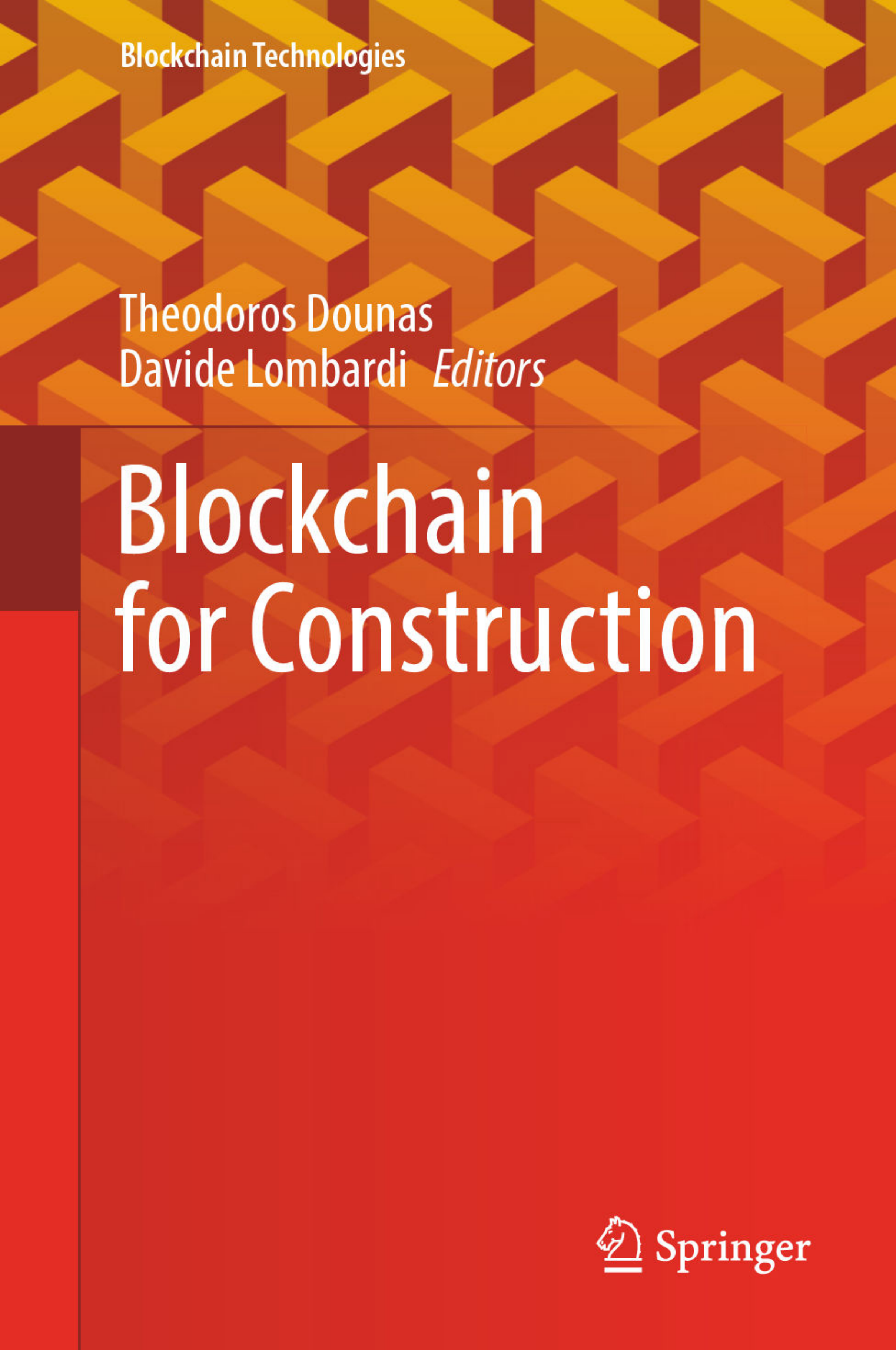

Blockchain Technologies

Theodoros Dounas
Davide Lombardi *Editors*

Blockchain for Construction

Springer

Blockchain Technologies

Series Editors

This book series aims to provide details of blockchain implementation in technology and interdisciplinary fields such as Medical Science, Applied Mathematics, Environmental Science, Business Management, and Computer Science. It covers an in-depth knowledge of blockchain technology for advance and emerging future technologies. It focuses on the Magnitude: scope, scale & frequency, Risk: security, reliability trust, and accuracy, Time: latency & timelines, utilization and implementation details of blockchain technologies. While Bitcoin and cryptocurrency might have been the first widely known uses of blockchain technology, but today, it has far many applications. In fact, blockchain is revolutionizing almost every industry. Blockchain has emerged as a disruptive technology, which has not only laid the foundation for all crypto-currencies, but also provides beneficial solutions in other fields of technologies. The features of blockchain technology include decentralized and distributed secure ledgers, recording transactions across a peer-to-peer network, creating the potential to remove unintended errors by providing transparency as well as accountability. This could affect not only the finance technology (crypto-currencies) sector, but also other fields such as:

Crypto-economics Blockchain
Enterprise Blockchain
Blockchain Travel Industry
Embedded Privacy Blockchain
Blockchain Industry 4.0
Blockchain Smart Cities,
Blockchain Future technologies,
Blockchain Fake news Detection,
Blockchain Technology and It's Future Applications
Implications of Blockchain technology
Blockchain Privacy
Blockchain Mining and Use cases
Blockchain Network Applications
Blockchain Smart Contract
Blockchain Architecture
Blockchain Business Models
Blockchain Consensus
Bitcoin and Crypto currencies, and related fields

The initiatives in which the technology is used to distribute and trace the communication start point, provide and manage privacy, and create trustworthy environment, are just a few examples of the utility of blockchain technology, which also highlight the risks, such as privacy protection. Opinion on the utility of blockchain technology has a mixed conception. Some are enthusiastic; others believe that it is merely hyped. Blockchain has also entered the sphere of humanitarian and development aids e.g. supply chain management, digital identity, smart contracts and many more. This book series provides clear concepts and applications of Blockchain technology and invites experts from research centers, academia, industry and government to contribute to it.

If you are interested in contributing to this series, please contact msingh@endicott.ac.kr OR loyola.dsilva@springer.com

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Contents

Blockchain Technologies in Construction

Theodoros Dounas and Davide Lombardi

1 The Purpose of the Book

The purpose of this volume is to inform the reader on the state of affairs of a new subset of construction informatics, Blockchain (B) and Decentralized Ledger Technologies (DLT)s. The initial motivation for writing and editing this volume was that we noticed the emergence of a range of ideas as a loose "body of work", produced from a variety of lenses and research stances in the informatics of construction. To shape this into a volume for a book, we made an international call for chapters and established a system of peer review as the basis of the editorial work we subsequently executed with the collaboration of all authors. The book comes out at a turning point for the world, and it would have been a cliché to say this, however, it is true not just because of the efforts to recuperate from the COVID-19 global crisis. Construction, as a component of the Architecture—Engineering—Construction industry in general faces a series of challenges, which amount to a radical shift in business and operating models.

Most readers unfamiliar with Blockchain would suppose that the purpose of B/DLT in construction is tied with economics and finance. This is, of course, one of the strands of research and industrial application that B/DLT has an impact on, however the applications are wider and deeper, involving not only supply chains but also the governance of projects, re-shaping the industry landscape and successfully enabling new modes of collaboration. On a more fundamental basis, blockchain technologies, by creating peer-to-peer economies, have the potential to reshape the

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manner in which we think about resources, the design, and structure of our (circular) economies, debt, trust, collectives, and collaboration.

This particular introductory text is placed here to deliver for the lay reader a series of definitions that will make the rest of the book accessible, but also to speculatively frame exciting ideas about blockchain in construction in a manner that positions some of the chapters as answers, and other chapters as questions for the community to resolve in the future. This is only true and brave for both blockchain in construction and crypto-economics as young fields of practice and research.

We would like to thank all authors for their tenacity and efforts to tackle important questions in a field that is still young, but highly promising in terms of shaping our collective future.

1.1 Some definitions

1.2 DLT—Decentralized Ledger Technologies

Distributed ledgers are distributed databases where each participant holds a copy of the data (across sites and geographies) and supported by a mechanism to synchronize and achieve consensus between these copies. DLTs also offer the feature of having the data accessible to multiple parties. The questions arise then of the need for a peer-to-peer network between the computing nodes holding the data and a consensus mechanism to synchronize the data unto a single version, as DLTs do not have a central administrator, in distinction to distributed databases who might be subject to a central control. This lack of a central authority is a feature rather than a weakness. When a new update to the ledger is needed, all nodes construct a transition which is then voted on by the use of a consensus algorithm, i.e., a process by which nodes vote for which update is true and which is not. Security is achieved by using public-key cryptography and cryptographic signatures to establish identities.

Consensus mechanisms follow in many cases scenarios of the “Byzantine Generals problem” [1]: a set of actors in a network need a reliable mechanism with which to arrive at a single version of the truth, even if some of the participants fail or actively undermine the network.

1.3 Blockchains

Blockchains are a special version of distributed ledgers which were invented to facilitate the idea behind digital cash in Bitcoin (Nakamoto 2009). In the Bitcoin blockchain, Nakamoto introduces a series of features that free the bedrock of what we call now a public permissionless blockchain:

- Incentives for the computing nodes to stay honest via the awarding of new crypto-tokens to the nodes,
- The collapse of all transactions at a given moment in a cryptographic hashing mechanism called a Merkle tree, where transactions are reduced to a single hash by progressively hashing them in pairs,
- A timestamp feature,
- A consensus mechanism using a proof of work algorithm, and
- A number used only once, the previous hash in a block of information that the computing nodes store on their ledger.

Each block is connected with the previous one by containing its root hash, creating a chain of blocks, hence the term blockchain. This mechanism along with the incentivization, secures the immutability of the blockchain, as users cannot go back and change the data, while incentives hold computing nodes true to the purpose and mission of the network which is reliability and security of the transitions in a peer-to-peer fashion.

Inspired by the Bitcoin blockchain, or rather attempting to expand its mechanisms for holding values, where the blockchain operates additions and subtractions, a group of programmers created the Ethereum blockchain, which expands the blockchain computing paradigm, acting as a decentralized, global, distributed computing platform capable of any Turing Complete computation [2].

Ethereum behaves as a state machine, i.e., a Turing machine that allows nodes to change their state. Thus, it is possible to record a variety of information on the Ethereum Blockchain. It also presents the benefit of being programmable through code, either in its native language solidity or even python. A code executed on the Ethereum blockchain is called a “smart contract” as its immutable nature equates the concept of code execution with law.

1.4 Smart Contracts

Smart contracts precede the “Ethereum” blockchain, having been introduced earlier by cryptographer Nick Szabo, who described them as “a set of promises, specified in digital form, including protocols within which the parties perform on these promises” [3]. Note that a smart contract does not necessarily have to constitute a valid binding agreement by law, as compliance with the valid legal framework is needed. However, smart contracts can be explained as the computing code equivalent of automated vending machines [4]. Smart contracts get deployed unto blockchain packaged unto a transaction. The Byzantine-fault tolerance mechanisms of the blockchain ensure then that the smart contract cannot be tampered within the same manner that transactions are secured, allowing only validated accounts on the network to act on the smart contract. Deployed smart contracts act then as automatons, with the blockchain automatically executing their code when specific events trigger the computation. This creates then an infrastructure automation layer where public permission blockchain can be used such as Ethereum as global computing state machines [5–7].

2 Cryptoeconomics

Cryptoeconomics have emerged as an experimental and intradisciplinary field of economics, peer-to-peer cryptography, systems design, and various other concepts such as game theory [6]. Cryptoeconomics attempt to guarantee certain outcomes and information security properties using incentives and penalties, to self-regulate digital economies. As such, the idea of external regulators and the state as guarantors of the validity of financial transactions do not exist as the system relies on the computing protocol for regulation [7]. Part of the epistemic and practical novelty of blockchains as cryptoeconomic systems lies in that trust, transactional infrastructure, and incentives are encoded in the computing protocol of the network rather than decided by existing structures. As such cryptoeconomics have the potential to radically change the manner in which various industries operate.

References

1. Lamport L, Shostak R, Pease M (1982) The byzantine generals problem. ACM Trans Program Lang Syst 4(3):20
2. Turing AM (1937) On computable numbers, with an application to the entscheidungsproblem. Proc London Math Soc s2–42(1): 230–265. https://doi.org/10.1112/plms/s2-42.1.230
3. Szabo N (1997) Formalizing and securing relationships on public networks. n.d. Accessed 27 Jan 2022. https://firstmonday.org/ojs/index.php/fm/article/download/548/469
4. Savelyev A (2016) Contract law 2.0: «Smart» contracts as the beginning of the end of classic contract law. SSRN Scholarly Paper ID 2885241. Social Science Research Network. https://doi.org/10.2139/ssrn.2885241
5. 'Ethereum Whitepaper'. n.d. Ethereum.Org. Accessed 27 Jan 2022. https://ethereum.org
6. Nakamoto S (2008) Bitcoin: A peer-to-peer electronic cash System
7. Wood—Ethereum a secure decentralised generalised transaction layer. n.d. Accessed 27 Jan 2022. https://ethereum.github.io/yellowpaper/paper.pdf

The Promise of Blockchain for the Construction Industry: A Governance Lens

Jens Hunhevicz, Theodoros Dounas, and Daniel M. Hall

Abstract This chapter outlines the promise of blockchain for the construction industry. Blockchain is an opportunity to create novel forms of economic coordination toward better collaboration within and across the built asset life cycle phases. Ongoing research tends to focus on blockchain to increase trust in existing processes. Instead, we argue blockchain's disruptive potential is the creation of novel economic coordination. Therefore, we intend to advance the thinking around the promise of blockchain as an institutional innovation in the construction industry. First, we explain how the underlying cryptoeconomic governance mechanisms of blockchain can facilitate new decentralized coordination mechanisms between both humans and machines. Next, we provide an alternative vision for the governance of construction 4.0 to explain how cryptoeconomic coordination can address long-standing problems in the construction industry. Finally, we propose an adoption framework that can guide researchers and practitioners to explore the promise of blockchain and cryptoeconomics for the construction industry.

1 Introduction

One of the most exciting aspects of blockchain is that it is an institutional innovation with the potential to disrupt and substitute existing economic coordination [1, 2]. However, many ongoing research projects develop blockchain solutions to increase trust in existing processes. While these are valid and beneficial in the short term, they

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can miss the opportunity to redesign processes and systems to the full potential of this new technology.

Blockchain allows for the creation of new ecosystems, where the benefits from network effects and shared digital infrastructure do not come at the cost of increased market power and data access by platform operators [3]. This is achieved through blockchain governance, where *cryptoeconomics* incentivizes participants through the exchange and distribution of tokens to secure the network. Cryptoeconomics enables new forms of economic activity beyond existing forms of monetary incentives by taking into account both endogenic and exogenic system variables [4]. This is a feature that might be particularly useful for more efficient means of coordination in the construction industry. Such new cryptoeconomic systems can be created by individuals for any economic system, independent of the traditional makers of economies [5]. Despite this new opportunity to individually tailor coordination mechanisms for the construction industry, less thinking has been done to imagine implications on a longer time horizon.

Therefore, we intend to advance the thinking around the promise of blockchain as an institutional innovation in the construction industry. We outline why blockchain can be an opportunity to foster collaboration through new economic coordination within and across the built asset life cycle phases by describing the connection of blockchain governance with the characteristics of the construction industry. First, we introduce how blockchain governance is an inherent feature of blockchain, enabling the specific affordances associated with the technology. We then discuss how those affordances can facilitate new decentralized governance mechanisms between humans and machines built on the underlying blockchain networks. Afterward, we highlight why blockchain-based governance is especially promising for the construction industry. We then introduce a framework to structure the adoption of blockchain in construction on three levels through a blockchain-based governance lens. Finally, we discuss the contribution, limitations, and outlook.

2 Governance of Blockchains

First, it is important to understand that governance mechanisms are an inherent feature of blockchains. Therefore, this section outlines how governance of public permissionless blockchains such as Bitcoin [6] enables the typical affordances associated with the technology for novel forms of economic coordination. However, we only explain these concepts on a high level. For the curious reader, there are many excellent publications available that give more technical details [7, 8].

2.1 The Three Technical Layers of a Blockchain Protocol

A blockchain consists of three main parts: a ledger to record transactions, the distribution of this ledger forming a network, and a governance layer that defines how participants interact with the ledger [9]. Together they form what is sometimes called the *protocol layer* of a blockchain (Fig. 1).

The ledger represents the data structure of a blockchain, where transactions are recorded. The main role of the ledger is to ensure integrity (i.e., explicit verifiability of the uniqueness of transactions) through timestamping transactions with the cryptographic process of hashing, and applying one-way mathematical functions repeatedly to the transaction data. These unique hashes are included in a block together with the hash of the previous block. This forms a growing sequential chain of transactions that allows noticing if past transaction data has been tampered. All data in the ledger is public, transparent, and accessible to everyone in the network.

The ledger runs then simultaneously on different computers, forming a distributed network of so-called *nodes*. This creates the possibility to cross-check the ledger among all copies in the network to detect malicious versions. It also ensures the decentralization of the network. It is very difficult to attack the network by taking down nodes since operations will still be ensured by all other nodes distributed across the globe.

Finally, the real challenge is coordinating how nodes in the network validate, agree, and write transactions to the ledger without relying on centralized coordinators. This was solved for the first time with Bitcoin using a cryptoeconomic governance mechanism—the real innovation behind blockchain. On the protocol level of a blockchain, this governance process is called the consensus mechanism. In the specific case of Bitcoin, a mechanism called proof-of-work protects the network effectively from attacks [11]. A native coin, e.g., bitcoin in Bitcoin or ether in Ethereum, incentivizes participants to behave in the interest of the blockchain network by compensating nodes that correctly validate and add transactions. As long as the majority of these so-called *miners* are more profitable to behave honestly, the chain is protected.

Overall, blockchain enables direct peer-to-peer transactions of value across a decentralized network. The network is not controlled by any single actor but by consensus code protocols that incentivize the participants toward coordination. Blockchains only work because of their cryptoeconomic governance mechanisms—a new way of trust-minimized social coordination. Bitcoin, a new decentralized monetary system and asset class, was the first and most popular example of such a network that has proven to be very secure and resilient.

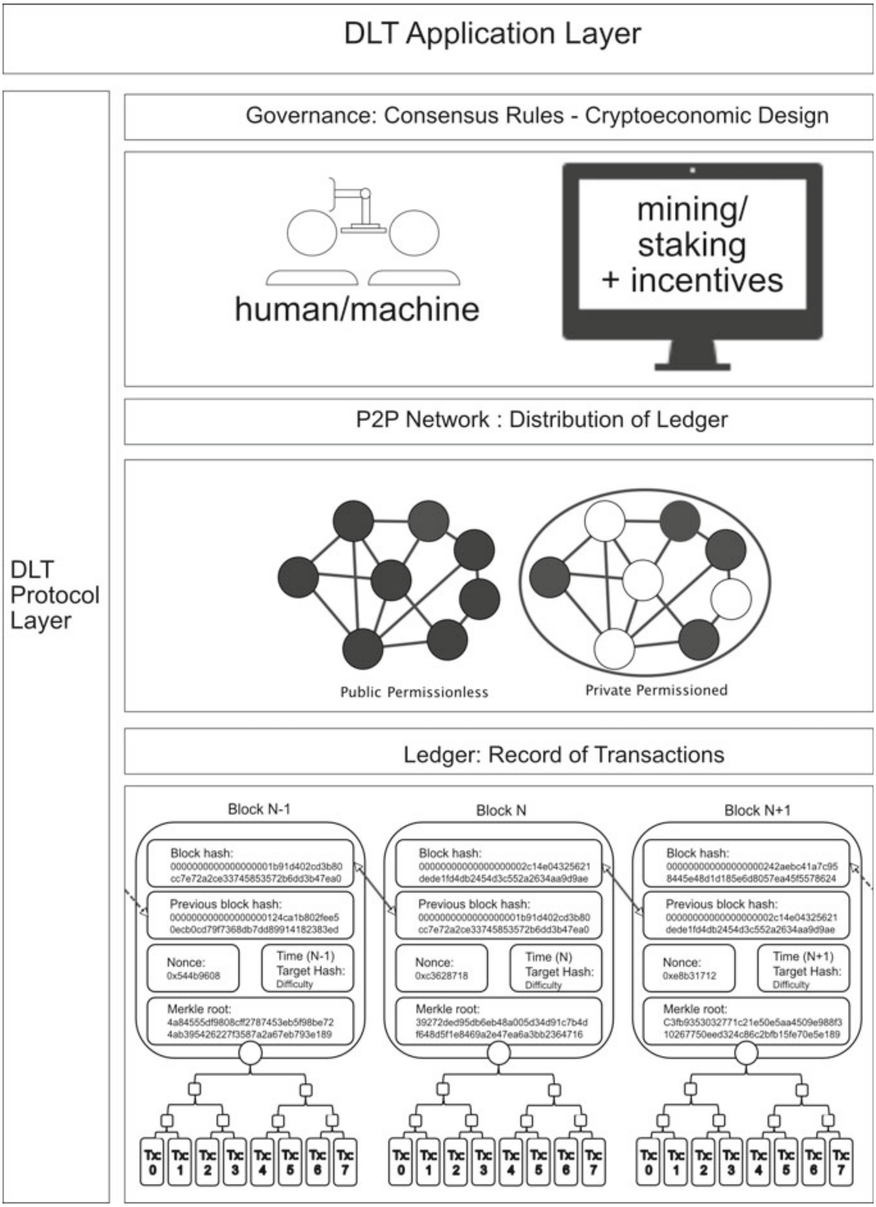

Fig. 1 The three technical layers of blockchain forming the protocol layer. P2P network figures adapted from Allessie et al. [10]

2.2 Blockchain Affordances

When blockchains have a transparent ledger, run in a distributed network, and have working cryptoeconomic governance mechanisms, they build confidence [12] in the affordances typically associated with the technology:

Immutable P2P Transactions (Fig. 2, [A1]) Transactions happen directly between users of the network. Services of third parties that previously enabled these functions are not needed anymore. This effect is sometimes referred to as "*disintermediation*". The network inherently ensures trust between the users through the implemented consensus mechanisms. They check transaction compliance and ensure immutability. Transactions are very hard to alter once agreed and written to the ledger.

Transparency (Fig. 2, [A2]) Transactions and data are visible to all participants in the network and can be verified for their integrity, meaning if they are still in the condition as initially written to the blockchain. Furthermore, the entire transaction history can be checked. Also, the underlying code is open source and can be verified by anyone.

Scalability (Fig. 2, [A3]) Blockchain networks can be scaled to large decentralized networks that connect many users. This contributes to the robustness of the network and its trustworthiness since many independent participants (especially running nodes) reduce the possibility of a single point of failure and keep each other in check.

Logic (Smart Contracts) (Fig. 2, [A4], [B2]) Smart contracts are composed of the logic of a prearranged agreement that can be encoded to interact with transactions on a blockchain network. Once deployed on the network, smart contracts execute automatically (anonymous and trustless) as soon as the defined conditions are met. The presence of smart contracts on a blockchain transforms it into a Turing complete state machine [15, 16]. Smart contracts can be used to create autonomous workflows

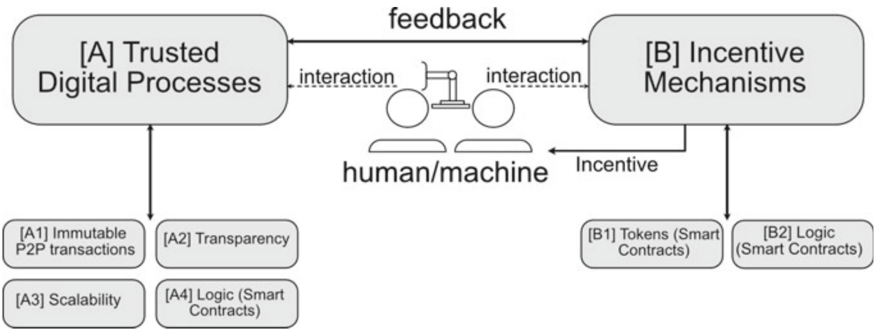

Fig. 2 Blockchain affordances allow to establish trusted digital processes (**a**) and incentive mechanisms (**b**) for decentralized governance mechanisms. Adapted from Hunhevicz et al. [13, 14]

for any process that can be formalized into programmable rules. In essence, smart contracts encode custom rules on the blockchain. Often these are conditional statements that will execute when predefined network state conditions are met. Since the code runs on a blockchain, it will perform exactly as specified, with no intermediary stopping the process.

Incentives (Tokens) (Fig. 2, [B1]) Smart contracts can also be used to create so-called tokens. Tokens represent value containers such as currencies, securities, utilities, or others [7, 17]. Tokens can then be transferred among users or smart contracts to move value across the network. Thus, through tokens, it becomes possible to create incentive systems that influence network participants in their behavior.

2.3 Short Excursion to Private Permissioned Blockchains

For now, we only talked about *public permissionless* blockchains such as Bitcoin that are open to all (*permissionless*), and transactions can be verified by anyone (*public*). They only exist because of the cryptoeconomic governance mechanisms that enforce the network rules between all anonymous network participants. Such blockchains are generally slow and expensive to use. On the upside, they provide the introduced affordances. When referring to blockchain without further specification in this chapter, we mean public permissionless blockchains.

Because it will be insightful to compare the potential path of blockchain-based governance adoption in the built environment with the different types of blockchains, we make here a short excursion to *private permissioned* blockchains.

Sometimes institutions are enticed by some blockchain characteristics, but the envisioned applications conflict with other affordances of public permissionless blockchains. This is often because they want to apply blockchain to existing use cases or industry particularities that require restricted infrastructure control or data visibility for only a known group. Setting up a blockchain so that only this group can join the network and verify transactions results in what is called a *permissioned* blockchain. If the network only allows this group to see the transactions, it is referred to as a *private* blockchain. If the use case indeed needs one of these properties, private permissioned blockchains could be a suitable solution [9].

Nevertheless, private permissioned blockchains replicate in some sense existing systems with their limitations and curtail possible new forms of economic coordination. This is because the rules and operation of the network are ensured and coordinated by known actors. Therefore, no cryptoeconomic governance is needed. This makes these networks typically faster than public permissionless blockchains.[1] It is also possible to launch smart contracts and tokens on private permissioned blockchains. However, such applications will always need to trust the operators of the network. Users must be confident that the operators will not shut down the

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[1] This argument becomes less relevant as scaling solutions for public systems are showing increasing maturity.

system or that the system could be manipulated by a few actors [12]. Of course, dependent on the number and diversity of stakeholders running the network, private blockchains can still be more trustworthy than traditional centralized platforms. In the end, the chosen system should reflect the requirements of a given use case by assessing whether and which blockchain is needed [9].

2.4 Blockchain-Based Governance for New Economic Systems

After introducing governance of blockchains, we now look at how blockchain-based governance can be leveraged to build applications on top of these networks: the *application layer*.

2.5 Trusted Digital Processes

The introduced affordances make the application of blockchain interesting for a wide selection of use cases. On the one hand, immutable P2P transactions (Fig. 2, [A1]), transparency (Fig. 2, [A2]), and scalability (Fig. 2, [A3]) allow creation of trusted digital processes to coordinate the global economic activity of actors in a decentralized way. Transactions can be conducted directly between parties and are not subject to control by other actors (Fig. 2, [A]). The simplest use case is transferring protocol native coins (e.g., bitcoin or ether) between users. However, other use cases can profit from reaching a consensus about individual transactions at the system level. To implement more advanced logic on-chain, smart contracts (Fig. 2, [A4]) can encode processes on the application layer for various purposes. Since blockchains identify network actors only through addresses, both humans and machines can trade with each other without the need to disclose their identities. The blockchain ensures confidence between pseudonymous (only address is known) actors to trade value peer-to-peer – facilitating decentralized market structures not controlled by anyone. For now, such decentralized applications (termed dApp’s) are predominantly decentralized financial applications (termed DeFi) that replicate existing financial services without the need for intermediaries [18].

2.6 Incentive Mechanisms

Such trusted digital processes can be complemented with incentive mechanisms (Fig. 2, [B]) that define new economic systems through the use of tokens (Fig. 2, [B1]) and their associated system logic encoded with smart contracts (Fig. 2, [B2]). With that, it is possible to create economic activity on the application level, similar to how the underlying blockchain protocols use cryptoeconomics to incentivize the operation of their networks. Applications can create their own networks with comparable blockchain characteristics, without the need to run their own network infrastructure.

2.7 New Forms of Economic Activity

Overall, cryptoeconomic systems can provide an institutional infrastructure that facilitates a wide range of socioeconomic interactions [19]. Cryptoeconomic systems have the potential to disrupt and substitute existing economic coordination [1, 2]. They leverage the innovation of blockchain for trust-minimized social coordination to create new forms of economic activity beyond the processes we can facilitate nowadays. There is an ongoing exploration of what forms of economic activity can be supported or replaced through cryptoeconomic systems. Within this chapter, it is impossible to cover all aspects of this new and rapidly evolving research field. Instead, we focus on two often mentioned concepts that we find aligned with the challenges of the construction industry: crypto-commons and DAOs.

3 Crypto-Commons

The alignment of stakeholders without any hierarchical management structures using cryptoeconomic governance is notably parallel to theories of common-pool resource (CPR) governance.

CPRs are natural (e.g., forests, pastures, or fishing grounds) or man-made (e.g., irrigation systems or wiki libraries) resources, which are freely shared among many users [20]. The *tragedy of the commons* occurs when users of a CPR “overuse”, e.g., “overfish” in the case of fishing grounds, by appropriating resources at a higher than the optimal rate in self-interested behavior, resulting in a downward spiral of total resource availability [21]. Historically, the common belief was that only centralized and top-down control can coordinate optimal resource appropriation, e.g. government interventions. More recent work pioneered by economist Elinor Ostrom [22–24] and others [25] showed that local actors without a central authority could be more successful in sustaining the commons. This self-coordination of resource appropriation can be guided by governance design principles—referred to as the eight Ostrom principles. The Ostrom principles have been successfully used in many commons-based communities to craft effective governance rules without any top-down control [26]. However, bottom-up coordination incurs a high cost of information exchange. It is tough to scale community governance based on the Ostrom principles to large and global systems [27].

Various scholars demonstrate how the governance of blockchain networks is very much aligned with the lens of CPR theory and the Ostrom principles [28, 29].

Blockchains have been described as commons-based peer production of free and open-source software [30]. Consequently, blockchains can be seen as early evidence of the successful scaling of real-world commons (software) on a global scale through new forms of bottom-up economic coordination.

Therefore, it is not surprising that emerging literature suggests blockchain as a tool to build applications that can scale real-world examples of commons [31]. The potential lies in overcoming collective action problems by using blockchain's transparency and incentive systems to build bottom-up coordination. Because of their cryptoeconomic governance mechanisms, blockchains decrease the cost of information exchange by minimizing opportunism and uncertainty by combining transparency with cryptographic enforcement [32, 33]. The adoption of blockchain-based transparent decision-making procedures and decentralized incentive systems for community governance in commons could help avoid the tragedy of the commons [34]. The Ostrom principles could guide such applications by encoding respective governance rules [35, 36]. With that blockchain could create networked governance to scale real-world commons, similar to how the stock market enabled corporations to scale [37]. Such crypto commons could allow new types of value creation with crypto assets rather than shares of stock, contributors rather than employees, and decentralized collaboration rather than centralized ownership [37]. Overall, collective action use cases might be more efficiently governed by crypto-commons rather than existing forms of centralized and top-down forms of coordination.

3.1 Decentralized Autonomous Organizations (DAOs)

One of the most interesting new organizational designs proposed to leverage cryptoeconomic coordination on the blockchain is called a decentralized autonomous organization (DAO). A DAO is a blockchain-powered organization that can run without any central authority [38]. The decentralized governance of a DAO is facilitated by a set of self-executing rules deployed with smart contracts on a blockchain to enable self-coordination and governance of people [39]. By defining governance mechanisms in smart contracts, the DAO can self-operate, self-govern, and self-evolve [38]. It is essential to note the difference between a DAO and operations that use artificial intelligence (AI) [15, 16]. An AI system is often designed to make internal autonomous decisions. By contrast, a DAO defines its own coordination rules and governance system. In this way, it can make decisions based on the external input of participating actors. These actors only need to own a recognized address, so the actors can be machines, another DAO, or a distributed group of human decision-makers.

DAOs are not just a theoretical concept. They exist already in various forms. Since there is no strict definition of a DAO beyond an organization governed by smart contracts, there is room for interpretation when such an organization is independent enough to be called a DAO. For now, we find it helpful to think about two high-level sorts of DAOs: protocol and application level DAOs.

Protocol-level DAOs are permissionless blockchains governed by code to coordinate stakeholders. Early versions of blockchain such as Bitcoin and Ethereum encode coordination mechanisms to create and protect the blockchain through cryptoeconomics. However, these blockchains only implement off-chain governance mechanisms for decision-making [32]. Newer blockchains like *Decred*, *Polkadot*, or *Tezos* attempt to also implement on-chain governance mechanisms for decision making [32]. These decisions can include how to evolve the protocol or what to spend the network-owned treasury. With that protocol-level DAOs increase their independence from external funding sources and decision-makers.

Application-level DAOs live on a blockchain encoding their governance rules with smart contracts. The first-ever application DAO was likely "*the DAO*" on Ethereum, which resulted in a catastrophic failure after a successful attack had stolen funds worth millions of US dollars [40]. Learning from this failure, new application-level DAOs are often based on frameworks like *Aragon* or *The DAO stack* [41]. They provide reviewed code building blocks that can be assembled to reduce the risk of similar fates as in "*the DAO*".

To the construction industry, application-level DAOs are probably more interesting. But blockchain applications should also choose the underlying network resembling their own characteristics. Application-level DAOs will likely use protocol-level DAOs as a secure foundation to build such organizations.

Finally, DAOs are not decoupled from the previous idea of scaling common pool resource scenarios. A DAO can be used to set up coordination mechanisms so that a community can co-create the respective organizational system in line with ideas of the sharing economy or CPR theory. Once the experimentation with DAOs moves past replicating existing corporate structures, the ideas of crypto commons and DAOs eventually blend. In the long run, DAOs might shift power structures away from centralized corporations toward user communities that decide on their own system's purpose and governance rules, fundamentally changing the structure and dynamics of organizations [42].

4 Cryptoeconomic Governance for the Construction Industry

After introducing the origin, characteristics, and applications of blockchain governance, we outline our thinking to spark ideas on the potential of blockchain-based governance in the construction industry. We discuss the observed potential alignment of cryptoeconomic governance with the construction industry through three lenses: fragmentation, complexity, and loosely coupled systems.

5 Lens 1—Cryptoeconomic Incentives to Embrace Fragmentation?

The construction industry has been described with three dimensions of fragmentation: horizontal, vertical, and longitudinal fragmentation [43], as depicted in Fig. 3. Vertical fragmentation occurs between project phases [44]. Each phase has a different set of stakeholders, decision-makers, and values. This creates a "broken agency"—where involved parties will engage in self-interested behavior and pass costs off to others in the supply chain in a subsequent phase [45]. Horizontal fragmentation occurs in the trade-by-trade competitive bidding environment of traditional project

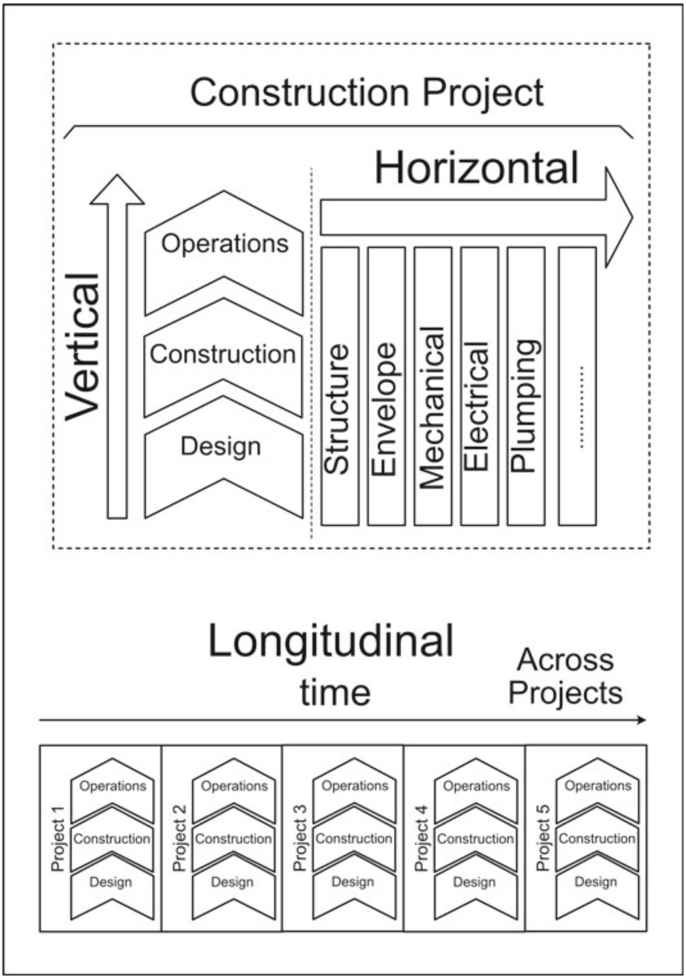


Fig. 3 Three degrees of fragmentation in the construction industry (adapted from Sheffer [43])

deliveries. Because it is difficult to cross-subsidize changes across trades, globally optimal innovations cannot compete with traditional solutions that are more cost-effective from the perspective of a particular building element or phase [46]. Longitudinal fragmentation occurs when project teams disband at the end of projects and select future projects by competitive bidding. They are thus unlikely to work with the same set of partner firms on future projects. Consequently, team members lose tacit knowledge about how to work together effectively [47], and organizations cannot build long-term trusting relationships across firm boundaries.

