces (Lawrenz et al., 2019). Loss of data during the whole product lifecycle is a critical issue in the recycling industry. According to Knieke et al. (2019), loss of valuable data in complex lifetime chains originates from degraded products and less well-tracked post-consumer waste. Subsequently, product deletion is reported as an impactful decision in losing product lifecycle information (Kouhizadeh et al., 2019a). By employing blockchain, one can either track and remove the goods with poor circularity from the supply chains or look back and track the life cycle information of goods that no longer exist in the market.

In summary, the literature review demonstrates that academic construction players are aware of the blockchain's disruptive power and its ability to create positive changes in the industry. The End-to-end visibility and transparency that blockchain offers have attracted many authors to explore new digital workflows for efficient supply chain operations and sorted-in-source waste management practices. Furthermore, BIM is acknowledged as a platform for linking the regular construction processes and objects to a broader digital ecosystem. However, little has been done regarding a blockchain-power and BIM-based post-consumer management of materials. In order to examine the potentials of using blockchain for EoL decision making and management, this research proposes a novel adaptive implementation framework and suggests a new blockchain-enabled business model for recyclable construction materials.

3. The Proposed Conceptual Framework

The theoretical idea behind this framework is to provide a take-back system for recyclable construction materials. If the responsibilities are clear, the location of the product is known and the reusability or recyclability status of products is verified, the original manufacturers can easily take back their own recyclable products after the first lifecycle is over. This would lead to optimised recycling processes and treatments with lower costs, energy and externalities. This is also in line with the Extended Producer Responsibility (EPR) policy (OECD, 2016). The contribution of the suggested framework for the uptake of the EPR policy in the construction sector is discussed in detail in Akbarieh et al. (2020a). The focus of this framework is on recyclable construction materials with high recyclability rates, such as steel, metals and glass among others. However, a provision is developed to include the reusable materials as well.

This framework is presented in three parts in this article. The first part focuses on the technological core and the main research questions behind this concept. The second part explains the accounting principles behind the suggested business model. The last part briefly explains how this framework can be implemented in the current market and suggests some instruments for a smooth transition towards a digital circular construction supply chain in an inclusive manner.

3.1. Part 1: Technological Core

The technological and information core of this framework is built upon BIM, blockchain, smart contracts and a BIM-compliant material bank. The stakeholders of the project, namely, construction product manufacturers, construction contractors, owners and M/C bank are connected together through these technologies. An overall schema of this conceptual framework is demonstrated in Figure 3.

This framework benefits from integrating BIM and smart contracts to impartially automate the M/C bank workflows, reduce paperwork, ease the recycling procedures, and bring transparency to the supply chain of available raw and secondary materials in the market. On top of that, a financial instrument will be introduced that is an advantage of using blockchain and smart contracts instead of ordinary information databases.

After the deconstruction of a building, the physical materials and components are assessed by the M/C bank against performance criteria. If materials pass the reusability criteria, a smart contract is automatically executed to notify the manufacturers that the product (be it a material or a component) is in the custody of the M/C Bank. The M/C bank's database, as well as the manufacturer's, will be updated accordingly with the new lifecycle information. The reusable product will be reintroduced to the market in order to be used in a new project and to reach the potentials of its full lifecycle.

However, if the evaluation of the materials shows that they are only suited for recycling, then a new smart contract action is triggered. Products Manufacturers will be notified that their product has finished the first lifecycle and can no longer be reused (path number 1 in Figure 3). Thus, they can take back the materials for recycling treatment. This would give them multiple benefits. Since the chemical composition of the materials and alloys are known to the original manufacturers, they can better sort, separate and recycle their own products. This could lead to secondary materials with similar compositions without major chemical modifications and additives.

3.2. Part 2: Accounting Base

This section addresses a blockchain-based accounting strategy for the uptake of the proposed material take-back framework. This is a novelty of this study since it suggests a new look at the current accounting practices. In (Desplebin et al., 2021), multiple evolutionary directions of accounting practices under the impact of blockchain technology is studied. Innovative Blockchain-based invoicing and payments, trace and tracking of the origin and history of purchases and operation, as well as transformation in the record-keeping tasks are in the outlook of smart and connected accounting.

