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# 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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## ► To cite this version:

Arghavan Akbarieh, William Carbone, Markus Schäfer, Danièle Waldmann, Felix Norman Teferle. 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. 2022. hal-03496635

**HAL Id: hal-03496635**

**<https://hal.science/hal-03496635v1>**

Preprint submitted on 4 Jan 2022

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

5  
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16           **Abstract:**

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

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

30           On the one hand, the value of recyclables is captured through salvage value based on  
31           accounting methods. Smart contracts administer the physical material transfer for recycling  
32           while automating the monetary value transactions between stakeholders. On the other hand,  
33           a financial instrument is proposed to link the on-chain captured value to the off-chain  
34           financial practices through the Recycling Requirement Rights. The right holders are  
35           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

43 **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.

## 88 **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.

### 93 **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).

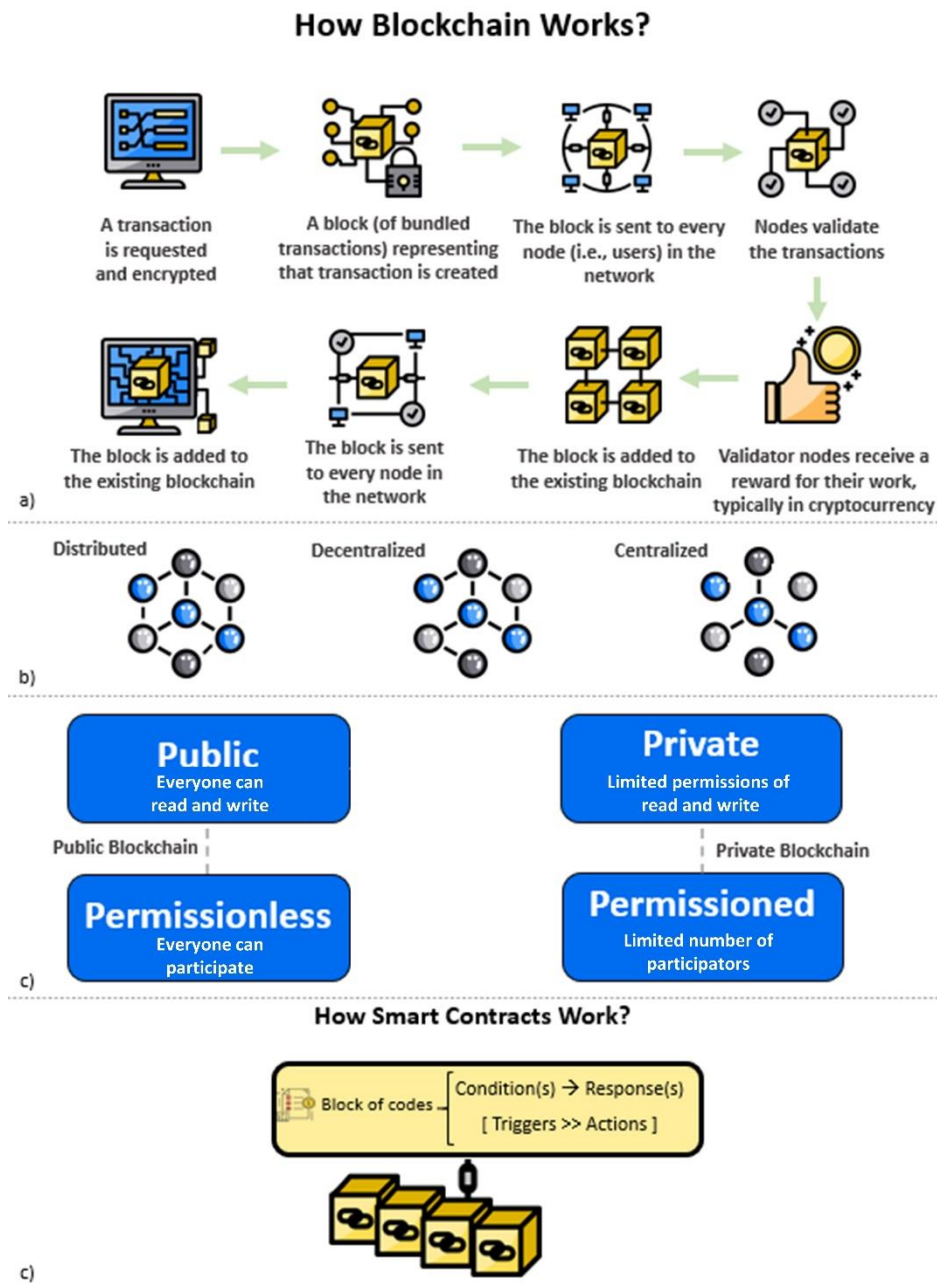
## 142 **2.2. Smart Contracts**

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.



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.