The prevailing fragmented structure is one of the reasons why the uptake of many systemic innovations such as BIM is challenging in the construction industry [48, 49]. Without addressing the structural issues related to the construction industry, the immense potential of digitalization will not yield better collaborations [50]. New digital technologies must be integrated with adaptations in management, contracts, and collaboration forms [51]. Blockchain can build new incentive systems to influence human behavior based on trusted digital processes (see Fig. 2). Cryptoeconomic incentives are promising to align stakeholders across phases, trades, and projects to reduce the impact of fragmentation.

The idea to incentivize better collaboration in a construction project is not new. For example, integrated project delivery (IPD) is a project delivery model that creates inter-organizational governance structures to jointly manage complex projects across firm boundaries [46]. While some project delivery models use only informal mechanisms of collaboration [46, 52, 53], the current trend has been the development of formalized incentive structures through the use of multi-party relational contracts. Project clients, contractors, and planners collaborate on equal standing with their own decision-making power and autonomy [54], yet are incentivized to make decisions for the collective good. Target Value Design and Shared Risk Rewards are examples of such performance-oriented bottom-up incentive structures [55, 56]. Cryptoeconomic governance could improve and extend such incentive structures with tokenization and smart legal contracts. In the longer term, embracing cryptoeconomic incentives could slowly reduce the negative impacts of fragmentation without the need to integrate the value chain through centralized approaches.

6 Lens 2—Guided Self-organization to Manage a Complex Construction Industry?

Complex systems are characterized by many interacting subsystems, where dependencies and interactions among these influence the functioning of the overall system [57, 58]. System-level characteristics cannot be understood as a simple sum of subsystem behaviors. Instead, properties such as emergence, adaptation, spontaneous order, feedback loops, and nonlinear behavior of the overall system need to be expected [57]. The internal interactions of the networked subsystems are often stronger than external control attempts [58]. This is why complex systems behave strangely in the eyes of humans that are used to think in linear ways with a proportional outcome to a given input, and therefore governance of such systems is often perceived as very difficult [59].

Construction projects have many complex system characteristics. They involve many multidisciplinary individuals and firms equally valuable in the system's operation [60, 61]. The construction workflow has high interdependence between stakeholders and many overlaps of construction stages and elements [62]. Design and coordination tasks often require reciprocal interdependence between the involved parties [63, 64]. Project outcomes and performance indicators must be already defined at the initial stage of a project, so they are likely to change throughout the project [65]. Finally, there are many uncertainties from external parties (e.g., from authorities, governments, or law), resources (labor, equipment, material), or the environment (e.g., weather, traffic) [62].

Construction projects are typically governed and managed using a project delivery model. Over the past several decades, the classical project delivery is managed using "command-and-control" project management with layers of contractual and organizational hierarchies [54]. A typical construction project hierarchy will spread across multiple vertical tiers and can include hundreds of subcontracted specialty firms across the supply chain. Even though cooperation would be crucial to deal with the mentioned challenges, insufficient and untimely communication is more the norm than the exception [66]. Contentious behavior and lack of cooperation reduce the system's efficiency compared to the sum of individual efforts [46]. Over time, this can result in sub-optimization and self-interest to the detriment of the overall project [65]. We can find indications of the failure of hierarchical management structures in many construction projects that ended up in court to resolve disputes over "unforeseen problems leading to cost and time overruns" [67].

According to Helbing and Lämmer [59], we must accept that a complex system does not always do what is desired. The internal nonlinear interactions often dominate the external control attempts. Sometimes small but right changes cause the system to change, while large efforts might remain useless. Classical, hierarchical control attempts are likely to fail. Instead, one should use self-organization as part of the management strategy. Self-organized networks need room to establish with increased flexibility of participants. Detailed regulations hardly ever create an effect. They rather reduce flexibility and make the required processes inefficient, complicated, and expensive. Harmonic overall dynamics is more important than individual performance at their limit, and faster end up to be often slower in complex systems.

In natural self-organizing systems, the agents act and interact with other agents based on some simple rules at the individual level, behaving towards an optimal overall system state. A well-known example in nature is bee hives, where simple rules govern the behavior of individual bees [68], but at the population level, maximize the payoff of foraging [69]. Even though self-organization works very well in nature, it will likely not meet the targeted outcome in many artificial systems. In most cases, it is not possible to find such simple rules at the individual level that optimize the overall system state. Therefore, complex engineered systems need to be directed minimally invasive to create desired outcomes with "guided self-organization" by changing the interactions in complex systems [70] through approaches of mechanism design or complexity science to guide individuals towards optimizing the overall system state. Guided self-organization can successfully optimize production systems [71], logistics [72, 73], traffic flow with bottom-up traffic light control [74], or the overall system output of wind farms [75]. Furthermore, changing human interactions can turn the so-called “madness of the crowd” into a “wisdom of the crowd” [76–78].

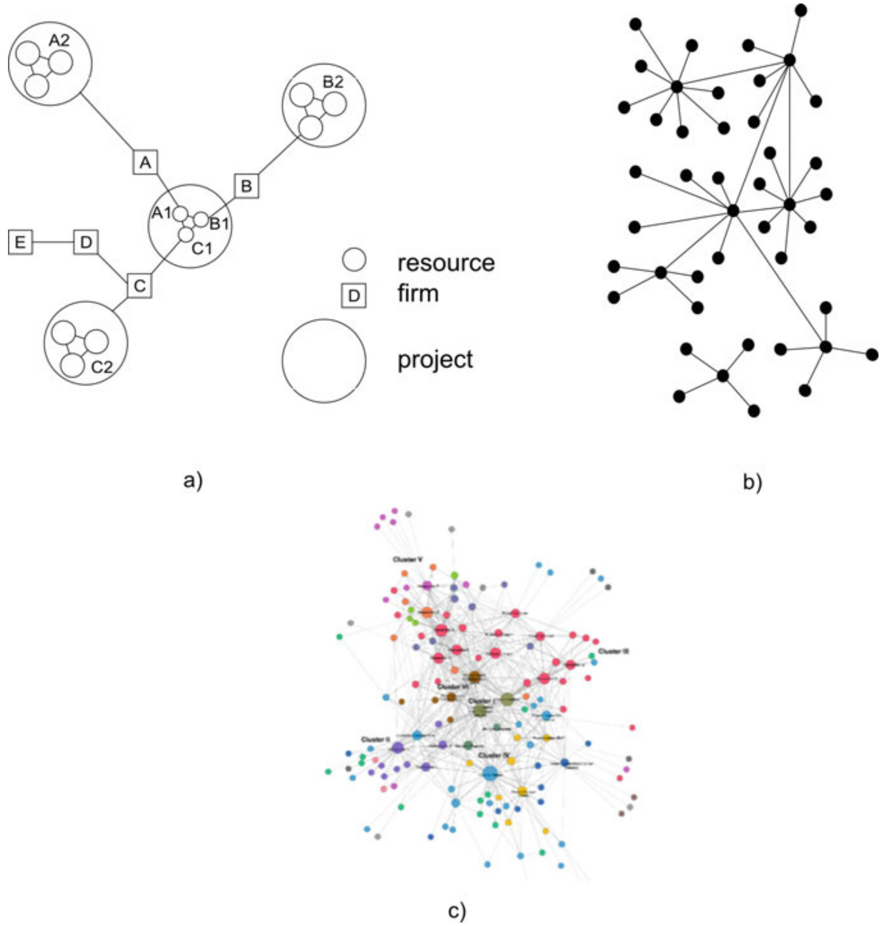
Consequently, guided self-organization is, in theory, an optimal management approach for a complex system like the construction industry. This is also in line with scholars [79] suggesting to use bottom-up control in construction projects to deal with its complex nature, instead of formalizing top-down control to plan for a linear and sequential process. The question arises of how such guided self-organization could be achieved in the construction industry?

Even though this question will need more investigation, governance of systems through cryptoeconomics can be an enabler for bottom-up coordination [42] toward self-organization. In decentralized systems, decreasing the cost of coordination is extremely important through real-time and transparent information feedback distributed to all relevant parties. This allows informed and coordinated bottom-up reactions to unexpected events. Currently, these information flows are passed through the hierarchical systems, leading to slow responses. New technological advances enable these needed fast feedback loops by providing an extensive real-time data baseline [70]. Blockchain-based governance processes are promising to support data-driven bottom-up and collective decision-making by creating cryptoeconomic incentives to guide individual actors toward behavior that optimizes the overall project.

7 Lens 3—Decentralized Governance for a Decentralized Industry?

Since the construction industry is mainly organized around projects, Dubois and Gadde [47] described the construction industry as a “loosely coupled system”. Firms in the industry are usually involved in different projects, where they contribute resources of various kinds (Fig. 4a). While they maintain loose couplings in the permanent network embedded in the community of practice, they need to keep tight couplings in the individual projects to perform and coordinate their activities with the many actors regarding resources, space, and time. The resulting networks are very similar to a decentralized network structure [80] (Fig. 4b).

Recent mapping of construction firm networks seems to confirm the decentralized nature of construction collaboration. Graser et al. [81] map the information network of a construction project showing this very typical form of collaboration with many coordinating smaller internal and external actors (Fig. 4c). Also, the network analysis of Bouck [82] shows that construction firms communicate extensively with outside players in their ecosystem, resembling again a decentralized network structure.



a) b)

c)

Fig. 4 The construction industry as decentralized collaboration network. *Sources* **a** Dubois and Gadde [47] **b** Baran [80] **c** Graser et al. [81]

Overall, decentralized network structures seem typical to the construction industry. Other industries have mostly bigger players that integrate and coordinate large parts of the value chain [82]. Since industries with more integrated and centralized structures have often higher productivity than construction, efforts under the term of industrialized construction trying to adopt these approaches have attracted major investments lately [83]. Industrialized construction tightens couplings of firms across construction projects, an approach that is successful in manufacturing. While this can also be successful strategies in the built environment, it involves restructuring a whole industry toward more vertical integration of the supply chain. Could decentralized collaboration mechanisms enabled by cryptoeconomic governance approaches provide an alternative pathway to make the prevalent decentralized and loosely coupled industry structure more efficient by decreasing cost of coordination?

7.1 Aligning Governance with the Industry Structure

The three different lenses indicate the potential for cryptoeconomic governance in the construction industry. The construction industry is characterized by complexity and can be described as a loosely coupled network managed with top-down approaches (Fig. 5, light gray dots). However, an efficient overall system should be either targeted toward hierarchies or networks [84]. Hypothetically, one option is to move the industry structure towards vertical integration, removing complexity through more streamlined supply chains (Fig. 5, industry structure arrow). This would lead to less fragmentation with the same actors across phases and trades and standardization across projects. The other option would be to move governance approaches toward bottom-up management and embrace complex aspects of the industry (Fig. 5, governance arrow). Both approaches are feasible if assuming that it is indeed possible to reduce complexity. However, it is somewhat hard to believe that all the complex aspects of the industry can be eliminated. Additionally, industrialization and digitalization will only increase in our world, directing global systems towards new socio-technical paradigms with inevitable cascading effects on interconnected and complex ecosystems [85]. As our world's complexity and interaction strengths increase, centralized and controlled systems can become unstable, and highly skilled, well-informed, and well-intentioned system managers can still lose control [85]. With this in mind, the decentralized nature of the construction industry could also be perceived as a strength that makes the industry more resilient to such risks. With the increased adoption of technology in the construction industry, cryptoeconomic governance provides an opportunity to build bottom-up coordination mechanisms towards "peer-production" of the built environment to better handle complex aspects of construction aligned with its decentralized and fragmented nature.

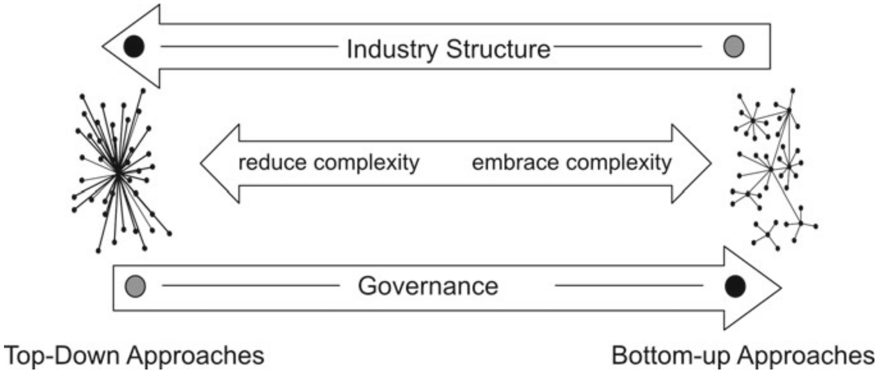


Fig. 5 Approaches to deal with complexity in construction. Light gray dots: the predominant situation today—a misalignment between top-down management and decentralized project organization (loosely coupled networks). The organization can either be adapted towards vertical integration (reducing complexity), or the governance can shift towards bottom-up approaches (embracing complexity)

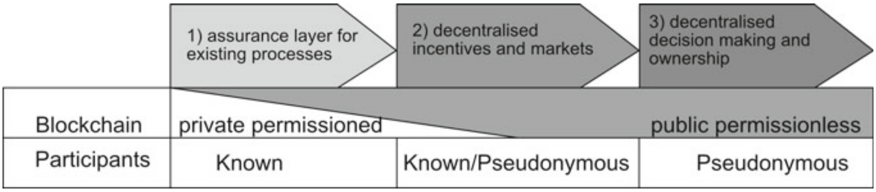


Fig. 6 Three steps of blockchain adoption through a blockchain-based governance lens

7.2 Blockchain Adoption Framework

Even though cryptoeconomic mechanisms are an opportunity to govern a complex construction industry, the industry is unlikely to move all at once towards blockchain-based governance. We imagine a stepwise exploration of blockchain applications, starting from applying the technology to existing processes, potentially adopting more affordances toward new economic systems governed by blockchain-based mechanisms. To lay out a potential pathway for research and industry alike, we introduce an adoption framework through the lens of blockchain-based governance and try to support it with emerging examples (Fig. 6).

7.3 Step 1—Blockchain for Existing Processes

In a first step, blockchain is used as an assurance layer for existing processes in the built environment (Fig. 6). Such use cases rely on blockchain-based governance to ensure confidence in the needed blockchain affordances. Blockchain affordances like immutability and transparency secure transactions, while smart contracts allow for interaction logic if needed (see Fig. 2, trusted digital processes). This can shift trust from relational to system-based and cognition-based, providing stakeholders in the construction supply chain with protection mechanisms to avoid the risk and costs of opportunistic behavior in collaboration [86].

Most current research and implementations fall under this adoption step [9]. Examining more recently published literature [87, 88] confirms this. Below we list the literature that we categorize into this first adoption level.

One of the most prominent affordances of blockchain is tracking and securing data. In its purest form, this means hashing and timestamping data. Research suggests blockchain records for construction-related data for liability control of design data [89], assurance of construction quality information [90–92], versioning and authenticity of construction documents [93], and tracing data from digital twins for accountable project-related [94] and life-cycle related [95] information. Tracking of construction data can then be combined with the automatic execution of construction contract clauses through smart contracts [96, 97].

Many papers also explore the tracing of information in a more specific construction supply chain context to assure reliable information about built assets [98], construction materials, and products [99–101], information in the precast supply chain [102], the facility management procurement process [103], construction logistics in Sweden [104], production of off-site modular housing [105], or for more transparency in construction waste management [106].

Finally, one of the most often mentioned use cases in the current literature is blockchain and smart contract enabled payments to make existing financial processes more transparent, secure, and efficient [107–114].

Since blockchain is applied to existing processes, all participants are generally known. Therefore, also private permissioned blockchains would be possible to use. In fact, they might be even better suited to test applications since they offer more control over the infrastructure, transaction privacy, involve no transaction costs for the user, and are usually faster without the need to use additional scaling solutions. Most of the above research uses a private permissioned blockchain. However, private permissioned blockchains make no use of blockchain governance mechanisms to create confidence in the affordances but rely on trusting the parties operating and running the network. Use cases in the built environment often have long time horizons, so trusting a system that actors can shut down is likely less of an option with real-world implementations and more capital involved. Consequently, we also expect uptake of use cases that rely on public permissionless blockchains as a trusted settlement layer in this first category.

Overall, this first step builds confidence in blockchain as a technology and is needed as a foundation for more advanced use cases leveraging blockchain-based governance for new economic systems through decentralized market structures and incentive mechanisms.

7.4 Step 2—Blockchain-Based Governance for New Incentives and Markets

In a second step, use cases will explore cryptoeconomic incentives to realign the economic interests of existing processes toward better collaboration and new business models (Fig. 6). Tokens and smart contracts (Fig. 2, incentive systems) can be used to move financial rewards, reputation, or ownership across space and time between industry participants to create new economic systems. Such performance and target-oriented incentives can increase cross-phase, cross-trade, and cross-project collaboration towards reducing the impact of fragmentation.

For this second blockchain adoption step, we see considerably less literature related to the construction industry. Some research goes in this direction by exploring how crypto assets can integrate the physical and financial supply chains [115] or enable novel financial mechanisms such as project bank accounts, reverse auction-based tendering for bidding, and asset tokenization for project financing [116]. Also, Tian et al. [117] explored new possibilities to finance infrastructure through tokenization, and Dounas et al. [118] how to use non-fungible tokens (NFTs) to represent physical building components in the digital world.

Related to cryptoeconomic incentives, O'Reilly and Mathews [119] propose blockchain incentivizing multidisciplinary design teams to design for the best possible building performance. Along these lines, Hunhevicz et al. [120] explored performance-based smart contracts to incentivize the design and building for the best possible performance across phases. Producers and owners might provide their built assets with publicly available service contracts on the blockchain, while other service providers and users can evaluate available offers and directly sign these contracts on the blockchain, getting paid or paying for services anonymously and peer-to-peer. Blockchain-based incentive mechanisms are further proposed for complete data sets in construction projects to prevent data loss, incentivize data quality across phases and trades [14], and create new economically profitable use cases to manage and reuse construction waste [121].

We believe that current research only scratched the surface of what will be possible with new tokenized economic systems. And with increasing tokenization, there is also an opportunity to build decentralized market structures for trading and exchanging assets directly between project participants or across projects. But so far, we are not aware of any decentralized marketplace research in a construction context.

With the use of governance on the blockchain for incentives, predominantly permissionless blockchains will be used. Trust at this point has shifted from interpersonal relations to confidence in the deterministic behavior of the technical infrastructure, opening the door for pseudonymous participation in processes. With that, the industry is ready to embrace new forms of decentralized coordination and ownership models that could replace current organizational structures.

7.5 Step 3—Decentralized Coordination Through Blockchain-Based Governance

In a third step, the industry could start to coordinate activities decentralized through blockchain-based governance mechanisms with commons like community governance, potentially in the form of a DAO (Fig. 6). Decentralized coordination can be more scalable and efficient in dealing with complexity aspects of the construction industry compared to current centralized approaches. It can integrate with other emerging technologies such as digital twins to create fast feedback loops for decision-making, potentially similar to concepts of guided self-organization. Public permissionless blockchains allow pseudonymous actors and machines to participate. Ownership and coordination will shift toward flexible and pseudonymous communities, or potentially even towards the built assets themselves.

Even though this sounds futuristic, early research proposes the evolution of AEC organization toward DAOs conceptually [122] and also investigates potential applications for the design, construction, and operation of built assets. These early examples give a glimpse into the possibilities of a future construction industry embracing blockchain-based governance for decentralized coordination.

Lombardi et al. [123] and Dounas et al. [124] envision a new collaboration organized through a DAO for the design process. The envisioned scenario simulates designers proposing multiple solutions for a given task and adopting shape grammars and environmental analysis and regulations as design drivers. Proposed solutions are uploaded, stored, presented, and evaluated in a DAO in which the decision process gets validated via the reputation of the participants and its governance system.

Furthermore, blockchain-based governance mechanisms could facilitate future forms of project delivery models [13]. The argument is based on the theoretical fit between new forms of delivery models such as IPD with CPR theory [125], and the alignment of blockchain-based governance to scale CPR scenarios. The Ostrom principles could be used as a guide to create blockchain-based governance building blocks to manage construction projects in a decentralized way on the crypto-commons [126].

Finally, the ongoing research project *no1s1* explores the concept of *decentralized autonomous space* to create self-owing built assets [127]. The prototype no1s1[2] demonstrates and explores how self-ownership of physical space would allow a self-sustaining and non-rent seeking built environment that could replace current organizational structures. The idea is that funds are owned by the house itself on its own blockchain address, while the decision-making of no1s1 is coordinated through a DAO.

7.6 Discussion

The chapter outlines the value proposition of blockchain-based governance for the construction industry. We are aware that the introduced concepts and the proposed roadmap need further confirmation and refinement. Nevertheless, we felt it is worthwhile sharing this holistic and long-term view to motivate and guide thinking around the development of blockchain use cases.

Overall, we see blockchain-based governance as a well-suited and simple lens to grasp the potential impact of blockchain on the construction industry. It helps to understand the core affordance of blockchain towards new forms of economic coordination, how these are aligned with the construction industry, and how the industry might adopt it. It also provides a novel and alternative way to classify blockchain use cases for the construction industry, focusing on how the applications leverage blockchain-based governance. While we find the focus on blockchain governance helps to grasp the future potential of blockchain in the construction

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[2] www.no1s1.space, accessed October 15th 2021.

industry, it neglects the interdependence with the industry's overall development, both technologically and organizationally.

From a technical viewpoint, the adoption of blockchain-based governance highly depends on the overall technology adoption rate of the industry, as well as the maturity of the blockchain ecosystem. Until now the construction industry has embraced digitalization at a slower rate than other industries [51, 128]. However, there is now hope that the construction industry will see a transformative change with the recent increasing maturity of technical advancements [129]. The new movement is often termed construction 4.0 – embracing industry 4.0 concepts within the construction industry [130–133]. The term industry 4.0 describes the overarching concepts to leverage digital and automation technologies to create interconnected, intelligent, autonomous, and self-learning cyber-physical systems [134].

Cryptoeconomic governance mechanisms for new incentives and coordination depend heavily on the adoption of construction 4.0 concepts. In contrast to other industries such as finance that can be shifted to a mostly digital environment, the construction industry will always build physical products. The interconnection and feedback loops from the physical to the digital world and the integration with existing software stacks need to be ensured. To build effective incentive and coordination systems, data need to reflect the physical state of the project and the asset to be governed. For that, the role of sensors (IoT), virtual reality capturing technologies, and digital twins will play a vital role [94, 120, 135]. Having said that, the construction industry is only at the beginning of its journey towards construction 4.0. According to the industry 4.0 maturity model developed by Reuter et al. [136], the construction industry is only at the initial stage to realize industry-wide information generation (digital models and sensors) and saving generated data accessible to all relevant industry stakeholders across phases, trades, and projects (common data environments).

It needs to be seen at what rate fast and reliable feedback data loops can be realized within the construction industry. Given that this can be achieved in the coming years, there are also many unanswered questions on efficiently connecting and using available blockchain technologies. What data needs to be stored on-chain? How to achieve trusted connections to off-chain data sources? Are existing scaling solutions sufficient for construction use cases? How can the financial transaction costs of blockchains be optimized so use cases become viable? These and many more technical questions need to be addressed towards the vision of blockchain-governed collaboration processes.

From an organizational viewpoint, the emergence of the above-mentioned construction 4.0 concepts comes at an interesting time given industry trends. Industry 4.0 creates opportunities to disintermediate physical supply chains, increase servitization, and create "light" firms with more local and regional assets [137]. By contrast, recent momentum in the construction industry trends toward vertically integrated firms [138] and increased conceptualization of the building as a product ([139], p. 391). The current vision of construction 4.0 seems very much oriented toward the adoption of successful concepts in the manufacturing industry, promising higher productivity levels for construction. Potential bottom-up coordination targeted toward a more decentralized industry structure organized around smaller firms and projects seems somewhat contrarian to this approach. More research should investigate how current visions of construction 4.0, such as platformization and productization, are connected to this vision. How would the construction industry organize through crypto-commons-based community structures and DAOs? Is this an alternative vision to current construction 4.0 roadmaps? Or is it a similar approach, just enabled through many smaller actors rather than big vertically integrated players? To motivate more research toward building decentralized and bottom-up coordination, the industry needs to perceive blockchain as valuable for the overall vision of construction 4.0. It is an opportunity to rethink the organizational relationships of the construction industry in the context of the ongoing cyber-physical convergence [140].

Summarized, we believe that the construction industry is very aligned with the potential of cryptoeconomic governance to overcome collective action problems as in CPR scenarios, potentially in the organizational form of a DAO. Commons-like structures for construction could enable new ways for individuals and communities of practice to contribute to value creation without formal affiliation to a centralized project organization or firm. Business ecosystems that bundle the expertise of highly innovative smaller actors such as individuals and SMEs could also thrive in such an organizational context. They could potentially match presumed benefits of vertically integrated large companies such as reduced transaction costs and inter-project knowledge preservation, without associated disadvantages such as lack of flexibility and high cost of new knowledge acquisition. Decentralized bottom-up coordination supported by cryptoeconomic governance mechanisms could be an alternative vision toward a decentralized construction 4.0 to better deal with its complexity and fragmentation characteristics.

References

1. Davidson S, De Filippi P, Potts J (2018) Blockchains and the economic institutions of capitalism. J Inst Econ 14(4):639–658. https://doi.org/10.1017/S1744137417000200
2. Miscione G et al (2019) Hanseatic governance: understanding blockchain as organizational technology. In: Fortieth international conference on information systems. Munich. https://doi.org/10.5167/uzh-177370
3. Catalini C, Gans JS (2020) Some simple economics of the blockchain. Commun ACM. Assoc Comput Mach 80–90. https://doi.org/10.1145/3359552
4. Tan LJ (2020) Economics and math of token engineering and DeFi : fundamentals of token economics. Economics Design
5. Brekke JK (2021) Hacker-engineers and their economies: the political economy of decentralised networks and "cryptoeconomics." New Polit Econ Routledge 26(4):646–659. https://doi.org/10.1080/13563467.2020.1806223
6. Nakamoto S (2008) Bitcoin: a peer-to-peer electronic cash system. www.Bitcoin.org, p 9. https://doi.org/10.1007/s10838-008-9062-0
7. Ballandies MC, Dapp MM, Pournaras E (2021) Decrypting distributed ledger design—taxonomy, classification and blockchain community evaluation. Cluster Comput 1–22, Springer. https://doi.org/10.1007/s10586-021-03256-w

8. Tasca P, Tessone CJ (2019) A taxonomy of blockchain technologies: principles of identification and classification. University Library System, University of Pittsburgh, *Ledger*, 4. https://doi.org/10.5195/ledger.2019.140
9. Hunhevicz JJ, Hall DM (2020) Do you need a blockchain in construction? Use case categories and decision framework for DLT design options. Adv Eng Inf. Elsevier 45(February):101094. https://doi.org/10.1016/j.aei.2020.101094
10. Allessie D, Sobolewski M, Vaccari L (2019) Blockchain for digital government. Publications Office of the European Union, Luxembourg (Luxembourg). https://doi.org/10.2760/942739
11. Gervais A et al (2016) On the security and performance of proof of work blockchains. In: Proceedings of the 2016 ACM SIGSAC conference on computer and communications security. ACM, New York, pp 3–16. https://doi.org/10.1145/2976749.2978341
12. De Filippi P, Mannan M, Reijers W (2020) Blockchain as a confidence machine: the problem of trust and challenges of governance. Technol Soc. Elsevier Ltd 62:101284. https://doi.org/10.1016/j.techsoc.2020.101284
13. Hunhevicz JJ et al (2020) Blockchain and smart contracts for integrated project delivery: Inspiration from the commons. In: EPOC 2020 working paper proceedings. Engineering Project Organization Society (EPOS). https://doi.org/10.3929/ethz-b-000452056
14. Hunhevicz JJ, Schraner T, Hall DM (2020) Incentivizing high-quality data sets in construction using blockchain: a feasibility study in the swiss industry. In: Hisashi O, Hiroshi F, Kazuyoshi T (eds) Proceedings of the 37th international symposium on automation and robotics in construction (ISARC). Japan (Online): International Association for Automation and Robotics in Construction (IAARC), pp 1291–1298. https://doi.org/10.22260/ISARC2020/0177
15. Buterin, V. (2014a) Ethereum: a next-generation smart contract and decentralized application platform, White Paper. Available at: https://github.com/ethereum/wiki/wiki/White-Paper (Accessed: 27 August 2018)
16. Buterin V (2014b) DAOs, DACs, DAs and more: an incomplete terminology guide. Ethereum Blog 1–10. Available at: https://blog.ethereum.org/2014b/05/06/daos-dacs-das-and-more-an-incomplete-terminology-guide/
17. Mougayar W (2017) Tokenomics—A business guide to token usage. Utility and Value
18. Schär F (2020) Decentralized finance: On blockchain- and smart contract-based financial markets. SSRN Electron J, Elsevier BV. https://doi.org/10.2139/ssrn.3571335
19. Voshmgir BS, Zargham M (2019) Foundations of cryptoeconomic systems. In: Cryptoeconomics working paper series, Vienna University of Economics, pp 1–18. Available at: https://epub.wu.ac.at/7782/. (Accessed: 11 Feb 2020)
20. Ostrom E (1990) Governing the commons: the evolution of institutions for collective action. Available at: https://books.google.ch/books?hl=de&lr=&id=4xg6oUobMz4C&oi=fnd&pg=PA1&ots=aObrwKjEXg&sig=HdhOJ1O3KNjbCKqXJoZLDcwHMWM (Accessed: 2 Mar 2020)
21. Hardin G (1968) The tragedy of the commons, science. Washington^ eDC, 162(3859):1243–1248
22. Ostrom E et al (1994) Rules, games, and common-pool resources. Available at: https://books.google.ch/books?hl=de&lr=&id=DgmLa8gPo4gC&oi=fnd&pg=PR13&dq=ostrom+1994&ots=N5_AooudPD&sig=mXRvQb_xsUq93CnaWjI7ze1duOk (Accessed: 2 Mar 2020)
23. Ostrom E (2010) Beyond markets and states: polycentric governance of complex economic systems. Am Econ Rev 100(3):641–672. https://doi.org/10.1257/aer.100.3.641
24. Ostrom E (2015) Governing the commons, canto classics. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781316423936
25. Gardner R et al (1990) The nature of common-pool resource problems. Rationality Soc Sage Publ 2(3):335–358
26. Cox M, Arnold G, Villamayor Tomás S (2010) A review of design principles for community-based natural resource management. Ecol Soc 15(4):38. https://doi.org/10.5751/ES-03704-150438
27. Ostrom E et al (1999) Revisiting the commons: Local lessons, global challenges. Science. American Association for the Advancement of Science, pp 278–282. https://doi.org/10.1126/science.284.5412.278

28. Shackelford S, Myers S (2016) Block-by-block: Leveraging the power of blockchain technology to build trust and promote cyber peace. SSRN Electron J 334:334–388. https://doi.org/10.2139/ssrn.2874090
29. Werbach K (2020) The siren song: algorithmic governance by blockchain. After the digital tornado: networks, algorithms, humanity, c(2016)
30. Red R (2019) Peer production on the crypto commons. Available at: https://cryptocommons.cc/download/
31. Fritsch F et al (2021) Challenges and approaches to scaling the global commons. Front Blockchain 4(April):1–16. https://doi.org/10.3389/fbloc.2021.578721
32. Machart F, Samadi J (2020) The state of blockchain governance. Available at: https://medium.com/greenfield-one/the-state-of-blockchain-governance-governance-by-and-of-blockchains-f6418c46077
33. Schmidt CG, Wagner SM (2019) Blockchain and supply chain relations: A transaction cost theory perspective. J Purchasing Supply Manage. Elsevier Ltd, 25(4):100552. https://doi.org/10.1016/j.pursup.2019.100552
34. Bollier D (2015) The blockchain: a promising new infrastructure for online commons. Available at: http://www.bollier.org/blog/blockchain-promising-new-infrastructure-online-commons (Accessed: 22 Sept 2020).
35. Rozas D, Tenorio-Fornés A, Hassan S (2021) Analysis of the potentials of blockchain for the governance of global digital commons. Front Blockchain. Front Media SA 4:15. https://doi.org/10.3389/fbloc.2021.577680
36. Rozas D et al (2021) When ostrom meets blockchain: exploring the potentials of blockchain for commons governance. SAGE Open. SAGE Publ Inc. 11(1):215824402110025. https://doi.org/10.1177/21582440211002526
37. Maples MJ (2018) Crypto commons. Available at: https://blog.usejournal.com/crypto-commons-da602fb98138
38. Wang S et al (2019) Decentralized autonomous organizations: Concept, model, and applications. IEEE Trans Comput Soc Syst Inst Electr Electron Eng Inc. 6(5):870–878. https://doi.org/10.1109/TCSS.2019.2938190
39. Hassan S, De Filippi P (2021) Decentralized autonomous organization. Internet Policy Rev 10(2). https://doi.org/10.14763/2021.2.1556
40. Mehar MI et al (2019) Understanding a revolutionary and flawed grand experiment in blockchain. J Cases Inf Technol 21(1):19–32. https://doi.org/10.4018/JCIT.2019010102
41. Faqir-Rhazoui Y, Arroyo J, Hassan S (2021) A comparative analysis of the platforms for decentralized autonomous organizations in the Ethereum blockchain. J Internet Serv Appl, Springer Science and Business Media Deutschland GmbH 12(1):9. https://doi.org/10.1186/s13174-021-00139-6
42. Jacobo-Romero M, Freitas A (2021) Microeconomic foundations of decentralised organisations. In: Proceedings of the ACM symposium on applied computing. Association for Computing Machinery, New York, pp 282–290. https://doi.org/10.1145/3412841.3441911
43. Sheffer D (2011) Innovation in modular industries: Implementing energy-efficient innovations in US buildings. Stanford University. Available at: https://purl.stanford.edu/rq526jy0504
44. Howard HC et al (1989) Summary for policymakers. In: Intergovernmental panel on climate change (ed.) Climate change 2013—The physical science basis. Cambridge University Press, Cambridge, pp 1–30. https://doi.org/10.1017/CBO9781107415324.004
45. Henisz WJ, Levitt RE, Scott WR (2012) Toward a unified theory of project governance: economic, sociological and psychological supports for relational contracting. Eng Project Organ J Eng Project Organ Soc 2(1–2):pp. 37–55. https://doi.org/10.1080/21573727.2011.637552
46. Hall DM, Algiers A, Levitt RE (2018) Identifying the role of supply chain integration practices in the adoption of systemic innovations. J Manag Eng 34(6):04018030. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000640
47. Dubois A, Gadde LE (2002) The construction industry as a loosely coupled system: implications for productivity and innovation. Constr Manag Econ. Taylor & Francis Group 20(7):621–631. https://doi.org/10.1080/01446190210163543

48. Miettinen R, Paavola S (2014) Beyond the BIM utopia: approaches to the development and implementation of building information modeling. Autom Constr. Elsevier 43:84–91. https://doi.org/10.1016/j.autcon.2014.03.009
49. Papadonikolaki E (2018) Loosely coupled systems of innovation: aligning BIM adoption with implementation in dutch construction. J Manage Eng Am Soc Civ Eng 34(6):05018009. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000644
50. Whyte JK, Hartmann T (2017) How digitizing building information transforms the built environment. Build Res Inf, Taylor & Francis 45(6):591–595. https://doi.org/10.1080/09613218.2017.1324726
51. Barbosa F et al (2017) Reinventing construction: a route to higher productivity. McKinsey & Company
52. Bygballe LE, Dewulf G, Levitt RE (2015) The interplay between formal and informal contracting in integrated project delivery. Eng Project Organization J 5(1):22–35. https://doi.org/10.1080/21573727.2014.992014
53. Larson E (1995) Project partnering: Results of study of 280 construction projects. J Manag Eng Am Soc Civ Eng (ASCE) 11(2):30–35. https://doi.org/10.1061/(ASCE)0742-597X(1995)11:2(30)
54. Levitt RE (2011) Towards project management 2.0. Eng Project Organ J Eng Project Organ Soc 1(3):197–210. https://doi.org/10.1080/21573727.2011.609558
55. Lee HW, Tommelein ID, Ballard G (2010) Lean design management in an infrastructure design-build project: A case study. In: Challenging lean construction thinking: What do we think and what do we know?—18th annual conference of the international group for lean construction, IGLC 18, pp 113–122
56. Zimina D, Ballard G, Pasquire C (2012) Target value design: using collaboration and a lean approach to reduce construction cost. Constr Manag Econ Routledge 30(5):383–398. https://doi.org/10.1080/01446193.2012.676658
57. Bar-Yam Y (1997) General features of complex systems. Knowl Manag Organisational Intell Learn Complex I(1):1–10
58. Miller JH, Page SE (2007) Complex adaptive systems: an introduction to computational models of social life. Princeton University Press, Introductory Chapters. https://doi.org/10.1515/9781400835522
59. Helbing D, Lämmer S (2008) Managing complexity: an introduction. In: Understanding complex systems, pp 1–16. https://doi.org/10.1007/978-3-540-75261-5_1
60. Nam CH, Tatum CB (1992) Noncontractual methods of integration on construction projects. J Constr Eng Manag 118(2):385–398. https://doi.org/10.1061/(ASCE)0733-9364(1992)118:2(385)
61. Thórisson KR (2003) Modeling multimodal communication as a complex system. In: Modeling communication with robots and virtual humans. Springer, Berlin, pp 143–168. https://doi.org/10.1007/978-3-540-79037-2_8
62. Gidado KI (1996) Project complexity: the focal point of construction production planning. Constr Manag Econ. Taylor & Francis Group 14(3):213–225. https://doi.org/10.1080/014461996373476
63. Thompson EP (2017) Time, Work-discipline, and industrial capitalism. In: Class. John Wiley & Sons, Ltd, Chichester, UK, pp 27–40. https://doi.org/10.1002/9781119395485.ch3
64. Tsvetkova A et al (2019) Workflow interdependence analysis of projects in business ecosystems. Eng Project Organ J. Available at: www.epossociety.org
65. Bertelsen S (2003) Complexity—a new way of understanding construction. In: Proceedings of the thirteen annual conference of the international group for lean construction, IGLC-13, pp 1–13
66. Tavistock Institute of Human Relations (1966) Interdependence and uncertainty: a study of the building industry. In: Crichton C (ed) Digest of a report from the tavistock institute to the building industry communication research project. Tavistock Pubs, London, UK
67. Davies A, MacAulay SC, Brady T (2019) Delivery model innovation: insights from infrastructure projects. Project Manag J 50(2):119–127, SAGE PublicationsSage CA: Los Angeles, CA. https://doi.org/10.1177/8756972819831145

