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

36   the threats and opportunities as well as weaknesses and strengths of the proposed framework
37   together with its potential to integrate with existing solutions conclude this study.
38

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

41

> **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.

42

1. Introduction

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

64 for the need for updated economic policies to catch up with the new revenue streams coming
65 from the synergies of disruptive technologies, such as blockchain, in the uncharted phase of the
66 building lifecycle, i.e., End-of-Lifecycle (EoL).

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

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

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

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

77 A framework is suggested to address these questions. The proposed framework is a digital,
78 sustainable and circular solution that offers manifold benefits that are in line with the other
79 advantages of CE, such as higher optimisation, eco-efficiency, eco-effectiveness, and waste
80 reduction, as well as more reuse and recycling (Kalmykova et al., 2018). Moreover, this solution
81 follows the existing policies such as Extended Producer Responsibility (EPR) that is actively
82 implemented in different waste categories.
83 The rest of this paper is organised as follows. Section 2 presents the theoretical background
84 concerning the key terms, concepts, and technologies used in developing this study, and looks at
85 other blockchain-based models in the literature. Section 3 describes the proposed Blockchain-
86 based model. Section 4 discusses further points regarding the suggested framework and explains
87 some limitations or future research avenues. Finally, Section 5 concludes the paper.

2. Background: key terms and concepts

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

2.1. Blockchain Technology

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

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

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

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

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

132 A more comprehensive description of blockchain can be found in the existing academic literature
133 reviews (Casino et al., 2019; Kitsantas et al., 2019; Liu et al., 2020; Xu et al., 2019). Blockchain
134 technology is studied in terms of cryptography, consensus mechanisms, tokens, smart contracts,
135 financial instruments, individual identity, marketplaces and supply chain potentials. The
136 experimental applications of blockchain technology are investigated in various contexts, from
137 money laundering (Moser et al., 2013), to human resource information management (Wang et al.,

138 2017), within the aerospace and automobile industries (Kar et al., 2019; Zhao et al., 2018) and with
139 respect to different supply chains (Boison and Antwi-Boampong, 2019; Saberi et al., 2019; Wang,
140 2019). Furthermore, blockchain technology's impact on business models is studied by Weking et
141 al. (2019).

142 **2.2. Smart Contracts**

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

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

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

160 Over time, there has been an extensive literature developed around smart contracts (Zheng et al.,
161 2020). This topic is comprehensively reviewed by Ante (2020), where future directions of this
162 technology are delineated that include disruption of existing processes through decentralised
163 business models, ecosystems and markets. Within the construction industry, Li et al. (2019)
164 reviewed blockchain and smart contract's chances and challenges. Many multidisciplinary
165 studies concerning the digital construction processes and products, including the present work,
166 have relied on the benefits of smart contracts more than other blockchain characteristics. Li et al.
167 (2020) proposed a smart contract-based framework for the semi-automated maintenance and
168 repairs of built assets for increased traceability of materials throughout the lifecycle. Likewise,
169 Wang et al. (2020) developed the blockchain-based information management framework for a
170 precast supply chain (BIMF-PSC), in which smart contracts (chaincodes) auto-regulate the
171 information traceability and sharing between project participants for real-time control of pre-case
172 scheduling. Fitriawijaya et al. (2019) conceptualised a supply chain model with a decentralised
173 blockchain-based Common Data Environment (CDE) in which smart contracts trace and
174 authenticate the movement of objects from suppliers, to contractors, to clients. A similar study
175 was conducted by Shojaei et al. (2019), where smart contracts track the purchase, shipment, on-
176 site reception and construction steps in the steel supply chain.

How Blockchain Works?

a)

b)

c)

How Smart Contracts Work?

c)