The fundamental questions are: why should manufacturers agree to join such a long-term take-back schema if there are no financial gains? What are the advantages of this framework over the business as usual practices? It is widely accepted that by tying the waste and recyclable materials to an anticipated sum of money, we are giving them tangible value (Katz, 2019). Revalorising the recycling materials can significantly benefit the circular built environment as it fosters transparency in the supply chain and prevents unregulated EoL treatments. Value creation in a sustainable supply chain is indeed another advantage of blockchain technology (Rejeb and Rejeb, 2020).

To revalorise the recyclables at the EoL phase through a smart contract-based mechanism, the concept of salvage value in the double bookkeeping methodology in accounting is used in this proposed framework. Salvage value is also known as disposal value, residual value, scrap value or terminal value and can be applied only when the asset still has some value at the end of its lifecycle regardless of its functionality. When the client is able to return the leftovers to the manufacturer, the salvage value is referred to as the buy-back price (Xu et al., 2017).

The assumption is that the manufacturers will take back the used recyclable elements at the end of the building lifecycle in the future. As a consequence, salvage value can be added to the bookkeeping from an accounting perspective. Salvage value is studied and proposed by previous researchers for waste and recycling revalorisation as well as transparency in the EoL profits. The use of salvage value for the aviation industry was studied and published (Cao and Fang, 2019; Zhao et al., 2020). The complexity of aircrafts could be comparable to buildings, while the aeroplane parts are also made from the most valuable metals and alloys. Another study explored the profitability of salvage value of the organic and recyclable wastes (Nath, 2015).

Typically, the bookkeeping of the manufacturer is closed after a product is sold, without any outlook for the future of these materials. This is because they no longer have any rights to claim the sold assets. However, if sustainable and circular regulations, such as EPR, make these manufacturers responsible for the extended lifecycle and EoL handling of their products, then they should look for ways to keep track of the EoL value of their sold products in order to treat the recyclables.

Suppose the M/C bank concluded that materials should be recycled. In that case, this decision is communicated to manufacturers through a smart contract. However, because of the long service life of buildings, there is a long time-span between the construction and the deconstruction phases, e.g., 50 years (European Union, 2002). Some manufacturers might not be in the market anymore. Therefore, the availability of the manufacturers must be first enquired about. If the manufacturer is still in service, two scenarios can be anticipated.

In the first scenario, the manufacturer does not accept the responsibility of recycling the recyclables after the building deconstruction (path number 2 in Figure 3). In this case, the M/C bank will take responsibility for recycling. Either a new smart contract will be invoked to start a bidding process for recyclers, or the materials will be available in an e-marketplace. In the latter case, further smart contract clauses could be coded for micropayments. However, this topic is beyond the scope of this research. Nevertheless, another smart contract will be activated in parallel to return the salvage value to the shareholders of the dissolved company. This is where the immutability, traceability and security of blockchain demonstrate its powers. The necessary information of the shareholders is recorded and periodically updated in the network. Thus, it would be possible that smart contracts automatically return the profits of the salvage value to the company's shareholders (or their next of kin, since the deconstruction is performed in the future). Any change in the details of shareholders can be automatically updated in the blockchain upon their request. This security could increase investment in long-term eco-sourced materials.

In the second scenario, the manufacturer accepts to take back the recyclables (path number 3 in Figure 3). A smart contract would be executed so that the company receives the salvage value as well as the recyclables for free. Within this framework, all the transactions and response actions are recorded in smart contracts to eliminate the manufacturers' fear of not receiving the expected funds in the future. This would be the ideal case in this framework. Not only are materials recycled and reinjected into the value chain, but also the original producer carries out the EoL treatment responsibility. High transparency in the supply chain, availability of resources, and clear lines of responsibility and roles in EoL handling processes are achieved.