68. Thuijsman F et al (1995) Automata, matching and foraging behavior of bees. J Theor Biol 175(3):305–316. https://doi.org/10.1006/jtbi.1995.0144
69. Pradelski BSR, Young HP (2012) Learning efficient Nash equilibria in distributed systems. Games Econom Behav 75(2):882–897. https://doi.org/10.1016/j.geb.2012.02.017
70. Helbing D (2014) Guided self-organization—making the invisible hand work (Chapter 4 of Digital Society). SSRN Electron J 1:1–24. https://doi.org/10.2139/ssrn.2515686
71. Helbing D et al (2006) Self-organization principles in supply networks and production systems. In: Econophysics and sociophysics. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany, pp 535–559. https://doi.org/10.1002/9783527610006.ch19
72. Gue KR et al (2014) GridStore: a puzzle-based storage system with decentralized control. IEEE Trans Autom Sci Eng 11(2):429–438. https://doi.org/10.1109/TASE.2013.2278252
73. Mayer S, Furmans K (2010) Deadlock prevention in a completely decentralized controlled materials flow systems. Logist Res 2(3–4):147–158. https://doi.org/10.1007/s12159-010-0035-4
74. Kesting A et al (2008) Decentralized approaches to adaptive traffic control. In: Understanding complex systems, pp 189–199. https://doi.org/10.1007/978-3-540-75261-5_8
75. Marden JR, Ruben SD, Pao LY (2013) A model-free approach to wind farm control using game theoretic methods. IEEE Trans Control Syst Technol 21(4):1207–1214. https://doi.org/10.1109/TCST.2013.2257780
76. Hänggli R, Pournaras E, Helbing D (2021) Human-centered democratic innovations with digital and participatory elements. In: ACM international conference proceeding series. Association for Computing Machinery, New York, pp. 227–233. https://doi.org/10.1145/3463677.3463708
77. Helbing D (2021) Digital democracy (democracy 2.0, 3.0, 4.0). In: Next civilization. Springer International Publishing, pp 249–268. https://doi.org/10.1007/978-3-030-62330-2_12
78. Helbing D, Klauser S (2018) How to make democracy work in the digital age. In: Towards digital enlightenment: essays on the dark and light sides of the digital revolution. Springer International Publishing, pp 157–162. https://doi.org/10.1007/978-3-319-90869-4_12
79. Bertelsen S, Koskela L (2004) Construction beyond lean: a new understanding of construction management. In: … the international group for lean construction, pp 1–11. Available at: http://www.iglc2004.dk/_root/media/13069_055-koskela-bertelsen-final.pdf
80. Baran P (1964) On distributed communications networks. IEEE Trans Commun 12(1):1–9. https://doi.org/10.1109/TCOM.1964.1088883
81. Graser K et al (2019) Social network analysis of DFAB house: a demonstrator of digital fabrication in construction. In: Proceedings of EPOC 2019. Engineering project organization society, pp 1–21. Available at: papers3://publication/uuid/6F6C2895-F3F6–4251-A1F1-A9839FF5D612 (Accessed: 14 Oct 2021)
82. Bouck W (2014) The information economy: a study of five industries, (June), pp 1–23
83. Pullen T, Hall DM, Lessing J (2019) A preliminary overview of emerging trends for industrialized construction in the United States. ETH Zurich Research Collection, Zurich, Switzerland. https://doi.org/10.3929/ethz-b-000331901
84. van Alstyne M (1997) The state of network organization: a survey in three frameworks. J Organ Comput Electron Commer 7(2–3):83–151. https://doi.org/10.1080/10919392.1997.9681069
85. Helbing D (2013) Globally networked risks and how to respond. Nature. Nature Publishing Group 497(7447):51–59. https://doi.org/10.1038/nature12047
86. Qian X (Alice), Papadonikolaki E (2020) Shifting trust in construction supply chains through blockchain technology. Eng Constr Architectural Manag, Emerald Group Holdings Ltd., 28(2):584–602. https://doi.org/10.1108/ECAM-12-2019-0676
87. Li J, Kassem M (2021) Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction. Autom Constr. Elsevier B.V., p 103955. https://doi.org/10.1016/j.autcon.2021.103955
88. Scott DJ, Broyd T, Ma L (2021) Exploratory literature review of blockchain in the construction industry. Autom Constr. Elsevier 132:103914. https://doi.org/10.1016/j.autcon.2021.103914

89. Erri Pradeep AS et al (2021) Blockchain-aided information exchange records for design liability control and improved security. Autom Constr. Elsevier B.V., 126:103667. https://doi.org/10.1016/j.autcon.2021.103667
90. Sheng D et al (2020) Construction quality information management with blockchains. Automat Constr Elsevier B.V., 120:103373. https://doi.org/10.1016/j.autcon.2020.103373
91. Wu H et al (2021) On-site construction quality inspection using blockchain and smart contracts. J Manag Eng. Am Soc Civ Eng (ASCE) 37(6):04021065. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000967
92. Zhong B et al (2020) Hyperledger fabric-based consortium blockchain for construction quality information management. Front Eng Manag. Springer Science and Business Media LLC 7(4):512–527. https://doi.org/10.1007/s42524-020-0128-y
93. Das M, Tao X, Cheng JCP (2021) A secure and distributed construction document management system using blockchain. In: Lecture notes in civil engineering. Springer, Berlin, pp 850–862. https://doi.org/10.1007/978-3-030-51295-8_59
94. Lee D et al (2021) Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. Autom Constr. Elsevier 127:103688. https://doi.org/10.1016/j.autcon.2021.103688
95. Götz CS, Karlsson P, Yitmen I (2020) Exploring applicability, interoperability and integrability of blockchain-based digital twins for asset life cycle management. Smart Sustain Built Environ. Emerald Group Holdings Ltd. https://doi.org/10.1108/SASBE-08-2020-0115
96. McNamara, AJ, Sepasgozar SME (2021) Intelligent contract adoption in the construction industry: Concept development. Autom Constr. Elsevier B.V., 122, p 103452. https://doi.org/10.1016/j.autcon.2020.103452
97. Shojaei A et al (2020) An implementation of smart contracts by integrating BIM and blockchain. Adv Intell Syst Comput 519–527, Springer. https://doi.org/10.1007/978-3-030-32523-7_36
98. Watson R, Kassem M, Li J (2019) Traceability for built assets: proposed framework for a digital record. Available at: http://nrl.northumbria.ac.uk/39912/ (Accessed: 23 July 2019)
99. Copeland S, Bilec M (2020) Buildings as material banks using RFID and building information modeling in a circular economy. In: Procedia CIRP. Elsevier B.V., pp 143–147. https://doi.org/10.1016/j.procir.2020.02.122
100. Lanko A, Vatin N, Kaklauskas A (2018) Application of RFID combined with blockchain technology in logistics of construction materials. In: Ilin I, Kalinina O (eds) MATEC web of conferences. EDP Sciences, 170, p 03032. https://doi.org/10.1051/matecconf/201817003032
101. Shojaei A et al (2021) Enabling a circular economy in the built environment sector through blockchain technology. J Cleaner Prod Elsevier Ltd 294:126352. https://doi.org/10.1016/j.jclepro.2021.126352
102. Wang Z et al (2020) Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Autom Constr, Elsevier B.V., 111:103063. https://doi.org/10.1016/j.autcon.2019.103063
103. Gunasekara HG, Sridarran P, Rajaratnam D (2021) Effective use of blockchain technology for facilities management procurement process. J Facil Manag. Emerald Group Holdings Ltd. https://doi.org/10.1108/JFM-10-2020-0077
104. Kifokeris D, Koch C (2020) A conceptual digital business model for construction logistics consultants, featuring a sociomaterial blockchain solution for integrated economic, material and information flows. J Inf Technol Constr. Int Counc Rese Innovation Building Constr 25(29):500–521. https://doi.org/10.36680/J.ITCON.2020.029
105. Li X et al (2021) Two-layer adaptive blockchain-based supervision model for off-site modular housing production. Comput Ind. Elsevier B.V., 128:103437. https://doi.org/10.1016/j.compind.2021.103437
106. Pellegrini L et al (2020) Digital transition and waste management in architecture, engineering, construction, and operations industry. Front Energy Res Front Media S.A., 8:282. https://doi.org/10.3389/fenrg.2020.576462

107. Ahmadisheykhsarmast S, Sonmez R (2019) (2020) ‘A smart contract system for security of payment of construction contracts.’ Autom Constr Elsevier 120:103401. https://doi.org/10.1016/j.autcon.2020.103401
108. Chong HYY, Diamantopoulos A (2020) Integrating advanced technologies to uphold security of payment: data flow diagram. Autom Constr. Elsevier B.V., 114, p 103158. https://doi.org/10.1016/j.autcon.2020.103158
109. Das M, Luo H, Cheng JCP (2020) Securing interim payments in construction projects through a blockchain-based framework. Autom Constr Elsevier 118(May):103284. https://doi.org/10.1016/j.autcon.2020.103284
110. Elghaish F, Abrishami S, Hosseini MR (2019) Integrated project delivery with blockchain: an automated financial system. Autom Constr Elsevier 114:103182. https://doi.org/10.1016/j.autcon.2020.103182
111. Di Giuda GM, Giana PE, Pattini G (2020) The shortening and the automation of payments: the potentiality of smart contract in the AECO sector. In: Proceedings of international structural engineering and construction. ISEC Press 7(2). https://doi.org/10.14455/isec.2020.7(2).con-12
112. Hamledari H, Fischer M (2021b) Role of blockchain-enabled smart contracts in automating construction progress payments. J Leg Aff Disput Resolut Eng Constr 13(1):04520038. https://doi.org/10.1061/(ASCE)LA.1943-4170.0000442
113. Nanayakkara S et al (2021) Blockchain and smart contracts: a solution for payment issues in construction supply chains. Informatics. MDPI AG 8(2):36. https://doi.org/10.3390/informatics8020036
114. Ye X, König M (2021) Framework for automated billing in the construction industry using BIM and smart contracts. Lect Notes Civ Eng 98(January):824–838. https://doi.org/10.1007/978-3-030-51295-8_57
115. Hamledari H, Fischer M (2021c) The application of blockchain-based crypto assets for integrating the physical and financial supply chains in the construction & engineering industry. Autom Constr. Elsevier B.V., 127:103711. https://doi.org/10.1016/j.autcon.2021c.103711
116. Tezel A et al (2021) Insights into blockchain implementation in construction: models for supply chain management. J Manag Eng Am Soc Civ Eng (ASCE) 37(4):(ASCE)ME.1943–5479.0000939. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000939
117. Tian Y et al (2020) Finance infrastructure through blockchain-based tokenization. Front Eng Manag, Springer Science and Business Media LLC 7(4):485–499. https://doi.org/10.1007/s42524-020-0140-2
118. Dounas T, Jabi W, Lombardi D (2021) TOPOLOGY GENERATED NON-FUNGIBLE TOKENS—Blockchain as infrastructure for a circular economy in architectural design. In: Globa A, van Ameijde J, Fingrut A, Kim N, Lo TTS (eds) PROJECTIONS—Proceedings of the 26th CAADRIA conference—Volume 2, The Chinese University of Hong Kong and Online, Hong Kong, 29 Mar, 1 Apr 2021, pp 151–160
119. O’Reilly A, Mathews M (2019) Incentivising multidisciplinary teams with new methods of procurement using BIM + Blockchain. In: CITA BIM gathering 2019. Available at: https://arrow.dit.ie/bescharcon/31 (Accessed: 11 June 2019)
120. Hunhevicz JJ, Motie M, Hall DM (2022) Digital building twins and blockchain for performance-based (smart) contracts. Autom Constr Elsevier 133:103981. https://doi.org/10.1016/j.autcon.2021.103981
121. McMeel D, Sims A (2021) Chip of the new block (chain): blockchain and the construction sector. Available at: https://d39d3mj7qio96p.cloudfront.net/media/documents/ER62_Blockchain_and_the_construction_sector_LR10482.pdf
122. Sreckovic M, Windsperger J (2020) Decentralized autonomous organizations and network design in AEC: A conceptual framework. SSRN Electron J. Elsevier BV. https://doi.org/10.2139/ssrn.3576474
123. Lombardi D et al (2020) Blockchain grammars for validating the design process. In: Blucher design proceedings. Editora Blucher, São Paulo, pp 406–411. https://doi.org/10.5151/sigradi2020-56

124. Dounas T, Lombardi D, Jabi W (2020) Framework for decentralised architectural design BIM and Blockchain integration. Int J Archit Comput. https://doi.org/10.1177/1478077120963376
125. Hall DM, Bonanomi MM (2021) Governing collaborative project delivery as a common-pool resource scenario. Project Manag J 875697282098244. https://doi.org/10.1177/8756972820982442
126. Hunhevicz JJ et al (forthcoming) Applications of blockchain for the governance of integrated project delivery: a crypto commons approach
127. Hunhevicz JJ et al (2021) 'no1s1 - a blockchain-based DAO prototype for autonomous space. In: Proceedings of the 2021 european conference on computing in construction. university college Dublin, pp 27–33. https://doi.org/10.35490/ec3.2021.185
128. Agarwal R, Chandrasekaran S, Sridhar M (2016) Imagining construction's digital future. McKinsey & Company. Available at: https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/imagining-constructions-digital-future (Accessed: 26 Sept 2018)
129. Singh V (2019) Digitalization, BIM ecosystem, and the future of built environment. Eng Constr Architectural Manage. Emerald Publishing Limited, ahead-of-p(ahead-of-print), p. ECAM-01–2018–0004. https://doi.org/10.1108/ECAM-01-2018-0004
130. Forcael E et al (2020) Construction 4.0: a literature review. Sustain MDPI AG 12(22):9755. https://doi.org/10.3390/su12229755
131. García de Soto B et al (2019) Implications of construction 4.0 to the workforce and organizational structures. Int J Constr Manage 1–13, Taylor and Francis Ltd.. https://doi.org/10.1080/15623599.2019.1616414
132. Klinc R, Turk Ž (2019) Construction 4.0—Digital transformation of one of the oldest industries. Econ Bus Rev 21(3):292–410. https://doi.org/10.15458/ebr.92
133. Sawhney A, Riley M, Irizarry J (2020) Construction 4.0. In: Sawhney A, Riley M, Irizarry J (eds) Routledge. https://doi.org/10.1201/9780429398100
134. Lasi H et al (2014) Industry 4.0, business & information systems engineering. Springer Fachmedien Wiesbaden 6(4):239–242. https://doi.org/10.1007/s12599-014-0334-4
135. Hamledari H, Fischer M (2021a) Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. Autom Constr Elsevier 132:103926. https://doi.org/10.1016/j.autcon.2021.103926
136. Reuter C et al (2016) Industrie 4.0 audit, *VDI-Z*. Available at: https://www.vdi-z.de/2016/Ausgabe-06/Forschung-und-Praxis/Industrie-4.0-Audit
137. Brun L (2019) The "lightness" of industry 4.0 lead firms: implications for global value chains. In: Transforming industrial policy for the digital age. Edward Elgar Publishing, pp 37–67. https://doi.org/10.4337/9781788976152.00008
138. Hall DM, Whyte JK, Lessing J (2020) Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study. Constr Manag Econ. Routledge 38(4):322–339. https://doi.org/10.1080/01446193.2019.1656814
139. Fischer M, Garcia-Lopez NP, Morkos R (2018) Making each workhour count: improving the prediction of construction durations and resource allocations. In: Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics). Springer, Berlin, pp 273–295. https://doi.org/10.1007/978-3-319-91635-4_15
140. Maciel A (2020) Use of blockchain for enabling Construction 4.0. In: Construction 4.0. Routledge, pp 395–418. https://doi.org/10.1201/9780429398100-20

Decentralised Autonomous Organisations for the AEC and Design Industries

Davide Lombardi and Theodoros Dounas

Abstract The chapter presents the concept of Decentralised Autonomous Organisation (DAO) and discusses what the current and possible applications are in relation to the AEC, design and design-linked industries. The chapter first introduces theoretical aspects of traditional organisations and then develops the ones behind the creation of automated, computer-based ones. Consensus mechanisms and smart-contracts integration are also presented in conjunction with diffused systems of DAOs' regulation. Scenarios are presented where DAOs are applied as a coordination tool for competitive and collaborative use within the design field. A comparison table of Ethereum-based DAOs as well as reflections on the pros and cons of DAOs applications are provided to better frame what the current boundaries are of a technology that is also expanding its range of utilisation thanks to the interest of town councils and institutions.

1 Introduction

Decentralised Autonomous Organisations (DAOs) can be described as completely transparent organisations run by automated programming codes and operated by the members of the organisation itself. In order to achieve and retain those characteristics, DAOs require to be built and supported by an infrastructure allowing automation, shared control and validation of decisions and actions, as well as participation. A suitable infrastructure for this purpose has been found in the combination of two emerging technologies: Distributed Ledger Technologies (DLT)/Blockchain (BC) and Smart Contracts (SC). The first allows, thanks to their distributed nature, to share across all participants the power of decision-making as well as ensuring that

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all decisions and actions are transparently recorded; the second instead are automated codes that run when certain conditions are met.

Beyond the narrow technical description, DAOs represent a form of governance that can be in theory applied to any sort of organisation, public or private, lucrative or no-profit, with their governance model scaling to the level of theoretically substitute entities like town councils and even governments.

The recent rise of DAOs and their development finds [1] its roots in the discourse concerning the limits of current governance schemes, which have been almost intact for centuries, and the opportunity provided by the Internet in terms of connecting people, fostering collaboration and, with the implementation of DAOs and BC, creating and ensuring trust via transparent processes, that are then supported by automation, distribution and uniqueness of information.

In the early stage of history, humans used to live in small isolated groups, with little or no contact with others and living in a pretty much self-sufficient way.

With the introduction of agriculture and the shift towards a more organised living system, humankind faced the necessity of creating media for large groups of individuals and started basic collaborations for defence, food production and supply, commercial purposes; it appeared natural that also some sort of more structured arrangement and hierarchy was necessary in order to coordinate and govern people activities.

As a result, pyramidal structures with robust top-down approaches became and remained the most diffused, if not the only way for people to live and operate together in a coordinated manner. Alongside individuals, a number of central organisations, often ruled by few selected people, were created over the centuries to manage the more diverse activities: banks for controlling currencies and financial exchanges, governments for ruling empires and nations, companies for managing the workforce and producing wealth to be somehow redistributed. Through the time, legitimacy was then gained in different ways based on the nature and scope of each specific form of organisation: via elections and representation for example in the case of democratic governments, or via the trust refunding loans in the case of the initial forms of banks and insurances.

This approach, which has been tested through centuries demonstrating to be effective but far away from being perfect, relied chiefly on the relation between two kinds of entities, the agents and those who get represented by them, as well as on the intrinsic trust between the two parties. Referring to politics, democracy and parliaments can be taken as a perfect example of this symbiosis, where a restricted number of agents, Members of Parliament, represent those who technically hold and enforce the power via voting, citizens.

Furthermore, what was described above found further support in the limited possibility of people to connect with and trusting others, which can be related to the concept drafted via the well-known Dunbar's number [2]. By acknowledging that each person can only well remember and trustfully interact with no more than 150 people, it appears immediately clear how, in a society counting millions of members, concentrating the power of decisions via layers where the number of points of control is further reduced appears to be like the only feasible solution to maintain social order.

In this scenario, the transfer of power from a majority of people to a selected minority helped to streamline and to take fast decisions; however, it also presented significant drawbacks when it came to agents taking excessive risks or acting for their own interest rather than for the collective's one.

While the above scheme remained unchanged for centuries, other fields which can be generically encompassed under the term information technology have seen advances that led people to slowly create tools that could represent a new way to organise societies. Starting from the past, one could refer, for example, to the invention of the press and the movable type, which created the concept of an expanded distribution of knowledge and data with potentially no limits in terms of numbers of reachable people and amount of sharable data.

The introduction of the Internet and its capacity to reach each corner of the planet and grant access to information and services to everyone dramatically shifted this concept covering all aspects of our daily life. With the spread of internet connections and the World Wide Web all over the world, and the combination of even more recent and powerful tools such as blockchain and smart contracts, the possibility of shifting the paradigm from a people-based trust (and overcoming the limitations of the Dunbar number) to technology-based trust became real and opened up to the opportunity of moving again towards a more decentralised way of living, where control is no longer kept within the boundaries of few people and institutions.

While this can occur as an idealistic or utopian view of coordinating a large number of people's life and activities, it is also interesting to note how city governments in different parts of the world are now looking into the implementation of DAOs and crypto technologies in their operations, creating new kind of incentives as well as providing platforms to support the more variegated initiatives. To some extent, those initiatives may recall the attempts taking place during the 70 s to create decentralised governance systems in the east of Europe, which clashed against the highly centralised government of the Soviet apparatus [3].

2 DAO Platforms

We present a simple classification of existing DAOs platforms on Ethereum. Note that in a true decentralised sense, blockchains themselves can be considered the first primitive form of a DAO as to maintain a blockchain one needs the coordination of a multitude of agents and their incentivised participation and maintenance of the computer network via consensus.

	Gnosis multisig	DAOstack	DAOHaus/Molloch	Aragon	Colony	Compound governance
Token	Ethereum*/xDai	GEN	Ethereum*/xDai	ANT	CLNY	COMP
Consensus	–	Holografic	Majority/Rage quitting	Multiple modes	Lazy consensus	–
Governance type	Consensus/majority	Consensus—Holografic	Consensus/Majority	Multiple	Cooperation	–

(continued)

(continued)

	Gnosis multisig	DAOstack	DAOHaus/Molloch	Aragon	Colony	Compound governance
Incentive—structure	–	GEN and reputation	Increase in value in DAO holdings	Multiple	Reputation	Increase in value in DAO holdings

3 DAOs Projects and Explorations in the AEC and Design Industry

Starting from the description of DAO that can be found in Buterin's words, "[…] a DAO contains some kind of internal property that is valuable in some way, and it has the ability to use that property as a mechanism for rewarding certain activities […]" [4], a question arises about what impact can have the concept of DAOs within the Architecture, Engineering and Construction (AEC) industry and what can be intended as internal property in that sector.

While it is widely acknowledged that business models and practices are facing a transformation due to the impact of blockchain technology [5, 6], this cannot be directly and immediately applied also to a field such as AEC, that is well-known for being reluctant to changes and slow in implementing innovation, with architects and designers mostly presenting themselves as the sole authors of concepts and designs [7]. As a result, a few theoretical and practical projects can be found exploring the potential of combining DAOs into AEC daily operations, with examples related to this field which also come from stakeholders apparently not directly connected with the building industry.

Proposals for the application of DAOs in the early design stage have been explored by envisioning them in both competition and cooperation scenarios, simulating designers who collaborate or compete to create new shape grammars assessed via a voting system deployed into the DAO. The voting system encompassed both qualitative and quantitative aspects, keeping into consideration the experience and knowledge of the participants [7, 8]. Further development of this approach has been later applied against more objective criteria such as building regulations and environmental analysis: application of generative design and shape grammar has been tested as a proof-of-concept for a system, where competitors produce solutions that are then shared on the DAO via IPFS system [9].

Sreckovic et al. [10] discuss how the DAO can contribute to enhancing trust and value in the workflow of the AEC industry by referring to the need of applying a system where knowledge and expertise, decisional power and blockchain can be integrated; however, the DAO application appears mostly confined to the level of the operations while keeping the innovation and coordination stages centrally coordinated.

An exploration of self-owned built space by Hunhevicz et al. [11] expands the concept of DAO to the one of DAS (Decentralised Autonomous Space) conceptualising a small meditation pod that is fully autonomous from the point of view of creation, management, finance, operation and maintenance. Being one of a kind attempts of connecting DAO' s-based governance system with the physical world via IoT devices, it opens up to future scenarios where buildings are self-owned, the concept of rent shifts towards self-maintenance only costs and, more notably, the entire set of operations from collecting funds to spend for necessary maintenance is controlled via predefined scripts running on the blockchain.

Decentralised organisations are also currently taking place in areas that are somehow close to the design and architecture industry but still not yet developed in a way in which impact can be recognised in the real-world practice but possibly drafting what the future will be. Examples of DAOs such as the platform Decentraland tries to combine elements of well-known gaming environments such as Minecraft and SecondLife with the proper aspects of a DAO in terms of tokens and decentralised government. Land can be bought and sold, as well as virtual goods, artists and content creators can be contracted to further personalise the owned plot or house, decisions can be taken, and policies updated via the decentralised governance interface but still under the umbrella of control of a so-called Security Advisory Board [12]. The example of Decentraland, which makes deep use of a gamified environment also to attract users, addresses questions like the proof of ownership, which can be applied to many aspects of both real and virtual life, but that can be connected to the AEC industry in terms of ownership of lands.

While Decentraland is mostly a platform where the fantasy of the users represents the only limit to expansion, the same concept of proof-of-ownership is applied in emerging countries, i.e., Ghana, for people to claim and demonstrate being the owners of plots of land bypassing costly registrations (which are often not available due to lacks in cadastral practices) and the standard verbal agreements between parties which are not traceable [13, 14].

As it often happens, art is ahead of the game in applying cutting-edge technologies and exploring new ways of making, as happened with the Plantoid project run by Primavera De Filippi [15, 16]. The project is based on a series of art pieces that exist both physically as well as digitally as a blockchain-based form of life. Each planetoid, physically represented by a mechatronic kind of sun-flower, embeds the concepts of autonomy, self-sustainability and ability of self-reproduction thanks to smart contracts deployed in the Ethereum blockchain and interactions with humans which feed them via bitcoin donations. Donations are later used to hire and fund artists to produce new art pieces that will ensure the reproduction process. Besides being an experiment that challenges people's understanding of what life is and what the extents of human–machine interactions on a DAO are, the research project tackles the limitations of copyright laws in the time of digital design and blockchain, providing at the same time new grounds for expanding the concepts of contractual relationships between people and companies as well as people and machines.

Others and possibly more interesting applications and experiments on DAOs are, on the other hand, running by the initiative of local governments. At the date of this text, city governments of Miami, Reno, Busan, Seoul are all looking into how DAOs and blockchain applications can either improve their current operations or to create new pathways to achieve more citizens oriented and driven goals.

Seoul is planning to launch its own crypto-currency to sustain and incentivise both private start-ups as well as public welfare initiatives, at the same time pushing for a full set of new national laws to be issued in order to regulate and simplify the access to such technology.

Busan is pioneering a vast application of blockchain-based services (spanning from tourism, to retail and finance to supporting local artists via NFTs) via its Blockchain Regulation Free Zone, and with the support of the town government. Applications have been already in place in terms of personal ID management to have access to services, as well as vouchers backed up by the local bank and to be used as a normal currency.

Miami incentives citizens and city supporters to mine within the frame of the MiamiCoin (as part of the CityCoin ecosystem) in order to support the city itself and get a revenue, either as BitCoin or Stacks. It is worthy to mention that 30% of the revenue is automatically transferred to the city wallet and that the funds can be used for any kind of purpose the city deems fit, apparently without a direct connection to specific projects which could be discussed and voted on a DAO.

In terms of impact on the shape and functioning of our cities, automobile manufacturers such as General Motors and Honda may also have an impact with their ongoing research on a common standard for the application of BC on a smart grid providing a charging network for electric vehicles [17]. This would potentially affect the way in which cities may be designed or upgraded in order to accommodate a new full set of devices to support the existence of a new digitalised layer for mobility.

4 Benefits and Drawbacks in DAOs

Traditional companies and organisations, either in simple or more complex forms, are associated with the fact that operations and members' roles and activities are regulated by legal contracts, which define duties and rights and which are enforced via the legal framework of the country they are registered in. Disputes are determined in front of a court of law that acts as an independent third party which is, by default, the trust of the ones disputing.

Decentralised Autonomous Organisations are instead operated by people respecting rules which are written in an automated open-source protocol running on a network. The task of maintaining the network operative and active is rewarded by an incentive-based system that has its roots in the network tokens native to the DAO itself. Protocols and tokens are deployed and run on the blockchain, smart contracts act as a further layer of automated cooperation between the involved agents, leveraging coding and automation to regulate the life of the DAO and to align the interest of the participants via consensus mechanisms.

Consensus mechanisms are the real core behind any blockchain application, with DAOs not being an exception. Its role, as per its definition, is to regulate the way in which decisions are taken amongst the participants of the DAO, or more in general, how to agree on a certain record of a computation activity [18]. Different applications can have different ways to reach consensus, such as change of state (i.e. Ethereum) or continuous update of the list of transactions (i.e. Bitcoin). However, once the mechanism is defined, a question still remains about how to accept computers, hence users, to participate to the consensus process. Previously, solutions were found in what can be considered a more traditional and permissioned approach, where closed infrastructures such as an intranet were applied. Thus, losing or yet not taking advantage of the full potential of such kind of technology.

The current concept of public permissionless blockchain instead, which can be seen as a mirror of what the Internet is nowadays, hence a system where anyone can connect and start communicating with strangers without the need of a previous identification, relies on a level of openness that make BC and DAOs applications potentially applicable to any kind of business and able to coordinate and to be scaled to encompass a large number of participants.

A further layer of discussion is added by the possibility of reaching consensus (as well as other operations) off-chain [19]. While this can appear as a betrayal of one of the main concepts behind BC technology, transparency, it has to be noted how keeping all the computations in the layer 1 blockchain may become too heavy and slow down at the same time single operations and general growth of the organisation. Storage, consensus and computation can be pushed out from the BC with evident pros and cons in terms of time, cost and data integrity. Off-chain data storage brings positive aspects like privacy of the data, when necessary, and alleviating the BC from the burden of redundant storage requirements [20]. On the other end, data availability is no longer ensured hence potentially interrupting the operations if data are not reachable, as well as their integrity can only be assessed when they are available.

Consensus strategies can be run off-chain and currently two major approaches can be described: the approach developed within Bitcoin, where miners are requested to reach consensus and later add blocks into the public chain (which can be seen as a non-fully decentralised approach to authority and consensus), and applications where the consensus is sought and reached off-chain with the aim of reducing the operational costs for the participants. In the latter case requests from participants are emitted as signals to off-chain miners that perform the computational tasks and send back their responses.

In both the above scenarios, the IPFS (Inter Planetary File System) is playing an important role being the open infrastructure acting either as storage space or via its pub-sub functionality, which makes it possible to create off-chain dedicated space, where seeking for consensus, while communicating with interested participants.

DAOs participants do not sign any contract nor are tied to a legal entity. The driver feeding the existence of the DAO is the incentives provided in the form of net-work tokens, regulated by the transparency of the rules represented by the source code of the software running the DAO itself. Agreements are not made between a single or group of participants; the protocol or specific smart contracts encapsulate the governing rules and regulates all the transactions taking place in the DAO.

Thanks to the automated and transparent nature of their roles, as well DAOs are no longer structured in a top-down scheme with the CEO on the top, a body of managers and employees. The pyramidal structure is replaced by a horizontal one, where contributors are ideally all on the same level and steer towards agreed goals via the selection processes supported by the consensus mechanism. By operating in this way, DAOs can be joined and open to people from different areas of the world (hence under different companies' regulations) who do not know each other but still rely on a system ensuring trust.

Moreover, the code which regulates a DAO cannot be changed or censored by one single participant nor by its own creator. Only a pre-established majority and under specific consensus conditions can modify the original code.

As described, a DAO carries the characteristics of being open-source and transparent, hence on paper incorruptible. All the transactions are stored on the blockchain, with the participants' interests coordinated by the incentive scheme linked with the DAO native token. The main way to decide in a DAO is by entering a proposal that will be voted by the participants and approved if they reach the majority of the consensus. As said, the actors may not share any physical space nor know each other, hence DAOs can be seen as a distributed entity with autonomous rules and lives, at the same time relying on experts to achieve certain tasks which otherwise could not be automated.

The Bitcoin Network can be seen as the first and so far, more resilient decentralised autonomous organisation created around a free consensus protocol. It resisted to any sort of fault and attack since the appearance of its first block keeping its mission to provide a platform for money transaction, which runs completely outside the control of any central bank. The existence of the Bitcoin network is so far assured by its contributors, which are incentivised by the token system, which also allows for a fully automated and transparent coordination.

The Ethereum network shifted the potentials of DAO running on the blockchain to the level of smart contracts, exponentially opening up to possible applications. Smart contracts simplified the operations to set up a DAO with the only need of a few lines of code and mostly removed the necessity of setting up a proper blockchain network.

DAOs present then a number of benefits due to their intrinsic nature, such as coordinating participants who do not know each other in a manner that leads to achieving certain results, keeping a record of contribution to a project which can be carried out in a collaborative or competitive way (much useful in the context of design), creating human–computer or human–objects interactions via external IoT applications and SCs [21].

The novelties and benefits provided by DAOs have been so far mostly related to financial applications, specifically with the evident benefit of preventing frauds and possible fund mismanagement carried out by delegating power to single points. Decisions and rules are enforced via codes that automate the operation of the institution itself, allowing the possibility of limitless and theoretically timeless expansion to new members and proposals. The current standard workflow of a DAO sees users submitting proposals that are voted and, if approved, they go to the next stage of getting funded via tokens or to the next step of the life of the proposal. Embedding SC in the process, hence removing almost completely any arbitrary aspect of human interaction, appears an even most secure way to operate.

In terms of voting systems, currently, there are different ways in which proposals get voted and either passed or rejected, with a range of techniques spanning from the more familiar quorum voting to those embedding stock-exchange inspired approaches.

Quorum voting is based on a predetermined threshold above which a proposal can have the opportunity to pass. It represents the most well-known and common system of voting since it has been implemented as one of the basic tools of the democracy since this concept exists. As in real-life democratic processes the defined threshold has to be carefully assessed in order to ensure that the final decision actually reflects the will of the majority of the community [22]. In the case of DAOs a low quorum may lead to an easy-to-pass system and, as a consequence, an easy-to-attach DAO. On the other hand, high quorums may lead to very few proposals to advance, hence the need for incentives as well as to allow more time for the voting process.

Holographic Consensus brings a component borrowed from the stock exchange processes into the voting system. It allows people to predict which proposal will pass in a similar manner in which brokers can predict which stock option will increase or decrease the value in the stock exchange market. If the prediction is correct, predictors gain a financial reward and the involved proposals are then no longer assessed via a quorum voting but via a simpler relative majority. The whole system is based on the possibility and will of predictors to stake vote on this or that proposal, hence by staking funds on them. Since the HC is based on funds it automatically cut off, all of those who are not really interested in the proposal or, in a worse scenario, those who aim at tampering with the system by misleading the vote.

As mentioned before, relative majority comes into place as one of the voting systems, nevertheless it is never used as a single and autonomous way of voting. Its simplified nature where even one single vote is enough to take a decision would expose the organization to high risks of getting attacked if other members of the DAO are not looking into the voting process. To overcome this situation, DAOs also implemented a sponsor-based approach that acts as an anti-chamber of the real vote. Proposals need to be first sponsored by members of the DAO before going into the voting stage. This voting system is pretty simple to be implemented and does not require many activities from the members.

All the previously described voting strategies have in common the characteristics of being based on an A versus B approach and that the voting takes place in a definite time with a definite result, A wins over B or vice versa. Conviction voting instead brings two more components into the voting system: the time and the possibility of diversifying one support. Rather than asking members of the DAO to decide between two options, they are allowed to stack their voting power on one or more proposals and their preference can change over time, so that proposals can accumulate or lose support. The more one proposal is supported the more its weight grows as well as its chances to get finally approved. The CV simulates somehow bio-inspired processes [23] of growth and decay, and with this approach aims to prevent large stakeholders from suppressing minority voters.

Lastly, the so-called “lazy consensus” mechanism allows proposals to get approved if no one objects to them. In case of objections, further steps may take place, such as a reputation-based vote, in order to decide how to proceed.

Current DAOs are developing more robust safety systems to protect investors and stakeholders from users with intents that go against the community. However, drawbacks are still recognisable in a system that relies on codes written by humans, hence perfect in running the operations they have been written for but possibly wrong in their overall scope due to lack in coding knowledge or more deliberate ability to write codes for purposes which are beyond the common good.

To some extent, one could argue that having the responsibility of each action distributed across the entire DAOs and its participants means inherently that no one is accountable for the DAOs decisions. Furthermore, the immutability of BC, which represents its most great quality, also represents a limit when it comes to the time of updates and bug fixing, which are the norm when dealing with information technology-based tools. A possible way to balance between the above aspects that characterise the current state of the art among DAOs could be by relying on them only for handling certain decisions and operations which do not require a full blind trust in a code, or more in general, for DAOs where the sole governance and interface for decision making is a public permissionless blockchain.