177
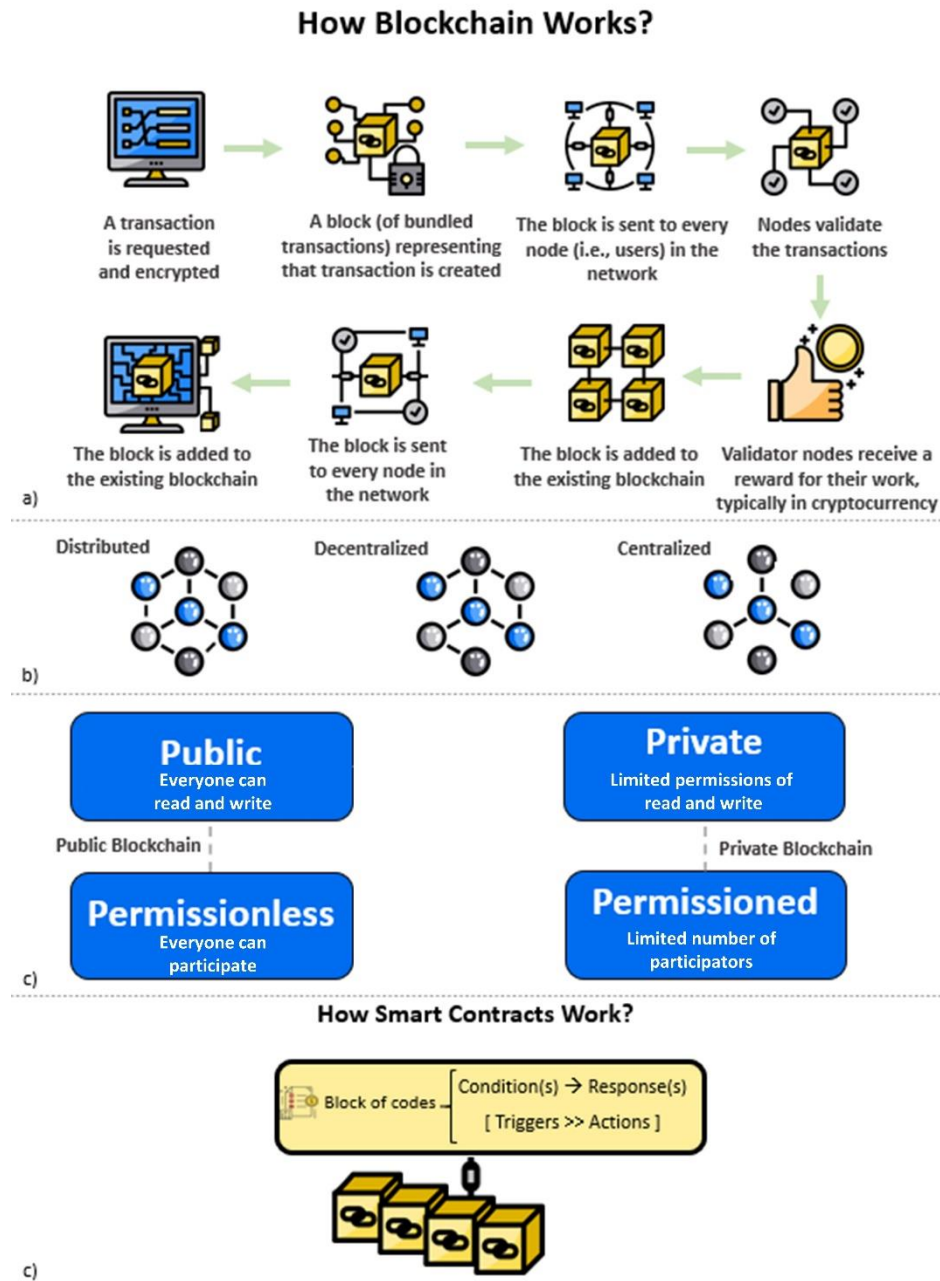
178   Figure 1 The different aspects of blockchain technology. a) A schemata of how a blockchain network
179   functions. b) the comparison between different types of networks. c) The difference between network
180   trust and anonymity levels that lead to the public, private, permission and permissionless networks. d)
181   The mechanism of the smart contracts in a blockchain network

182   **2.3. Building Information Modelling (BIM)**

183   BIM is a methodology to create a digital and object-oriented representation of a built asset where
184   three-dimensional measurements, as well as other building information, are modelled together
185   as illustrated by Figure 2.a. The output model of this methodology is called BIM or BIModel. All

186 the information related to a building can be modelled, stored, and queried through a BIM.
187 Therefore, this model provides a data platform for which other technologies can plug in and reuse
188 the building information (Sacks et al., 2018).