However, if the manufacturing company is no longer operational in the future when the building is being deconstructed, another smart contract clause would be executed. This situation would be treated similarly to the scenario where the manufacturer does not accept the recycling responsibility (path number 4 in Figure 3).

This salvage value-based framework suggests a win-win deal for all the stakeholders. In current practices, when a product is sold, the full costs are realised. Simultaneously, the full price is paid by the customers (here: building contractor or owner). By enacting this framework, the cost of products will slightly come down since the buyer pays for "the full price minus salvage value". In other words, instead of buying the materials at full price, clients would pay for the depreciable cost, which is the difference between the original price and the salvage value. Therefore, buyers will pay less. The question is, how this is a win situation for the manufacturer? Although manufacturers will receive slightly less revenue at the beginning of this schema, the salvage value is sent back to manufacturers in the future once they announce their capability. However, the significance of this framework for the manufacturer is that they will also receive recyclable materials free of charge. Their dependency on raw materials will decrease as they can recycle their products, reinject the secondary raw materials into their production line while adding value to their capital budget.

To ensure the integrity of the framework and to reduce the vulnerability of parties, some example smart contract triggers are elaborated:

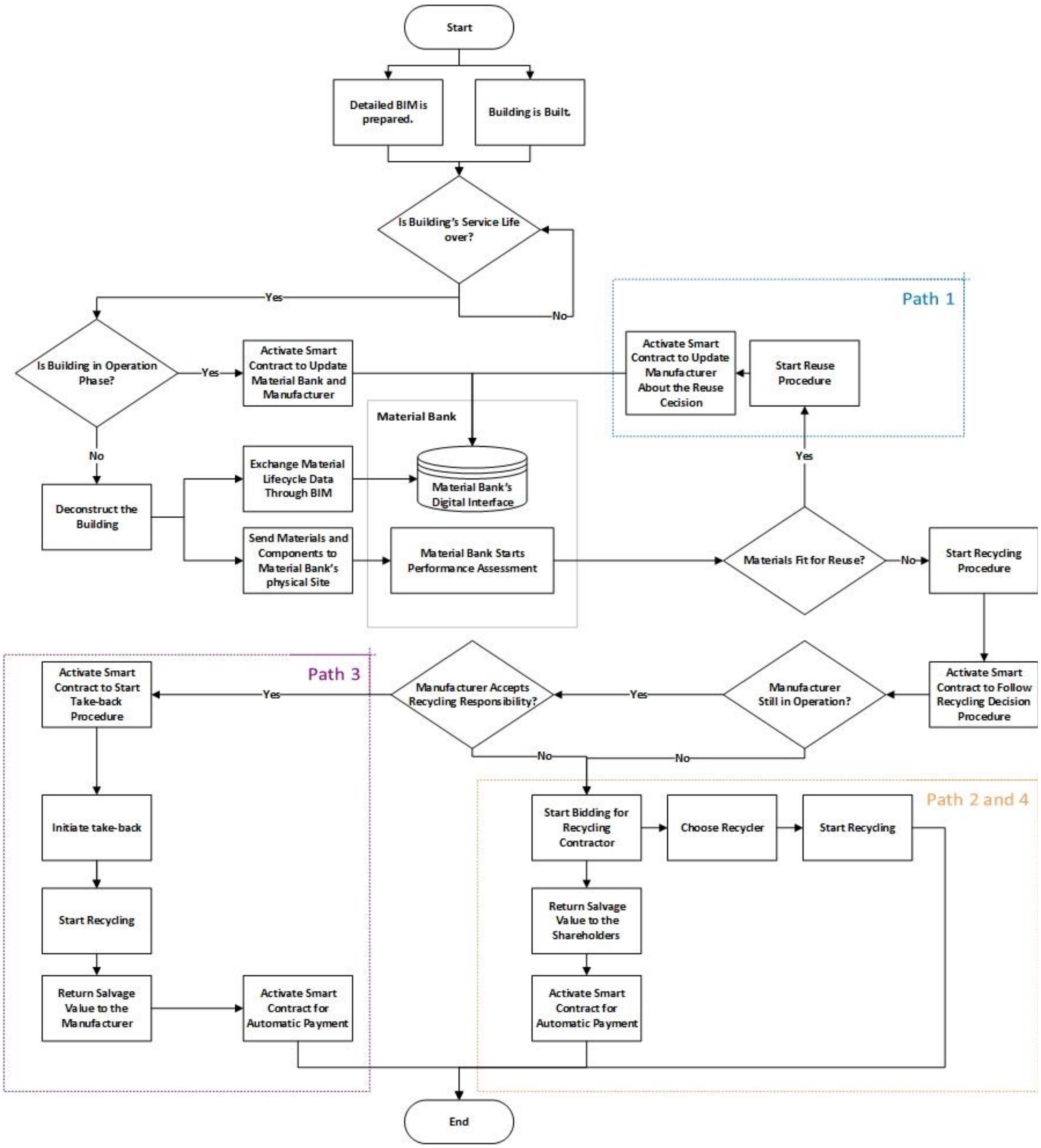

Figure 3 The Proposed Adaptive Conceptual Framework. This figure demonstrates the decisions and situations which activate various smart contracts. The process eventually end in the payment of salvage value to the right shareholders and recycling of the materials.

- At the end of the expected service life of a building, an automatic smart contract reminder will be activated. The status of the building will be enquired to check whether it will be deconstructed or will be in operation longer than the expected lifecycle if the regulations allow. In the latter case, a new expected service life will be estimated by the M/C Bank. The smart contract will be updated accordingly.

- In case of a hazardous natural or man-made accident (e.g., earthquake or fire), a smart contract will automatically report the accident to insurance companies and manufacturers. The M/C bank's database would be populated with this new information. If the building is no longer operational, the deconstruction can be performed before the end of the expected service life. Therefore, manufacturers can take in the recyclables earlier than anticipated. In this case, a new salvage price must be calculated, if any. This case poses new legal and economic questions that should be further studied.