References

1. Gitcoin Report (2021) DAOs—The new coordination frontier (2021). https://opensea.io/collection/daos-coordination-frontier. Accessed Jan 2022
2. Dunbar RIM (1992) Neocortex size as a constraint on group size in primates. J Hum Evol 22(6):469–493. https://doi.org/10.1016/0047-2484(92)90081-J
3. Illner M, Wollmann H (2003) Decentralization: lessons for reformers. In: Baldersheim H, Illner M, Wollmann H (eds) Local democracy in post-communist Europe. Urban research international, vol 2. VS Verlag für Sozialwissenschaften, Wiesbaden. https://doi.org/10.1007/978-3-663-10677-7_14
4. Buterin V (2014) DAOs, DACs, DAs and more: an incomplete terminology guide. https://blog.ethereum.org/2014/05/06/daos-dacs-das-and-more-an-incomplete-terminology-guide/. Ethereum Blog. Accessed Aug 2021
5. Adams R, Parry G, Godsiff P, Ward P (2017) The future of money and further applications of the blockchain. Strateg Chang 26(5):417–422. https://doi.org/10.1002/jsc.2141
6. Li J, Greenwood D, Kassem M (2018) Blockchain in the construction sector: a socio-technical systems framework for the construction industry, advances in informatics and computing in civil and construction engineering. In: Proceedings of the 35th CIB W78 2018 conference: IT in design, construction, and management, pp 51–57
7. Dounas T, Lombardi D (2019) Blockchain grammars—Designing with DAOs—The blockchain as a design platform for shape grammarists’ decentralised collaboration. In: “Intelligent & informed” CAADRIA 2019 international conference, 12–14 April 2019. Victoria University, Wellington, New Zealand

8. Dounas T, Lombardi D, Jabi W (2021) Framework for decentralised architectural design BIM and Blockchain integration. Int J Archit Comput 19(2):157–173. https://doi.org/10.1177/1478077120963376
9. Lombardi D, Dounas T, Cheung LH, Jabi W (2020) Blockchain for validating the design process. In: "Transformative Design" SIGraDI 2020 international conference, 18–20 November 2020 (Universidad Pontifica Boliviana, Medellin, Colombia)
10. Sreckovic M, Windsperger J (2019) Decentralized autonomous organizations and network design in AEC: A conceptual framework. Available at SSRN: https://ssrn.com/abstract=3576474 or http://dx.doi.org/10.2139/ssrn.3576474
11. Hunhevicz J, Wang H, Hess L, Hall D (2021) no1s1—a blockchain-based DAO prototype for autonomous space. In: European conference on computing in construction. https://doi.org/10.35490/EC3.2021.185
12. Dedezade E (2020) Why decentraland is more than minecraft with crypto, https://decrypt.co/20141/why-decentraland-is-more-than-just-minecraft-with-crypto. Accessed Aug 2021
13. Miller M (2020) Bitland: property rights for the world's poor, https://borgenproject.org/tag/bitland/. Accessed Mar 2021
14. Aitken R (2016) Bitland's African blockchain initiative: putting land on the ledger, https://www.forbes.com/sites/rogeraitken/2016/04/05/bitlands-african-blockchain-initiative-putting-land-on-the-ledger/?sh=7a4e537f7537. Accessed Mar 2021
15. Mustatea K (2018) Meet plantoid: blockchain art with a life of its own 2018, https://www.forbes.com/sites/katmustatea/2018/01/31/meet-plantoid-blockchain-art-with-a-life-of-its-own/?sh=5f54ffc53f64. Accessed Apr 2021
16. Hassan S, De Filippi P (2021) Decentralized autonomous organization. Int Policy Rev 10(2):2021
17. Haig S (2020) GM and Honda publish specs for decentralized electric car charging network, https://cointelegraph.com/news/gm-and-honda-publish-specs-for-decentralized-electric-car-charging-network. Accessed Nov 2020
18. Van Valkenburgh P (2017) What does "permissionless" mean? https://www.coincenter.org/education/advanced-topics/what-does-permissionless-mean/. Accessed March 2021
19. Ellul J (2021) Blockchain, decentralisation and the public interest: The need for a decentralisation conceptual framework for d apps. IPS J 1(1)
20. Mota M (2019) Evolution of blockchain components to off-chain models, https://medium.com/@miguelmota/evolution-of-blockchain-components-to-off-chain-models-ca3649fe2c83#:~:text=Off-chain%20computation%20reduces%20to%20high%20extent%20redundant%20computations,the%20deterministic%20output%20of%20the%20state%20transition%20function. Accessed May 2021
21. Kim JS, Shin N (2019) The impact of blockchain technology application on supply chain partnership and performance. Sustainability 11:6181. https://doi.org/10.3390/su11216181
22. Arsenault E (2020) Voting options in DAOs, https://medium.com/daostack/voting-options-in-daos-b86e5c69a3e3. Accessed Feb 2021
23. Emmet J (2019) Conviction voting: A novel continuous decision making alternative to governance—A commons stack component explainer, https://medium.com/giveth/conviction-voting-a-novel-continuous-decision-making-alternative-to-governance-aa746cfb9475. Accessed Dec 2021

The Integration of Automatic BIM Validation and Smart Contracts for Design Compliance and Payment Reliability in the Design Process

Giulia Pattini, Giuseppe Martino Di Giuda, and Lavinia Chiara Tagliabue

Abstract The research aims at streamlining the execution of the design phase by combining the automatic BIM validation and smart contracts. The construction industry is generally reluctant in accommodating new technologies, but with the promise of transforming information management, Building Information Modelling (BIM) is currently leading its digitalisation. Despite that, its adoption showed issues of information integrity and reliability. Misunderstanding about information requirements can cause delays, unforeseen costs and need for reworks. For these reasons, the chapter suggests the integration of information management based on BIM and blockchain, highlighting their prospective bond. The chapter illustrates the framework of the research that applies the automatic BIM validation and smart contracts in the design phase, pointing out their potential impact on the automation of information review, reduction of late deliveries and overdue payments. The architecture of the potential technological tools is presented and discussed. The research proposes a data-driven process, where all the essential information related to the design verification is recorded and where, at the automatic validation of each BIM model, the approval of payment release is issued automatically. The system intends to ensure full compliance with project information requirements and protect the contracting parties against potential late payment. The framework is still theoretical, however, the expected outcomes from its future test through a proof of concept are finally discussed.

Keywords Information management · Information validation · Design automation · Blockchain · Smart contracts · BIM · Payment reliability

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1 Introduction

Since the construction sector is among those with the lowest degree of digitalisation, innovative methodologies and tools are identified as the drivers for the transformation of the traditional approach and the improvement of efficiency [1]. The digital transformation, therefore, appears to be the first impulse for change [2], and, in particular, the introduction of Building Information Modelling (BIM) has supported transparent project development, through the information management based on structured procedures and protocols. The production, review and maintenance of information in a structured digital environment foster exhaustive information sharing and collaboration among participants (see Sect. 2.1) [3, 4]. With the promise of optimising the digital information management, BIM has led the growth of the digitalisation recently observed in the construction industry. Its implementation primarily aims at improving information definition and exchange. Secondly, it targets at eliminating the traditional information asymmetry that hinders compliance with requirements, transparent information sharing and consistency among the project documents. Despite the expectations, the adoption of BIM has shown problems related to the management of a considerable information flow. In particular, the issues are related to the attribution, reliability, integrity and accuracy of information exchanged during the process [2]. Misunderstandings or ambiguities in the information requirements and produced information can cause delays, the need for reworks, and, consequently, unforeseen costs. [5, 6]. Recently, the existing literature has identified the application of blockchain technology as a stimulating area of research and testing in the construction industry [3, 7, 8]. Further studies have also identified smart contracts as a valuable tool for optimising and automating some activities and payment systems [9, 10]. For these reasons, among the technological innovations that can positively enhance the digitalisation sector, the presented research proposes digital information management based on blockchain for entailing the reliability of information and for shortening and automating the process development through the use of smart contracts [11, 12]. Despite the hurdles, BIM is currently the most suitable solution for the collaborative and structured production, validation and management of information. Thus, blockchain can be a possible answer to the problem of information asymmetry and reliability in the design, tender, construction and maintenance phases [13, 14]. Besides, the deployment of smart contracts ensures the programming and automatic execution of specific activities.

Concerning these premises, the proposed framework of the research, through its future tangible development, intends to investigate the digital information management using BIM and blockchain to highlight their potential and useful link within the current digitalisation of the processes in the construction sector. In particular, the research objectives focus on both how the integration of blockchain in the information management using BIM could ensure the trustworthiness of information and how the integration between the automatic BIM validation and the implementation of smart contracts could shorten the time needed to carry out a specific work phase. Indeed, the automatic approval of the design through the integrated use of the automatic

BIM validation and smart contracts could optimise the efficiency of the process by reducing late deliveries, due to the waiting times for the approval, and late payments, due to reworks or changes.

The ambition to propose and develop a framework of the research that combines the automatic BIM validation and smart contracts to shorten the execution time of the design phase by automating approval procedures, is sustained by the analysis of European and Italian reports [15, 16]. Firstly, late payments and long payment terms represent a challenge for the entire European economy, causing administrative and financial burdens, which can lead to disputes that affect business growth. Across the European Union, the construction sector appears to suffer the most from late payments [16]. Differences in payment behaviour undermine the proper functioning of the industry and threaten increasingly the survival of the small and medium-sized enterprises (SMEs) [16, 17]. Certainly, the nature of the construction industry contributes to the unfair length of payment terms and the high number of delays. In particular, the causes of late payments are often directly linked to the behaviour of the construction companies and, in some cases, of the public authorities working with consultants. Faced with this situation, late payments have gained increasing attention among policymakers and private sector associations. Focusing on the Italian construction sector, a country-specific analysis reveals that public authorities in the industry tend to have longer than average payment terms, hence affecting the liquidity of consultants and companies. In 2017, almost 70% of companies declared payment delays by the public administration [18, 19]. The delays in payments come alongside the second main issue, namely late deliveries during the construction process. In particular, the Italian "Report on the implementation time of public works" [15] highlights the long execution periods required to carry out the process phases (design, procurement, construction and maintenance). Specifically, the report highlights the incidence of the "waiting times", i.e. the time interval between the end of one phase and the beginning of the following phase, on the total duration of each phase. The report points out that the overall design phase is most characterised by long waiting times between the end of one phase and the beginning of another, which negatively affect its total duration. Verification and validation procedures, authorisations and bureaucratic steps are the main causes of the cited waiting times during the design phase [15].

This analysis confirms the valuable scope of experimentation of the research in the design phase. Regarding what stated so far, the research question that triggered the development of the framework of the research is about how the digital methodologies and tools could affect the reduction of late deliveries and overdue payments in the design phase. The proposed research framework provides a theoretical response to the above-mentioned question. It illustrates a process that, if concretely carried out, permits the distancing from the traditional practices ensuring the shortening of the process development and the satisfaction of the contracting parties. Further developments of the research will experience and demonstrate the framework through the implementation of a proof of concept, proving its validity and innovation.

The chapter is organised according to the following sections. Section 2 outlines the state of the art in the main research areas, namely the information management based on BIM and blockchain technology. Section 3 illustrates the high-level research framework, proposing the digital information management based on BIM and blockchain through the adoption of the automatic BIM validation and smart contracts. Section 4 shows both the operating architecture of the rulesets for the automatic validation of information and the potential configuration of the blockchain network. Section 5 discusses the major benefits achievable from the illustrated framework. Since the proposed framework remains at a theoretical level, the results discussed are those expected. Finally, in Sect. 6 the main value of the research and the future developments are disclosed.

2 Digital Information Management Based on BIM and Blockchain: A State of the Art

As anticipated, the research proposes the integration of the automatic BIM validation and smart contracts to automate and shorten the design phase development. The suggested framework of the research underlines the potential offered by the information management based on these technologies. In particular, the implementation of a BIM process based on blockchain could improve the information management thanks to the recording of any activity, constant monitoring of the progress, exhaustive verification and validation of the information requirements and identification of the responsible parties. This combination could give confidence and harmony to the information shared, produced, reviewed and stored. The framework could correspondingly improve the process execution and management. In the contractual environment typical of the construction sector, the opportunity of automating certain processes that are traditionally performed by interaction and pursued based on decisions promoted by agreement among multiple parties is a valid area for experimentation. To support and motivate the development of the framework, this section discusses two main topics. At first, the information management using BIM is illustrated with a focus on the procedures for the verification and validation of the information requirements. Then, the current areas of research on blockchain in construction, with a focus on digital information management, as well as the potential blockchain network to be adopted in the framework are discussed.

2.1 Digital Information Management Based on BIM

The progressive digital transformation of information management is driving a revolution in the procedures during the overall construction process. In this context, both public and private clients are becoming interested in innovative practices that exploit information management to improve communication, efficiency, safety and productivity of the built environment. The digitalisation is stimulating greater automation of the design, tender, construction and maintenance phases, optimising the building life cycle and improving the client's satisfaction and end-user's experience [20]. In this context, Building Information Modelling can be considered the methodology that is driving the digital transformation. As an approach based on digital information management, it can indeed be crucial for better decision-making, predictability and confidence in obtaining the expected results. It significantly influences the system of creating, collecting, using and sharing the digital information throughout the asset life cycle, involving all the stakeholders. The ISO 19650 series, as international standards that define digital information management procedures during the asset life cycle, encourages the introduction of BIM and uniformly guides the experts in its use [21]. ISO 19650 defines BIM as a beneficial method based on the better specification and digital delivery of the right amount of information about design, construction, operation and maintenance of an asset using appropriate technologies [22]. The information management process covers the activities of defining information requirements and the production, delivery and review of information. Within such a process, each participant is responsible for certain information management functions to be fulfilled. Each party engaged has, therefore, an involvement and interaction with information management according to their role and responsibilities. Indeed, ISO 19650 undertakes the identification of the main actors in the process, denoted as the appointing party, the lead appointed party and the appointed party(s) [22]. The first, usually represented by the client, is the one who defines the information requirements. The second is the party responsible for the coordination of the exchanged information and the third is the one accountable for the information production. According to ISO 19650, to achieve a successful information management using BIM, each actor involved must fulfil three main tasks. The first is the clear definition of the information requirements, and standards for their production and review. The second is the proper production of the quantity and quality of the required information, and the third is the efficient and effective exchange of information among the involved parties. Specifically, the appointing party is the one who starts the process, stating the information requirements and ensuring their clear definition. This statement defines the type of information and clarifies how different types of information should be structured and exchanged. Then, each prospective lead appointed party responds to the information requirements stated, through the development of the BIM Execution Plan (BEP), which is considered by the appointing party when selecting the lead appointed party. After this stage, all the actors collaborate to agree on the key roles and responsibilities and arrange an information delivery plan that outlines coordination and delivery schemes. This allows the configuration of an appropriate information management, that provides and considers the requirements of the involved parties, the delivery process, and the use of appropriate technologies. At the end of every project stage, a review of the information produced is needed to validate the appropriate achievement of the information requirements. This review process is commonly performed through a mixture of manual and automated methods and applications.

The aforementioned definition of the information requirements is based on structured information management, allowing the explicit definition of the requirements, their availability to the different parties and the continuous review of their fulfilment [23]. Each information produced must be reviewed to double-check the compliance with the information requirements and, consequently, accepted (or rejected). In this context, the ISO 19650 series [22] outlines the client as the person in charge of defining the project objectives and information requirements and reviewing the information delivered for each phase of the asset life cycle. However, since ISO 19650 does not provide the organisation or project-specific details and considers the high level of client's involvement, starting from the general standards recommended, the need of BIM guidelines containing the personalised client's requirements has become progressively evident. The customisation of the standards allows the client to create proprietary BIM guidelines for the identification of the information requirements in a structured way and the regulation of subsequent procedures based on the specific needs. The customisation of procedures for organising the client's needs boosts BIM to be integrated into the construction industry in a controlled and gradual manner. In particular, to guide large clients in the preparation of effective BIM guidelines [20], ISO/TS 12911 supports the definition of personalised methods for information management [24]. Indeed, ISO/TS 12911 provides a structured and reusable framework to guide the BIM process development [24]. The suggested framework allows the creation of a common structure for the application of BIM and makes BIM guidelines manageable and testable. BIM guidelines are prepared and used for: (i) defining the desired information outputs and their expected quality, (ii) customising the structured implementation of project information, (iii) identifying the resources and tools and their appropriate management, (iv) obtaining and maintaining a common knowledge within the project and (v) supporting the technologies behind BIM. The preparation of proprietary BIM guidelines, before the start of the design phase, allows the client to develop the information requirements in a structured way and it is fundamental to ensure the contracting parties have a clear definition of all the types of information to be produced and managed [25]. Since proprietary BIM guidelines are drafted by a specific client, they allow the standardisation and guidance of processes based on precise needs. For these reasons, the existing proprietary guidelines can differ widely from one another, in their goals, approach to standardisation, technology requirements and level of information needed [26]. However, they are a powerful tool to promote and guide the adoption of information management using BIM. Since the generation of value in the construction industry depends on the identification, processing and fulfilment of the client's requirements, the presence of specific guidelines can support the process development and guarantee the achievement of the requirements. BIM guidelines, regulating a structured information request, production, review and management in the BIM environment, enable the creation of coherent information among different participants, enhancing a transparent and collaborative workflow and reducing the event of information asymmetry or misunderstanding of the requirements.

In the context of the framework of the research, these concepts are fundamental. The research environment is indeed located in the design phase required by a specific client (see Sect. 3). The target client has proprietary BIM guidelines on which the design phase must be developed. Therefore, the first objective of the research is to identify an application able to automatically verify and validate the information included in BIM models in compliance with the client's BIM guidelines and to outline its potential architecture and functioning (see Sect. 4.1).

2.2 Digital Information Management Based on Blockchain

Due to its growing interest, the introduction of blockchain technology has promoted new types of applications, and therefore it could be considered the main technology qualifying the digital transformation currently studied by the most advanced world economies [27, 28]. Belonging to the Distributed Ledger Technologies (DLTs), blockchain is defined as a *trustless* technology, that ensures an extraordinary degree of trustworthiness, integrity and immutability [29] and that allows parties to send transactions using a peer-to-peer network, without the control of a trusted third party (TTP) [30, 31]. The creation and maintenance of trust are guaranteed by the design of the technology. The level of transparency, accessibility and traceability of information shared and stored using the technology is defined by its architecture design. Among DLTs, blockchain offers unique features, including a considerable number of use cases and the possibility to implement smart contracts. As previously stated, smart contracts will be an important topic of investigation and application in the presented research. Undeniably, according to some researchers, late payments in the construction industry led to several claims, but the adoption of smart contracts could significantly reduce the actual negative concerns [32–34]. The selection and configuration of the suitable blockchain network make it possible to draw up and execute smart contracts. Although smart contracts are automatic and deterministic, they are not perfectly *trustless*. Since blockchain cannot access data outside its network on its own, the main limitation with smart contracts is the communication with the real world. For these reasons, it is necessary to integrate a third-party system that allows access and verification of what is happening in the real world and sends the information to the blockchain via smart contracts. Such services are defined as oracles [35]. In this way, the entire network can validate the request, and the contract is able to accept or reject it automatically. When the conditions comply with the planned process, smart contracts automatically execute, approving the release or directly issuing the payment [36]. The use of such services is of great importance to the framework of the research, since they can guarantee the connection of the external world, i.e. the information production and validation during the design phase, and the blockchain world, i.e. the recording of information and the automatic approval of the process stages.

Thanks to the main benefits offered by the technology such as the transparency and immutability of information, which make it possible to limit the occurrence of misunderstandings, and the automation of the process, which guarantees the disbursement of payments and respect of the deliveries, the proposed research is placed among other emerging studies and experimentations related to the integration of the information management based on BIM and blockchain in the design phase. Indeed, the possibility to develop and maintain the information inside the BIM models using blockchain allows the recording of any activity, therefore controlling at any time the real progress of the considered phase and the responsible parties. The integration of blockchain in the BIM process gives confidence and synchronization to the information shared, produced, reviewed and stored. The information is stored on a distributed platform shared among all the participants, which allows the notarisation of each piece of information created, modified and updated as the process progresses. In this way, the progress of the process and the monitoring of the compliance with project objectives are known by both the client and all the involved appointed parties. In the existing literature, it is possible to recognise some different studies related to the adoption of blockchain in digital information management during the design phase. Dounas et al. proposed a framework for decentralised architectural design that allows multiple participants to solve the design problems in both collaborative and competitive ways and, thanks to the integration of blockchain, it is able to record all the design attempts, including the ones that have 'failed', and all the positive steps towards design optimisation [12]. Schönhals et al. proposed an approach that makes it possible to protect developed ideas and early concepts even during their systematic development. It intends to protect the intellectual property through the digital record of verbal, written or sketched, and even modelled or constructed outcomes during the innovation development in real-time [37]. Another work to be cited is from Zheng et al. that proposed an application for mobile devices that allowed users to check on their portable devices whether a BIM model is the latest version, whereby, a hash of the BIM model is stored on the blockchain that allows a search service to cross-check the hash of a downloaded model with the hash stored on the chain, after which, the application will provide users with a verification receipt that declares the validity of the model [38].

The description of some of the main existing research topics highlights the cutting-edge scope of the proposed research that intends to integrate and contribute to the current evolving research field. To identify the most appropriate network to support the framework of the research and configure its components, an analysis of different types of blockchain networks has been carried out. Even though blockchain technology was first designed for the deployment of public, *permissionless* and *trustless* network, which do not require the presence of a TTP, its design has progressed towards the creation of private and permissioned networks. In these networks, participation is permissioned. Participants have restrictions on writing rights (data validation) or/and reading rights (access to data). As the public networks, permissioned ones are immutable and nodes share the same ledger, but the access to the network is permissioned, this means that the role of each node has to be granted [39].

As specified in Sect. 3, the framework of the research focuses on the design phase where a specific client appoints a design team to produce and manage information related to a specific project in compliance with BIM guidelines. For these reasons, the architecture of the blockchain network must be the response and balance the requirements of both the client and the contracting parties involved. Therefore, evaluating the structured environment in which the design process is implemented, the initial theoretical investigations of blockchain networks concern the permissioned ones. In order to set up a permissioned blockchain to support the research framework implementation, among the existing private networks [40], Hyperledger Fabric (HLF) has been analysed and selected as the potential most suitable network to be configured and integrated in the framework of the research (see Sect. 4). HLF, which is the most popular permissioned network, is well adjustable to a wide range of distributed applications written in general programming languages. For these reasons, companies that create and deploy blockchain applications within their businesses use it. The network consists of various peers that host blockchain, execute smart contracts and mutually maintain the state of the ledger. Smart contracts in HLF are called *chaincodes*, they can be shared by all entities within a company, or they can be shared privately and accessed by a specific group of entities [40]. Smart contracts are executed only on nodes with which the network is shared, thus being inaccessible to others. The possibility of selecting specific nodes is guaranteed by the channel concept: information and smart contracts present in a specific channel are only accessible to the channel participants. In the network setup phase, the participating nodes are identified and authenticated, hence it is possible to identify if a certain node belongs to a certain channel. Currently, HLF supports Ethereum Virtual Machine (EVM) bytecode smart contracts, allowing the contracts to be written and managed with the same tools of Ethereum, thus simplifying the configuration procedures. Based on the investigation of the existing literature [39, 40], Hyperledger Fabric is shown to be the network that performs better in terms of performance, architecture, and components, therefore it is the one identified to be potentially set up and tested in the framework of the research. Thanks to permissions, network participants are known and acknowledged when setting up and running the network. The adoption of blockchain technology in the development of the research will allow the creation of a network through which selected participants can share information transparently and perform transactions securely.

Based on the exploration of the current areas of research and application and on the potential identification of the most appropriate blockchain network, the second main objective of the research is to outline the potential setup conditions of the chosen network. Participants, assets and expected transactions are illustrated as well as the need to introduce an oracle service in the scheme (see Sect. 4.2). The adoption of a blockchain network supports the implementation of automated activities. This means that the network could come along the information management in the design phase, eliminating any intermediaries and ensuring the confidentiality of shared data using consensus protocols and smart contracts.

3 Framework of the Research

The topics discussed in the previous section illustrate the two main innovative areas underlying the presented research. Through the integration of information management based on BIM and the implementation of a blockchain network, the research intends to offer an innovative approach to the traditional development of the design phase. Currently, no research related to blockchain in construction focuses on the integration of BIM-based digital information management and blockchain-based protocols to automate the production, verification and validation of the information according to specific client's information requirements during the design phase. The proposed framework of the research offers a new point of view for the research of blockchain applications in the design phase developed in a BIM environment, boosting and optimising the reliability and accuracy of the process.

With the ambition of emphasising the automation of the process, minimising the errors or misunderstanding due to human intervention, and fulfilling contracting parties' requirements, this combined system differentiates positively from the traditional approaches. Concerning the research scope and what has been discussed in Sect. 2, a detailed description of the high-level framework is here provided, highlighting its value and innovation. The overall process framework is illustrated through a graphical representation, explaining each activity and goal. The brief discussion of the main critical issues (see Sect. 1) and the description of the main innovative technologies considered in the research (see Sect. 2) allow a better outlining and understanding of the framework. Specifically, the combination of automatic information validation and smart contracts to support the development of the design phase for a specific client mainly aims at:

- Improving the transparency of communication between the client and the design team, through a trusted network for information exchange;
- Reducing the delivery time of the assigned tasks, through automatic and efficient design validation;
- ensuring timely payments, through the automation of the approval procedure and actuation system.

Therefore, the value of the research is mainly related to the shortening of the design phase time execution, the automatic validation of the project and the trustworthiness of the compliance with its objectives, and the automatic release of payments. The innovation of the research relies on the possibility to notarise the automatic BIM validation and connecting the approval procedure to payment release.

The suggested framework (Fig. 1) proposes how the integration between information management using BIM and blockchain could improve the engagement between the client and the design team. The use of a common digital environment allows participants to share and access the same information during the process. Its connection with blockchain enables information to become traceable and unchangeable, thus the trust among the parties increases. Indeed, the distributed environment can help in

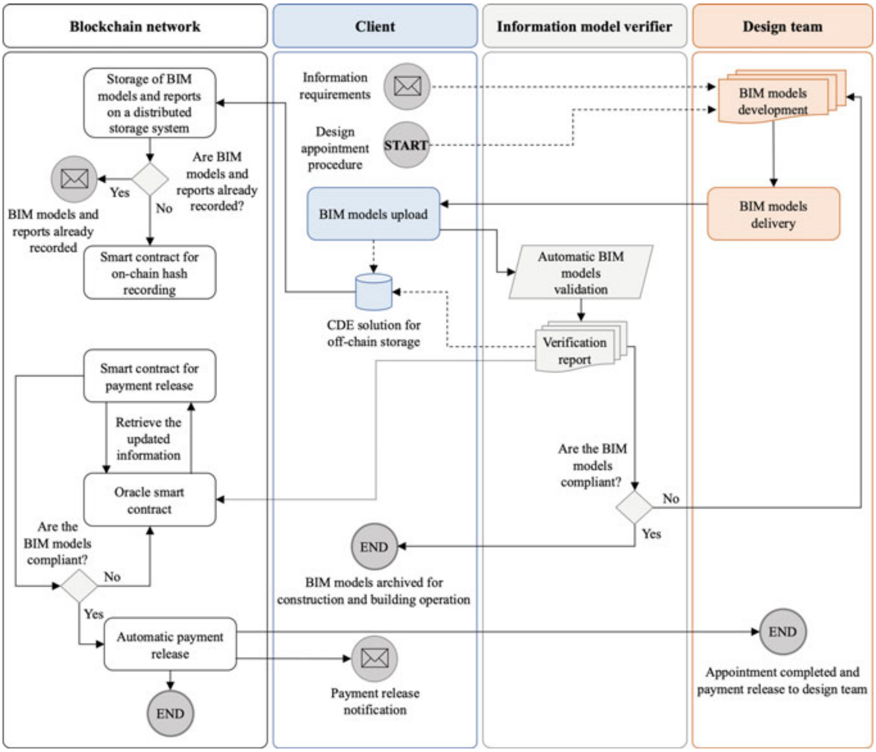


Fig. 1 High-level framework of the research

reducing the misunderstanding frequently due to discrepancies and non-conformities among the client's requirements and the design team's documents.

The combination of information management procedures and blockchain could offer enormous value and could be considered the appropriate direction for the efficient development of the sector. As stated at the beginning of the section, the research framework delineates the performing process of the design phase, created on the adoption of innovative methods and technologies, which promise considerable benefits. The main purpose of the framework is, at the present time, limited to the automatic compliance of the client's information requirements, therefore other verifications to be accomplished in the information models (such as code checking and clash detection) are out of the research scope. This means that the automatic payment release concerns the completion of one part of the overall BIM model checking expected for the final approval of the design documents. During the progress of the research, the framework could be extended and generalised to include other types of model verification and define the entire automation process for the validation of the BIM models.

This decision is related to the project selected for the implementation and validation of the framework of the research, through a proof of concept. The selected project is placed in the design phase and is led by a specific private client. The client is represented by RAI, the exclusive concessionaire of public service broadcasting in Italy. RAI has developed the RAI-BIM guidelines to digitalise its real estate assets, composed of both new construction and existing buildings used for offices, recording studios, theatres and warehouses. The result of this innovation consists of an integrated digital system, structured in several proprietary BIM guidelines, respectively for the information modelling and management of: (i) new construction interventions, (ii) interventions on existing buildings and (iii) ordinary and extraordinary maintenance interventions. The presented framework of the research will be then configured, customised and tested in the design process followed by RAI that generally consists of the development by appointed design teams, of the BIM models (i.e. architectural, structural, mechanical and electrical) and their verification in compliance with the RAI-BIM guidelines. In the case of RAI, the level of compliance for which the delivered models are approved by the client is 90%.

To show the business logic of the research, the dynamics of interaction among the parties and the use of innovative technological tools, here below an example of the application of the framework is explained step-by-step. With the commitment to verify the client's information requirements during the execution of the design phase driven by the content of proprietary BIM guidelines, the process outlined is based on structured procedures for information management as recommended by the ISO 19650 series. As previously stated, the participants in the information production and management process have specific responsibilities and tasks. In the research case, the acting parties are the client, the design team and the verifier (Fig. 1). The client, as the owner or for whom the project is carried out, must conduct all the activities to ensure that accurate information management is satisfied. Therefore, the client defines the project information requirements, protocols for information production, delivery milestones and sets a common data environment (CDE) solution to support the production, sharing and archiving of models and information among the interested parties. In compliance with what is stated in the ISO 19650 series and ISO/TS 12911, the client has personalised and set out the desired information requirements, protocols and milestones in the proprietary BIM guidelines. These guidelines are transmitted to the design team during the appointment process. Once the appointment has been awarded, the design team develops the project based on proprietary BIM guidelines content. The team produces all the information included in BIM models following the defined information requirements. In this way, the produced information will respond entirely to the requirements set out by the client, and therefore the design will be realised in a compliant and optimised way. Simultaneously with the development of the information models, the verifier, appointed by the client, also receives the proprietary BIM guidelines. The verifier is a consultant of the client that undertakes the detailed analysis of the guidelines to translate the information requirements from semantic language to machine-readable language through the configuration of adequate tools. Since the creation and management of a BIM project requires the production of a large amount of digital information, manual verifications are difficult to be performed objectively and exhaustively. For these reasons, to ensure that the information requirements are completely met, the verifier identifies a suitable application to develop automatic rulesets compliant with the content of the guidelines. Such a tool, which can be implemented in the modelling software, is capable of automatically and completely validating the information content produced according to the client's requirements (see Sect. 4). Once the production of information is completed, the design team delivers the BIM models produced for each project discipline (i. e. architectural, structural, mechanical and electrical) to the client. The delivered models are uniquely stored in the CDE solution, considered the off-chain database. The files stored in the CDE are also stored and linked with a blockchain network, using a distributed storage system, to keep track of the model delivery cycle. Due to the large size of the models, the system creates for each delivered BIM model a cryptographic hash that is stored in the blockchain network through smart contracts. The hash added to the blockchain network enables the inspection of the mapped BIM model that is stored on the computer memory of the peer with the same name as the hash. This makes it possible to control access and changes to the BIM models in a uniform and secure way. When a new model is delivered, its hash and the hash of the already stored models are compared. This makes it possible to check transparently both that the same model has been delivered twice and that the model, claimed to have been revised after validation procedures, has not been modified.

Following the delivery procedure, the verifier uses the programmed application to automatically verify and validate the information included in the BIM models. For each model verified, the application independently produces a report containing the results of the verification. The created reports are stored in the CDE and, likely for the models, their hashes are recorded on the blockchain network hence the progress of the modelling process could be recorded and mapped transparently. In this environment, project verification and validation activities are managed evidently, improving the communication between the client and the design team. The automatic validation of the information speeds up and optimises the review and delivery process. The archiving of results allows the client to assess the compliance with the information requirements. This framework also ensures the absence of non-conformities and disputes during the phase progress. The outcome of the report reveals the compliance of the information produced with the client's requirements and the timing of the delivery. The level of compliance for which the delivered models are approved is defined at the beginning by the client and communicated to the design team at the time of the appointment. The automatic validation of information included in the models takes place separately for each discipline, so four separate reports are created for each verification cycle.

If the automatic verification of information models produces a report with a result that is below the set level of compliance, the design team receives the report containing all the detected non-conformities and it must proceed with the changes and indicated corrections. The design team must then subsequently make a new delivery. If, on the other hand, the set level of compliance is met, i.e. information produced has met the client's information requirements, the model is accepted and stored in the CDE, for the future steps towards construction and/or building operation and maintenance. Therefore, the automatic validation process, connected to a blockchain network, is combined with the automation of contractual performance through the adoption of a smart contract between the client and the design team. Since blockchain cannot retrieve directly external information, an oracle is required to create the connection between the smart contract and the off-chain data source. At the time of the appointment, the client and the design team have established the terms and conditions of payment approval upon the completion of the assigned tasks. These conditions impose the authorisation for the release of payment when the delivered models' verification lines up to the set level of compliance. To automate this approval process and link it directly to the results of the model verification, the payment conditions are translated into a smart contract. Therefore, a back-end oracle ensures the connection between the verification report's result and blockchain to transmit and store the result in an oracle smart contract. The data stored in the oracle smart contract can be retrieved by the smart contract for payment that compares whether the level of compliance achieved is equal to or greater than the established level and, if so, initiates the transaction. The smart contract for payment is linked with an escrow account, that holds and only disburses funds when the task is completed as expected, ensuring the payment release to the design team.

The pursued business logic makes the coded payment conditions self-execute at the end of each verification cycle of the information model, if the level of compliance is equal to or higher than the one set by the client. Indeed, in each model verification cycle, the application operation reports the type of model verified, the time of verification and the level of compliance reached and automatically compares it with the set level agreed upon between the parties. This process incentivises the participants to perform their assigned tasks as stated under the contract. Information produced and included in the BIM models is developed by observing the client's requirements and the design team is approved for payments through a smart contract for each completed delivery step. Therefore, the design cycle, and the subsequent validation, is an iterative process. Design information models are only approved when they meet the information requirements contained in the proprietary BIM guidelines. Only when the outcome of the report equals or exceeds the defined threshold of the level of compliance allowing the verification flag, the model is archived and the payment for the activity is automatically approved.

4 Proposed Technologies for the Framework of the Research

The previous section illustrated the overall process on which the framework of the research is based on. The innovation and value of the framework lie in the integration between automatic BIM validation and smart contracts applications. For these reasons, although the explanation of the suggested framework remains at a theoretical level, this section is committed to describing the general functioning of the technologies that are intended to be configured and used in the actual testing of the framework through the proof of concept. Therefore, in principle, the importance of the verification and validation of information is highlighted. Then, the general approach for setting up the application for automatic verification of BIM models based on the client's requirements is explained. The second part focuses on the architecture of the potential blockchain network, defining the components and rules for its use. The integration between the design development and validation using BIM and the design tracking using blockchain is illustrated.

4.1 Approach to the Automatic Validation of Information

Information production, review, validation and management underlying the research framework are accomplished with the agreement of the information requirements made clear by the client in the proprietary BIM guidelines. As stated above, the scope of the research is limited to the design phase, where a client plays the role of the appointing party, requiring the production and management of digital information in accordance with its BIM guidelines. The proposed framework of the research is developed to test its operation, validity and innovation tangibly on a project briefly presented in Sect. 3, considered as the proof of concept of the research. For these reasons the software requested by the client and used by the design team for the realisation of the models in the design phase is known and it is the Autodesk Revit authoring tool. Consequently, the application identified to perform the automatic validation of the digital information must be able to communicate with that modelling software. Among the Revit applications that permit the performance of personalised checks on BIM models, Autodesk Model Checker for Revit has been chosen as it allows the creation of customisable verification and validation rulesets for data and naming conventions checks. The progressive digitisation of information during the project development has caused a significant increase in its quantity and complexity. BIM models can be defined as repositories of all project information that must comply with the information requirements expressed by the client [22, 24]. Indeed, according to the international standards, information produced and managed during the project development must be verified at the end of each planned phase of the process. In the context of the research, the review and validation of information produced and included in the BIM models, therefore, becomes a fundamental activity to achieve the compliance with the guidelines content.