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

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

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

226 **2.4. The Material and Component Bank (M/C Bank)**

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

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

256 In the scientific literature, blockchain and BIM are discussed from the design phase to the
257 construction and then operation phases. However, among studies that have been conducted by
258 many authors, an EoL phase-specific solution that interoperates with all these digital technologies
259 is still insufficiently explored. Ganter and Lützkendorf (2019) briefly mentioned the potentials of
260 blockchain for lifecycle management, deconstruction and reconstruction. While Cao and Fang
261 (2019) suggested future research on the collation of suppliers and assemblers in a supply chain to
262 reduce the supply chain risk due to supply uncertainty. Wang (2019) studied the reaction of
263 construction actors to smart contract-based supply chain models and the subsequent business
264 impacts. Furthermore, Yadav and Singh (2020) identified major causes of a successful integration
265 of blockchain information technology with sustainable supply chains operations, namely data

266 safety and decentralisation, accessibility, laws and policy, documentation, data management, and
267 quality.

268
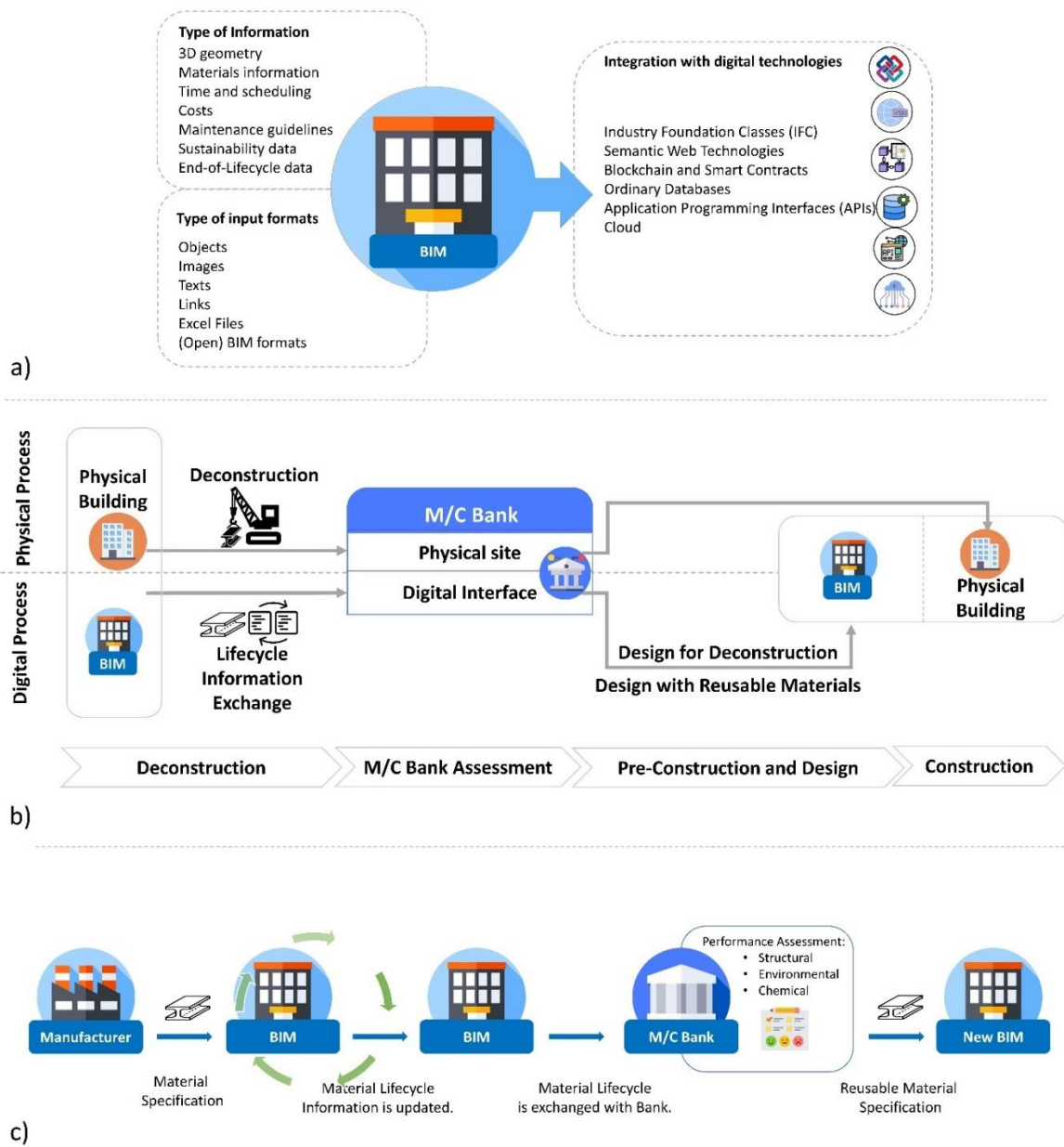
269 Figure 2 BIM and Material Bank. a) BIM as a Data Lake to prepare construction information interoperable
270 with other digital technologies to construction data, b) Detailed material and lifecycle information flow in
271 two parallel processes involving BIM and M/C Bank, c) 3 The mechanism of BIM and M/C Bank
272 interaction for circular reuse of materials and components.