- No stakeholder or manufacturer has the right to demand any monetary compensation for recyclables before the building is deconstructed. The same holds true in cases where the expected service life of a building is over, but the building is still in operation. Consequently, an agreement will be signed between parties as a requirement in the legal documentation and contracts to avoid this situation. This will be discussed further in the next section.

3.3.Part 3: Financial Transition

The World Economic Forum has anticipated that 10% of the global Gross Domestic Product (GDP) will be stored on blockchain technology by 2027. This would impact the global market as blockchain offers the ability to make everything a tradable asset, which could lead to a burst in tradable assets, novel blockchain-based services, and value exchanges, and finally, increased financial transition in emerging markets (World Economic Forum, 2015). Considering that the suggested framework can be technologically and economically feasible, two questions remain. One, how this framework can be integrated into the business-as-usual financial systems? Two, how can current financial and business models move towards an inclusive digital circular solution?

These questions can be addressed by creating a third part in this framework to enhance the suggested model's transition and flexibility. Before information is recorded in the blockchain, a requirement clause can be added to the actual contracts between manufacturers and building contractors. This requirement is consequently added to the contract between contractors and building owners and is known as Recycling Rights Requirements (RRR). The RRR states that the manufacturer will receive their sold products or materials in the future once the building is deconstructed. Furthermore, no claims can be made about the value of the materials as long as the building is in operation phase, or is owned by the owner even after the lifecycle is over. In the latter case, to eliminate the manufacturer's fear of never receiving the salvage value of the recyclable materials, the M/C Bank can regulate a smart contract trigger to release the salvage value to the manufacture's account if the building remains in the custody of its owner for twice as long as its expected (and stated) lifecycle without any occupants. It is a measure that must be taken to encourage manufacturers to join this financial schema and to support them from financial damage and to provide equal gaining opportunities.