The setting up of an application for the automatic information validation becomes crucial as frequently the verification of the BIM models is manually implemented. This activity is time-consuming and error-prone, with the plausible generation of disputes and discontent in the subsequent phases. Since these operations for verification demonstrate to be critical, the creation of an automated BIM validation process is vital in the digital information management. To start solving these issues, the first objective of the research is the description of the tool-operating framework for the information validation. Aiming at giving greater reliability and integrity to the information review process, the overall approach defined to validate the activities

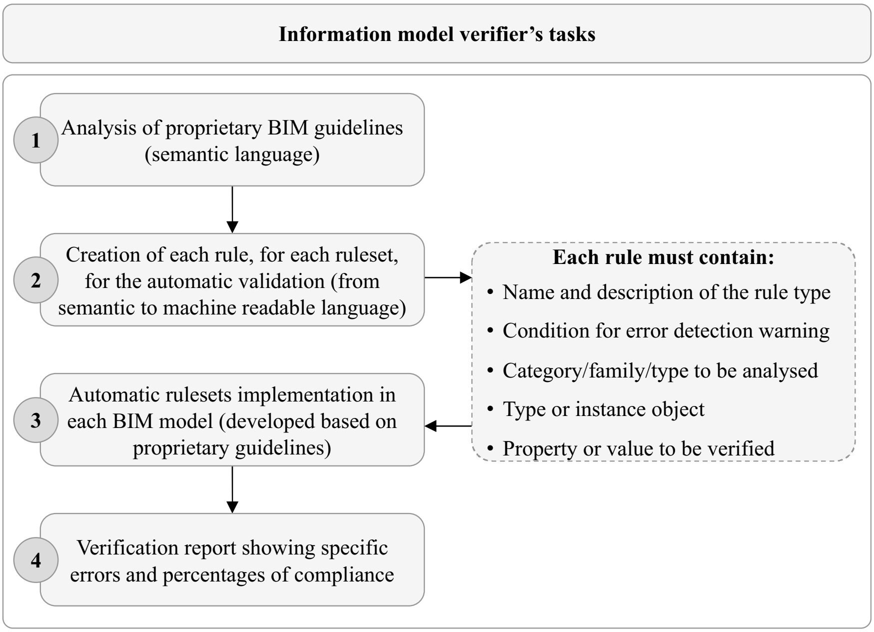
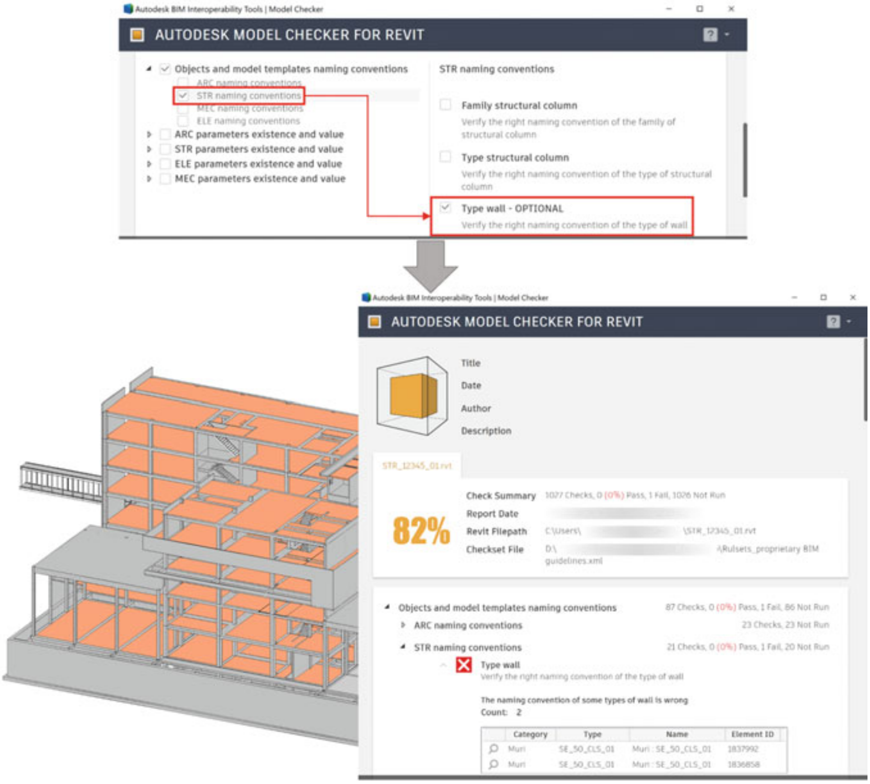


Fig. 2 Process approach to automatic validation

of the BIM models is illustrated in Fig. 2. The approach is implemented starting from the analysis and interpretation of the proprietary BIM guidelines. The client uses a semantic language to define the information requirements for the design and, to integrate them in an application for automatic validation, they must be translated into a machine-readable language that can be interpreted by the chosen software (i.e. Autodesk Model Checker Configurator). The mediation between the two languages takes place through a domain-oriented language, whose terms allow a simple and immediate definition of the domain in which professionals operate. The identified application does not modify the information model to be analysed, however based on rulesets, it reports any error messages if the model presents inconsistencies with respect to the domain. The rulesets consist of the translation of the guidelines information requirements and represent the verification domain.

Therefore, the functioning logic of the automatic verification is based on the creation of a validation domain (i.e. the content of the guidelines) used as a reference to verify that the model falls within this domain. The rulesets implementation in the BIM models generates the result "approved" or "rejected" for each verified requirement. The rulesets are in fact implemented and executed in each BIM model (i.e. architectural, structural, mechanical and electrical), concluding an exhaustive verification cycle. The activity ends with the production, for each BIM model, of a report containing the results of the verification. The reports contain all errors and inconsistencies between information contained in the models and the information requirements contained in the proprietary BIM guidelines. The approach for the setup of the automatic information validation process starts with the identification of the content of the proprietary BIM guidelines to be translated and included in the application and with the definition of the general organisation to be respected for the setup of each ruleset. Since the amount of information is increased due to the digital transformation of the construction process, the information requirements established by the client are abundant. In particular, the content of the proprietary BIM guidelines of the selected project can be divided into three macro-categories of information requirements to be verified: (i) BIM objects naming conventions, (ii) BIM model templates naming conventions and (iii) BIM object parameters. In the first category are defined, for each discipline (i.e. architectural, structural, mechanical and electrical), the naming conventions of the BIM model, the designations of loadable families, system families and their types, the designations of sheets and materials. In the second category, for each discipline, the naming conventions of the levels, views (drawings, fronts, and sections), schedules and grids are defined. Finally, the third category defines the association of the parameters with each object and their value. Evaluated the significant content of the proprietary BIM guidelines, the work related to the interpretation and translation of the information requirements using the Autodesk Model Checker for Revit application is undoubtedly onerous. The operating framework of the application has to involve the two macro-categories of rulesets identified for each discipline, namely one related to all naming conventions rules and the other related to rules for parameters. Through the support of the chosen application, these two macro rulesets are translated from semantic language to machine-readable language to be implemented in the BIM models.

In this way, each rule to be included in the larger ruleset founding the verification domain is created. Each verification ruleset is then implemented in the model, and at the end of the performance of the application, the verification report, containing the errors detected, is automatically obtained. In order to display a tangible example, Fig. 3 shows the implementation and verification of a rule within a structural BIM model developed in accordance with the proprietary BIM guidelines to test the automatic verification tool. The implemented rule intends to verify the naming conventions of the structural wall types and, at the end of the performance, the verification report is obtained. The report is detailed for each identified element. In this case, two types of structural wall, compared to those included in the structural BIM model, are detected with different names from the guidelines. The percentage of compliance between the naming conventions applied for the wall types used in the structural model and the naming conventions defined in the client's requirements, according to the application report is 82%. As this illustration intends to show, as an example, only the verification of the naming convention of the structural wall types, the 82% obtained represents the level of compliance of the model related to a single information requirement, and not to the overall content of the BIM guidelines. Figure 3 illustrates that for each rejected element the report shows the ID, thus facilitating its rapid identification in the model and appropriate correction. Through the brief illustration of the architecture setup of the chosen application, it is possible to understand that, once the logical process has been defined, the exhaustive realisation of the rulesets in the application initially requires time to be invested in its creation



☑ Objects and model templates naming conventions
  ☐ ARC naming conventions
  ☑ STR naming conventions
  ☐ MEC naming conventions
  ☐ ELE naming conventions
☐ ARC parameters existence and value
☐ STR parameters existence and value
☐ ELE parameters existence and value
☐ MEC parameters existence and value

STR naming conventions

☐ Family structural column
Verify the right naming convention of the family of structural column

☐ Type structural column
Verify the right naming convention of the type of structural column

☑ Type wall - OPTIONAL
Verify the right naming convention of the type of wall

Title
Date
Author
Description

STR_12345_01.rvt

82%

Check Summary 1027 Checks, 0 (0%) Pass, 1 Fail, 1026 Not Run
Report Date [redacted]
Revit Filepath C:\Users\ [redacted] \STR_12345_01.rvt
Checkset File D:\ [redacted] \Rulsets_proprietary BIM guidelines.xml

Objects and model templates naming conventions 87 Checks, 0 (0%) Pass, 1 Fail, 86 Not Run
ARC naming conventions 23 Checks, 23 Not Run
STR naming conventions 21 Checks, 0 (0%) Pass, 1 Fail, 20 Not Run
☒ Type wall
Verify the right naming convention of the type of wall

The naming convention of some types of wall is wrong
Count: 2

	Category	Type	Name	Element ID
⌕	Muri	SE_50_CLS_01	Muri : SE_50_CLS_01	1837992
⌕	Muri	SE_50_CLS_01	Muri : SE_50_CLS_01	1836858

Fig. 3 Example of the implementation of a rule in the structural BIM model

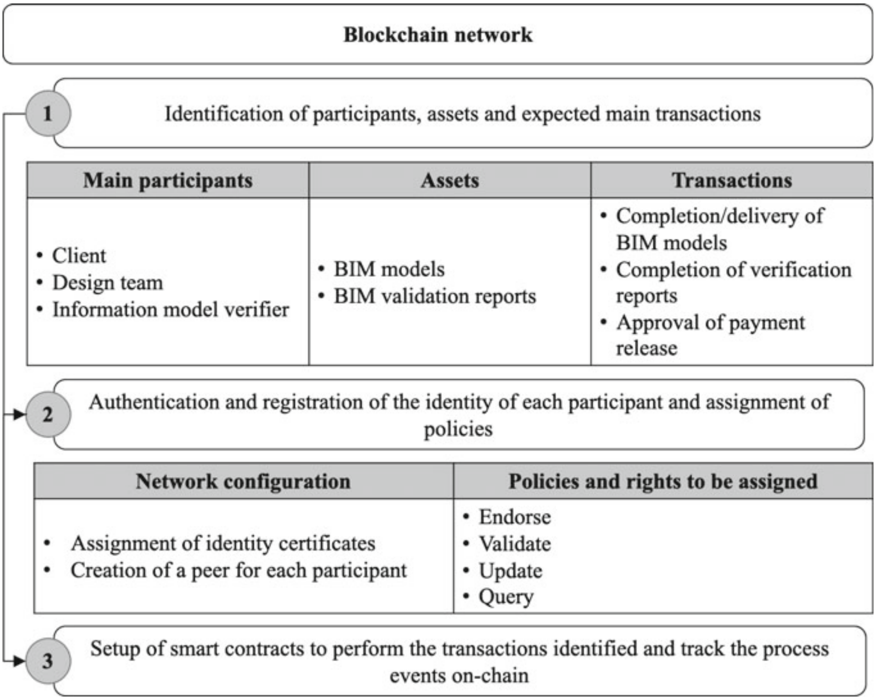
and definition nevertheless it saves a lot of time in the future design and verification processes.

4.2 *Potential Blockchain Network to Be Integrated with the Automatic Validation of Information*

As illustrated for the automatic validation of information included in the BIM models, the second main objective of the research framework is the definition of the architecture of the potential blockchain network selected. Section 2.2 indicates Hyperledger Fabric (HLF) as the potential blockchain network to be evaluated. As previously declared, the research project is contextualised in a proprietary environment. For this reason, the identification and the future use of a network that stands out for identity management, privacy and efficient processing are shown to be appropriate. From a technological point of view, the key features of HLF architecture include (i) identity management, (ii) channels, (iii) ledger, (iv) consensus mechanism, (v) smart contracts and (vi) policies. Unlike *permissionless* networks, where unknown identities participate in the network, HLF enrols members via the assignment of a digital identity certificate, that manages user IDs and enables the authentication of all the network participants, creating an access control list [41]. In this way, privacy becomes a key requirement for the functioning of the network in which parties, known to each other, exchange sensitive and confidential information. By creating channels, participants can form groups to create different transaction ledgers. The channel enables the exchange of information (transactions) to a set of peers (participants), pursuant to the agreed policies. The creation of private channels enables any groups that require confidential transactions to coexist on the same permissioned network. As a blockchain network, the HLF ledger is immutable, and it encodes the history and current state of transactions in each channel. There is one ledger for each channel and each peer keeps a copy of the ledger for each channel in which it is a member. In HLF the consensus mechanism is chosen by the network to identify the one that best represents the type of relationships existing among the participants. The consensus mechanism allows the network to verify the correctness of transactions included in a block. The consensus is achieved when the order and result of the transactions in a block satisfy the policies of the network. The use of endorsement policies is what differentiates HLF from other blockchains. In fact, HLF models the actual world more realistically, so transactions must be validated by trusted parties of the network. The endorsement policies are associated with each *chaincode* that, in HLF, represents smart contracts (see Sect. 2.2). Each smart contract allows the encoding of the logic with which a certain type of transaction is invoked on the channel. Other policies exist, e.g. relating to who can query or update the ledger, or who can add or remove participants. Finally, HLF can manage assets that represent tangible or non-tangible values through which almost anything with monetary value is exchanged on the network.

The above overview facilitates the understanding of the possible HLF architecture suggested for the research framework. Indeed, regarding the key features described and the parties pinpointed in the high-level framework (Fig. 1), the components of HLF that define and determine the capabilities of the system are here identified and illustrated in the consecutive order of creation (Fig. 4). In particular, the participants are the parties involved in the blockchain network, the assets are the values exchanged between the participants and the transactions are the logical smart contracts that specify certain events of the process and control its development. Thanks to identity management, each participant is identified reliably with a name and unique ID. Through the privacy of the network, accesses are controlled based on the roles of each participant that, in this environment, are known to each other. Each asset is recognised with name, ID and type. Likewise, each transaction is defined with a unique ID, name, timestamp and sender. Policies and rules based on consensus are defined and checked before each transaction takes place.

The endorsement policy is established to indicate which participants must sign the transactions to declare them valid. Only valid transactions can indeed update the state of the ledger. In the research, this policy is mainly entrusted to the client who is responsible for validating the transactions. The design team proposes the transaction for



Blockchain network

1 Identification of participants, assets and expected main transactions

Main participants	Assets	Transactions
• Client • Design team • Information model verifier	• BIM models • BIM validation reports	• Completion/delivery of BIM models • Completion of verification reports • Approval of payment release

2 Authentication and registration of the identity of each participant and assignment of policies

Network configuration	Policies and rights to be assigned
• Assignment of identity certificates • Creation of a peer for each participant	• Endorse • Validate • Update • Query

3 Setup of smart contracts to perform the transactions identified and track the process events on-chain

Fig. 4 Blockchain network components

the BIM models delivery and the verifier proposes the one for the verification report produced. The second policy concerns the responsibility of updating and querying the ledger. In the research, the design team and verifier are the parties primarily responsible for updating and maintaining the data in the ledger, while the client can query to retrieve point-in-time data. The identification of the elements and logic of the HLF network to be implemented in the research allows a complete picture of the integration and operation architecture of the technologies involved in the system. Since the scope of the proposed framework is the combination of the automatic BIM validation and smart contracts, the architecture requires the implementation of oracles. The introduction of an oracle requires the creation of a dedicated channel, namely the global channel, in which a network participant operates as the trusted person responsible for maintaining and updating the ledger with external sources. This channel is provided with an oracle smart contract that updates the network and that can be queried for the updated data (Fig. 5).

The participants, operating in the other channel, can indeed query the ledger to consult and obtain certain updated information. As already explained, the process starts with the definition of the client's information requirements through proprietary BIM guidelines. Then, the BIM models developed by the design team, based on the guidelines, are submitted and automatically verified by the verifier, through the use

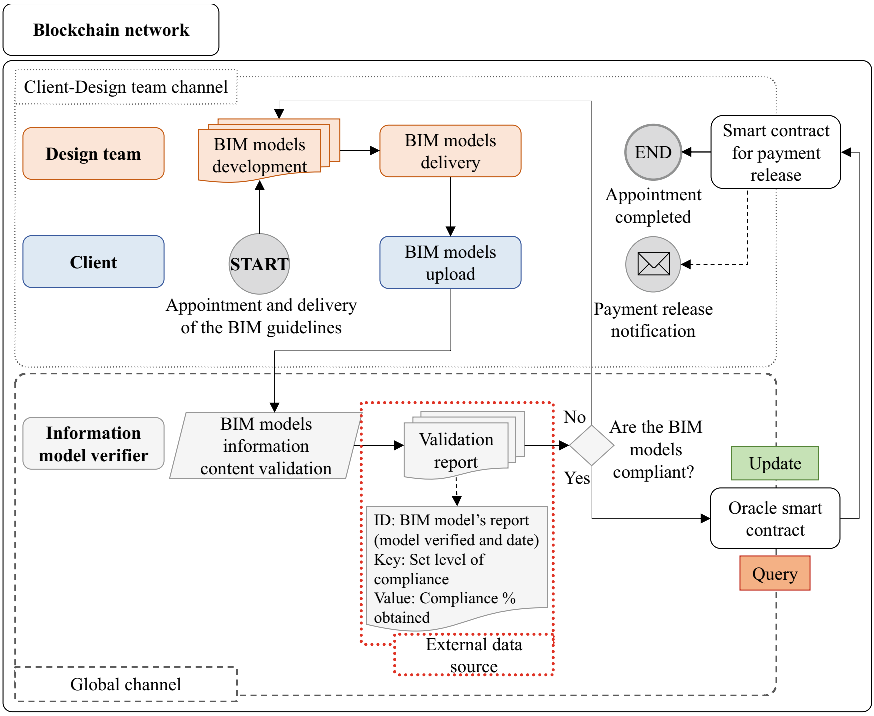


Fig. 5 High-level integration structure

of the setup application. The verification automatically produces a validation report containing the level of compliance achieved. The report, containing the indication of the model verified, the date of the verification, the failed elements and the percentage of compliance, represents the external data source to be connected to the blockchain network (i.e. the smart contract protocol) because it is produced by a tool external to the network. The verifier, as the supervisor of the verification activity, operates in the global channel representing the trusted provider of data. The verifier is indeed authorised by rules and policy to invoke the update of the ledger with the validation report. The smart contract deployed on the global channel, requests the external data and provides an update and a query transaction. From the other channel, namely the client-design team channel, the client can then invoke the smart contract which, exploiting the cross-channel query capability, retrieves the latest updated value. The smart contracts logic is activated, verifying that the value of the external source is equal to or greater than the established compliance level. If this is the case the logic executes, in compliance with rules based on consensus, issuing the approval to release the payment. This means that the smart contract logic setup executes the given instructions if some other given conditions are met. It could repeatedly verify the condition established (the achievement of the set level of compliance) and only perform the planned action when the condition has been met (BIM model has reached the set level of compliance).

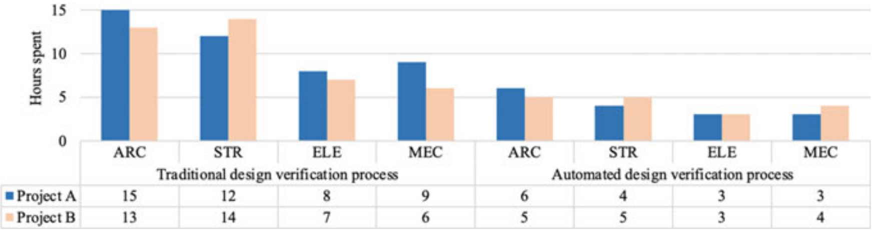
5 Discussion of the Expected Outcomes

Through the automatic validation of the information content of the BIM models and the application of smart contracts, the research framework aims at shortening the execution time of the design phase, ensuring the fulfilment of the client's requirements and the approval for the release of payment to the design team. Due to the increased complexity of the projects, the information requirements achievement and late payments are relevant factors in the trend of the industry [1]. The presented framework of the research is still at its theoretical level, in Sect. 3 the project on which the framework will be tangibly tested as a proof of concept has been anticipated. The future testing of the framework and the analysis of the results obtained will indeed be the next steps of the proposed research development. Therefore, in this section, the expected outcomes are disclosed and discussed, and their identification can be considered as a benchmark for comparing the future results. The main purpose of the framework relies on the integration between the information management based on BIM and the blockchain network to improve the link between the client and the design team, in the design phase. The combined environment presented in the research enables contracting parties to produce, review and maintain the same information exhaustively. Using the focus on process automation, the activities of controlling and validating the information, as well as those of approving the payment release, are executed by coded applications instead of humans' implemented procedures. This innovative approach boosts the shortening of the design phase execution, facilitates the control of any rework and ensures the approval for the release of payments when the contractual conditions are met.

The information management practices recommended by the ISO 19650 series promote constant interaction among the parties in the process. The information management based on BIM is characterised by the complete exchange of digital information whose revisions are dynamically reported and integrated, improving control over the project's progress and reducing non-conformities. Due to the high information content of BIM models, it is appropriate to adopt applications that automatically detect errors and non-conformities, facilitating a positive response to the client's information requirements. Once all information included in the BIM models is completed, it is necessary to proceed with its verification to confirm compliance with the guidelines' requirements. As earlier underlined, in the BIM environment the validation of information produced by the design team becomes a fundamental activity for the respect of the client's requirements. Indeed, the imprecise execution of this activity would not only have a negative effect on the project development and management, nevertheless, it would also generate potentially costly inaccuracies, therefore, necessarily to be avoided. To support this task, the development of an application that allows the automatic verification of information becomes crucial to check comprehensively the compliance with the BIM guidelines.

With the aim of automatically and digitally validating the fulfilment of the client's information requirements, the architecture of the application was developed through four main activities. Thanks to the first tests of this application, some expected benefits can be summarised. Firstly, the setup of an application for automatic information validation could provide the client with an effective tool for reviewing carefully the information produced by the design team. The adoption of such a verification process supports the improvement of the communication between the client and the design team. The validation of information produced during the design phase is no longer a manual, time-consuming and jagged activity, in fact it becomes comprehensive and detailed. Secondly, the design team would, therefore, be encouraged to produce information in compliance with the client's information requirements to reduce working time and the likelihood of rework. At the same time, in the event of a negative review result, obtaining a detailed report containing all the rejected elements facilitates the design team in implementing targeted and fast corrections and supplementations. Finally, the client can monitor the actual progress of the project and the accuracy of the design teams. The detailed verification of the models ensures that the information requirements are met, and the automation of the process considerably reduces the traditional verification and validation time. Based on some initial experimentations, a statistical comparison between the time spent to verify the project using the traditional process and the automated one shows a time reduction of nearly 60% with a sample of two buildings (Fig. 6). The BIM models related to these buildings were developed by the external design teams for the real digitalisation of the real estate assets requested and initiated by RAI. The BIM models are related to office buildings and recording studios, and their surface is about 15000sqm for project A and 12000 sqm for project B. For each BIM model, the appointed design teams developed four BIM models covering the four main disciplines. To highlight the innovative value of the automatic verification proposed in the research, the verifications of these models were carried out in both manual and automatic ways, in compliance with the two macro-categories of rule sets illustrated in Sect. 4.1. The statistical analysis will be further developed and improved during the evolution of the research.

Meaning to implement a blockchain network in the design phase, its architecture requires an appropriate selection and configuration. Among the possible types



	ARC	STR	ELE	MEC	ARC	STR	ELE	MEC
	Traditional design verification process				Automated design verification process			
■ Project A	15	12	8	9	6	4	3	3
■ Project B	13	14	7	6	5	5	3	4

Fig. 6 Time comparison between manual and automatic design verification and validation

of blockchains, the permissioned ones were considered the most suitable types of networks for the research, which is set in a proprietary environment. Hyperledger Fabric was proposed as it is built for enterprise business. The permissioned network allows only selected participants to collaborate and transact, indeed network participants are known and acknowledged when setting up and running the network. This network guarantees privacy and the control of identity. Thanks to the correspondence between the digital identities and the social ones of each peer, the private network is easier to be implemented in the real scene than the public one, with higher operating efficiency, better transactions performance and lower costs [42]. In the explored design phase, the use of such a network allows the client to filter accesses, identify participants and guarantee the privacy and security of communication and information exchange. To set up and test the identified network in the research, its architecture was defined by pinpointing the working channel, participants, assets and expected transactions. The goal of automating both the validation of information included in BIM models and the consequent approval of the release of the payment, using smart contracts, highlighted the need to reliably connect the BIM process with the blockchain network. The import of external data into blockchain is made using an oracle, able to connect in a trusted way the application previously defined for the automatic BIM validation and the automatic business logic at the basis of the smart contract. This means that a participant, in this case, the verifier of the BIM models, becomes the trusted organisation operating in a separate channel. Only the oracle is authorised to post updates to the oracle smart contract, these updates would be the external data related to the results of the automatic validation. Since the oracle added operates in a different channel, the smart contract between the client and the design team would access the desired data (i.e. the validation report) via an inter-channel smart contract query.

The potential setup of a permissioned network allows the identification of some expected advantages. Firstly, the integration of a blockchain network in the general framework supports the implementation of automated activities. This means that the network can come along with the information management in the design phase, eliminating any intermediaries and ensuring the confidentiality of shared information using consensus protocols and smart contracts. Secondly, the smart contract between the client and the design team would assure the contracting party of the client's willingness to pay and the certain delivery of payment upon automatic approval.

In this theoretical stage of the research, a permissioned network was chosen because, from an architectural and functional point of view, it offers the appropriate network for the environment of the framework of the research. In addition, considering the selected real project, this choice was made to avoid the problems related to the public visualisation of information and the operating costs due to the fees for using a public network. During the actual development of the blockchain network for the proof of concept, it will be possible that other types of networks will be considered, investigated and tested as well as the possible link with a public blockchain, to maintain the nature and original meaning of the technology. The possible adoption of a public network should consider the organisational, economic and regulatory problems, and also analyse possible alternative solutions capable of minimising the operating costs. The system that better will truly perform and respond to the research objectives will be the one chosen and used during the implementation of the proof of concept in the future research development. To conclude, the main expected outcomes are related to: (i) the growth of the process efficiency, (ii) the improvement of information production, review and validation, (iii) the increased automation of procedures and (iv) the respect for delivery times and release of payments.

6 Conclusion and Further Developments

The presented framework of the research intends to demonstrate that the advent of new technologies could support positively the digitalisation of the construction industry. The proposed framework illustrates how the adoption of the automatic BIM validation and smart contracts could streamline and shorten the design phase execution. The chapter points out the integration between the information management based on BIM and blockchain as a solution to the weaknesses of the client's requirements fulfilment, reliable information review and validation, and late payments. The combination of the two technologies offers enormous value and could be considered an appropriate direction for the efficient development of the design phase, thus attracting industry players. The potential offered by the framework could fully exploit the information of a BIM-based project. During the discussion of the expected outcomes, it was briefly shown how the automated verification of the information contained in the BIM models can significantly reduce the time taken to verify the project in compliance with the client's information requirements. The application of the automatic design validation would allow, through the integration and use of blockchain, to automate the entire process until complete validation and this would be demonstrated through the development and testing of the proof of concept. Further developments of the research could involve the validation of the framework for the other verification procedures such as clash detection and code checking, so that the approved BIM models could be used as a legal reference both in the tender and construction phase, as a reference for monitoring the fulfilment of all the project requirements and specifications, or in the maintenance and operational phase, as an updated database of the building life cycle.

References

1. European Construction Sector Observatory (2018) Country profile Italy, p 27
2. European Construction Sector Observatory (2019) Building information modelling in the EU construction sector, pp 1–22
3. Li J, Greenwood D, Kassem M (2019) Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. Autom Constr 102(January):288–307

4. Antwi-Afari MF, Li H, Pärn EA, Edwards DJ (2018) Critical success factors for implementing building information modelling (BIM): A longitudinal review. Autom Constr 91(November 2017):100–110
5. Nawari NO, Ravindran S. (2019) Blockchain and the built environment: Potentials and limitations. J Build Eng 25(June)
6. Tezel A, Papadonikolaki E, Yitmen I (2019) Preparing construction supply chains for blockchain: An exploratory analysis. CIB World Build Congr (June):17–21
7. Scott DJ, Broyd T, Ma L (2021) Exploratory literature review of blockchain in the construction industry. Autom Constr 132(July):103914
8. Hunhevicz JJ, Hall DM (2019) Managing mistrust in construction using DLT: a review of use-case categories for technical decisions. In: Proceeding of the 2019 European conference on computing in construction, vol. 1, pp 100–109
9. Dakhli Z, Lafhaj Z, Mossman A (2019) The potential of blockchain in building construction. Buildings
10. Wu L (2018) Blockchain-based smart contract for smart payment in construction: A focus on the payment freezing and disbursement cycle, pp 4–6
11. Maciel A (2019) CBC symposium 2019 no(June)
12. Dounas T, Lombardi D, Jabi W (2020) Framework for decentralised architectural design BIM and Blockchain integration. Int J Archit Comput
13. Mathews M, Robles D, Bowe B (2017) BIM+blockchain: A solution to the trust problem in collaboration? CITA BIM Gather 2017:11
14. Rodrigues B, Bocek T, Stiller B (2018) The use of blockchains: Application-driven analysis of applicability, 1st ed, vol. 111. Elsevier Inc.
15. Agenzia per la Coesione Territoriale (2018) Rapporto sui tempi di attuazione delle opere pubbliche. Temi CTP 6:1–43
16. European Construction Sector Observatory (2020) Late payment in the construction sector, pp 1–64
17. Windaus D, Tebbett S, Rosier H, Rafuse J, Vettoretti R, Greaves P (2019) Working capital report 2019/20: Creating value through working capital
18. NBS (2019) National BIM report 2019, pp 1–28
19. European Construction Sector Observatory (2019) Country profile Italy
20. UK BIM Alliance (2020) Information management according to BS EN ISO 19650—Guidance Part 1: concepts 3:42
21. Oraee M, Hosseini MR, Edwards DJ, Li H, Papadonikolaki E, Cao D (2019) Collaboration barriers in BIM-based construction networks: a conceptual model. Int J Proj Manag 37(6):839–854
22. BSI Standards Publication (2018) ISO 19650–1:2018, pp 1–46
23. Baldauf JP, Formoso CT, Tzortzopoulos P, Miron LIG, Soliman J (2020) Using building information modelling to manage client requirements in social housing projects. Sustainability 12(7):1–21
24. BSI Standards Publication (2012) PD ISO/TS 12911: Framework for building information modelling (BIM) guidance
25. Kensek K (2015) BIM guidelines inform facilities management databases: A case study over time. Buildings 5(3):899–916
26. Sacks R, Gurevich U, Shrestha P (2016) A review of building information modeling protocols, guides and standards for large construction clients. J Inf Technol Constr 21:479–503
27. Yli-Huumo J, Ko D, Choi S, Park S, Smolander K (2016) Where is current research on blockchain technology?—A systematic review. PLoS One
28. Tapscott D, Tapscott A (2017) Realizing the potential of blockchain a multistakeholder approach to the stewardship of blockchain and cryptocurrencies. Whitepaper (June), 46
29. Foschini L, Gavagna A, Martuscelli G, Montanari R (2020) Hyperledger fabric blockchain: Chaincode performance analysis. In: IEEE international conference on communications, 2020
30. Tapscott D, Tapscott A (2016) Blockchain revolution—How the technology behind Bitcoin and other cryptocurrencies is changing the world. Portfolio/Penguin

31. Wust K, Gervais A (2018) Do you need a blockchain?. In: Proceeding of the 2018 crypto valley conference blockchain technolonogy CVCBT 2018, no. i, pp 45–54
32. Cardeira H (2015) Smart contracts and possible applications to the construction industry. In: New perspectives in construction law conference held Bucharest, 2015
33. Das M, Luo H, Cheng JCP (2020) Securing interim payments in construction projects through a blockchain-based framework. Autom Constr 118
34. Ahmadisheykhsarmast S, Sonmez R (2020) A smart contract system for security of payment of construction contracts. Autom Constr 120
35. Caldarelli G (2020) Understanding the blockchain oracle problem: a call for action. Inf 11(11):1–19
36. Schaad A, Reski T, Winzenried O (2019) Integration of a secure physical element as a trusted oracle in a hyperledger blockchain. In: ICETE 2019—proceeding of the 16th international. joint conference e-business and telecommunications, vol. 2, no. January, pp 498–503
37. Schönhals A, Hepp T, Gipp B (2018) Design thinking using the blockchain. In: Proceeding of the—1st work on cryblock*,* pp 105–110
38. Zheng R, Jiang J, Hao X, Ren W, Xiong F, Ren Y (2019) BcBIM: a blockchain-based big data model for bim modification audit and provenance in mobile cloud. Math Probl Eng 2019
39. Polge J, Robert J, Le Traon Y (2020) Permissioned blockchain frameworks in the industry: a comparison. ICT Express
40. Nanayakkara S, Rodrigo MNN, Perera S, Weerasuriya GT, Hijazi AA (2021) A methodology for selection of a Blockchain platform to develop an enterprise system. J Ind Inf Integr 23
41. Javaid H, Hu C, Brebner G (2019) Optimizing validation phase of hyperledger fabric. In: Proceeding of the IEEE international symposium on MASCOTS, pp 269–275
42. Yang L, Dong X, Tong W, Ma S, Qiao H, Xing S (2020) Secure off-chain payment in consortium blockchain system. In: Proceeding of the 2020 international NaNA 2020, pp 259–264

Capturing and Transforming Planning Processes for Smart Contracts

Marijana Srećković, Goran Šibenik, and Dominik Breitfuß

Abstract This chapter presents a conceptual framework for the application of blockchain technology with Building Information Modeling (BIM) in the design phase, with a further use case exploration of Smart Contracts implementation. One of the main challenges in BIM workflows is the traceability of changes within a BIM model and closely coupled with it, the accountability for clearances and the sharing of model information. We argue that the different value chain activities, actors, and digital assets in the design phase could be linked on the basis of Blockchain (BC) and Smart Contracts (SC). Our BIMd.sign framework shows mainly three factors why BC and SC can be considered to deliver benefits to a BIM-based process if implemented: documentation, traceability, and transparency. We argue that the gained information from this analysis will give enough insight to evaluate the needed "level of detail" of repeating acts or sequences, in which traceability through SC can deliver a sufficient supplement respectively optimization for planning processes in the design phase. Furthermore, based on our research, we suggest that possible applications of SC in the design phase require a transformation of existing workflows for the implementation of digital technologies.

Keywords Design phase · Blockchain · Framework · 3A · BIMd.sign

1 Introduction

The implementation of Blockchain (BC) and Smart Contracts (SC) in the design phase and planning processes of building projects, has not been sufficiently addressed

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so far or found its application in practice, although numerous pieces of the literature suggest possible theoretical or conceptual applications of this technology in the Architecture, Engineering, Construction (AEC) industry [14, 18, 30]. As far as research shows, AEC could potentially benefit from the implementation of BC and SC [25, 32] and gain efficiency in the design phase of a building project through more transparency and traceability. Nevertheless, the applied technology has to be analyzed through the lens of a sociotechnical system and its applicability for differing value chain activities existing in the design, construction, and operational phase.

One of the main challenges in Building Information Modeling (BIM) workflows is the traceability of changes within a BIM model and closely coupled with it, the accountability for clearances and the sharing of model information [10]. In order to understand BIM workflows and find possible intersection points with BC and SC in AEC, an extensive exploration of process participants, data exchanges, and process steps is imperative.

We present the results from the ongoing research project BIMd.sign, which has been developed so far, including: (1) a conceptual framework for process modeling and (2) a 3A pattern for process analysis, needed for the digitalization of the design phase. A prototype with a demonstration application is currently in its development stage and therefore not the focus of this chapter. In our research, we argue that the different value chain activities, actors and digital assets in the design phase could be linked on the basis of BC and SC. Hence in the first step, a developed methodological framework for the analysis of design workflows, which is a combination of three underlying theories—design, configuration, and task-technology fit, is presented. In the second step, based on a quantitative study, a 3A pattern analysis is displayed. The pattern divides each process into three sub-layers: stakeholders (actors), data (assets), and processes (activities). This separation into three layers ensures a highly detailed representation of the processes, showing the sequenced work of the stakeholders and the occurring communication and collaboration during the design phase. The used method allows identification of iterating processes as well, which can be seen on two different levels: a repeating act (a singular action) in the regular process, or a repeating sequence (a number of actions in the same order) due to insufficient outcomes. Based on the framework for process modeling and the 3A pattern, which are extended into the BIMd.sign framework, a conceptual application of SC in the design phase is proposed, grounded in a use case, where we explore the process/workflow, domain-specific data exchange, stakeholders, and existing iterating processes in practice. The BIMd.sign framework focuses herewith on the design phase and the use of BC and SC for traceable documentation of the delivery and approval of BIM models. Thus, important activities and decisions during the design phase are documented transparently.

We argue that the gained information from this analysis will give enough insight to evaluate the needed "level of detail" of repeating acts or sequences, in which traceability through SC can deliver a sufficient supplement, respectively, optimization for planning processes in the design phase. Furthermore, based on our analysis, we suggest that possible applications of SC in the design phase require a transformation of existing workflows, which will be implemented as a proof-of-concept prototype in the final stage of our research project.

2 Background

2.1 Processes in the Design Phase

The characteristics of AEC are represented in its "loose organization of the different participants that each perform a specific role in a building project and have a specific view on the building project data" [45], due to their domain-specific expertise and assigned tasks within the design process.

The design process can be viewed as an endless reciprocal flow [24], where dependencies need to be understood [22] in order to be managed. Design process definitions exist in various forms as plans of work and services or organizational models in building projects—specific to a country (e.g., [17, 26, 35]) or field, such as project management [33]. They explain the stages, their desired core tasks and outcomes, as well as necessary information exchanges in each stage. Although this literature on design processes can be useful as a point of departure for further development—since it promotes common structures in the highly heterogeneous AEC industry, it can also slow down innovation while referring to traditional workflows without considering the latest technological developments [43].

Both processes and standards need to evolve together if the digitalization potentials are to be fully realized [43]. There are approaches to standardize the processes as information delivery manuals (IDMs) [19, 20], which originate from the work of the buildingSmart organization. buildingSmart [6] recognizes that the development of IDMs is difficult for some domains, and that it should be accompanied by software development. IDM is a standard, which "*provides help in getting the full benefit from a BIM*" [19]. It describes a methodology to identify and describe processes within the context of BIM to support use cases by providing the information of a satisfactory quality at the required time. It is another component, which forms a fundamental part of our analysis framework. Nevertheless, for our research purposes, a deviation from IDMs was necessary—where the focus is on the detail of the comprehensive procedures of the complete project; whereas our framework connects aspects from a theoretical point of view and a practice point of view, delivering an integrative configurational fit of task-technology-people, embedded in an organizational structure resp. environment. Additionally, the focus in our presented conceptual model development is on smaller and more scaled process scenarios, which furthermore are the entry points for an SC implementation.