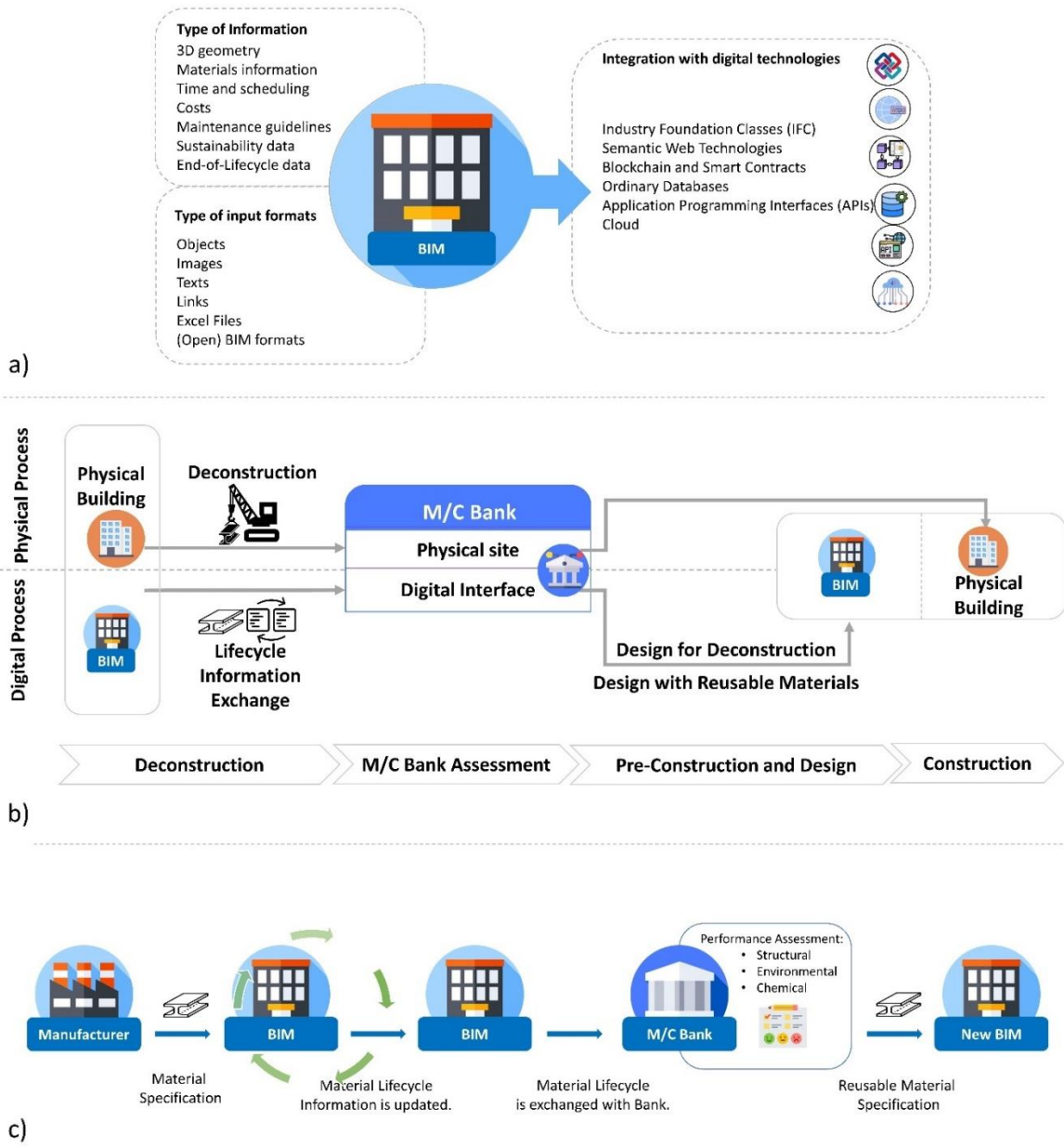
## 226        2.4. The Material and Component Bank (M/C Bank)

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 (Saberli 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:

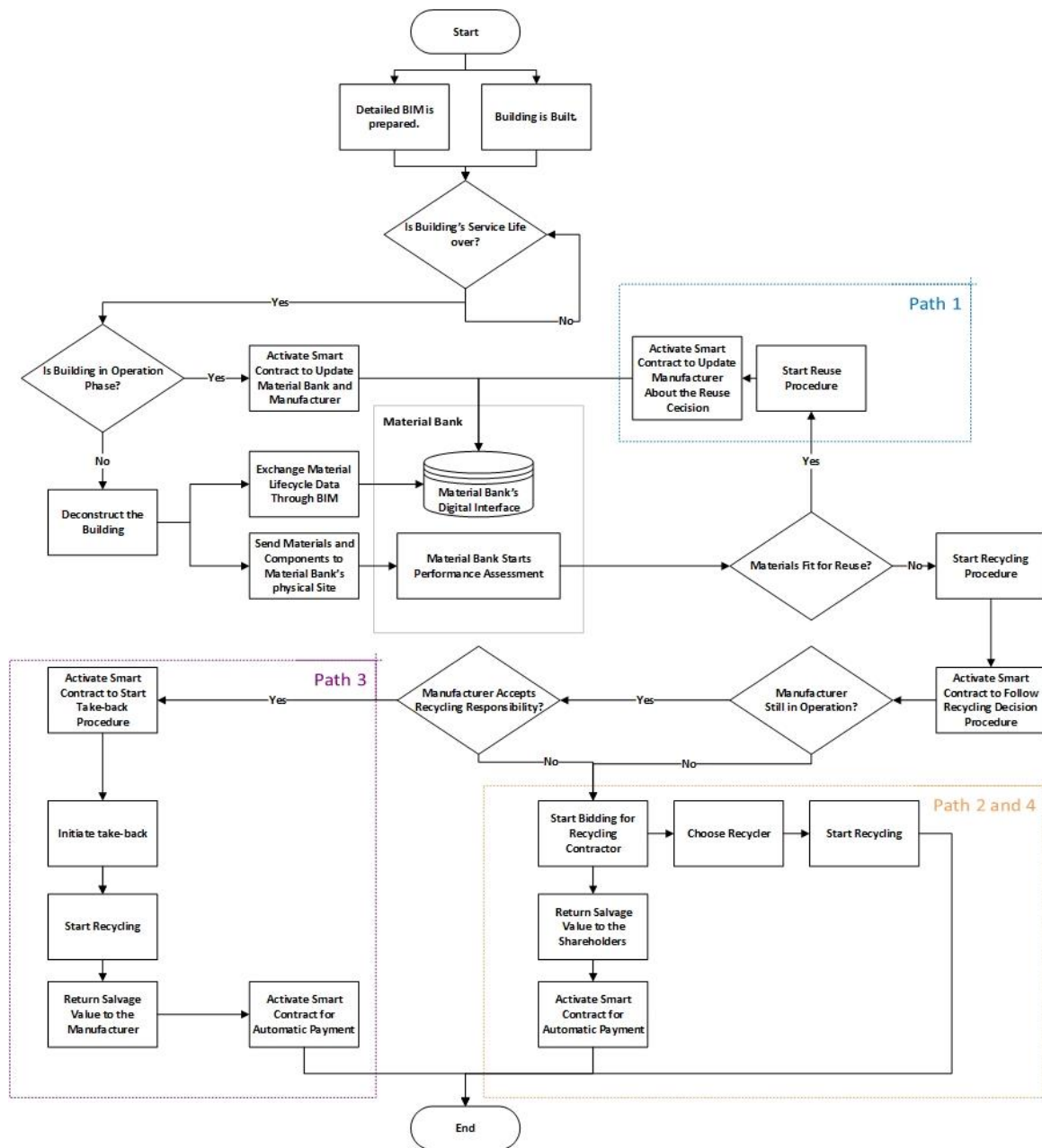


Figure 3 The Proposed Adaptive Conceptual Framework. This figure demonstrates the decisions and situations which activate various smart contracts. The process eventually end in the payment of salvage value to the right shareholders and recycling of the materials.

428  
429  
430  
431  
432

- 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.

- 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

## 654        **6. Declaration of Competing Interest**

655        The authors declare no potential conflicting interests.

## 656        **7. Acknowledgements**

657        This study was carried out by the sixth work-package of the Eco-Construction for Sustainable  
658        Development (ECON4SD) project at the University of Luxembourg. This project has received  
659        funding from Investissement pour la Croissance et l'emploi—European Regional Development  
660        Fund (2014-2020) under the grant agreement 2017-02-015-15.

661        The authors also would like to thank Ms Sabina Craciunescu for offering their expertise and  
662        constructive comments to help with this project.