273 **2.5. Recycling, Reuse, Waste and Blockchain**

274 The application of blockchain for natural resources, conservation, recycling and waste
275 management that has been explored and categorized in prior studies (Gopalakrishnan and
276 Ramaguru, 2019; Saberi et al., 2018). An automated Blockchain and IoT-based waste management

277 model to track, categorise and transfer waste for making smart decisions about the recycling
278 process was proposed by Latif et al. (2019). Gupta and Bedi (2018) suggested similar concepts for
279 e-waste. In order to create information symmetry and transparency between regulators,
280 consumers, producers, transportation and treatment companies for the management of
281 hazardous wastes, a framework is suggested (Song, 2021). Researchers in the project "Recycling
282 4.0" studied the possible integration of recycling materials with databases and blockchain
283 (Kreutzmann et al., 2019). Schmelz et al. (2019) suggested a blockchain-enabled schema for trans-
284 border waste tracking followed by an audit. Subsequently, the audit-critical information is stored
285 on the blockchain to be accessible, transparent and simultaneously immutable. With this
286 architecture, it is possible to audit waste flows without compromising data privacy. Other studies
287 inspected the data quality in blockchain-based recycling marketplaces (Lawrenz et al., 2019). Loss
288 of data during the whole product lifecycle is a critical issue in the recycling industry. According
289 to Knieke et al. (2019), loss of valuable data in complex lifetime chains originates from degraded
290 products and less well-tracked post-consumer waste. Subsequently, product deletion is reported
291 as an impactful decision in losing product lifecycle information (Kouhizadeh et al., 2019a). By
292 employing blockchain, one can either track and remove the goods with poor circularity from the
293 supply chains or look back and track the life cycle information of goods that no longer exist in the
294 market.

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

305 ## 3. The Proposed Conceptual Framework

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

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

321   3.1. Part 1: Technological Core

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

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

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

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

346   3.2. Part 2: Accounting Base

347   This section addresses a blockchain-based accounting strategy for the uptake of the proposed
348   material take-back framework. This is a novelty of this study since it suggests a new look at the
349   current accounting practices. In (Desplebin et al., 2021), multiple evolutionary directions of
350   accounting practices under the impact of blockchain technology is studied. Innovative
351   Blockchain-based invoicing and payments, trace and tracking of the origin and history of

352 purchases and operation, as well as transformation in the record-keeping tasks are in the outlook
353 of smart and connected accounting.

354 The fundamental questions are: why should manufacturers agree to join such a long-term take-
355 back schema if there are no financial gains? What are the advantages of this framework over the
356 business as usual practices? It is widely accepted that by tying the waste and recyclable materials
357 to an anticipated sum of money, we are giving them tangible value (Katz, 2019). Revalorising the
358 recycling materials can significantly benefit the circular built environment as it fosters
359 transparency in the supply chain and prevents unregulated EoL treatments. Value creation in a
360 sustainable supply chain is indeed another advantage of blockchain technology (Rejeb and Rejeb,
361 2020).

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

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

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

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

388 In the first scenario, the manufacturer does not accept the responsibility of recycling the
389 recyclables after the building deconstruction (path number 2 in Figure 3). In this case, the M/C

390   bank will take responsibility for recycling. Either a new smart contract will be invoked to start a
391   bidding process for recyclers, or the materials will be available in an e-marketplace. In the latter
392   case, further smart contract clauses could be coded for micropayments. However, this topic is
393   beyond the scope of this research. Nevertheless, another smart contract will be activated in
394   parallel to return the salvage value to the shareholders of the dissolved company. This is where
395   the immutability, traceability and security of blockchain demonstrate its powers. The necessary
396   information of the shareholders is recorded and periodically updated in the network. Thus, it
397   would be possible that smart contracts automatically return the profits of the salvage value to the
398   company's shareholders (or their next of kin, since the deconstruction is performed in the future).
399   Any change in the details of shareholders can be automatically updated in the blockchain upon
400   their request. This security could increase investment in long-term eco-sourced materials.