2.2 BIM and BC

Building Information Modeling enables information from all project phases to be stored in a single digital model [27]. In connection with BIM, the potential of BC lies in the so-called record of changes, where traceability of modifications and updates to the BIM-Model could help the standardization of BIM processes [29], and make design workflows more transparent and in parts even automated through the implementation of SC.

While BC forms the infrastructure, SCs functionalize it, i.e., the properties are often not clearly separable and are partly dependent on each other [3]. On the basis of BC, the immutability of the data is one of the key factors for its implementation in the AEC. Oraee et al. [31] describe this property as the starting point for better collaborations in the context of BIM projects. A so-called "BIM execution plan" (BeP), in combination with SCs, could help to define services and deliverables and accelerate their implementation. The definition of responsibility is also highlighted by Dounas et al. [13]. Another effect that Dounas et al. [13] emphasize is the possibility of creating decentralized planning teams, as intellectual property and BIM models can be referenced through BC due to the transparency of data and the traceability of the origin of this data [31]. Perera et al. [32] see traceability as an essential tool to operate an efficient asset management. While asset management is only mentioned as a secondary benefit in the digital area, Cecconi et al. [8] describe BIM as a digital object-oriented process and combine asset management with BIM models.

The automatic documentation in the BC also leads to an exact image of the decisions and actions made. Dounas et al. [13] explain in this context how BIM models with hash references could be stored in the BC. In this way, the individual versions of the BIM models would be verified and used as a log in the case of legal disputes. This could make the resolution of such disputes much easier, if not even preventable [1, 29].

2.3 Information Management and Exchange

The increasing use of BIM as a working method has enhanced the need for close and coordinated collaboration and information management. Common Data Environments (CDEs) offer further support in terms of data exchange and collaboration. CDEs are […] internet-based platforms for the management of processes and information in all phases of the life cycle of a building [12, p. 9]. They serve as a platform for the exchange of data and information in a regulated environment [34]. In Srećković et al. [41] the CDE is defined as a combination of different technologies that promote the exchange of information. An "Information Container for linked Document Delivery" [11] is used, in which the exchanged data, structured (e.g. geometry models, XML files, mass calculations, etc.) or unstructured (photos, PDF files, etc.) are filed (see use case). A CDE is a well-suited and secure data storage for digital assets in construction projects. Storing a large amount of data on a public BC is very expensive and not efficient, otherwise private BC is critical in terms of security and trust. Hence, it is proposed to keep all the sensitive and important information in a centralized off-chain storage. Thus, only unique cryptographic hashes of the files deposited in the CDE can be recorded on the BC.

3 Frameworks

3.1 Conceptual Framework for Process Modelling

An implementation of SC and BC in the increasingly complex system of BIM-based planning requires an analysis from different points of view. In order to investigate a BIM workflow during the design phase of a building project, and keep the focus on process modeling, a framework was developed, based on three underlying theories—design, configuration, and task-technology fit as presented in Table 1 and Fig. 1. The conceptual framework shown in Fig. 1 connects theory and practice. The analysis framework constitutes the connection between people, organization, and technology interaction. Hence, the design of a process with a task-technology-configurational fit requires an adaptive interaction of implemented processes (through people), organization (actions and delivery order), and technology (software and data) [40].

Table 1 Integration of 3 theories (from Srećković et al. [40])

Theory	Main idea	Point of our analysis
Design	Conceptualization of design principles and action	Design workflow
Configuration	Alignment of structure, process, environment	Process modeling Information processing
Task-technology fit	Fit between IT and business processes	BIM, Blockchain, DApps, data exchange and transferability, data formats

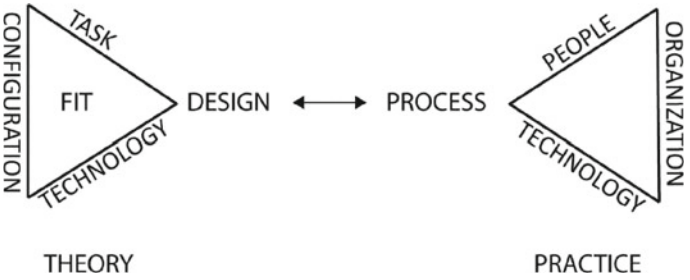

Fig. 1 Connecting theory and practice (from Srećković et al. [40])

We define ***design workflow*** as the flow of information, deliverables, specifications, and other design resources between the project stakeholders [16], which are included in numerous processes in the building design phase (e.g., information process, data management process, BIM workflow). In practice, these processes are not linear or rigid, but rather dynamic and very complex. Hence, workflow is more than a technique to model a process. It is a method to analyze and improve a process, including its modeling. ***Processes*** are relationships between inputs and outputs, where inputs are transformed into outputs using a series of activities or tasks which add value to the inputs [2]. One or more software systems, one or a team of humans, or a combination of these can perform a task. ***Task-technology fit*** (TTF) is the degree to which a technology supports the performance of tasks, where task requirements, individual abilities and the functionality of technology are in accordance [15]. In the context of TTF theory, technology has to match business processes [23], enabling a tight coupling of IT function, business strategy, and the organization's information needs [42].

3.2 3A Pattern

Dynamic, spontaneous, and informal communication patterns occur during unexpected events during the construction project, which is not supported by most of the available technological solutions [44]. With our developed triple-A or 3A method [38], patterns are recognized by analyzing the actor, activity, and asset sequences separately as well as their combinations. In the later presented BIMd.sign framework, the 3A analysis divides the design workflow into actor, action, and asset from a single sub-process in the design process. The definition of an ***actor*** from ISO [19] being a "person, organization or organizational unit involved in a construction process". Further on, ISO [19] distinguishes two types of actors: initiator who makes a request and executor who responds to the request. ***Activity*** is used as an atomic sub-process of a design phase, required for digitalization purposes. We consider the process a sequence of activities, which transforms inputs into outputs. ***Assets*** as in Succar and Poirier [43] are addressing both digital and physical assets used in construction. They are interrelated, whereby the digital ones can be documents, models, and data. The patterns were identified by statistical analysis of the 3As, where multiple sequences of actor, activity, and asset were compared. For this quantitative analysis, in total 100 listings of protocols and respective process documentation of two existing building projects, at different stages in the design process were explored, which is explained in more detail in Sibenik et al. [38]. This quantitative analysis enabled the patterns extrapolation and discovery of commonly occurring sequences that provide a base for future automation of processes. Our approach was validated by BC experts involved with the project BIMd.sign, who expressed their views regarding the required scope of the design activities information, for supporting and eventually automating the workflows with BC. They acknowledged the usefulness and usability of the 3A analysis for future implementation, especially due to a lack of documented workflows on the building element level.

3.3 *BIMd.Sign Framework*

As previously shown, in order to capture processes, it is necessary first to understand how they are designed, second how they need to be configured for BIM, BC and SC and third, how to continuously adjust the fit between digital technologies and business processes or workflows. Figure 2 presents the configuration of an exemplary workflow in the design phase based on our methodological framework and 3A pattern, showing information processing of digital assets (data-flow) and coordination of activities (process flow) between different actors (client, domain-specific planners). It reflects the exchange during a design activity and shows the complexity resp. interrelatedness in the information processing of different digital assets. Each step in the process flow has actors responsible for their own domain-specific tasks and fulfillment.

In the BIMd.sign framework, the role of BC and SC in the design phase is to trace the activities performed on the specific digital assets (e.g., BIM-Model, plans) during the whole phase and allow these activities to be transparent for the relevant participating actors. Hence, SCs would facilitate the traceability of relevant modifications in the digital model, where the author and date of a change would be documented on the BC. Furthermore, process steps, which are executed in iterative loops (such as the repeated exchange of digital assets between different domain-specific planners), could be automatized with SC, generating a more efficient workflow (see also Chapter Use Case).

The conceptual framework starts with the commissioning of the design services according to the contract by the client (Fig. 3). The services of the General Planner (GP)—based on the procurement model in Austria resp. Germany [17, 26]—usually assumed by a superordinate architecture firm, including the complete design package and often further management services in the project if so contractually agreed. The project requirements are defined by the client and are the basis for the execution of the project and the assessment of all activities addressing function, form, budget, and time [7], as well as the evaluation of the delivered digital and physical assets.

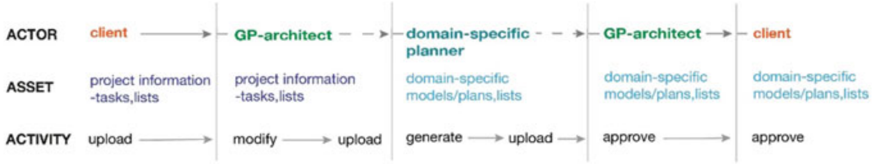

Fig. 2 Actor/asset/activity workflow (from Srećković et al. [41])

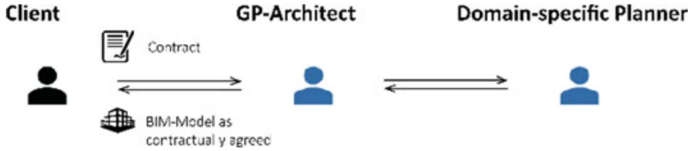

Fig. 3 Procurement model

At the end of each process or stage in the design phase, the GP presents the results to the client, who either accepts to move forward or requires changes, which end in iteration until the design is approved. According to the procurement model, the GP is coordinating and organizing all design services and acting as the intermediary between the client and the domain-specific planners.

In the BIMd.sign framework (Fig. 4), the architect (domain-specific planner) develops, e.g., the conceptual design and uploads it to the common data environment (CDE, see [21]). The structural engineer (domain-specific planner) is responsible to check if the uploaded model fulfills all the domain-specific requirements. If not approved, a list of required changes is uploaded for the architect, who modifies the design and uploads the updated model for the structural engineer to the CDE. If approved by the structural engineer, the architect then authorizes further steps. In this case, the SC would be able to document the changes and responsibilities of the

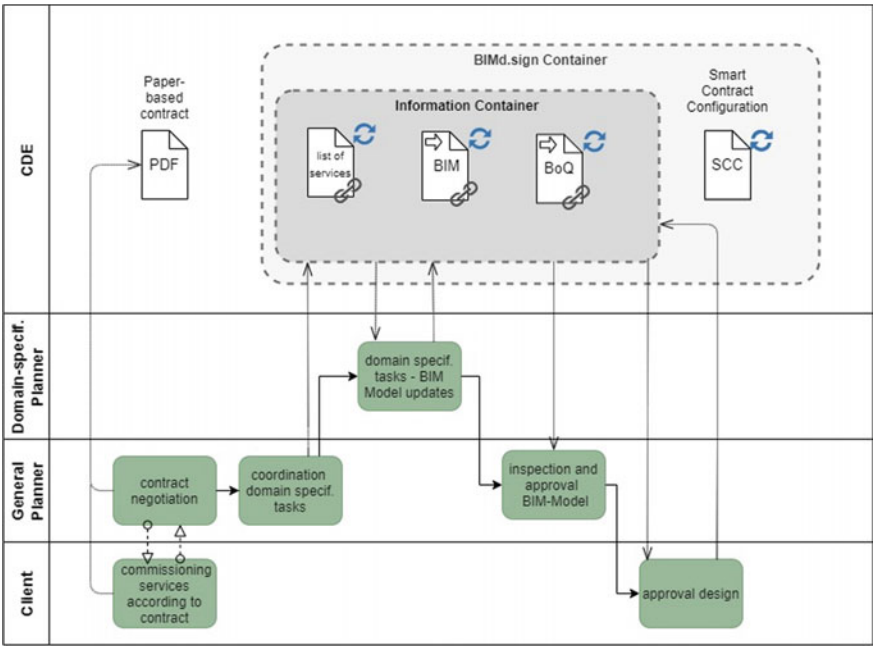

Fig. 4 BIMd.sign framework (from Srećković et al. [41])

involved actors, as well as give clearance for further steps, when all approvals are met, completing this SC and possibly triggering a new one. Hence, each of these steps is supported with an SC, which also partly automatically defines the possible next steps. The actors are also able to define the next steps by choosing an SC, which is regarded as another digital asset during the design phase.

In the BIMd.sign framework, any new version of digital assets could reference the previous one, which creates a transparent design workflow progress. Hence, based on the data stored on the BC, the SC enables the tracing of the workflow progress' status and automatically (according to code) permits further processing of data, if the specified requirements, defined within an SC, are fulfilled.

4 Use Case Scenario

As mentioned in the introduction, this chapter presents the research results achieved so far from the BIMd.sign project, where the focus is on the use of BC and SC for traceable documentation of delivery and approval of BIM models or parts of it. Thus, important activities and decisions during the design phase are documented transparently. For the contextualization of our framework, two conditions are assumed:

- The implementation of BIM has progressed so far that data can be exchanged between those involved in the project without any problems.
- Central data management using CDE is used, which makes it possible to ensure that all data is stored in a central location.

Basically, the framework (Fig. 5) can be divided into four parts, each of which forms a relevant component. The described process step (action) in the use case scenario is the first "column" of the framework. The second part is the BC. As a decentralized memory, it maps the process and the actions carried out in the form of references (hash) and the executed SCs. The third part is a central data storage, such as a CDE. It is responsible for the storing of all relevant data (documents, models, etc.). The fourth and last part are the SCs themselves, which functionalize the system.

For a more detailed conceptual demonstration of an SC implementation in the design phase, based on this framework, we have chosen the following scenario as the base layer, which occurs in numerous iterations in practice: the architect makes a necessary change in design to a load-bearing wall. The next step includes a needed verification and clearance from the structural engineer, as the aforementioned change includes a structural element. Figure 5 shows this process, where our proposed system is divided into four columns, as mentioned: Action, Blockchain, Database (CDE), and Smart Contract. The first column describes the actions, which are taking place during this process. The framed actions are additionally indicating an SC implementation. The blockchain hosts the SCs and the model references, the database mainly contains the model data in an exchangeable format.

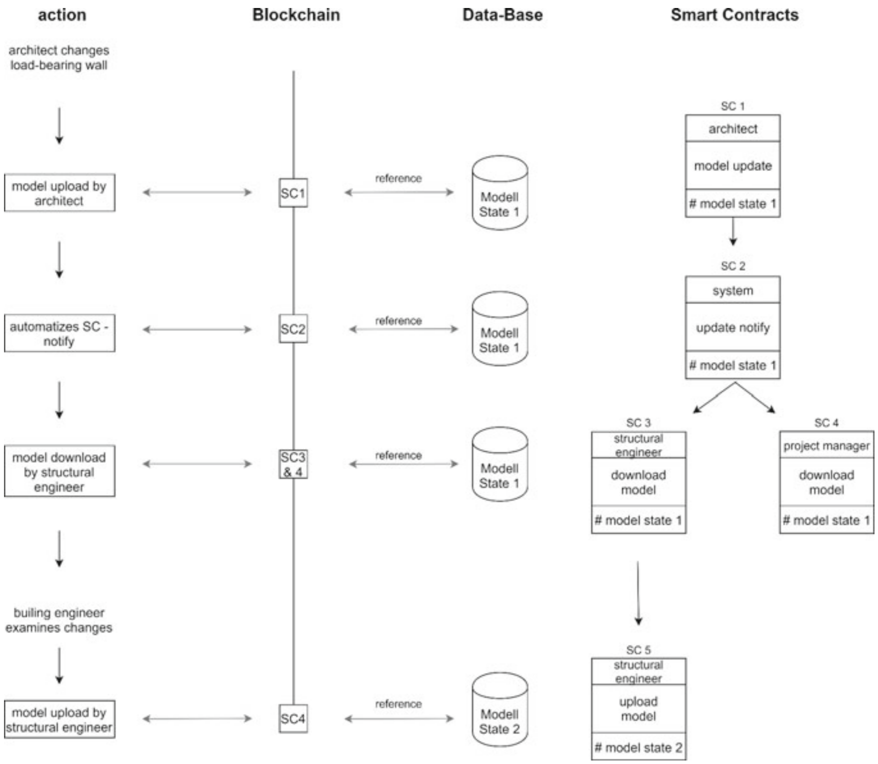

Fig. 5 Use case scenario with SC (from Breitfuß et al. [5])

An SC is basically addressed through two different approaches. Firstly, a manually triggered input is needed. This could be for instance the upload of a new model version to the system. In this case, the SC is responsible for creating a reference and storing it on the BC. Secondly, an SC could be triggered by another SC. When the before mentioned SC creates the reference, it simultaneously can monitor the changes in the model version. Due to an object-based file, object parameters could be one possible indicator for an automatization, such as the parameter load-bearing indicates a verification from the structural engineer, who then will be automatically informed. The project manager, in this case, will only be notified of the progress and will not be bothered to intervene.

Within the scenario that we analyzed, data management in the context of a BIM workflow has been file-based. However, to achieve object-based change management a data-centric approach is required. The potential of data-centric management has not been fully exhausted within the AEC industry [9]. In order to provide a suitable data management concept, we reformatted the industry foundation classes (IFC) models to a JSON format. In that way, the IFC models can be used on a database such as Mongo DB [37].

IFC is the most widely used standard to define neutral building models. This format can be used for the file-based data exchange which is still burdened with many problems [36]. Lack of standards, heterogeneous building model representations, and slow digitalization make this task highly complex. As a first step, we use the available IFC models, but the issues such as inconsistent building element IDs and non-synchronous links with the database, prevent it from being suitable for all data management aspects which are required.

The existing solution provides a way to reference a building element from the SC, but it does not fully correspond to BIM-based workflows from the technical side. To further improve data management, the aim is to directly connect proprietary software tools with the central database.

5 Discussion and Conclusion

With our BIMd.sign framework, we have demonstrated how different value chain activities, actors, and digital assets in the design phase could be linked on the basis of BC and SC. This could lead to higher quality in building design, as well as faster and more efficient processes, due to an easy adaption for each project through modular sets of SCs. The information filtered from a BIM model could help to automatize certain tasks during a project and save redundant steps. This automatization requires a step-by-step description [4] of each process and its possible outcomes to fully use all potentials. An overall automatization of all the BIM-based processes is not seen at this point, as there is a need for human input to start and direct certain processes [28]. In addition, the high complexity of data exchange and a vast number of activities present in the design workflow, which are not standardized, make an effort for overall automatization impossible in practice so far.

Our conceptual framework shows mainly three factors, why BC and SC can be considered to deliver benefits to a BIM-based process is implemented:

- Documentation: In the traditional planning processes, documentation was not an issue, as each document was stamped and in paper version [39], but due to BIM methods, the exchange rate of data increased drastically, which often leads to data loss and unused information [14].
- Transparency: Due to the process design conducted through SC, a new level of process integrity can be reached, which is transparent to all project stakeholders and agreed upon, before the project starts. This could foster and strengthen a new way of trust between the project stakeholders [13, 25].
- Traceability: Documentation and Transparency create the base layer for traceability in the design phases. SC can enable automatized reference-making on a BC and therefore create a revision-safe database. With a BIM element-based system, SCs facilitate the traceability of each change in the model. Author and

date of a change, can be tracked on the BC. The traceability enforces a responsible decision-making process and can help avoid legal disputes upfront, as well as minimize the restraint of using BIM in an inter-organizational setting.

In conclusion, we argue, that the implementation of process-based SCs could foster a better environment for BIM-based projects, due to a required standardization of these processes, which would also deliver benefits in the form of efficiency and speed. Nevertheless, the identification of intersections between people (project-stakeholders), technology (data-flow and software), and tasks (process flow) has not yet been fully adjusted to the needed requirements for SCs. The next steps in our research will include exploitation of further scenarios and use cases, standardization of terms for SCs (taxonomy), and the development of a proof-of-concept application in the final stage of our research project. Furthermore, the significant digitalization potential identified within this research, will be realized as a high-quality meta-analysis of the 3A pattern in the future steps of BIMd.sign.

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References

1. Abrishami S, Elghaish F (2019) Revolutionising AEC financial system within project delivery stages: a permissioned blockchain digitalised framework. 36th CIB W 78:2019
2. Aguilar-Savén RS (2004) Business process modelling: review and framework. Int J Prod Econ 90(2):129–149. https://doi.org/10.1016/S0925-5273(03)00102-6
3. Altay H, Motawa I (2020) An investigation on the applicability of smart contracts in the construction industry. Paper presented at the workshop proceedings
4. Bore N, Kinai A, Mutahi J, Kaguma D, Otieno F, Remy SL, Weldemariam K (2019) On using blockchain based workflows. In: 2019 IEEE international conference on blockchain and cryptocurrency (ICBC). IEEE, pp 112–116
5. Breitfuß D, Šibenik G, Srećković M (2021) Digital traceability for planning processes. In: ECPPM 2021—eWork and eBusiness in architecture, engineering and construction. In: Proceedings of the 13th European conference on product & process modelling (ECPPM 2021), 15–17 Sept 2021, Moscow, Russia
6. buildingSmart (2021) viewed 14 April 2021. https://technical.buildingsmart.org/standards/information-delivery-manual/
7. Cavka HB, Staub-French S, Poirier EA (2017) Developing owner information requirements for BIM-enabled project delivery and asset management. Autom Constr 83:169–183. https://doi.org/10.1016/j.autcon.2017.08.006
8. Cecconi FR, Dejaco MC, Moretti N, Mannino A, Cadena JDB (2020) Digital asset management. In: Digital transformation of the design, construction and management processes of the built environment. Springer, Cham, pp 243–253
9. Chassiakos A, Sakellaropoulos S (2008) A web-based system for managing construction information. Adv Eng Softw 39(11):865–876
10. Coyne R, Onabolu T (2018) Blockchain for architects. Arch Res Q 21(4):369–374. https://doi.org/10.1017/S1359135518000167

11. DIN EN ISO 21597-1:2021-07-00, Informationscontainer zur Datenübergabe—Austausch-Spezifikationen—Teil 1: Container (ISO 21597-12020); Deutsche Fassung EN ISO 21597-1:2020
12. DIN SPEC 91391-1:2019-04 Gemeinsame Datenumgebungen (CDE) für BIM Projekte—Funktionen und offener Datenaustausch zwischen Plattformen unterschiedlicher Hersteller—Teil 1: Module und Funktionen einer Gemeinsamen Datenumgebung, mit digitalem Anhang, Deutsches Institut für Normung e.V.
13. Dounas T, Lombardi D, Jabi W (2021) Framework for decentralised architectural design BIM and Blockchain integration. Int J Archit Comput 19(2):157–173. https://doi.org/10.1177/1478077120963376
14. Erri Pradeep AS, Yiu TW, Amor R (2019) Leveraging blockchain technology in a BIM workflow: a literature review. In: International conference on smart infrastructure and construction 2019 (ICSIC), pp 371–380. https://doi.org/10.1680/icsic.64669.371
15. Goodhue DL, Thompson RL (1995) Task-technology fit and individual performance. MIS quarterly:213–236
16. Hattab MA, Hamzeh F (2016) Analyzing design workflow: an agent-based modeling approach. Procedia Eng 164:510–517. https://doi.org/10.1016/j.proeng.2016.11.652
17. HOAI—Honorarordnung für Architekten und Ingenieure (2013) HOAI 2013 Volltext,, viewed 16 December 2020. https://www.hoai.de/online/HOAI_2013/HOAI_2013.php
18. Hunhevicz JJ, Hall DM (2020) Do you need a blockchain in construction? Use case categories and decision framework for DLT design options. Adv Eng Inform 45:101094. https://doi.org/10.1016/j.aei.2020.101094
19. ISO (International Organization for Standardization) (2016) ISO 29481-1:2016: building information models—information delivery manual—part 1: methodology and format. ISO, Geneva, Switzerland
20. ISO (International Organization for Standardization) (2012) ISO 29481-2:2012: Building information models—information delivery manual—part 2: interaction framework. ISO, Geneva, Switzerland
21. ISO (International Organization for Standardization) (2018) ISO 19650-2:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM)—information management using building information modelling—part 2: delivery phase of the assets. Geneva, Switzerland
22. Kalsaas BT, Sacks R (2011) Conceptualization of interdependency and coordination between construction tasks. Proceedings of the IGLC-19 Lima, Peru
23. Karim J, Somers T, Bhattacherjee A (2007) The impact of ERP implementation on business process outcomes: a factor-based study. J Manage Inf Syst 24(1):101–134. https://doi.org/10.2753/mis0742-1222240103
24. Knotten V, Svalestuen F, Hansen GK, Lædre O (2015) Design management in the building process-a review of current literature. Procedia Econ Finance 21:120–127
25. Li J, Greenwood D, Kassem M (2019) Blockchain in the built environment and construction industry: a systematic review, conceptual models and practical use cases. Autom Constr 102:288–307. https://doi.org/10.1016/j.autcon.2019.02.005
26. LM.VM (2014) In: Lechner H, Heck D (eds) Leistungsmodelle + Vergütungsmodelle. Verlag der Technischen Universität Graz, Graz, Austria
27. Love PED, Matthews J, Lockley S (2015) BIM for built asset management. Built Environ Project Asset Manag 5(3). https://doi.org/10.1108/BEPAM-12-2014-0062
28. Mason J (2017) Intelligent contracts and the construction industry. J Leg Aff Disput Resolut Eng Constr 9(3):04517012
29. Mason J, Escott H (2018) Smart contracts in construction: views and perceptions of stakeholders. In: Proceedings of FIG conference, Istanbul May 2018
30. Nawari NO, Ravindran S (2019) Blockchain technology and BIM process: review and potential applications. J Inform Technol Constr 24(12):209–238
31. Oraee M, Hosseini MR, Edwards D, Papadonikolaki E (2021) Collaboration in BIM-based construction networks: a qualitative model of influential factors. Eng Constr Archit Manag, ahead-of-print(ahead-of-print). https://doi.org/10.1108/ECAM-10-2020-0865

32. Perera S, Nanayakkara S, Rodrigo MNN, Senaratne S, Weinand R (2020) Blockchain technology: Is it hype or real in the construction industry? J Ind Inf Integr 17:100125. https://doi.org/10.1016/j.jii.2020.100125
33. PMI—Project Management Institute (2017) A guide to the project management body of knowledge (PMBOK guide), 6th edn. Project Management Institute, Pennsylvania, USA
34. Preidel C, Borrmann A, Mattern H, König M, Schapke S-E (2018) Common data environment. In: Borrmann A, König M, Koch C, Beetz J (eds) Building information modeling: technology foundations and industry practice. Springer International Publishing, Cham, pp 279–291
35. RIBA Plan of Work (2020) Viewed 16 December 2020, https://www.architecture.com/-/media/GatherContent/Test-resources-page/Additional-Documents/Printfriendly2020RIBAPlanofWorkoverviewpdf.pdf
36. Sibenik G, Kovacic I (2020) Assessment of model-based data exchange between architectural design and structural analysis. J Build Eng 32:101589
37. Sibenik G, Petrinas V (2020) IFCtoJSON [Software]. https://zenodo.org/badge/latestdoi/246248514 (accessed 31.7.2020)
38. Sibenik G, Sreckovic M, Radu A (2021) Modular process patterns in the design phase. In: 2021 European conference on computing in construction (EC3). Proceedings of the European conference on computing in construction. Rhodes, Greece, pp 1–9; 26.07.2021–28.07.2021. ISBN 978-3-907234-54-9
39. Singh S, Ashuri B (2019) Leveraging blockchain technology in AEC industry during design development phase. Computing in civil engineering 2019: visualization, information modeling, and simulation. American Society of Civil Engineers Reston, VA, pp 393–401
40. Srećković M, Šibenik G, Breitfuß D, Preindl T, Kastner W (2021) Analysis of design phase processes with BIM for blockchain implementation. In: Semenov V, Scherer RJ (eds) ECPPM 2021—eWork and eBusiness in Architecture, Engineering and Construction: Proceedings of the 13th European Conference on Product & Process Modelling (1st edn). CRC Press, London, UK, 2021. https://doi.org/10.1201/9781003191476
41. Srećković M, Šibenik G, Sigalow K, Ye X, König M, Reitmayer K (2021) Upkeeping digital assets during construction using blockchain technology, paper for the 38th CIB W78 conference on information and communication echnologies for AECO, Luxembourg, 11–15 Oct 2021
42. Strnadl CF (2006) Aligning business and IT: the process-driven architecture model. Inf Syst Manag 23(4):67–77
43. Succar B, Poirier E (2020) Lifecycle information transformation and exchange for delivering and managing digital and physical assets. Autom Constr 112:103090. https://doi.org/10.1016/j.autcon.2020.103090
44. Turk Ž, Klinc R (2017) Potentials of blockchain technology for construction management. Procedia Eng 196:638–645. https://doi.org/10.1016/j.proeng.2017.08.052
45. van Nederveen GA, Tolman FP (1992) Modelling multiple views on buildings. Autom Constr 1(3):215–224

Blockchain for Supply Chain Ledgers: Tracking Toxicity Information of Construction Materials

Emina Kristina Petrović, Alan Colin Brent, Catherine Iorns Magallanes, Lydia Hamer, and Daniel van Eijck

Abstract Reducing toxicity in construction materials is paramount to improving the sustainability of the construction industry. This necessitates better knowledge of the content of these materials or products. However, there is no central register nor mandated ledger of component materials. Furthermore, from a global supply chain management perspective, it is very difficult to have access to full value chain information even from the manufacturer of the final product. This chapter explores ways to establish a supply chain ledger to track components of construction materials by using blockchain technology; to provide reliable and fully disclosed information on their chemical content and providence. It focuses on the example of PVC, but its findings are relevant to the manufacture of any other products from different component parts or materials. The findings depend on what are the most desirable features in supply chain networks. But, in general, the most suitable solution appears to be a permissioned blockchain using a proof of authority consensus mechanism. Such a system can be a closed, private network, with a set of verified and trustworthy stakeholders as participants that provide public verification via a device such as a QR code. Such a system is fast and can accommodate a large number of transactions per second, so can thus scale up in the future even if a network starts small. Given the concern with tracing materials for the purposes of sustainability, the chapter also highlights the issue of energy consumption, which is necessary for maintaining the blockchain itself, and suggests that this should be a relevant feature in the design of any supply chain system. The framework of analysis emphasises the complexities in choosing the various technical and non-technical aspects of any such supply

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chain systems. Nevertheless, it is achievable with existing, bespoke blockchain-based solutions, as is illustrated with the PVC supply chain network.

1 Introduction

The construction industry is key to achieving ecological sustainability worldwide. For example, construction contributes significantly to global warming: according to the United Nations Environment Programme [61], when adding emissions from the building construction industry on top of operational emissions, the sector accounted for 38% of total global energy-related CO_2 emissions. Also, by volume, the construction industry makes a very significant impact: it contributes well over 40% of global extractions of natural resources [51, 52], and subsequent construction and demolition waste disposal, can contribute more than two-thirds of total municipal waste generated [18]. Toxicity of construction materials is also an issue: it is well known that toxicity in construction materials can have an adverse impact not only on the building users, but also on the natural environment [43, 45]. Therefore, improvements in how the construction industry removes toxicity from the materials could have a very real positive impact on human and planetary health.

Currently, it is challenging to find detailed information on all chemicals used in the production of construction materials, and especially to ensure that these are not toxic. Yet an increasing number of sustainability labelling schemes, including the Living Building Challenge, require such information [31, 39]. Many synthetic materials are comprised of a number of components that are manufactured in various facilities by different companies dispersed geographically, making it very difficult to obtain access to full value chain information, even from the manufacturer of the final product. A real challenge is how to provide such information in a way that effectively captures the difference between different variations of the same core material manufactured in more than one country, under different regulatory frameworks. Developing upon the existing work by Petrović [46, 47], this chapter explores if Blockchain technology can offer real opportunities to assist with tracking and reporting the issues with toxicity as the materials are manufactured. Emerging digital technologies offer real opportunities for innovation in terms of how to drive change in this area. To this end, this chapter evaluates the effectiveness of blockchain technology for collecting such information, and explores how blockchain technology can be applied to identify the toxicity of construction materials. The particular focus is on establishing the applicability of blockchain technology for sharing information on the sustainability of construction materials, by providing reliable and fully disclosed information on their chemical content and provenance.

This chapter uses one specific example, namely polyvinyl chloride (PVC). As established in the earlier work, there is a range of issues with the toxicity of PVC and its manufacture [47]. For this reason, PVC is a good example for exploring potential blockchain applications aimed at an effective recording of toxicity information in construction materials. This chapter develops upon the earlier work by identifying a range of key thresholds in the manufacturing value chain, where records would be required as part of normal contractual and financial transactions between companies. Based on this, the chapter proceeds to evaluate the (blockchain) technical frameworks suitable for the management of such records.

One important issue to recognise with all applications of blockchain technology for sustainability is the ongoing energy consumption, which is necessary for maintaining the blockchain itself. This could question whether blockchain technology can be usefully or validly used for sustainability purposes.

Finally, the chapter proposes a preliminary methodological framework to evaluate the potential for using blockchain transactions for construction material selection and acquisition in the construction sector. The framework highlights the complexities that are necessary to consider in terms of technical and non-technical aspects that are necessary for any applications of this nature.

2 Polyvinyl Chloride (PVC)

This chapter focuses on PVC in the construction industry. This section develops on the results of the previous projects and summarises elements of findings from these [46, 47]. Currently, the construction industry is the single most significant user of PVC, representing as much as about 60–70% of its total consumption [10, 28]. Because of its toxicity, Greenpeace has been campaigning for a global ban on PVC/vinyl manufacture for the past 30 years [25]. Similarly, some of the more progressive systems in architecture already identify PVC as an issue. For example, the Living Building Challenge insists on the removal of all chemicals from their Red List, which stipulates chlorinated polymers, thus including all PVC products [31]. Yet, despite these limitations, PVC is the third largest commodity plastic [67], and in 2016, world consumption of PVC was around 40 million tonnes, and this is still expected to rise by 2.3% per year until 2024 [10]. It is thus an important product to consider in relation to sustainability.

In the construction industry, PVC is used in applications such as pipes, wiring, films, profiles, sheets, fastening elements, flooring, wallpaper, and coatings. Therefore, any significant changes in construction applications could have a direct impact on global production and consumption of this toxic material. While the full phasing out of PVC is the best long-term approach, by examining the supply chain of PVC, this chapter contributes to raising the awareness of how problematic its use is, and maps out the series of steps for the potential application of blockchain technology in tracking toxicity in construction materials.

2.1 Issues Associated with Vinyl Chloride (VCM) in the Manufacture of PVC

PVC is a polymer of vinyl chloride or VCM, which is a known human carcinogen and therefore classified as a Group A by the US Environmental Protection Agency (EPA) [16]. It is toxic to cardiovascular, liver, organ development, and immune systems, genotoxic, and harmful to aquatic life [48]. In 2017, the Agency for Toxic Substances and Disease Registry (ATSDR) ranked vinyl chloride fourth on the Substance Priority List, after arsenic, lead, and mercury [2].

Unfortunately, there is a long history of limited recognition of the toxicity of vinyl chloride starting with two studies undertaken in 1930 at the Pittsburgh Experiment Station of the US Bureau of Mines and focused on assessing acute toxicity from single exposure to guinea pigs [44, 50]. Although high-level exposure led to the deaths of testing animals, harmfulness of vinyl chloride was reported in relative terms, emphasizing that there was no observed damage at lower levels of exposure and by comparing these to other chemicals, leading to a suggestion of its possible use for surgical anaesthesia [44], and subsequent research on such applications [41].

The carcinogenicity of vinyl chloride was formally recognised in 1974, based on studies of liver cancer and angiosarcoma of the liver in workers involved with the production of vinyl chloride or PVC [30]. Subsequently, in many countries, regulations were set to limit exposure to vinyl chloride. These vary between countries, but even with low exposure limits which are considered to minimise the potential for cancer [64], it is recognised that vinyl chloride might cause damage to other systems.

Although some of the chloride-containing chemicals are essential to life, such as sodium chloride (table salt), unfortunately, a number of issues have also been observed with many synthetically generated organic chemicals which contain chloride. It is most alarming that chloride-containing chemicals tend to be persistent organic pollutants [57]. In plastics, a number of chlorinated polymers have been developed often with excellent performance properties, such as chlorinated polyethylene (CPE), chlorinated polyvinylchloride (CPVC), and chlorosulfonated polyethylene (CSPE), which have all been introduced into the construction industry [4]. However, chlorinated polymers can contain volatile components which can be released while in use, and it is increasingly known that the use of such products can lead to the potential for the release of dioxins and other issues [4]. Consequently, there has been a reduction in the manufacture of many such materials. The exception to this trend is the use of chlorine in PVC.

2.2 Issues Associated with PVC Additives

However, vinyl chloride is not the only risk associated with PVC. On its own, PVC is a white powdery dust, which is why it took more than 50 years after it was discovered for its potential application to be recognised [3]. In order to make this powdery dust to be useful, other materials need to be added to it. The most common additives are heat stabilisers, fillers, pigments, gliders, and plasticisers [12]. The most important additives are heat stabilizers and gliding agents which stop thermal decomposition during processing and moulding [67]. Otherwise, PVC would thermally decompose into VCM. Historically, common stabilizers included heavy metals, such as cadmium, lead, tin, and zinc, only recently have such toxic heavy metals cadmium and lead begun to be removed from PVC, even when PVC is used for water supply piping [59, 67].

Other common PVC additives improve the appearance of the product and, if needed, add flexibility. Plasticisers are commonly used to increase flexibility and achieve transparency of PVC, and for this, often plasticisers might be used in fairly high proportions as 10–60% of the final PVC products [37]. There is a range of substances that can be used as plasticisers including phthalates, aliphatics, epoxy, terephthalates, trimellitates, polymerics, and phosphates [29]. Phthalates have been the group of the most commonly used plasticisers, until the increase in recognition of issues associated with phthalates. Since 2008, an increasing number of phthalate plasticisers have been listed as substances of very high concern [20]. Plasticisers have been known to be released from the plasticised PVC while in use, and this tends to be the area of most recognised concerns when it comes to PVC in use [46].