## 663        **8. Author Contributions:**

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

## 668        **9. References**

- 669        Ablyazov, T., Petrov, I., 2019. Influence of blockchain on development of interaction system of investment and  
670        construction activity participants. Presented at the IOP Conference Series: Materials Science and Engineering.  
671        <https://doi.org/10.1088/1757-899X/497/1/012001>
- 672        Akbarieh, A., Carbone, W., Schäfer, M., Waldmann, D., Teferle, F.N., 2020a. Extended Producer Responsibility in the  
673        Construction Sector through Blockchain, BIM and Smart Contract Technologies, in: Proceedings of the 2020  
674        World Congress on Sustainable Technologies (WCST-2020). Presented at World Congress on Sustainable  
675        Technologies (WCST-2020), Infonomics Society, London; United Kingdom.  
676        <https://doi.org/10.20533/WCST.2020.0004>
- 677        Akbarieh, A., Jayasinghe, L.B., Waldmann, D., Teferle, F.N., 2020b. BIM-Based End-of-Lifecycle Decision Making and  
678        Digital Deconstruction: Literature Review. Sustainability 12, 2670. <https://doi.org/10.3390/su12072670>
- 679        Akbarnezhad, A., Ong, K.C.G., Chandra, L.R., 2014. Economic and environmental assessment of deconstruction  
680        strategies using building information modeling. Autom. Constr. 37, 131–144.  
681        <https://doi.org/10.1016/j.autcon.2013.10.017>
- 682        Aleksandrova, E., Vinogradova, V., Tokunova, G., 2019. Integration of digital technologies in the field of construction  
683        in the Russian Federation. Eng. Manag. Prod. Serv. 11, 38–47. <https://doi.org/10.2478/emj-2019-0019>
- 684        Ante, L., 2020. Smart contracts on the blockchain – A bibliometric analysis and review. Telemat. Inform. 101519.  
685        <https://doi.org/10.1016/j.tele.2020.101519>
- 686        Bodkhe, U., Mehta, D., Tanwar, S., Bhattacharya, P., Singh, P., Hong, W.-C., 2020. A Survey on Decentralized Consensus  
687        Mechanisms for Cyber Physical Systems. IEEE Access. <https://doi.org/10.1109/ACCESS.2020.2981415>
- 688        Boison, D.K., Antwi-Boampong, A., 2019. Blockchain Ready Port Supply Chain Using Distributed Ledger.  
689        NBICTbrInnovation Regul. Multi Bus. Model Innov. Technol. 1–32–1–32. <https://doi.org/10.13052/nbjict1902-097X.2020.001>
- 690        Bukunova, O.V., Bukunov, A.S., 2019. Tools of Data Transmission at Building Information Modeling, in: 2019  
691        International Science and Technology Conference "EastConf." pp. 1–6.  
692        <https://doi.org/10.1109/EastConf.2019.8725373>
- 693        Cai, G., Waldmann, D., 2019. A material and component bank to facilitate material recycling and component reuse for  
694        a sustainable construction: concept and preliminary study. Clean Technol. Environ. Policy 21, 2015–2032.  
695        <https://doi.org/10.1007/s10098-019-01758-1>
- 696