To stimuli the market to adopt this suggested business model, the RRR must be easily tradeable. In other words, manufacturers can cash out the RRRs before waiting for the building to be deconstructed. The ownership of the RRR can change, but not the agreement. Therefore, the materials will remain in the closed-loop value chain. This would be an off-chain transaction that offers several advantages:

- Small-sized manufacturers or those with an urgent need for liquidity can benefit from this schema. Subsequently, the strongest players will not dominate the market.
- Manufacturers can trade the RRR for money whenever they want. Hence, a new natural or legal person could be assigned to receive the recyclables and the salvage value in the future.
- Manufacturers can trade the RRRs between themselves and exchange their recycling materials with each other or even with carbon credits.
- A new trade market of RRRs will spur further financial gains by introducing new jobs, roles, and business opportunities.

These financial requirements open up future research directions to see how such exchanges can be formulated and added to the Enterprise Resource Planning (ERP). Furthermore, this requirement can be stated in the Information Exchange Requirements (IER) and correspondingly in the BIM Execution Plan (BEP). The RRR is a transition mechanism for the linear economy towards the circular economy. They link the current financial and business agreements to the proposed framework for quick, non-discriminative adaption in the construction industry. Finally, no cycle is perfect. Thus, there could be pitfalls in the suggested schema that should be further investigated. Finally, in Figure 4, different aspects of the suggested framework are shown to demonstrate how the 3 layers of this framework. Different technologies and stakeholders are divided based on the material or value in the real and digital world.

Figure 4 The four different aspects of the suggested framework. The real-world materials are linked to their digital twins via BIM and M/C bank, while different monetary instruments are used to revalorise the recyclable CDW and secure producers' gains.

4. Discussion

The adoption of Blockchain technology in the construction industry requires technological maturity plus adaptable and sustainable business models. This requires a synergy between accounting, auditing, and the business side of the construction workflows with blockchain. The proposed framework is an example of how a new business model can tangibly contribute to a sustainable and circular built environment.

The salvage value (that will be paid to manufacturers in the future) can be paid in cryptocurrency or as fiat currency. An eco crypto-coin can be envisioned for this framework to regulate the time-value of money. This would be a challenging topic for future researchers to develop a cryptocurrency that adjusts the future value and present value debacles of assets. The future value of, e.g., steel, could be vastly different from its present value. That said, a regulated market of recyclable materials can stabilise the prices in the long-term due to higher transparency regarding the available amount of materials in supply and demand. Previous studies have shown that waste and recycling policies affect scrap prices. In return, price feedback determines the costs of waste and recycling policies (Kaffine, 2014). Therefore, a regulated and transparent recycling system with clear lines of responsibility of actors backed by self-executing smart contracts can significantly affect construction material recyclables' prices and policies.

Furthermore, it is possible to shift recycling responsibility to the original manufacturers of construction products and implement the EPR policy in the construction industry. A forward-looking recycling strategy, supported by tamper-proof data, makes the producers accountable and reduces the reported confusion in the EoL phase of buildings (Densley Tingley et al., 2017). Smart contracts can make the highly fragmented construction industry more united. The significance of this unification regarding the EoL phase of the building lies in the considerable time that passes between the construction phase and the deconstruction phase. Having lifecycle data stored in an incorruptible database will assure future construction actors that the data is accurate and safe to use.

Other industrial parties, such as steel mills, can directly join this framework. The steel industry has a large carbon footprint and governments try to control their emissions through carbon credits. New adaptive measures can be anticipated so that they can trade carbon credits with recyclables materials and tokens. There is a growing number of studies in the direction of carbon trade and blockchain (Hua and Sun, 2019; Khaqqi et al., 2018; Pan et al., 2019). For instance, an integration of smart contracts and carbon credits schema for carbon emission rights verification systems and carbon contracts is suggested by Kim and Huh (2020). Similarly, Hua and Sun (2019) proposed a carbon trade monetary incentive system for carbon reduction to realise tax neutralising without market interventions. The possibility of tax reduction for contractors and manufacturers based on the recyclability score of buildings that are linked to the proposed framework can be studied in the future. Joining the reusable material markets and carbon credit markets can fulfil the ambitions of the new European Green Deal in helping companies become leaders in green products and services while contributing to a sustainable and carbon-neutral economy (European Commission, 2019).