Unfortunately, in recent years, replacement substances for the heavy metal stabilizers and the phthalate plasticisers have tended to be introduced without being thoroughly tested for their impacts on human health [46, 47]. One of the core problems with the use of PVC is that it will always require the use of a number of additives, and additives tend to be released relatively easily from the polymer mixture under a range of conditions while in use, during disposal, or while recycled. The toxicity of the additives used means that any release can have adverse health effects, human and environmental. However, if it is not known what is in any particular PVC product, no one knows exactly what or how to provide for it.

In addition to these problems caused by toxic additives, there are many other issues of toxicity related to the manufacture, use, and disposal of PVC [47]. Figure 1 summarises the key issues, by signalling toxic steps in red. For example, mercury or asbestos are commonly used as part of the process for obtaining the initial ingredients for PVC [17, 22, 34, 36, 40]. For another example, the intermediate chemicals, such as vinyl chloride and ethylene dichloride, which have to be used in the manufacture of PRC are also toxic and are thus barriers to environmental sustainability [20, 47, 48]. The final processing and shaping of the products use heat, which is associated with additional toxicity issues [47]. Because of the range of different toxic ingredients and steps, it is hard to recycle the PVC without exposing workers to these toxins, and landfill disposal also causes them to leach into the environment over time. There are thus many human and environmental health problems potentially caused by PVC at the different stages of its life cycle. If they are to be avoided, the first step is to know what is in any particular PVC product. And for that, its production needs to be documented and tracked from start to finish.

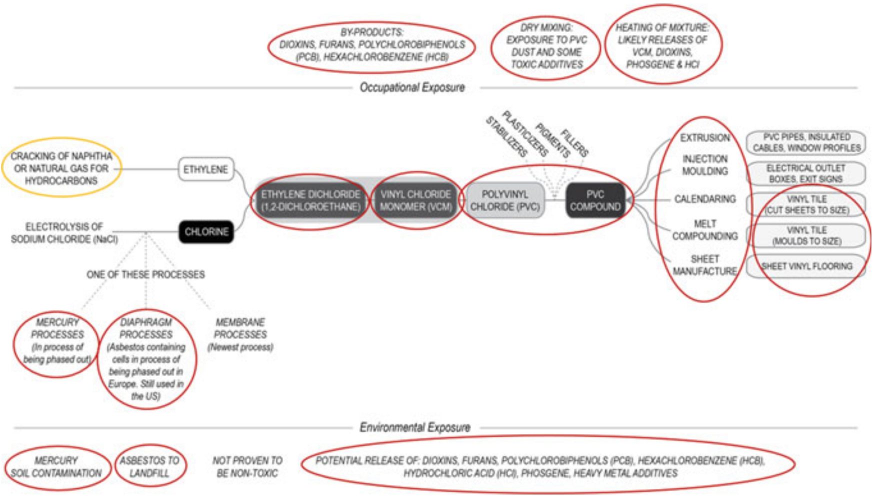

Fig. 1 Diagram summarising the most common PVC manufacture processes: circled in red are toxic stages; circled in yellow are other concerning steps. *Diagram* Lydia Hamer and Emina Kristina Petrović

3 PVC Production in Europe and China

Following the existing work on the toxicity issues associated with PVC, an analysis of the manufacture of PVC was undertaken in order to identify points for blockchain tracking of transactions. The manufacture of PVC can use a range of different processes, and each might be undertaken by a series of different companies. It is thus hard even for the manufacturer of a final PVC product to know exactly what it contains. This section reviews the production chain to illustrate this, and to provide a context for the information that any supply chain materials ledger will need to collect and from whom.

This review focuses on the typical PVC production chain in Europe and China because these are significant manufacturers of PVC and have very different regulative settings. The information provided here represents either specific or general production information, based on what is available in scientific literature and freely online. Industry body reports and websites of specific manufacturers were significant sources of useful information. Other sources included reports from government or research agencies and news articles.

The two main methods or processes for producing PVC are the 'ethylene' and 'acetylene' processes. The main production method used in Europe is the ethylene process. The main production method used in China is the acetylene process.

3.1 PVC Production in Europe

The PVC industry in Europe consists of four main parts: PVC resin manufacturers, PVC stabiliser producers, PVC plasticiser producers, and PVC compounding and converting manufacturers. Each of these groups is represented by their own industry organisations: The European Council of Vinyl Manufacturers (ECVM), European Stabilizer Producers (ESPA), European Plasticisers, and European Plastics Converters (EuPC) [24].

Even for those using the ethylene method, there are different models for PVC resin production in Europe, four of which are shown in Table 1. The main model for PVC resin production in Europe is ‘integrated’ production from chlorine through to PVC resin (Method 2). In this model, chlorine, EDC, VCM, and PVC are produced in the same company (or partner companies) in the same or multiple manufacturing locations [21]. Many companies also rely on occasional purchases of EDC or VCM to supplement their own production [21] (Fig. 2).

According to the European Council of Vinyl Manufacturers (ECVM), the ‘six leading European PVC resin manufacturers’ are Ercros (Spain), Inovyn (Belgium, France, Germany, Italy, Norway, Spain, Sweden, United Kingdom), Mexichem

Table 1 PVC resin manufacturing models in Europe

Model number	Figure	Type	Details
1	2	Fully integrated	Ethylene and chlorine produced within the company
2	2	Integrated up to chlorine	Ethylene supplied by others
3	2	Integrated up to EDC	EDC supplied by others
4	2	Partially integrated up to chlorine	A mixture of Methods 2 and 3

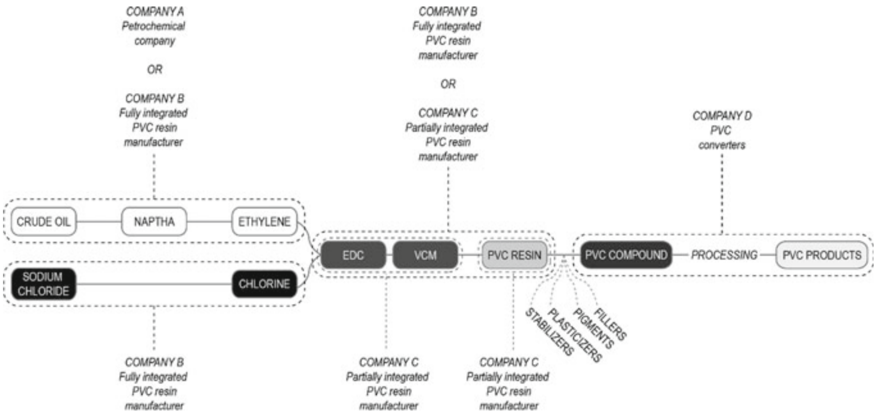

Fig. 2 Diagram summarising PVC resign manufacture for ethylene process. *Diagram* Lydia Hamer and Emina Kristina Petrović

Table 2 Primary production models of some European PVC resin manufacturers

Company	Primary method	Supplementary information and references
Anwil	1	Anwil is a subsidiary of Orlen. Orlen produces ethylene via other subsidiaries [5, 21]
Spolana	1	Spolana is a subsidiary of Orlen which produces ethylene via other subsidiaries [56]
Inovyn	2	Receives ethylene via ARG pipeline [1, 35]
Vynova	2	Receives ethylene via ARG pipeline [1, 35]
Mexichem (formerly Vestolit)	2	Ethylene supplied by others [21]
Vinnolit	2	Ethylene supplied by others [21]
BorsodChem	2	Ethylene supplied by others [21]
Fortischem	2	Ethylene supplied by others [21]
Shin Etsu	3	Ethylene and chlorine currently supplied by others [53]. As of 2014 Shell and Akzo respectively supplied ethylene and chlorine [21]
Ercros	4	Ercros produce some EDC and purchase some EDC [19, 21]

(formerly Vestolit GmbH & Co. KG, Germany), Shin Etsu (The Netherlands), Vinnolit (Germany, United Kingdom) and Vynova (Belgium, Germany, France, The Netherlands, United Kingdom) [15]. These manufacturers produce approximately 75% of European PVC resin [15]. Some other former members of the ECVM and current European PVC resin manufacturers include Anwil (Poland), BorsodChem (Hungary), Fortischem A.S. (Slovakia), and Spolana (Czech Republic) [42] (Table 2).

PVC additives include stabilisers, plasticisers and pigments are produced within separate industries. These are combined by ‘converters’, to produce PVC products [24].

3.2 *PVC Production in China*

China is the world’s largest PVC producer and consumer [8], accounting for more than one-third of global production [62]. Despite this, there is relatively little detailed information about the production chain from raw materials through to consumable products.

There are two main production processes used for PVC resin production in China. The most common method used is the acetylene process, used by 83% of China’s 21 largest PVC resin producers [62]. The other production process is via ethylene. Of those using the ethylene process, many rely on imported ethane, ethylene dichloride, and/or VCM from the Middle East, Indonesia, and U.S. [62]. Unlike in Europe, it is not as clear as to whether the PVC resin and additives manufacturers, and PVC converters are partially or fully separate industries.

There are three main models for PVC resin production in China (Table 3), which vary between regions due to the availability of raw materials. In general, abundant coal resources are concentrated in the north-western, northern, and south-western regions, whilst salt sources are situated along the eastern coastline and in mid-west China [11]. Consequently, manufacturers in the north- and mid-west use the acetylene process and are fully integrated or partially integrated up to chlorine. Manufacturers along the eastern coast (i.e. in Tianjin and Shandong) are integrated up to chlorine and rely on imported ethylene and/or imported EDC and VCM [11, 62]. Of the 27 largest Chinese Chlor-alkali plants, all but one also produce PVC or VCM on-site [62] (Fig. 3).

The three largest PVC resin producers in China are Xinjiang Zhongtai Chemical Co., Ltd., Xinjiang Tianye Co., Ltd, and Shaanxi Beiyuan Chemical Co., Ltd. [27,

Table 3 PVC resin manufacturing models in China

Method number	Figure	Type	Details
5	3	Fully integrated	Acetylene and chlorine in the same company
6	3	Integrated up to chlorine	Acetylene supplied by others
1	2	Fully integrated	Ethylene and chlorine in the same company
2	2	Integrated up to chlorine	Ethylene supplied by others
3	2/3	Integrated up to EDC/VCM	EDC and/or VCM supplied by others

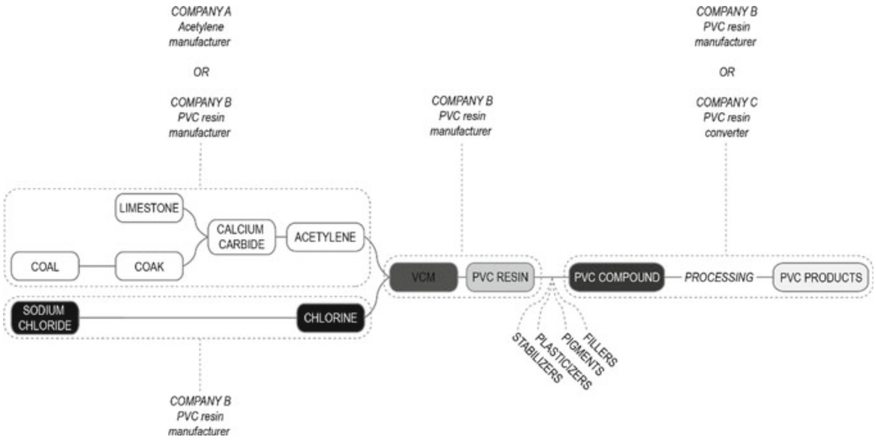

Fig. 3 Diagram summarising PVC resign manufacture using acetylene process. *Diagram* Lydia Hamer and Emina Kristina Petrović

Table 4 Primary production models for some Chinese PVC resin manufacturers

Company name	Primary method	Supplementary information and references
Xinjiang Zhongtai Chemical	5	Acetylene process [27]. Salt and coal sources in the same company [65]
Tianye Group	5 or 6	Acetylene process [27] and producer of chlorine [65]
Shaanxi Beiyuan Chemical (Group) Co., Ltd.	5 or 6	Acetylene process [27]. Coal and chlorine produced within the company or subsidiaries
Tianjin Dagu Chemical Co., Ltd.	2	Ethylene process [27]. Chlorine produced within the company. Ethylene supplied by others via pipeline to the Dagang Oil Field
Inner Mongolia Junzheng Energy & Chemical Group Co., Ltd.	5 or 6	Acetylene process [27]
Shandong Qilu Petrochemical Co., Ltd. (QPEC) Chlor-Alkali Plant	1	Ethylene process [27]. Ethylene produced within the company
Shandong Xinfa Chemical Co., Ltd.	5 or 6	Acetylene process [27]
Hongda Xingye Group	5 or 6	Acetylene process [27]
Inner Mongolia Elion Chemical Industry Co., Ltd.	5 or 6	Acetylene process [27]
Qinghai Salt Lake Magnesium Industry Co., Ltd.	5 or 6	Acetylene process [27]

62]. Like the majority of PVC resin manufacturers in China, these manufacturers use the acetylene process. Although final numbers vary between sources, these producers each have a PVC production capacity of over 1 million tonnes [62]. Table 4 shows the 10 largest PVC resin manufacturers, and their primary production methods.

The most common downstream PVC products in China are construction materials [27]. PVC produced via the acetylene process is generally used in the production of low-end pipes, due to large amounts of toxic VCM residue. PVC produced via the ethylene process is used to produce 'high-end' PVC products, including doors and windows, pipes, and other construction materials [8]. These products are used domestically and exported [62]. In 2017, approximately 85% of imported PVC floor, wall, and ceiling coverings in the United States (U.S.) came from China [62]. In recent years, despite political debates over trade between China and the US, large numbers of Chinese products have continued to enter the US [62].

3.3 Issues with Tracking Toxic Material Components

As discussed above, and listed in the tables, there are several components of PVC that are toxic, and can have adverse environmental and human health effects at the different stages of its life cycle. If we are concerned with managing the product in the best way so as to avoid the effects of PVC's toxic components, we need to know all chemicals and substances, which form component parts of the resulting product. As it cannot be determined simply by looking at the final product, this information needs to be gathered throughout the process, especially where different companies manufacture different components. There thus needs to be some kind of ledger providing a record of these for each finished product.

Information on any product's life cycle is essential for anyone purchasing that product to make an informed choice about its use. This applies to the intended end-use—such as by architect, builder or consumer—to its disposal afterwards, or even use by another manufacturer. If one PVC product is produced more sustainably than another, or without a particular toxic additive, then users will want to know this, and for there to be a verified and trusted statement about its component parts. Without such visibility, unsustainable practices can continue without anyone other than the manufacturer knowing. Certainly, in the absence of regulatory mechanisms within and between states, the only method of management for sustainability purposes will come via more open knowledge about the contents of the construction materials being considered. It is with this goal in mind that we now turn to the use of blockchain as a potential method for recording and tracking the component parts of a finished product.

4 PVC Supply Chain Solution Using Blockchain

Blockchain is ideal for recording and tracking the materials used in PVC production, and for enabling purchasers to verify the different components and thus its sustainability. Other chapters in this book have addressed the background and technical workings of Blockchain; so, the remainder of this chapter addresses how it could usefully be used to track PVC production. There are different choices to be made for options available at different stages, with some options being more suitable than others.

Figure 4 demonstrates how blockchain could be utilized to keep track of assets in the PVC manufacturing supply chain. The first digital mirror asset that is produced is for acetylene. In order for the digital asset to be created, a set of trusted oracles are needed that can capture the information associated with the physical asset and upload this information to the blockchain. These would perhaps be a set of measurements, such as the weight of the acetylene batch collected by hardware oracles, which a software oracle could then verify and upload to the blockchain (oracles are discussed below). Once the digital mirror asset has been created, some kind of tags, such as a

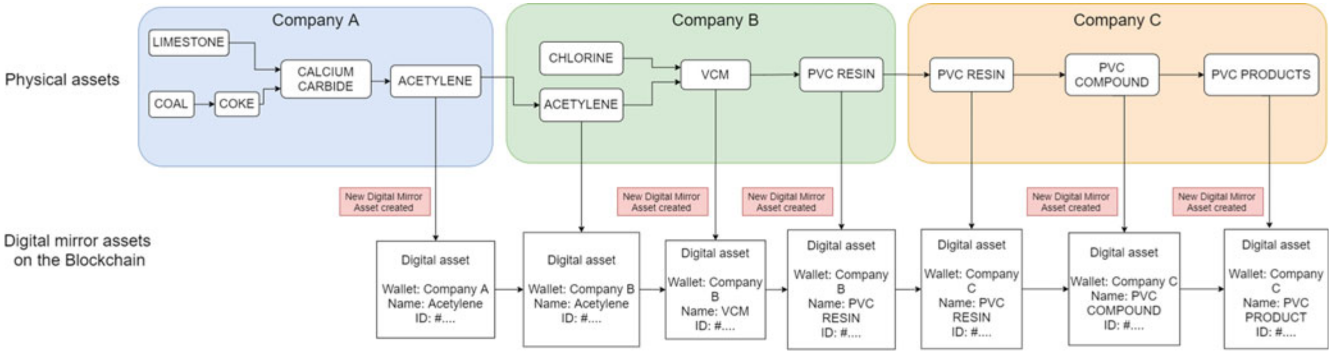

Fig. 4 Conceptual blockchain for the PVC supply chain. *Diagram* Alan Colin Brent and Daniel van Eijck

Radio Frequency Identification tag or a QR code, would be attached to the physical asset, linking it to the digital one.

Then the acetylene is purchased from Company A by Company B through a transaction. In the physical world, the asset is picked up for transit and sent to Company B. It would be possible for the courier to scan the physical asset's tag upon pickup and then use special oracles to upload information to the blockchain, such as live location tracking and confirmation of delivery. Once the asset has been marked as delivered, smart contracts can be used to automatically send the digital asset to Company B's wallet. When Company B processes the acetylene with chlorine to produce VCM, a new digital mirror asset is created for VCM. This digital asset is linked to the digital asset of the acetylene. The link between digital mirror assets is needed for the ability to track the production history of an asset. Company B then produces the PVC resin, along with its own digital mirror asset, which is given to Company C through another transaction process.

Company C then converts the PVC resin into the PVC compound, and a new digital mirror asset is created that contains information on what additives were used to convert the resin into the PVC compound. Then PVC products are produced, with their own digital mirror assets that are linked to the batch of PVC compound that was used to produce them.

Finally, when the PVC products make it into the hands of the consumer through the retail process, information about each product can be accessed through the Radio tag or QR code that is attached to the physical product. The consumer will be able to see a complete history of the manufacturing process that was used to produce the product.

A number of options need to be considered when implementing an appropriate blockchain for the PVC supply chain.

4.1 Permissioned Versus Non-permissioned Blockchains

There are commonly two types of blockchains: permissioned and non-permissioned. A non-permissioned blockchain allows anyone to join the network. This means that everyone in the system can interact anonymously without having to trust each other [7]. In a permissioned blockchain, a user requires access in order to join the network. This feature eliminates the ability to interact with the blockchain in an anonymous way. Permissioned blockchains are crafted to take advantage of blockchain technology without losing the central authority aspect of a centralized system [32]. For the purposes of supply chains, permissioned networks are most appropriate as they are faster and only expect to have a defined set of users adding information blocks to the ledger chain. Yet their advantages and disadvantages still need to be clear and identified in order to ensure the integrity of a system.

Permissioned blockchains often have a much smaller number of nodes in the system compared to a normal blockchain. This makes the process of verifying transactions much more efficient, because permissioned blockchains often have predetermined nodes for performing the consensus mechanism. However, due to the small number of nodes in a permission blockchain, it is easier for the security of the system to be compromised. The security of a permissioned blockchain is proportional to the member's integrity. If enough members work together, then information on the blockchain can be modified [32].

Permissioned blockchains have a proper governance structure, which comes with a few benefits. Updating the rules of the network can be completed much faster compared to a public network due to the smaller number of nodes. Every node in a permissioned blockchain works together to move the updates faster. However, there are also some drawbacks that come with having a governance structure and regulations. Having regulations on the network introduces censorship. An example of such censorship is where the central authority can choose to restrict a transaction or even stop it from occurring. This is a major threat to any of the organizations that are part of the system, because their cash flow can be interrupted at any time by the central governing authority.

Permissioned blockchains are much more cost-effective than public blockchains, especially when using a consensus mechanism like proof of stake [38] with predetermined nodes for performing validation.

4.2 Scalability

In the domain of blockchain technology, scalability refers to the ability of a blockchain to accommodate a growing number of users, while still retaining a fast consensus. Currently, public blockchains are unable to scale up because of the inefficiency of consensus protocols when used with large numbers of users. This inefficiency results in a longer 'block time', which is the time it takes for new blocks to be added to the chain. A long block time means that transactions on the network take longer to verify and complete. Permissioned blockchains often have much smaller block times compared to public blockchains. For example, Bitcoin (public and non-permissioned) has a block size of 1 megabyte that fits 2000 transactions [26]. It takes approximately 10 min for one block to be mined and added to the chain, which results in a transaction throughput of 7 transactions per second. The Ethereum blockchain (also public and non-permissioned) can process a maximum of 20 transactions per second. In contrast, the permissioned HyperLedger blockchain can process up to 100,000 transactions per second [58]. It is unclear how many transactions per second might be needed for the purposes of supply chain ledgers, but a permissioned proof of authority [6] blockchain will be more scalable than those made using other formats.

4.3 Decentralized Autonomous Organizations (DAO)

A decentralized autonomous organization (DAO) is a network of agents interacting with each other according to an open-source self-enforcing blockchain protocol [54]. In traditional organizations, all agents involved with the organization have some kind of employment contract that states their relationship with the organization and with each other. If an agent breaks the rules of their employment contract or something else goes wrong, the legal contract will be enforced in a court of law according to the law of the country the organization resides. However, in a DAO, there are no legal contracts that determine the relationships between agents. Instead, agents are steered by incentives tied to the network tokens and fully transparent rules that are written into smart contracts.

DAOs have many advantages over traditional organizations [54], for example: coordinating resources when not all parties know/trust one another,aligning a large number of stakeholder contributions towards shared goals; running organizations in a way that is resistant to censorship; tracking and validating participation and contribution to a project; accommodating a variety of levels of contribution; allowing people and entities to contribute work in a jurisdiction-agnostic fashion.

Given the type of networks and information involved with supply chains, a DAO appears to be ideal for the creation of supply chain ledgers. Because of the ability to add smart contracts, Ethereum has been the most popular platform to date for DAOs to be built upon [49]. If scalability is not an issue—or if Ethereum 2.0 fixes the current low throughput of Ethereum—then this would work well for the creation of supply chain ledgers.

4.4 Supply Chain DAOs

As discussed with the PVC supply chain, it is desirable for companies in a supply chain to track physical assets digitally in order to be informed about the location, to trigger processes, to certify ownership, and to perform the corresponding payments. Although it is often stated that certain organizations in the same supply chain are in ‘trusted partnerships’, they are still different organisations each pursuing their own interests, which means there is only a limited amount of trust.

When there is a high rate of exchange of goods it becomes hard to monitor, especially at a global scale. In traditional systems, this information is stored and used in many different systems that are most likely in many different countries. This is one of the key problems that using the blockchain can solve: the tracking and tracing of exchanged goods on a global scale. A DAO enforces trust between parties with different interests, so that they can work together towards a shared goal in a unified way. The DAO allows products to be tracked and traced throughout the supply chain and this provides an immutable dataset of history for each product that is open and transparent.

A challenge for any system is having a trusted source of input data that translates events in the real world into data on the blockchain. One method for achieving this is the use of ’oracles’: devices or entities that translate events in the real world into transactions on the blockchain [13]. The use of oracles to ensure the effectiveness of blockchain technology for sustainability issues has received little attention [9]. However, we suggest that they could be very effective for this purpose.

The key features of such a supply chain management system would be as follows:

Digital ownership certificates: A digital ownership certificate is a digital mirror asset that links to the physical asset. The blockchain maintains information about each asset such as a unique ID or serial number that links the physical asset and the wallet address of the owner. The blockchain is immutable, so only legitimate transactions can take place, and therefore the ownership of an asset cannot be stolen by manipulating the blockchain.

Asset tracking: Assets need to be tracked as they move along the supply chain. For each transaction, a timestamp, and which parties were involved, are recorded. In order to implement asset traceability, smart contract trees are used to link different assets to a common product. Transactions become expensive, because each time a product is passed on, the ownership certificates for each asset linked to that product need to be updated.

Proof of origin: There needs to be a mechanism to allow both producers and consumers to validate that an asset is genuine and original, and is not a pirated or fake product.

Trusted maintenance tracking: The lifecycle of a product does not end as soon as it is in the hands of the customer. Maintenance of products is an important part of the supply chain for many different reasons, such as ensuring safety and providing additional services to the consumer. For warranty concerns, it is important that maintenance events are stored with a timestamp and remain unmanipulated. Smart contracts can be used to issue maintenance work to a worker via the product’s unique ID. The worker then completes the work and records the work tasks and required work effort and submits a confirming transaction on the blockchain. The owner then signs the transaction, confirming that the work has been done.

Integrated financial transaction: Because smart contracts allow for the linking of data transactions and financial transactions, it is possible to make payments to agents in the network as soon as a task is completed. For example, as soon as a PVC material shipment is scanned as delivered, payment for the shipment can be executed immediately via the use of an integrated financial transaction linked to the chain.

Distributed product master data: Places such as retail stores that are selling products that come from the supply chain can use the blockchain to get a comprehensive overview of product master data, such as title, description, pictures, serial numbers, and a breakdown of where each component of the product came from.

4.5 Components that Enable the Features of a Supply Chain DAO

Trusted devices, or oracles, change the state of the blockchain. For example, such an oracle might be a device that spawns a digital mirror asset on the blockchain at the moment the physical asset is produced. Or it may be a mobile phone scanning a product QR code in order to confirm the delivery of a product.

Another essential component is an asset management platform, or in-the-field interface, which allows manufacturers or owners of assets to manage their assets. It is a platform to manage everything from checking transaction history to transferring assets to a new owner. However, this should not just be designed to run on a standard desktop computer. The use of NFC and QR codes allows assets to be physically scanned in the field to access information.

4.6 Existing Blockchain-Based Solutions

There are already some existing services and products that target supply chains using the blockchain. Here, we summarise three that are relevant to the tracing of component materials within products for the purposes of sustainability.

Everledger is an independent technology company that provides businesses with secure technologies including blockchain, artificial intelligence, and the linking of products to the internet [23]. The company utilises the IBM Blockchain Platform Hyperledger, it thereby provides permissioned systems that are each open only for a community of users, who are known in advance and are therefore identifiable and traceable [55]. Everledger has a range of industry solutions that are being used today. An example of one of their supply chain solutions is Everledger minerals. This platform provides traceability throughout the lifecycle of high-risk products and helps to support the reuse and responsible recycling of material. One of the key features of the system is the ability to monitor sustainability. Being able to trace assets through the production line enables higher visibility and control over responsible and ethical sourcing throughout supply chains.

Transparency-One enables companies to discover, analyse, and monitor all suppliers, components and facilities from source to store [60]. It is built on Microsoft Azure's blockchain service, which uses the Ethereum protocol to encrypt data [49]. Transparency-One claims to help companies identify potential issues in their supply chains, such as modern slavery and product fraud. Companies have complete access to information on where and when assets are modified and exchanged, which helps them prove that their products come from ethically sound sources.

VeChain is an open-source blockchain platform made to enhance supply chain management and business processes [63]. The VeChain platform consists of two coins, or tokens, called VeChain Token (VET) and VeChainThor Energy (VTHO). VET is used to store and transfer value, while VTHO is used to pay for interacting with the blockchain (transaction fees). Users are rewarded with VTHO for holding VET. This essentially allows users to use their VET for free as long as they own an adequate amount of VET that is generating VTHO. As more parties begin using the VeChainThor blockchain, the demand for VTHO will also increase, along with its price. This will also drive up the price of VET, since it can be used to generate VTHO.

The platform allows authorized stakeholders to view a full breakdown of information linked to a product and its business processes, such as storage, transportation, and supply. In order to accomplish this, VeChain uses Radio-Frequency Identification tags and smart sensors that broadcast relevant product information onto the blockchain network. VeChain uses a proof of authority consensus mechanism to validate transactions and incorporates a unique governance structure and voting mechanisms for deciding on changes to the platform. VeChain uses a permissioned blockchain, meaning that all nodes are validated and approved by a central trusted party (the VeChain foundation), which means that blocks can be validated faster and more efficiently compared to proof of work or proof of stake consensus mechanisms.

Any of these products would work for the PVC supply chains described above; they would all be a vast improvement on not using any blockchain system. VeChain may appear to be developed for a situation most closely resembling the PVC supply chain, and most closely matching the suggested options discussed above.

4.7 Energy Consumption

The energy consumed by a blockchain supply chain solution comes down to two main components: the energy used to process each transaction on the blockchain, and the energy used by the hardware and software oracles that capture information and upload it to the blockchain [14]. The latter is dependent on factors that will be specific to a real-world setup, including the power efficiency of the hardware being used, and the throughput of the supply chain.

In terms of the blockchain itself, for the hypothetical PVC supply chain, the most suitable solution would be a permissioned blockchain using a proof of authority consensus mechanism, as the system is comprised of a set of verified and trustworthy stakeholders as participants. Unlike with proof of work consensus [33], there is no technical competition between block validators, which means that the proof of authority mechanism requires almost no computing power and therefore almost no electricity for its operation.

5 Conclusion

Currently, it is very hard to find detailed information on all of the chemicals used in the production of construction materials. If one wants to reduce toxicity in construction materials, it is necessary to know what is in a particular product; yet there is no central register nor mandated ledger of component materials. Moreover, for many synthetic materials, different components are manufactured in different facilities by different companies, making it very difficult to have access to full value chain information even from the manufacturer of the final product. Yet an increasing number of sustainability labelling schemes, including the Living Building Challenge, require such information. And there is increasing realisation that the use of toxics worldwide is producing adverse effects on environmental and human health, and that they need to be phased out.

The first step to action is knowledge, which is why we have focused on the ways to establish a supply chain ledger to track components of construction materials. This chapter has focused on the use of blockchain technology for providing reliable and fully disclosed information on their chemical content and providence. It has focused on the example of PVC, but its findings are relevant to the manufacture of any other products from different component parts or materials.

The findings depend on what are the most desirable features in your supply chain network. For example, for a generic, hypothetical supply chain, the most suitable solution appears to be a permissioned blockchain using a proof of authority consensus mechanism. Such a system can be a closed, private network, with a set of verified and trustworthy stakeholders as participants. Yet it can provide a public verification via a device such as a QR code at the end. Such a system is fast and can accommodate a large number of transactions per second, so can thus scale up in the future even if a network starts small. Yet, if there is a need to add smart contracts and use an existing technology, and no need for speed because of a small number of operators on a network, then perhaps one based on Ethereum might be more appropriate. Moreover, as technology evolves, this preference may change. For example, Ethereum 2.0 aims to be much faster while still having the capability to attach smart contracts. Overall, all of those kinds of decisions will need to be based on the particular features needed for the supply ledger network in question.

Given we are concerned with tracing materials for the purposes of sustainability, we have also chosen to mention the issue of energy consumption, which is necessary for maintaining the blockchain itself. We suggest that this should be a relevant feature in the design of any supply chain system, and there should be more of a move toward proof of authority systems instead of proof of work systems if only for this reason.

Our framework has highlighted the complexities in choosing the various technical and non-technical aspects of any such supply chain systems. But the important part is to note that it can be done, and can probably even be achieved with existing blockchain-based solutions. Bespoke solutions will no doubt add functionality, and our suggested PVC supply chain network illustrates what might be achieved. It is essential that we address the issues posed by the uses of toxics in construction materials, for the health of ourselves as well as of the natural world, and blockchain just might be able to help us in that quest.

References

1. ARG mbH & Co. KG. (2016) Pipeline connected. Avaialble online: https://argkg.com/connected/ (accessed May 2019)
2. ATSDR (Agency for Toxic Substances and Disease Registry). Available online: www.atsdr.cdc.gov (accessed on 6 Dec 2017)
3. Akovali G (2012a) Plastic materials: chlorinated polyethylene (CPE), chlorinated polyvinylchloride (CPVC), chlorosulfonated polyethylene (CSPE) and polychloroprene rubber (CR). In: Pacheco-Torgal F, Jalali S, Fucic A (eds) Toxicity of building materials. Woodhead Publishing, Cambridge, UK, pp 54–75
4. Akovali G (2012b) Plastic materials: polyvinyl chloride (PVC). In: Pacheco-Torgal F, Jalali S, Fucic A (eds) Toxicity of building materials. Woodhead Publishing, Cambridge, UK, pp 23–53
5. Anwil SA (2019) History. Available online: http://www.anwil.pl/EN/Company/Pages/History.aspx (accessed May 2019)
6. Avasthi AA, Saxena A (2018) Two hop blockchain model: resonating between proof of work (PoW) and proof of authority (PoA). Int J Inf Syst Manag Sci 1(1):128–131
7. Bai Q, Zhou X, Wang X, Xu Y, Wang X, Kong Q (2019) A deep dive into blockchain selfish mining. IEEE international conference on communications (ICC), 1–6. https://doi.org/10.1109/ICC.2019.8761240
8. Business Wire, Inc. (2018, November 02). China polyvinyl chloride (PVC) Industry Report, 2018–2022—ResearchAndMarkets.com. Available online: https://www.businesswire.com/news/home/20181102005262/en/China-Polyvinyl-Chloride-PVC-Industry-Report-2018-2022 (accessed May 2019)
9. Caldarelli G, Rossignoli C, Zardini A (2020) Overcoming the blockchain oracle problem in the traceability of non-fungible products. Sustainability 12(6):2391. https://doi.org/10.3390/su12062391
10. Ceresana. Market Study: Polyvinyl Chloride—PVC (2016) Available online: www.ceresana.com (accessed on 15 Sep 2017)
11. China Chlor Alkali Online (2008) China Chlor views. China Chlor Alkali Online, Beijing
12. Ciacci L, Passarini F, Vassura I (2017) The European PVC cycle: in-use stock and flows. Resour Conserv Recycl 123:108–116
13. Collins P (2020) What is a blockchain oracle? 2020. Available online: https://betterprogramming.pub/what-is-a-blockchain-oracle-f5ccab8dbd72 (accessed July 2021)
14. Cuen L (2021) The debate about cryptocurrency and energy consumption. TechCrunch. Available online: https://techcrunch.com/2021/03/21/the-debate-about-cryptocurrency-and-energy-consumption (accessed 30 June 2021)
15. ECVM—The European Council of Vinyl Manufacturers (2019) About ECVM. Available online: https://pvc.org/ (accessed May 2019)
16. EPA (Environmental Protection Agency) (2000) Toxicological Review of Vinyl Chloride; U.S. Environmental Protection Agency: Washington, DC, USA, pp 1–197
17. EPA (Environmental Protection Association) (2017) Preliminary information on manufacturing, processing, distribution, use, and disposal: asbestos; office of chemical safety and pollution prevention, U.S. Environmental Protection Agency: Washington, DC, USA, pp 1–15
18. Environmental Protection Agency, US (EPA) (2018) Sustainable management of construction and demolition materials. Available at: https://www.epa.gov/smm/sustainable-management-construction-and-demolition-materials Accessed: Nov 2021
19. Ercros (2019) Barcelona: Ercros. Avaialble online: http://www.ercros.es/index.php?lang=en (accessed May 2019)

20. European Chemicals Agency (ECHA) (2017) Chemicals search from European Chemicals Agency (ECHA). Available online: www.echa.europa.eu (accessed on 6 Dec 2017)
21. European Commission (2014) Commission decision: case M.6905—Ineos/Solvay/JV. European Commission, Brussels
22. European Commission (2017) Reach restrictions. Available online: https://ec.europa.eu/growth/sectors/chemicals/reach/restrictions_en (accessed on 22 Dec 2017)
23. Everledger (2021) Available online: https://everledger.io (accessed July 2021)
24. Fråne A, Miliute-Plepiene J, Almasi AM, Westöö A-K (2019) PVC waste treatment in the Nordic countries. TemaNord, Oslo
25. Greenpeace (2001) PVC-free future: a review of restrictions and PVC free policies worldwide, 8th ed.; Greenpeace International: Amsterdam, The Netherlands, 2001. Available online: www.greenpeace.org (accessed on 15 Sep 2017)
26. Göbel J, Krzesinski AE (2017) Increased block size and Bitcoin blockchain dynamics. In: 27th international telecommunication networks and applications conference (ITNAC), pp 1–6. https://doi.org/10.1109/ATNAC.2017.8215367
27. Hao G (2018) PVC sector accelerates the elimination of outdated capacities. China chemical reporter, pp 15–18
28. IHS Chemical (2016) Chemical economic handbook: IHS chemical: plasticizers. Available online: www.ihs.com (accessed on 14 Sep 2016)
29. IHS Market (2017) Available online: www.ihs.com (accessed on 6 Dec 2017)
30. International Agency for Research on Cancer (IARC) (2012) Vinyl chloride. IARC monographs: chemical agents and related occupations; IARC working group on the evaluation of carcinogenic risks to humans; international agency for research on cancer: Lyon, France, vol 100F, pp 451–478. ISBN 9789283213239
31. International Living Future Institute (2021) The red list. Available online: https://living-future.org/declare/declare-about/red-list/ (accessed 29 June 2021)
32. Jabbar S, Lloyd H, Hammoudeh M, Adebisi B, Raza U (2020) Blockchain-enabled supply chain: analysis, challenges, and future directions. Multimedia Syst. https://doi.org/10.1007/s00530-020-00687-0
33. Kibet A, Karume SM (2018) A synopsis of blockchain technology. Int J Adv Res Comput Eng Technol 7(11):789–795
34. Lakshmanan S, Murugesan T (2014) The chlor-alkali process: work in progress. Clean Technol Environ Policy 16:225–234
35. Leunis L (2017) The impact of the cost of energy on a large industrial user. Febeliec press conference. Vynova, Brussels
36. Lin Y, Wang S, Wu Q, Larssen T (2016) Material flow for the intentional use of mercury in China. Environ Sci Technol 50:2337–2344
37. Liu Z, Little JC (2012) Semivolatile organic compounds (SVOCs): phthalates and flame retardants. In: Pacheco-Torgal F, Jalali S, Fucic A (eds) Toxicity of building materials. Woodhead Publishing, Cambridge, pp 122–137
38. Nguyen CT, Hoang DT, Nguyen DN, Niyato C, Nguyen HT, Dutkiewicz E (2019) Proof-of-Stake consensus mechanisms for future blockchain networks: fundamentals, applications and opportunities. IEEE Access 7:85727–85745. https://doi.org/10.1109/ACCESS.2019.2925010
39. OECD (2016) Environmental labelling and information schemes. Accessed 30 June 2021, available from: https://www.oecd.org/env/policy-persectives-environmental-labelling-and-information-schemes.pdf
40. O'Brien TF, Bommaraju TV, Hine F (2005) Chlor-alkali technologies. In: Handbook of chlor-alkali technology: volume I: fundamentals, vol 1. Springer, Boston, pp 387–442. ISBN 978-0-306-48623-4
41. Oster RH, Carr CJ (1947) Anesthesia; narcosis with vinyl chloride. Anesthesiology 8:359–361
42. PVC Forum (2010) Members. Avaialble online: http://www.seepvcforum.com/en/content/96-members (accessed May 2019)
43. Pacheco-Torgal F, Jalali S, Fucic A (eds) (2012) Toxicity of building materials. Woodhead Publishing, Cambridge