- 697 Cao, X., Fang, X., 2019. Component Procurement for an Assembly Supply Chain with Random Capacities and Random  
698 Demand. *Decis. Sci.* 50, 1259–1280. <https://doi.org/10.1111/dec.12371>
- 699 Casino, F., Dasaklis, T.K., Patsakis, C., 2019. A systematic literature review of blockchain-based applications: Current  
700 status, classification and open issues. *Telemat. Inform.* 36, 55–81. <https://doi.org/10.1016/j.tele.2018.11.006>
- 701 Chenli, C., Li, B., Shi, Y., Jung, T., 2019. Energy-recycling Blockchain with Proof-of-Deep-Learning, in: ICBC 2019 - IEEE  
702 International Conference on Blockchain and Cryptocurrency. Institute of Electrical and Electronics Engineers  
703 Inc., pp. 19–23. <https://doi.org/10.1109/BLOC.2019.8751419>
- 704 Clack, C., Bakshi, V., Braine, L., 2016. Smart Contract Templates: essential requirements and design options, C.D. Clack,  
705 V.A. Bakshi and L. Braine. arxiv:1612.04496. 2016.
- 706 Clack, C., Bakshi, V.A., Braine, L., 2016. Smart Contract Templates: foundations, design landscape and research  
707 directions.
- 708 Densley Tingley, D., Cooper, S., Cullen, J., 2017. Understanding and overcoming the barriers to structural steel reuse,  
709 a UK perspective. *J. Clean. Prod.* 148, 642–652. <https://doi.org/10.1016/j.jclepro.2017.02.006>
- 710 Desplebin, O., Lux, G., Petit, N., 2021. To Be or Not to Be: Blockchain and the Future of Accounting and Auditing\*.  
711 *Account. Perspect.* <https://doi.org/10.1111/1911-3838.12265>
- 712 European Commission, 2019. Communication from the Commission to the European Parliament, the European  
713 Council, the Council, the European Economic and Social Committee and the Committee of the Regions - the  
714 European Green Deal (No. COM(2019) 640 final). Brussels.
- 715 European Union, 2017. The precautionary principle : decision-making under uncertainty. (Website). Publications Office  
716 of the European Union, Luxembourg: Publications Office of the European Union.
- 717 European Union, 2002. EN 1990 Eurocode - Basis of structural design.
- 718 Fitriawijaya, A., Hsin-Hsuan, T., Taysheng, J., 2019. A blockchain approach to supply chain management in a BIM-  
719 enabled environment. Presented at the Intelligent and Informed - Proceedings of the 24th International  
720 Conference on Computer-Aided Architectural Design Research in Asia, CAADRIA 2019, pp. 411–420.
- 721 Ethereum.org. 2021. Home | ethereum.org. [online] Available at: <<https://ethereum.org/en/>> [Accessed 10 October  
722 2021].
- 723 Ganter, M., Lützkendorf, T., 2019. Information management throughout the life cycle of buildings - Basics and new  
724 approaches such as blockchain, in: Passer A., M.M., Lutzkendorf T., Habert G., Kromp-Kolb H. (Ed.), IOP  
725 Conference Series: Earth and Environmental Science. Institute of Physics Publishing,  
726 <https://doi.org/10.1088/1755-1315/323/1/012110>
- 727 Gopalakrishnan, P., Ramaguru, R., 2019. Blockchain based waste management. *Int. J. Eng. Adv. Technol.* 8, 2632–2635.
- 728 Gupta, N., Bedi, P., 2018. E-waste Management Using Blockchain based Smart Contracts, in: 2018 International  
729 Conference on Advances in Computing, Communications and Informatics, ICACCI 2018. Institute of  
730 Electrical and Electronics Engineers Inc., pp. 915–921. <https://doi.org/10.1109/ICACCI.2018.8554912>
- 731 Haig, S., 2020. Boeing Uses Blockchain to Track and Sell \$1 Billion in Aerospace Parts [WWW Document].  
732 Cointelegraph. URL [https://cointelegraph.com/news/boeing-uses-blockchain-to-track-and-sell-1-billion-in-](https://cointelegraph.com/news/boeing-uses-blockchain-to-track-and-sell-1-billion-in-aerospace-parts)  
733 [aerospace-parts](https://cointelegraph.com/news/boeing-uses-blockchain-to-track-and-sell-1-billion-in-aerospace-parts) (accessed 5.23.20).
- 734 Hijazi, A., Perera, S., Alashwal, A., Calheiros, R., 2019. Enabling a Single Source of Truth Through BIM and Blockchain  
735 Integration, in: Proceedings of the 2019 International Conference on Innovation, Technology, Enterprise and  
736 Entrepreneurship (ICITEE 2019). Presented at the International Conference on Innovation, Technology,  
737 Enterprise and Entrepreneurship, Applied Science University, Bahrain.
- 738 Howson, P., 2019. Tackling climate change with blockchain. *Nat. Clim. Change* 9, 567. [https://doi.org/10.1038/s41558-](https://doi.org/10.1038/s41558-019-0567-9)  
739 [019-0567-9](https://doi.org/10.1038/s41558-019-0567-9)
- 740 Hua, W., Sun, H., 2019. A Blockchain-Based Peer-to-Peer Trading Scheme Coupling Energy and Carbon Markets, in:  
741 2019 International Conference on Smart Energy Systems and Technologies (SEST). pp. 1–6.  
742 <https://doi.org/10.1109/SEST.2019.8849111>
- 743 Hunhevicz, J.J., Hall, D.M., 2020. Do you need a blockchain in construction? Use case categories and decision  
744 framework for DLT design options. *Adv. Eng. Inform.* 45. <https://doi.org/10.1016/j.aei.2020.101094>
- 745 Hyperledger. 2021. About – Hyperledger. [online] Available at: <<https://www.hyperledger.org/about>> [Accessed 10  
746 October 2021].
- 747 Jayasinghe, L.B., Waldmann, D., 2020. Development of a BIM-Based Web Tool as a Material and Component Bank for  
748 a Sustainable Construction Industry. *Sustainability* 12, 1766. <https://doi.org/10.3390/su12051766>