Other big industrial players, such as the Boeing Company, have invested in investigating the potentials of DLT integration with disassembly and recycling practices to tracking lifecycle information, bring transparency and stop fraud and forgery (Haig, 2020). To trace and track for aircraft spare parts for certification and inspection purposes, a blockchain-based data model is proposed by Ho et al. (2021). On that note, a blockchain-enabled recycling and reuse mechanism in the construction industry can be linked with other blockchain-enabled industries for the exchange of recyclables or spare parts. This could lead to a massive global marketplace for reusable components, especially for metals and alloys. This would foster creativity in design, transparency in transactions as well as new business opportunities. Considering the increasing interest in blockchain-based e-waste management systems, a link can be established between the metal scraps of the e-waste market and the construction metal market. In the same vein, if materials carry IoT or RFID tags, this framework could empower these connected objects to be linked to their financial records through blockchain-based connected record-keeping.

Furthermore, this framework is adaptive and could be applied to future space exploration scenarios and space colonies. Transparent and inclusive supply and demand would remove material sourcing monopoly in future space colony projects. It would also offer a trustable and third party-free way for different space companies to work and communicate with each other, standardly, in a circumstance where resources are scarce and expensive. The European Green Deal also supports the supply of sustainable and critical raw materials for clean technologies, digital, space and defence applications through a secure and competitive supply chain of both primary and secondary sources (European Commission, 2019).

Another adaptive future direction is to explore the possibility of long-term leasing, also known as Product-As-A-Service, (PAAS), of some reusable materials from the M/C Bank in order to proliferate their use in future construction. Leasing could reduce the prices for potential clients and will give the reusable materials a competitive advantage because of the sunk costs and depreciated prices compared to new materials.

4.1. Limitations and challenges

Previous studies agree that despite the benefits of blockchain, the construction industry's digital maturity level is not high enough to absorb and scale this technology fully. Therefore, at this moment, it is essential to be cautious about addressing all the issues through blockchain technology alone (Gopalakrishnan and Ramaguru, 2019). Only through the fusion of blockchain with other active research areas can the limitations and potentials of blockchain-based projects be revealed. Thus, the suggested framework has some limitations since it is one of the first salvage value and blockchain-based business models to our knowledge.

The first limitation is the suggestion of using salvage value in a not business-as-usual way in accounting. This is because manufacturers will receive profits in the distant future. Since the proposed adaptive framework suggests a new salvage value-based recycling bookkeeping system, it should be checked against the "Precautionary" principle. This principle provides a systematic tool to assess whether a new technology or activity is safe if it entails scientific uncertainty (European Union, 2017). All the EU environmental policies are checked against the Precautionary principle. Hence, policymakers who work on new regulations to incorporate long-term blockchain-based environmental frameworks should consider this principle.

More importantly, from the accounting perspective, the possibility of using salvage value in long-term bookkeeping must be checked against the "Prudence" principle (Măciucă et al., 2015). Adherence to this principle ensures that recyclables' real values based on the suggested framework do not interfere with the manufacturers' or clients' accounting reports as it might risk overvaluing assets or understating losses. These are new cross-disciplinary research avenues that future studies can pursue.

A significant controversy regarding the use of blockchain for sustainable projects is its heavy energy consumption. Chenli et al. (2019) believed that energy waste reduces the value of the blockchain and can hinder its progress if not adequately addressed. Hence, the following questions are worth contemplating to delineate the irrevocable limitations of blockchain in the context of the suggested framework. Do the energy and cost of maintaining the whole lifecycle building data (at all, if immutable) in a blockchain network offset the future value of the lifecycle data? Should data be selected and then stored for long-term applications in order to avoid the proliferation of database centres and blockchain rig farms?