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

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

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

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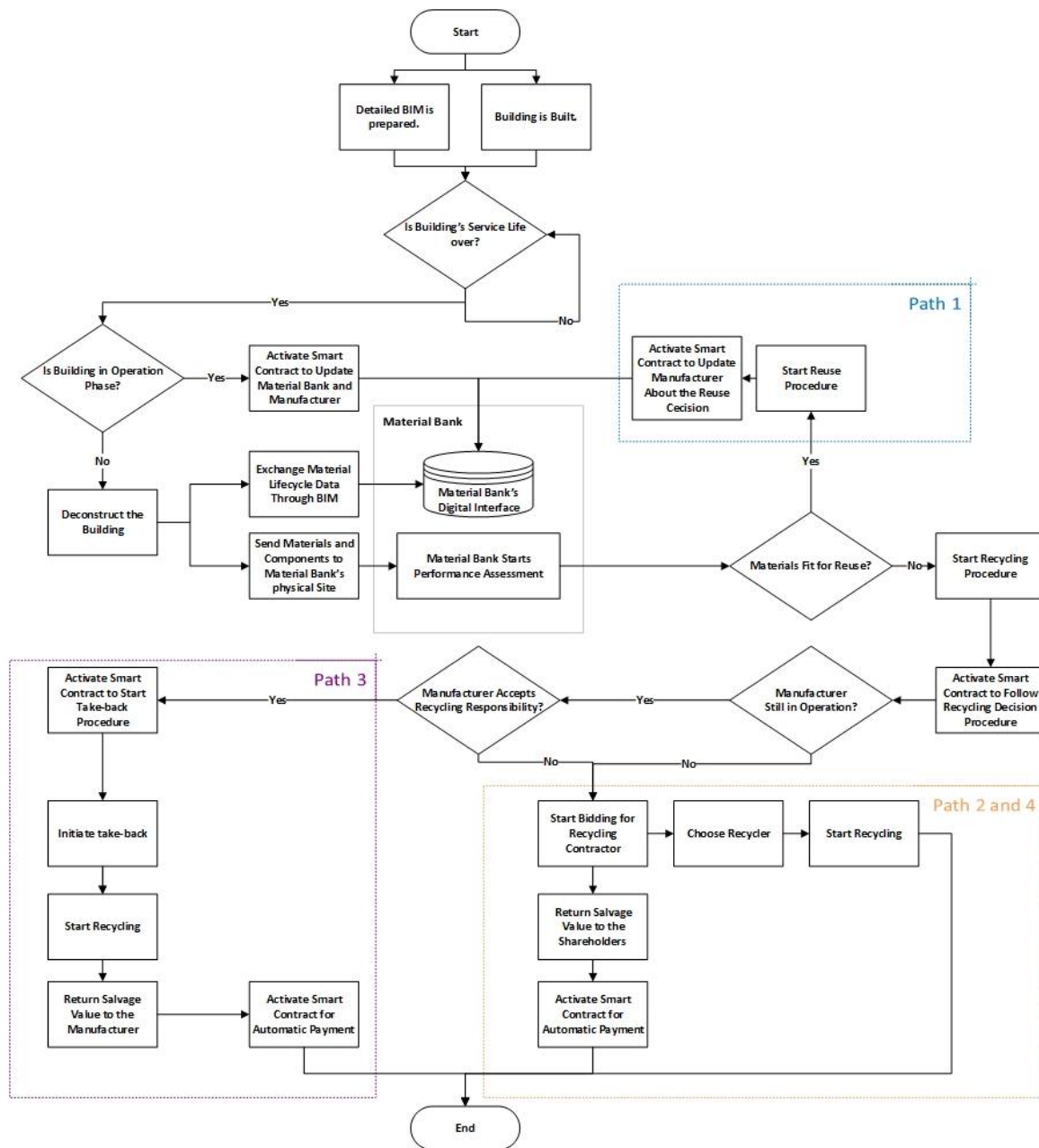427   smart contract triggers are elaborated:

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.