- 749 Kaffine, D.T., 2014. Scrap Prices, Waste, and Recycling Policy. *Land Econ.* 90, 169–180.  
750 <https://doi.org/10.3368/le.90.1.169>
- 751 Kalmykova, Y., Sadagopan, M., Rosado, L., 2018. Circular economy – From review of theories and practices to  
752 development of implementation tools. *Resour. Conserv. Recycl., Sustainable Resource Management and the*  
753 *Circular Economy* 135, 190–201. <https://doi.org/10.1016/j.resconrec.2017.10.034>
- 754 Kar, S., Kasimsetty, V., Barlow, S., Rao, S., 2019. Risk Analysis of Blockchain Application for Aerospace Records  
755 Management. *SAE Tech. Pap.* <https://doi.org/10.4271/2019-01-1344>
- 756 Katz, D., 2019. Plastic Bank: launching Social Plastic® revolution. *Field Actions Sci. Rep. J. Field Actions* 96–99.
- 757 Khaqqi, K.N., Sikorski, J.J., Hadinoto, K., Kraft, M., 2018. Incorporating seller/buyer reputation-based system in  
758 blockchain-enabled emission trading application. *Appl. Energy* 209, 8–19.  
759 <https://doi.org/10.1016/j.apenergy.2017.10.070>
- 760 Kim, S.-K., Huh, J.-H., 2020. Blockchain of Carbon Trading for UN Sustainable Development Goals. *Sustainability* 12,  
761 4021. <https://doi.org/10.3390/su12104021>
- 762 Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour.*  
763 *Conserv. Recycl.* 127, 221–232. <https://doi.org/10.1016/j.resconrec.2017.09.005>
- 764 Kitsantas, T., Vazakidis, A., Chytis, E., 2019. A Review of Blockchain Technology and Its Applications in the Business  
765 Environment. Presented at: International Conference on Enterprise, Systems, Accounting, Logistics &  
766 Management. Chania, Crete, Greece.
- 767 Knieke, C., Lawrenz, S., Fröhling, M., Goldmann, D., Rausch, A., 2019. Predictive and Flexible Circular Economy  
768 Approaches for Highly Integrated Products and their Materials as Given in E-Mobility and ICT [WWW  
769 Document]. *Mater. Sci. Forum.* <https://doi.org/10.4028/www.scientific.net/MSF.959.22>
- 770 Kouhizadeh, M., Sarkis, J., Zhu, Q., 2019a. At the Nexus of Blockchain Technology, the Circular Economy, and Product  
771 Deletion. *Appl. Sci.* 9, 1712. <https://doi.org/10.3390/app9081712>
- 772 Kouhizadeh, M., Zhu, Q., Sarkis, J., 2019b. Blockchain and the circular economy: potential tensions and critical  
773 reflections from practice. *Prod. Plan. Control* 1–17. <https://doi.org/10.1080/09537287.2019.1695925>
- 774 Kreutzmann, C., Sharma, P., Lawrenz, S., 2019. A Data Driven Approach for Efficient Re-utilization of Traction  
775 Batteries. Presented in: ADAPTIVE 2019 : The Eleventh International Conference on Adaptive and Self-  
776 Adaptive Systems and Applications. Venice, Italy. ISBN: 978-1-61208-706-1
- 777 Latif, S., Rehman, A., Zafar, N.A., 2019. Blockchain and IoT Based Formal Model of Smart Waste Management System  
778 Using TLA+, in: 2019 International Conference on Frontiers of Information Technology (FIT). pp. 304–3045.  
779 <https://doi.org/10.1109/FIT47737.2019.00064>
- 780 Lawrenz, S., Sharma, P., Rausch, A., 2019. Blockchain Technology as an Approach for Data Marketplaces, in:  
781 Proceedings of the 2019 International Conference on Blockchain Technology, ICBCCT 2019. Association for  
782 Computing Machinery, New York, NY, USA, pp. 55–59. <https://doi.org/10.1145/3320154.3320165>
- 783 Li, J., Greenwood, D., Kassem, M., 2019. Blockchain in the built environment and construction industry: A systematic  
784 review, conceptual models and practical use cases. *Autom. Constr.* 102, 288–307.  
785 <https://doi.org/10.1016/j.autcon.2019.02.005>
- 786 Li, J., Kassem, M., Watson, R., 2020. A Blockchain and Smart Contract-Based Framework to Increase Traceability of  
787 Built Assets (EasyChair Preprint).
- 788 Liu, Y., He, D., Obaidat, M.S., Kumar, N., Khan, M.K., Raymond Choo, K.-K., 2020. Blockchain-based identity  
789 management systems: A review. *J. Netw. Comput. Appl.* 166, 102731.  
790 <https://doi.org/10.1016/j.jnca.2020.102731>
- 791 Liu, Z., Jiang, L., Osmani, M., Demian, P., 2019. Building Information Management (BIM) and Blockchain (BC) for  
792 Sustainable Building Design Information Management Framework. *Electronics* 8, 724.  
793 <https://doi.org/10.3390/electronics8070724>
- 794 Măciucă, G., Hlaciuc, E., Ursache, A., 2015. The Role of Prudence in Financial Reporting: IFRS versus Directive 34.  
795 *Procedia Econ. Finance, Emerging Markets Queries in Finance and Business* 2014, EMQFB 2014, 24-25 October  
796 2014, Bucharest, Romania 32, 738–744. [https://doi.org/10.1016/S2212-5671\(15\)01456-2](https://doi.org/10.1016/S2212-5671(15)01456-2)
- 797 Mora, C., Rollins, R.L., Taladay, K., Kantar, M.B., Chock, M.K., Shimada, M., Franklin, E.C., 2018. Bitcoin emissions  
798 alone could push global warming above 2°C. *Nat. Clim. Change* 8, 931–933. <https://doi.org/10.1038/s41558-018-0321-8>
- 800 Moser, M., Bohme, R., Breuker, D., 2013. An inquiry into money laundering tools in the Bitcoin ecosystem. Presented  
801 at the eCrime Researchers Summit, eCrime. <https://doi.org/10.1109/eCRS.2013.6805780>