There is no definite answer to whether the blockchain is sustainable. Scientific literature shows that researchers are both optimistic and pessimistic about a future with blockchain technology. For instance, while Howson (2019) believed that blockchain is not sustainable, at least now, Vranken (2017) argued otherwise. To maintain the blockchain networks that run with PoW or PoS mechanisms, miners must conduct intensive computations that require considerable amounts of energy. The latest generations of mining hardware and rigs are reportedly more energy-efficient (Vranken, 2017). However, Mora et al. (2018) estimated that keeping the Bitcoin network alone might raise the global temperature by 2 °C by 2050. The newly introduced blockchain networks use, reportedly, less energy-intensive validation protocols. Furthermore, there are active research projects concerning multi-purpose and less energy-intensive consensus mechanisms to overcome the energy-intensiveness drawback (Chenli et al., 2019). Nevertheless, the sustainable inefficiency of the main blockchain networks should not discourage researchers from exploring the idea of blockchain-based green incentives/investments (Howson, 2019).

5. Conclusions

This paper proposed a framework for creating a digital take-back system for recyclable construction materials where all parties receive financial gains through smart and connected accounting. This framework is built on three pillars, technological core, accounting base and financial transition instruments. BIM, blockchain, smart contracts and BIM-complaint material banks are the technologies where this model is established upon. The EoL responsibilities and rewards are coded into a blockchain network through smart contacts, while their respective lifecycle information is modelled and managed through the integration of BIM and material banks. The accounting base produces new revenue cycles for the participants of the take-back system and revalorises the CDW and recyclables. The producers take back their recyclable products once they are disassembled without any additional costs. They will also receive the salvage value of the products that was subtracted from their bookkeeping when they sold the product to a client. Since the salvage value is recorded in the system and the manufacturer anticipates it in the future, the client would buy the product at a lower price. Thus, this would make a win-win-win solution for producers, consumers, and the environment. With the uptake of this model, construction products are better managed and treated. As a result, recycling efficiency, in terms of quantity and workflows, will be improved and automated. Since this framework suggests three types of business transitions, i.e., circular, digitalised, blockchain-based, a financial transition action plan is also anticipated. Hence, this schema's inclusive and adaptive nature makes the transition from linear to circular and digital economic markets easy. As such, the ownership and EoL treatment responsibility rights of the materials, i.e., Recycling Rights Requirements (RRR), should be available for exchange and trade off-chain or outside of the digital world. This framework follows the Extended Producer Responsibility (EPR) policy's principles and, in fact, could propel the implementation of EPR in the construction sector.

This model offers several benefits, including the connection of recyclable or reusable construction material markets with the spare parts market of other industries. Similarly, if recyclable products are treated as valuable assets, they can be exchanged with other valuable assets or even carbon credits. Consequently, ownership rights and RRR can be traded in the market. As companies' ecological ethics can be traced through their contribution to the suggested framework, reputation rewards, tax reductions, or other financial amnesties can be given to companies.

One of the future research possibilities delineated in this study was the development of a cryptocurrency to adjust the future value and present value of assets to reduce the risks and market fear of joining long-term green investments. This could also proliferate PAAS business models in the construction industry, as most elements are used for at least 50 years in a building. Furthermore, off-chain material RRRs in this framework need integration with regular BIM-based construction agreements. Therefore, provisions must be made to include recyclable materials' EoL treatment and exchange requirements in the IER and BEP documents. This study demonstrates that for an efficient take-back system in the construction industry, more work should be done in the calculation of the salvage value of recyclable materials under different assumptions.

Overall, this framework conceptualises a blockchain-based implementation of the financial and material take-back system in the construction industry with the currently available technologies in order to pave the way for a smooth transition towards a circular and sustainable construction industry.

6. Declaration of Competing Interest

The authors declare no potential conflicting interests.

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8. Author Contributions:

Arghavan Akbarieh: Conceptualization, Investigation, Writing- Original draft preparation. William Carbone: Writing- Reviewing and Editing. Markus Schäfer: Writing- Reviewing and Editing. Danièle Waldmann: Funding acquisition, Writing- Reviewing and Editing. Felix Norman Teferle: Supervision, Writing- Reviewing and Editing.

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