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

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

440 ▪ No stakeholder or manufacturer has the right to demand any monetary compensation for
441   recyclables before the building is deconstructed. The same holds true in cases where the
442   expected service life of a building is over, but the building is still in operation.
443   Consequently, an agreement will be signed between parties as a requirement in the legal
444   documentation and contracts to avoid this situation. This will be discussed further in the
445   next section.
446

447 **3.3. Part 3: Financial Transition**

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

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

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

476 ▪ Small-sized manufacturers or those with an urgent need for liquidity can benefit from this
477 schema. Subsequently, the strongest players will not dominate the market.

478 ▪ Manufacturers can trade the RRR for money whenever they want. Hence, a new natural
479 or legal person could be assigned to receive the recyclables and the salvage value in the
480 future.

481 ▪ Manufacturers can trade the RRRs between themselves and exchange their recycling
482 materials with each other or even with carbon credits.

483 ▪ A new trade market of RRRs will spur further financial gains by introducing new jobs,
484 roles, and business opportunities.

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

495

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

499   **4. Discussion**

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

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

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

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

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

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

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

565 **4.1. Limitations and challenges**

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

573 The first limitation is the suggestion of using salvage value in a not business-as-usual way in
574 accounting. This is because manufacturers will receive profits in the distant future. Since the
575 proposed adaptive framework suggests a new salvage value-based recycling bookkeeping
576 system, it should be checked against the "Precautionary" principle. This principle provides a
577 systematic tool to assess whether a new technology or activity is safe if it entails scientific

578   uncertainty (European Union, 2017). All the EU environmental policies are checked against the
579   Precautionary principle. Hence, policymakers who work on new regulations to incorporate
580   long-term blockchain-based environmental frameworks should consider this principle.

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

587   A significant controversy regarding the use of blockchain for sustainable projects is its heavy
588   energy consumption. Chenli et al. (2019) believed that energy waste reduces the value of the
589   blockchain and can hinder its progress if not adequately addressed. Hence, the following
590   questions are worth contemplating to delineate the irrevocable limitations of blockchain in the
591   context of the suggested framework. Do the energy and cost of maintaining the whole lifecycle
592   building data (at all, if immutable) in a blockchain network offset the future value of the lifecycle
593   data? Should data be selected and then stored for long-term applications in order to avoid the
594   proliferation of database centres and blockchain rig farms?
595

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

609   **5. Conclusions**

610   This paper proposed a framework for creating a digital take-back system for recyclable
611   construction materials where all parties receive financial gains through smart and connected
612   accounting. This framework is built on three pillars, technological core, accounting base and
613   financial transition instruments. BIM, blockchain, smart contracts and BIM-complaint material
614   banks are the technologies where this model is established upon. The EoL responsibilities and
615   rewards are coded into a blockchain network through smart contacts, while their respective

616 lifecycle information is modelled and managed through the integration of BIM and material
617 banks. The accounting base produces new revenue cycles for the participants of the take-back
618 system and revalorises the CDW and recyclables. The producers take back their recyclable
619 products once they are disassembled without any additional costs. They will also receive the
620 salvage value of the products that was subtracted from their bookkeeping when they sold the
621 product to a client. Since the salvage value is recorded in the system and the manufacturer
622 anticipates it in the future, the client would buy the product at a lower price. Thus, this would
623 make a win-win-win solution for producers, consumers, and the environment. With the uptake
624 of this model, construction products are better managed and treated. As a result, recycling
625 efficiency, in terms of quantity and workflows, will be improved and automated. Since this
626 framework suggests three types of business transitions, i.e., circular, digitalised, blockchain-
627 based, a financial transition action plan is also anticipated. Hence, this schema's inclusive and
628 adaptive nature makes the transition from linear to circular and digital economic markets easy.
629 As such, the ownership and EoL treatment responsibility rights of the materials, i.e., Recycling
630 Rights Requirements (RRR), should be available for exchange and trade off-chain or outside of
631 the digital world. This framework follows the Extended Producer Responsibility (EPR) policy's
632 principles and, in fact, could propel the implementation of EPR in the construction sector.

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

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

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

653

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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