- 802 Nakamoto, S., 2009. Bitcoin: A Peer-to-Peer Electronic Cash System. Cryptogr. Mail. List [Https://metzdowd.com](https://metzdowd.com).
- 803 Nath, A., 2015. Profitability and sustainability from waste management practices in hotels and its impact on  
804 environment.
- 805 Nawari, N.O., Ravindran, S., 2019a. Blockchain and the built environment: Potentials and limitations. *J. Build. Eng.* 25,  
806 100832. <https://doi.org/10.1016/j.jobe.2019.100832>
- 807 Nawari, N.O., Ravindran, S., 2019b. Blockchain technology and BIM process: review and potential applications. *J. Inf.*  
808 *Technol. Constr.* ITcon 24, 209–238.
- 809 Nellemann, C., Henriksen, R., Kreilhuber, A., Stewart, D., Kotsovou, M., Raxter, P., Mrema, E., Barrat, S., 2016. The Rise  
810 of Environmental Crime – A Growing Threat To Natural Resources Peace, Development And Security. A  
811 NEPINTERPOL Rapid Response Assessment. United Nations Environment Programme and RHIPTO Rapid  
812 Response–Norwegian Center for Global Analyses.
- 813 OECD, 2016. Extended Producer Responsibility: Updated Guidance for Efficient Waste Management.
- 814 Pan, Y., Zhang, X., Wang, Y., Yan, J., Zhou, S., Li, G., Bao, J., 2019. Application of Blockchain in Carbon Trading. *Energy*  
815 *Procedia, Innovative Solutions for Energy Transitions* 158, 4286–4291.  
816 <https://doi.org/10.1016/j.egypro.2019.01.509>
- 817 Perera, S., Nanayakkara, S., Rodrigo, M.N.N., Senaratne, S., Weinand, R., 2020. Blockchain technology: Is it hype or real  
818 in the construction industry? *J. Ind. Inf. Integr.* 17. <https://doi.org/10.1016/j.jii.2020.100125>
- 819 Rejeb, A., Rejeb, K., 2020. Blockchain and supply chain sustainability. *Logforum* 16, 3.
- 820 Saberi, S., Kouhizadeh, M., Sarkis, J., 2018. Blockchain technology: A panacea or pariah for resources conservation and  
821 recycling? *Resour. Conserv. Recycl.* 130, 80–81. <https://doi.org/10.1016/j.resconrec.2017.11.020>
- 822 Saberi, S., Kouhizadeh, M., Sarkis, J., Shen, L., 2019. Blockchain technology and its relationships to sustainable supply  
823 chain management. *Int. J. Prod. Res.* 57, 2117–2135. <https://doi.org/10.1080/00207543.2018.1533261>
- 824 Sacks, R., Eastman, C., Lee, G., Teicholz, P., 2018. BIM handbook : a guide to building information modeling for owners,  
825 managers, designers, engineers and contractors, Third edition.. ed. Wiley, Hoboken, New Jersey.
- 826 Schmelz, D., Pinter, K., Strobl, S., Zhu, L., Niemeier, P., Grechenig, T., 2019. Technical mechanics of a trans-border  
827 waste flow tracking solution based on blockchain technology, in: *Proceedings - 2019 IEEE 35th International*  
828 *Conference on Data Engineering Workshops, ICDEW 2019*. Institute of Electrical and Electronics Engineers  
829 Inc., pp. 31–36. <https://doi.org/10.1109/ICDEW.2019.00-38>
- 830 Shojaei, A., 2019. Exploring Applications of Blockchain Technology in The Construction Industry, *Proceedings of*  
831 *International Structural Engineering and Construction*. <https://doi.org/10.14455/ISEC.res.2019.78>
- 832 Shojaei, A., Flood, I., Izadi Moud, H., Hatami, M., Zhang, X., 2019. An Implementation of Smart Contracts by  
833 Integrating BIM and Blockchain. pp. 519–527. [https://doi.org/10.1007/978-3-030-32523-7\\_36](https://doi.org/10.1007/978-3-030-32523-7_36)
- 834 Sivula, Ari, Shamsuzzoha, A., Helo, P., 2018. Blockchain in Logistics: Mapping the Opportunities in Construction  
835 Industry. In *Proceedings of the International Conference on Industrial Engineering and Operations*  
836 *Management*. Washington DC, USA, September 27-29, 2018.
- 837 Sivula, A., Shamsuzzoha, A., Helo, P., 2018. Blockchain in logistics: Mapping the opportunities in construction  
838 industry, in: *Proceedings of the International Conference on Industrial Engineering and Operations*  
839 *Management*. IEOM Society, pp. 1954–1960.
- 840 Succar, B., Poirier, E., 2020. Lifecycle information transformation and exchange for delivering and managing digital  
841 and physical assets. *Autom. Constr.* 112, 103090. <https://doi.org/10.1016/j.autcon.2020.103090>
- 842 Szabo, N., 1996. Smart Contracts : Building Blocks for Digital Markets.
- 843 Tapscott, D., Tapscott, A., 2016. Blockchain Revolution How the Technology Behind Bitcoin and Other  
844 Cryptocurrencies is Changing the World. ISBN: 1101980141.
- 845 Turk, Ž., Klinc, R., 2017. Potentials of Blockchain Technology for Construction Management. *Creat. Constr. Conf. 2017*  
846 *CCC 2017 19-22 June 2017 Primosten Croat*. 196, 638–645. <https://doi.org/10.1016/j.proeng.2017.08.052>
- 847 Van Moergestel, L., Van Bremen, M., Krieger, B., Van Dijk, M., Puik, E., 2018. Using blockchains for agent-based  
848 auctions, in: van den Herik J., R.A.P. (Ed.), *ICAART 2018 - Proceedings of the 10th International Conference*  
849 *on Agents and Artificial Intelligence*. SciTePress, pp. 192–199.
- 850 Vranken, H., 2017. Sustainability of bitcoin and blockchains. *Curr. Opin. Environ. Sustain., Sustainability governance*  
851 28, 1–9. <https://doi.org/10.1016/j.cosust.2017.04.011>
- 852 Wang, X., Feng, L., Zhang, H., Lyu, C., Wang, L., You, Y., 2017. Human Resource Information Management Model  
853 based on Blockchain Technology, in: *2017 IEEE Symposium on Service-Oriented System Engineering (SOSE)*.  
854 pp. 168–173. <https://doi.org/10.1109/SOSE.2017.34>

- 855 Wang, Y., 2019. Designing a Blockchain Enabled Supply Chain. IFAC-Pap., 9th IFAC Conference on Manufacturing  
856 Modelling, Management and Control MIM 2019 52, 6–11. <https://doi.org/10.1016/j.ifacol.2019.11.082>
- 857 Wang, Z., Wang, T., Hu, H., Gong, J., Ren, X., Xiao, Q., 2020. Blockchain-based framework for improving supply chain  
858 traceability and information sharing in precast construction. *Autom. Constr.* 111, 103063.  
859 <https://doi.org/10.1016/j.autcon.2019.103063>
- 860 Weking, J., Mandalenakis, M., Hein, A., Hermes, S., Böhm, M., Krcmar, H., 2019. The impact of blockchain technology  
861 on business models – a taxonomy and archetypal patterns. *Electron. Mark.* <https://doi.org/10.1007/s12525-019-00386-3>
- 862
- 863 World Economic Forum, 2015. Deep Shift - Technology Tipping Points and Societal Impact.
- 864 Xu, J., Kebblis, M.F., Feng, Y., Chang, Y., 2017. Optimal sourcing from a pool of suppliers with nonidentical salvage  
865 values. *Int. J. Prod. Econ.* 193, 392–405. <https://doi.org/10.1016/j.ijpe.2017.08.007>
- 866 Xu, M., Chen, X., Kou, G., 2019. A systematic review of blockchain. *Financ. Innov.* 5, 27. <https://doi.org/10.1186/s40854-019-0147-z>
- 867
- 868 Yadav, S., Singh, S.P., 2020. Blockchain critical success factors for sustainable supply chain. *Resour. Conserv. Recycl.*  
869 152, 104505. <https://doi.org/10.1016/j.resconrec.2019.104505>
- 870 Yang, R., Wakefield, R., Lyu, S., Jayasuriya, S., Han, F., Yi, X., Yang, X., Amarasinghe, G., Chen, S., 2020. Public and  
871 private blockchain in construction business process and information integration. *Autom. Constr.* 118, 103276.  
872 <https://doi.org/10.1016/j.autcon.2020.103276>
- 873 Ye, Z., Yin, M., Tang, L., Jiang, H., 2018. Cup-of-Water theory: A review on the interaction of BIM, IoT and blockchain  
874 during the whole building lifecycle, in: ISARC 2018 - 35th International Symposium on Automation and  
875 Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things. International  
876 Association for Automation and Robotics in Construction I.A.A.R.C).
- 877 Zhao, D., Jia, G., Ren, H., Chen, C., Yu, R., Ge, P., Liu, S., 2018. Research on the Application of Block Chain in automobile  
878 industry. Presented at the IOP Conference Series: Materials Science and Engineering.  
879 <https://doi.org/10.1088/1757-899X/452/3/032076>
- 880 Zhao, X., Verhagen, W.J.C., Curran, R., 2020. Disposal and Recycle Economic Assessment for Aircraft and Engine End  
881 of Life Solution Evaluation. *Appl. Sci.* 10, 522. <https://doi.org/10.3390/app10020522>
- 882 Zheng, R., Jiang, J., Hao, X., Ren, W., Xiong, F., Ren, Y., 2019. bcBIM: A Blockchain-Based Big Data Model for BIM  
883 Modification Audit and Provenance in Mobile Cloud. *Math. Probl. Eng.* 2019, 5349538.  
884 <https://doi.org/10.1155/2019/5349538>
- 885 Zheng, Z., Xie, S., Dai, H.-N., Chen, W., Chen, X., Weng, J., Imran, M., 2020. An overview on smart contracts:  
886 Challenges, advances and platforms. *Future Gener. Comput. Syst.* 105, 475–491.  
887 <https://doi.org/10.1016/j.future.2019.12.019>