44. Patty FA, Yant WP, Waite CP (1930) Acute response of guinea pigs to vapors of some new commercial organic compounds: V. vinyl chloride. Public Health Rep. 45, 1963–1971
45. Petrović EK, Vale B, Pedersen Zari M (2017) Materials for a healthy, ecological and sustainable built environment: principles for evaluation. Woodhead Publishing, Cambridge
46. Petrović EK (2017) How substances get regulated against in the building industry: formaldehyde, phthalate plasticisers in polyvinylchloride/vinyl. In: Petrović EK, Vale B, Pedersen Zari M (eds) Materials for a healthy, ecological and sustainable built environment: principles for evaluation. Woodhead Publishing, Cambridge, pp 175–189
47. Petrović EK, Hamer LK (2018) Improving the healthiness of sustainable construction: example of polyvinyl chloride (PVC). Buildings 8(28). https://doi.org/10.3390/buildings8020028
48. PubChem Compound—Review of Chemicals by the National Center for Biotechnology Information (NCBI). Available online: www.ncbi.nlm.nih.gov (accessed on 6 Dec 2017)
49. Roberts J (2020) Ethereum, Bitcoin's closest rival, faces its moment of truth. Fortune. 20 Feb 2020. Fortune Media IP Limited. Available online: https://fortune.com/2020/02/19/ethereum-bitcoin-closest-rival-cryptocurrency/ (accessed 7 July 2021)
50. Sayers RR, Yant WP, Waite CP, Patty FA (1930) Acute response of guinea pigs to vapors of some new commercial organic compounds: I. ethylene dichloride. Public Health Rep 45:225–239
51. Schandl H, Eisenmenger N (2006) Regional patterns in global resource extraction. J Ind Ecol 10(4):133–147
52. Schandl H, Fischer-Kowalski M, West J, Giljum S, Dittrich M, Eisenmenger N, Geschke A, Lieber M, Wieland H, Schaffartzik A, Krausmann F, Gierlinger S, Hosking K, Lenzen M, Tanikawa H, Miatto A, Fishman T (2018) Global material flows and resource productivity: fourthy years of evidence. J Ind Ecol 22(4):827–838
53. Shin Etsu PVC BV (2019) Production plants. Available online: https://www.shinetsu.nl/en/production-plants (accessed May 2019)
54. Singh M, Kim S (2019) Chapter four—blockchain technology for decentralized autonomous organizations. Adv Comput 115:115–140. https://doi.org/10.1016/bs.adcom.2019.06.001
55. Smits M, Hulstijn J (2020) Blockchain applications and institutional trust. Front Blockchain 3(5). https://doi.org/10.3389/fbloc.2020.00005
56. Spolana SRO (2019) About Us. Avialable online: http://www.spolana.cz/En/AboutUs/Pages/default.aspx (accessed May 2019)
57. Stockholm Convention. Available online: www.pops.int (accessed on 6 Dec 2017)
58. Thakkar P, Nathan S, Viswanathan B (2018) Performance benchmarking and optimizing Hyperledger fabric blockchain platform. In: IEEE 26th international symposium on modeling, analysis, and simulation of computer and telecommunication systems (MASCOTS), pp 264–276. https://doi.org/10.1109/MASCOTS.2018.00034.
59. The European Council of Vinyl Manufacturer (ECVM) (2017) Available online: www.pvc.org (accessed on 6 Dec 2017)
60. Transparency-One (2021) Available online: https://www.transparency-one.com (accessed July 2021)
61. United Nations Environment Programme (UNEP) (2020) Global status report for buildings and construction—towards a zero-emissions, efficient and resilient buildings and construction sector. Available online: https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf (accessed 30 June 2021)
62. Vallette J (2019) Chlorine and building materials—a global inventory of production technologies and markets—phase 2: Asia. Healthy Building Network, Washington, D.C.
63. VeChain (2021) Available online: https://www.vechain.org (accessed July 2021)
64. Work Safe New Zealand (2017) Workplace Exposure Standard (WES) Review: Vinyl Chloride; Work Safe New Zealand: Wellington, New Zealand
65. Xinjiang Zhongtai Chemical. Available online: https://xjzhongtai.lookchem.com/ (accessed May 2019)

66. Xue T, Yuan Y, Ahmed Z, Moniz K, Cao G, Wang C (2018) Proof of contribution: a modification of proof of work to increase mining efficiency. In: IEEE 42nd annual computer software and applications conference (COMPSAC), pp 636–644. https://doi.org/10.1109/COMPSAC.2018.00096
67. Zhang M, Buekens A, Jiang X, Li X (2015) Dioxins and polyvinylchloride in combustion and fires. Waste Manag Res 33:630–643

The Proof-of-Concept of a Blockchain Solution for Construction Logistics Integrating Flows: Lessons from Sweden

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Abstract The economic, information and material flows in construction logistics are usually disintegrated—but blockchain could integrate them into a shared digital ledger supported by smart contracts, thus creating value for the relevant actors (e.g. contractors, suppliers). Therefore, we explore such a solution's potential by conceptualizing, developing, implementing, and testing a relevant pilot in the Swedish context. Theoretically, we adopt sociomateriality, thus understanding blockchain as a digital facilitator of transactions, flow integration, social interactions, and trust development. Methodologically, we review the literature on blockchain for construction logistics, and report from our empirical studies in Sweden. The literature review showed that core blockchain properties can generate value for construction logistics (e.g. reduction of accounting rework)—however, there currently exist no use cases beyond concepts and pilots. Moreover, implementation can be challenging due to practical and security constraints—also reflected in our own empirical material. Regardless, the solution was conceptualized as a permissioned private proof-of-authority blockchain named BlogCHAIN, and developed into an online application based on Hyperledger Besu. Testing BLogCHAIN revealed that the practitioners' resistance and powerplay required a simplification of our initial concept. Indeed, the flows were integrated, more decentralization and transparency were achieved, and previously time-consuming processes were facilitated—but the main contractor retained control over critical logistics segments. Our lessons-learned showed that several issues can jeopardize the adoption of blockchain, like existing power balances and unrealistic hopes of transparency and accountability beyond established business practices. The solution could be integrated with the IoT and machine learning in the future.

Keywords Construction logistics · Blockchain: integrated flows · Proof-of-concept · Sweden

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1 Introduction

The integration of flows within construction supply chains and logistics has long been identified as crucial for the optimization of logistics and the overall success of construction projects [1, 2]. The information, material, and financial flows have been identified in [3], where the criticality of their integration for effective construction supply chain and logistics management had also been noted. The information flow can be understood as the bidirectional flow of prompts and requirements received and released by a construction supply chain partner [3]; the material flow as the flow of physical assets, and the financial flow as the exchange of pecuniary assets while encompassing things like the operational cost [3, 4]. Other descriptions for the latter flow include 'cash flow' (i.e. cash transactions) [5, 6], and 'money flow' (i.e. monetary affairs) [7]. More recently, it was considered that such descriptions of the latter flow only partially account for transactions integrating data on prices, billing, and invoices [8]. Therefore, the term 'economic flow' was introduced in [8], in order to complement the information and material flows. The flow disintegration was also noted in [8], given that such flows can include material and service supplies, payments, accounting, and other tasks that are often treated second-handedly by site management, subcontractors, transporters, retailers, and suppliers. The economic flow is a source of disturbances and delays in construction, including partial, delayed, or even absent payments, cost of finance, long payment cycle, retention, disputes over payments, and security of payments [9, 10].

It has been envisioned that a way to ameliorate the disintegration of the three flows is by integrating them in an event-driven way; such 'events' can include the issuing of invoices and payments to the associated actors (e.g. suppliers) via direct peer-to-peer information exchange after the successful completion of other 'events', such as the delivery of materials, correct on-site component placement, and completion of related work packages [11]. However, the actual benefits, framework, appropriate technology, and implications of such an integration, have been explored in only a few studies (e.g. in [8]), while the evaluation of a relevant solution's live testing and user experience has not been adequately investigated yet.

Given the aforementioned considerations, the research question for the current chapter is: What would a solution for construction logistics, in which the information, material and economic flows are integrated in an event-driven way via a suitable technology, be—and what results would come out of its conceptualization, development, implementation and testing in a context-conscious manner? We aim to answer this question by following the work in [8, 12–14], and exploring the functionality and potential value of such a solution realized through blockchain. We report from our research in the Swedish context, where we conceptualized, developed, implemented, and tested a blockchain pilot (named *BLogCHAIN—Building Logistics blockCHAIN*) for digitalized construction logistics with integrated flows. We adopt the theory of sociomateriality, in order to understand blockchain as a digital facilitator of transactions and flow integration, and relate it to social interactions and the development of trust. Methodologically, we systematically review the literature on blockchain-related research for construction logistics, and report from two years of empirical studies in Sweden, including the results of implementing and testing BLogCHAIN on a large construction site.

Following this introduction, we elaborate on the theoretical framework of this chapter. Afterward, the research method adopted is described. Then, a systematic literature review is offered. The empirical part of our study includes the establishment of our empirical context, the iterative development and testing of BLogCHAIN, and the evaluation of the test results through an appropriate analysis. The chapter then proceeds with a critical discussion and concludes with some final remarks and recommendations for future work.

2 Theory

2.1 Sociomateriality

Sociomateriality is an approach that emphasizes the way technologies are co-shaped with practices (also applying to digital technologies) [15, 16]. According to sociomateriality, the material and social aspects of digital technologies are inseparable and fused in practice [16]. This is reflected in the agency of the actors while they are utilizing the digital technology, since actions are considered to cease being exclusively human properties but are rather performed through interactions between humans and non-humans [17]. This sociomaterial co-shaping can affect the structure of an organization or a constellation of actors [17, 18].

Important notions in understanding sociomateriality are entanglement and performativity [16]. Entanglement implies that a technology's material and social aspects are not merely realized as being progressively intertwined (which could foster an understanding that they initially exist separately), but actually understood as not having an independent, self-contained state [15, 16, 19]. Performativity alludes to a world getting reshaped through ongoing reconfigurations [16, 19]. This position, posing that a technology's performativity emerges through social practices, strongly contrasts with the more dominant one posing a world that is made up of self-standing entities of technology and actors with a priori properties [15, 16].

We argue that the inseparable entanglement of the material and social aspects is particularly suitable to describe the reconfigurations of work practices induced by the introduction of a digital technology [16].

2.2 A Sociomaterial Blockchain Solution for Construction Logistics with Integrated Flows

Sociomaterial understandings of blockchain are relatively few, but have given particular insights. In detail, blockchain is intertwined with the social world in both its protocol and implementation levels [20]. Thus, the stakeholders' actions and issues of governance are critical when it comes to the consensus mechanisms of the operation protocols (e.g. smart contracts, permission regulation, etc.), as well as the framing and constraints of the technology's implementation [20]. This framing also shapes the way the actors in the blockchain constellation understand trust, information privacy, scalability, security, user behavior, disintermediation, and environmental sustainability [20]. It can also lead to blockchains with different privacy settings [20]. Furthermore, blockchain can facilitate a complex sociomaterial system among actors, by digitizing the value chain, integrating various flows, shifting routines and capabilities, and reconfiguring existing infrastructure [18].

Building on those sociomaterial insights, a sociomaterial definition of a blockchain solution for construction logistics with integrated flows was offered in [8], as a permissioned private digital ledger for partially decentralized peer-to-peer information and economic transactions across a project-specific network/constellation of supply chain actors (e.g. clients, contractors, logistics consultants, and suppliers). This digital ledger is append-only, permanent, stored and accessed in a historical record updated through consensus, and shared across all network nodes reflecting the actors in the constellation [8]. As a permissioned system, it features a reduced but existing need for in-between verification, security and settlement of transactions, and the consensus updates are based on proof-of-authority—where consensus features identity as a stake and is agreed between the authorized participants [8]. In addition, it creates power shifts within the constellation, aligned with the sociomaterial autonomy-control paradox [21]. The economic transactions are event-driven and event-inducing, i.e. they are triggered when certain events in the information flow (e.g. issuing purchasing orders) and/or the material flow (e.g. on-site material deliveries) take place, and can trigger other events (e.g. issuing invoices when transactions are completed); thus, the economic, material and information flows get integrated [8].

As such, a solution for the latter segment of downstream construction supply chains and logistics within Sweden was conceptualized in [8] (see Fig. 1).

As shown in Fig. 1, this concept considers that the solution is implemented by independent logistics consultants (usually hired as third-party logistics facilitators by the clients), and the suppliers are interchangeable with the transporters and/or subcontractors (as is the case in many real projects) [8]. The order placement, approval and renewal (economic + information flows) can be done directly through the blockchain system itself (e.g. with the storing of hashes of files pertaining to these transactions), and subsequently trigger the on-site transportation and delivery (economic + information + material flows). Finally, the successful on-site checks of the deliveries are stored as smart contracts (information + material flows), the issuing of invoices is

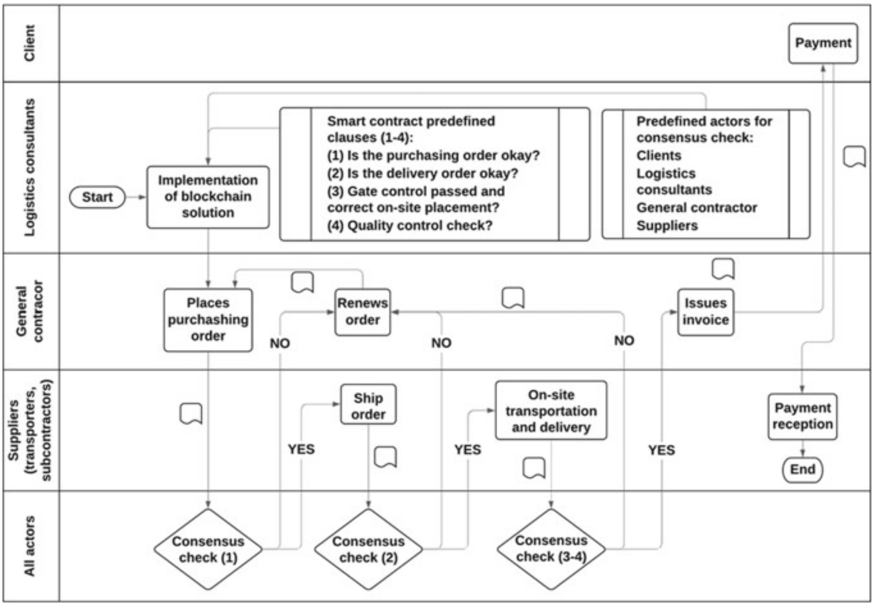


Fig. 1 Supply chain and logistics setup sociomaterially facilitated by the blockchain solution (adapted from [8])

event-triggered within smart contract clauses (economic + information + material flows), and the release of payments is predefined, again, through smart contracts (economic + information flows). As such, the solution is shown to simplify and integrate the flows, thus accelerating processes and countering delivery failures, imprecise data retrieval, delays, withheld payments, multiple ledger structures, and faulty intra-systemic data transfers [8].

Moreover, the setup's transparency and traceability are enhanced through all the actors' active involvement in the consensus checks of the smart contracts—even clients and the suppliers, who were more passive in a pre-blockchain setup [8]. By being actively involved in shaping all three flows, clients and suppliers can have a more detailed and transparent overview of the construction supply chain and logistics [8]. Moreover, the independent logistics consultants actively help shape the flows by implementing the solution and fostering accountability through the consensus checks [8]. However, it should also be noted that in line with the sociomaterial autonomy-control paradox [21], the general contractor may lose a lot of their centralized power over the supply chain—as this power would be diffused, through the consensus checks and the automated processes of the blockchain, to the rest of the actors. On the other hand, blockchain solutions also risk getting too decentralized, leading to participants developing their own variants ('forks') [22].

In this study, we pick up after the concept in [8], combine it with our aforementioned underpinnings about flow integration, sociomateriality, and value, inform it with our literature review and empirical insights, and develop, implement, test and evaluate the relevant proof-of-concept, namely BLogCHAIN.

3 Method

The research method consists of: (a) a systematic literature review on blockchain research for construction logistics (both in general, and particularly in the Swedish context), (b) BLogCHAIN's iterative development and testing, and the collection of empirical data before, during, and after each phase, and (c) evaluating BLogCHAIN by integrating our sociomaterial understanding, literature review results, empirical data, and test results.

For the systematic literature review, we used the concept-centric framework augmented by units of analysis [23]. The units of analysis emerged during the review, facilitating its revision in iterations. These iterations, partly attributed to the quickly expanding related research field, followed the abductive reasoning of qualitative research [24]. Furthermore, the review was strengthened with the use of the references-of-references and 'snowballing' techniques [25], while the conducted search was comprehensive in order to avoid a narrow sample [26]. Finally, exclusion and inclusion criteria were applied [27], for finally selecting the references featured in the review section, such as the sources' relevance, high quality (impact factor of their publication contexts, and the number of cross-references), methodological rigorousness, clarity of results, and sound basing on previous research output.

When it comes to the study's empirical part, we focused on the Swedish construction sector context; this methodological choice accounted for the national institutional and socioeconomic forces uniquely impacting each industry (even if it can share similarities or interfaces with others). As such, we were initially informed by the empirical mapping of the Swedish context featured in [8, 12–14]. Then, we gathered new empirical data to establish a testing context (i.e. a construction site with willing testers) and the iterative development, testing and evaluation of BLogCHAIN, by following the sociomaterial qualitative techniques described in [17]: contextual zooming in-and-out, observations, interviews, and participant mapping.

In particular, the search for a suitable construction site started in the autumn of 2018 and ended in the summer of 2020. In early September 2020, a site was found (a school building), and we commenced the collaboration with the associated actors (i.e. suppliers and the contractor's operatives and site managers) willing to test our prospective prototype there. Seven semi-structured interviews were carried out in September 2020 and provided material on the supply chain and logistics work practices in that specific context (e.g. the existence of other IT solutions, and different degrees of systemic integration between the contractor and each supplier).

The results from the aforementioned interviews, as well as our previous conceptualizations, constituted the platform for developing BLogCHAIN—but also introduced constraints and alterations, eventually leading its design, functionality, and user interface to depart (in certain respects) from the initial concept in [8]. This platform informed the first development iteration (before the first field testing iteration), roughly between September and early November 2020 and starting before the last round of the preliminary interviews was finished. In the second development iteration (in January 2021, before the second field testing iteration), evaluation results after the first field testing iteration were considered. As such, three improvements were introduced in the subsequent development: the conditional re-involvement of the client and the logistics consultants, the deployment of a notification function for the transporters approaching the construction site, and accommodating the different roles of sales managers and invoice issuers within the same supplier company.

The tests were carried out in two iterations, each following the corresponding development round. When the first test round was planned for August 2020, it was hoped that we could conduct on-site introductory training, observations, and interviews. However, all of these were carried out online through Microsoft Teams, due to COVID-19-related restrictions that were still ongoing as of the second half of 2020 and the first half of 2021. In the first field testing iteration, a series of meetings were conducted with the testers over the span of two weeks, in order to guide them through the installation, functionality and interface of BLogCHAIN. Afterward, the tests took place through the rest of November and December, having designated the end-of-year vacation period as the stopping point of the tests. The tests consisted of the collaborating suppliers and contractor's operatives carrying out logistics transactions through BLogCHAIN. In order to not disturb the everyday work, we agreed with the testers that the implementation of BLogCHAIN would run in parallel to the established way in which the supply chain transactions were already made—and not in replacement of those practices. During the tests, we conducted semi-structured interviews with the testers and engaged in observations as they used the application. The feedback after the first field testing iteration was received through semi-structured interviews with all the testers, in order to record their user experiences. This amounted to four interviews with supplier representatives and one group interview with four of the contractor's site managers, where the previously mentioned improvements for the second development iteration were proposed.

The second field testing iteration was carried out in February 2021. Some new suppliers served as the testers, and more transactions occurred. The feedback after this iteration was also organized as a series of interviews with site management and suppliers. Moreover, we attempted to include interviewees from transport companies, but this was hampered by practical barriers. This feedback was used to evaluate the proof-of-concept, by aiming at understanding the potential alterations in the work practices realized through BLogCHAIN, noting which of the previously envisioned benefits and drawbacks of the blockchain solution did or did not materialize, documenting the pilot's limitations, and gathering recommendations for its improvement and expansion. This was complemented by our literature review insights, our sociomaterial understanding, and the ten-step decision path to determine when to use blockchain technologies in [28].

4 Literature Review

Although there have been numerous studies mapping the potential of blockchain technology within several fields of the construction industry (see, e.g. in [29]), the current chapter is particularly interested in blockchain research for construction supply chains and logistics [30]. Within that focus, it has been claimed that digital distributed ledger technologies (DLTs), which include blockchains, can mitigate the disorder caused by changes in the construction supply chain strategy, thus reducing the suppliers' uneasiness due to withheld payments or other insolvencies [31]. References [11, 32, 33] posed that the information flow in downstream supply chain segments can be improved through the transparency and traceability brought by blockchain, and following [33], an expert panel feasibility assessment of blockchain's ability to mitigate payment issues was carried out in [10]. The possible improvement of on-site logistics through the integration of blockchain with RFID sensor data was studied in [34]. The claim that transactions through a blockchain network can result in dynamic and instant payments for suppliers, transporters, and subcontractors, as well as better communication with the main contractor, was made in [35]; however, in [10] there is more caution in the evaluation of possible improvements of payment practices, which on the other hand do point to the potential of shorter payment times (even if not instant). Moreover, the visibility of the complete transactional history across the supply chain, as well as the consensus requirement for the block updates, are positively noted for possibly tackling the tampering with past logistics data [35], and productivity and efficiency issues [36, 37]. Furthermore, blockchain is envisioned to reduce administrative rework (e.g. matching data among different supplier ledgers for multiple deliveries) and data errors and outages across the supply chain, thus leading to time and cost savings, better change management, better planning, and quick (even instant) delivery notice for the contractors [35]. Accordingly, three key legal issues were identified in the potential of a relevant implementation: the restricted use of smart contracts to prescribed outcomes, the shared data access and ownership, and multi-jurisdiction concerns related to governing regulations and laws [38]. The utility of blockchain in making data transactions transparent and immutable in order to estimate the embodied carbon emissions along construction supply chains, was explored in [39]. To accommodate blockchain, construction supply chains and logistics would require the conceptualization and development of operational processes that align with the roles and responsibilities of the supply chain actors [40]. This alignment involves tackling issues of data tracking and contracting and transferring resources—thus mitigating the opportunistic behaviors of supply chain actors and shifting the trust from relational to system- and cognition-based [41]. Furthermore, it has been shown that crypto-assets [42] and non-fungible tokens (NFTs) [43] can enhance both the granularity and the atomicity of the integration between the 'cash' and 'product' flows in construction supply chains. In a relevant vein, three blockchain-based models were developed, namely project bank accounts for payments, reverse auction-based tendering for bidding, and asset tokenization for project financing; the need to upscale the legacy IT systems and facilitate regulatory compliance, was highlighted [44]. Finally, while in [30] blockchain is envisioned to streamline a 'green lean' construction supply chain, [45] elaborates on turning construction resources (e.g. materials, components) into smart construction objects by infusing their properties with a 'smart' layer of awareness, communicativeness, and autonomy, and then using those as blockchain oracles in construction supply chain management. In this context, an oracle is understood as a middleware capturing, validating, and then feeding information into a smart contract [45].

These studies largely investigate the relevant blockchain solutions on a conceptual level, mostly consider the economic and information flows, place the potential for added value for construction logistics within core blockchain properties, and focus mainly on the aspects of DLTs and smart contracts. Nevertheless, [40, 41, 44] have also considered social issues, such as the facilitation of trust across the supply chain. However, none of the aforementioned studies elaborate explicitly on the simultaneous integration of the information, material, and economic flows, nor do they adopt sociomateriality.

When it comes to construction logistics in the Swedish context, [12–14] and then [8] have gradually investigated the integration of the material, economic and information flows along the supply chain, through a blockchain solution forming part of the value proposition in independent logistic consultants' business models. In particular, [12] investigated the suitability of Swedish construction supply chains and logistics for accommodating a blockchain solution integrating the logistics flows, by involving independent logistics consultants that can incorporate such a solution in their digital business model; the study then proceeded with a preliminary mapping of such consultancies operating in Sweden. The perspective of sociomateriality in relation to a potential blockchain solution for integrated logistics flows, and the power shifts that such a solution would bring in constellations of supply chain actors in the Swedish context, were introduced in [13]. These constellations included the typical case of large contractors internalizing logistics services, the atypical case of using independent logistics consultants, and the emergent case of third-party actors offering dedicated digital building logistics services [13]. Moreover, sociomateriality was used to map potential benefits and threats related to blockchain visions and prototypes for construction (documented mainly in industry reports), and discuss the way those can be extrapolated to a solution for integrated supply chain and logistics flows in the Swedish context [14]. Finally, a sociomaterial conceptualization of such a solution was offered in [8], where the ways a generic logistics setup can be transformed, were mapped; then, it was planted in a conceptual digital business model canvas for independent logistics consultants, and the canvas was customized on the business case of a specific firm (with the input of the company's representatives themselves) [8].

The aforementioned Sweden-specific references [8, 12–14] represent a gradual research development undertaken by the authors of the current chapter and serve as a backdrop for the study shown here. However, those efforts are not referenced here in a manner of obtuse iteration—but rather, we hereby comment upon them for their delimitations. Particularly, it can be understood that the Sweden-specific studies introduce sociomateriality for a deeper consideration of the transformation of work practices that could be realized through the implementation of a blockchain solution and bring attention to the issue of flow integration. However, while their context-specific approach can be considered methodologically strong due to taking institutional particularities into account, it also makes their conceptualizations (especially in [8]) vulnerable to any departure from that particular context.

Critically, this vulnerability also serves as the basis of insights for the final developmental steps and then evaluation of the current study, showing the evolution of the undertaken research beyond the aforementioned references and into the material presented only in this current chapter. In particular, such a vulnerability materialized in the empirical part of our research, since the absence and/or inactivity of certain supply chain actors initially considered in the conceptualized solution (the logistics consultants and clients, respectively), forced the development and testing of a proof-of-concept that was reduced in comparison to the initial vision.

Finally, the potential constraints and security issues regarding the implementation of blockchain in construction logistics, were explicitly considered only in [8, 14, 36]. Interestingly, all of these studies looked into blockchain-related research outside construction to formulate their argumentation. Regarding implementation constraints, these studies collectively posed that for supply chains and logistics, blockchain should only be adopted if it leads to the achievement of strategic objectives (e.g. reduction of rework), and that there are strategic factors that can impede blockchain's adoption, including a limited engagement with the technology and a limited context awareness. Considering security, these studies highlight two common denominators. The first is a presumptive mistrust of the potential of blockchain as a viable technological investment. The second is an anticipated abuse of the properties of blockchain; the anonymity of the distributed node network could lead to illicit activities, the use of cryptocurrencies to losing grasp of the value of fiat currencies, and the inflexibility of transactions through smart contracts to potentially emerging tensions among the actors in the blockchain network.

5 Development and Testing of Prototype

5.1 Development and Testing Iterations

The findings from our preparatory interviews at the elected test site showed that the development of our application would have to depart from the concept in Fig. 1, and lead to a simplified and/or altered proof-of-concept (see also 'Method'). Specifically, the only actors enacting transactions, as well as participating in the consensus checks, would be the contractor's site managers, the suppliers' sales representatives, and (conditionally) the transporters. The design of the prototype was updated to reflect that the stream of the material, economic and information flows on which it was to be implemented and attempt the flow integration, would start when the supplier issued

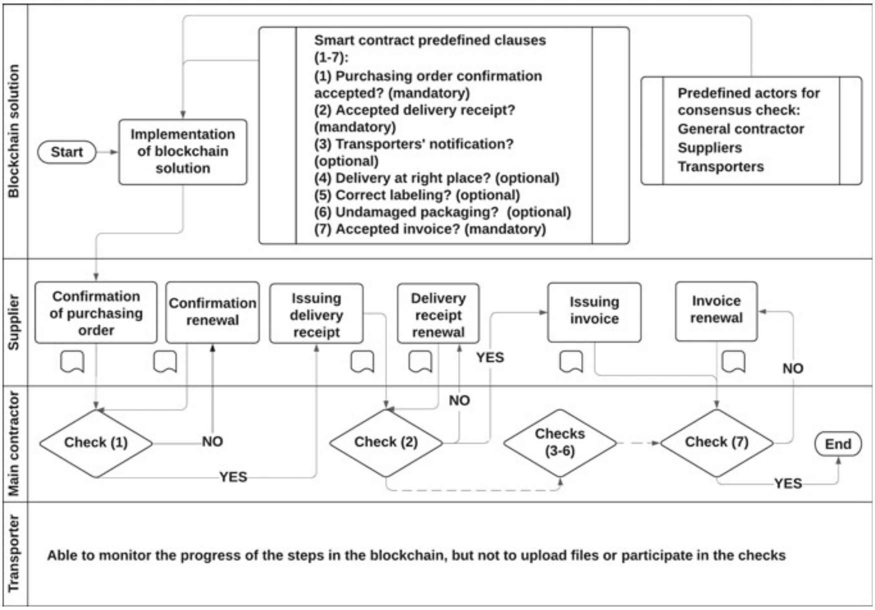


Fig. 2 Updated concept of the blockchain solution

the confirmation of the order already placed by the contractor, and finish with the contractor accepting (or not) the supplier's invoice (issued after the material delivery had taken place). As such, the new concept, used for the first development iteration of BLogCHAIN, is summarily depicted in Fig. 2.

The smart contract clauses and checks depicted in Fig. 1 were replaced with the following partially different statements:

1. Is the purchasing order confirmation accepted? (mandatory)
2. Is the delivery receipt accepted? (mandatory)
3. Did the transporters of the delivery notify the construction before their arrival (if such an action had been agreed upon beforehand)? (optional check)
4. Was the material delivered to the right place? (optional check)
5. Were the labeling and the quantities of the delivery correct? (optional check)
6. Is the delivery's packaging (when applicable) undamaged? (optional check)
7. Is the invoice accepted? (mandatory)

The difference between the mandatory and optional clauses reflects their ability (or inability, respectively) to block the process in case of non-satisfaction. Non-satisfaction with the mandatory clauses prevents the transaction from being completed, while non-satisfaction with the optional clauses shows stumbles in the process but does not prevent the next step from initiating. The clauses were deemed mandatory or optional according to the overall interpretation of the interviewees' input. Moreover, the setting of the sociomaterial constellation of actors led to a setup where, within the proof-of-authority algorithm, the consensus checks were to be replaced by checks performed by the contractor, and the transporters assumed a passive observant role.

BLogCHAIN was then developed as an online application. Its user interface is suitable for both desktop computers and smartphones, and is in Swedish. The blockchain infrastructure of BLogCHAIN utilizes the open-source Hyperledger Besu framework, and can be accessed through MetaMask, a crypto-wallet and gateway to blockchain applications. MetaMask functions as an extension for Google Chrome, and can also be downloaded as an app in Google Play and the App Store (for smartphones, and iPhones, respectively). The files to be uploaded to the online repository connected to BLogCHAIN (e.g. invoices) should be in PDF format, and they are encrypted in Microsoft Azure. As BLogCHAIN constitutes a private permissioned blockchain that is eligible for access only through an actively permitted MetaMask account, the website cannot be openly accessed, and as such, the respective URL is not shown here.

The choice, combination, and implementation of the aforementioned tools and setup were contextually dictated, in a sociomaterial manner, by the needs of the case at hand—but also pragmatically bounded by the available resources in the relevant research project. However, it should be noted that relevant publications have framed different ways of integrating blockchain with the Architecture, Engineering and Construction (AEC) industry, also providing evidence of computational strategies to achieve such an integration [46, 47]—as well as getting inspired by blockchain-powered business models in other industries [48].

Indicatively, Figs. 3 and 4 (next page) feature screenshots showing the user interface (UI) of the first iteration of BLogCHAIN (smartphone version). As the interface of the actual app is in Swedish, we modified the screenshots to feature the English translations of the respective prompts, and thus appeal to the international audience of this book. It should be noted that the UI can be differentiated according to the role of the respective user (contractor, supplier, and transporter).

By tapping on 'Show the order list', the user can advance on the order list menu (Fig. 4), where they can navigate through drop-down menus to, respectively, choose the supplier and then the active and/or already finished orders they need to oversee. It should be noted that while a contractor can see all suppliers and all orders, a transporter can see only the suppliers (and their respective orders) with which they are affiliated. The interface in Fig. 4 is followed by screens where the supplier can initiate a new blockchain transaction by following the ensuing steps: uploading an order confirmation (in PDF format); choosing the transporter affiliated to them, and the contractor to whom they are going to deliver; giving an ID to the order (in alphanumeric characters); and confirming the initiation of the transaction.

The subsequent process flow is shown from the supplier's and transporter's perspective in Figs. 5, 6 and 7 (next page), which relates to the updated concept in Fig. 2. The status of each of the three mandatory ((1–2) and (7)) and optional ((3–6)) smart contract clauses, is color-coded: green for an accepted clause, yellow

Fig. 3 Starting screen (contractor, transporter)

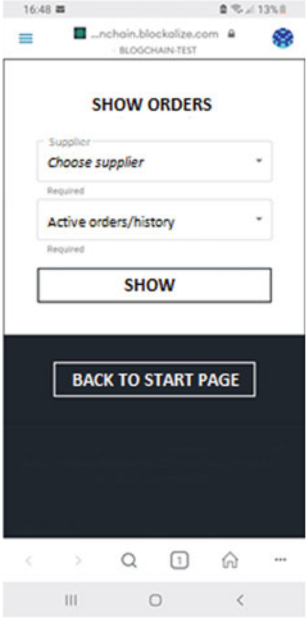
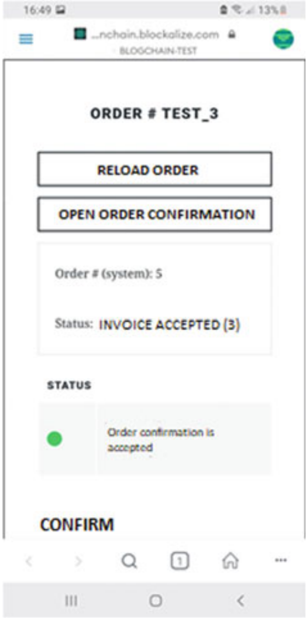


Fig. 4 Order lists (contractor, supplier, transporter)

Fig. 5 Order processing 1 (contractor, supplier, transporter)



16:49

...nchain.blockalize.com

BLOGCHAIN-TEST

ORDER # TEST_3

RELOAD ORDER

OPEN ORDER CONFIRMATION

Order # (system): 5

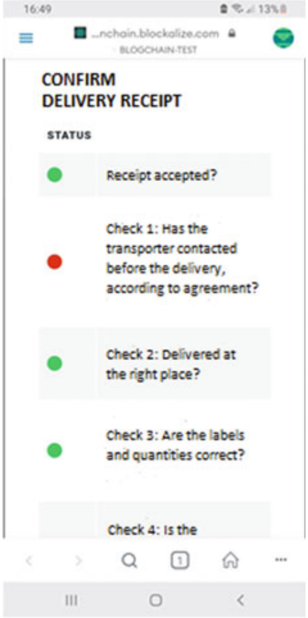
Status: INVOICE ACCEPTED (3)

STATUS

🟢 Order confirmation is accepted

CONFIRM

Fig. 6 Order processing 2 (supplier, transporter)



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BLOGCHAIN-TEST

CONFIRM DELIVERY RECEIPT

STATUS

🟢 Receipt accepted?

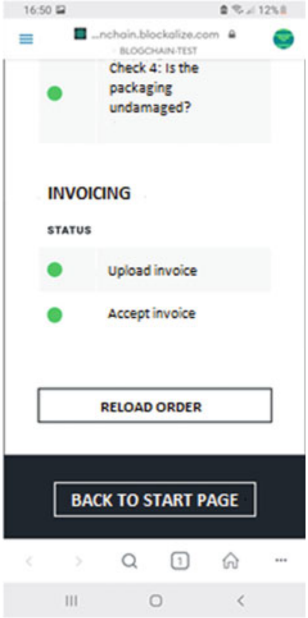
🔴 Check 1: Has the transporter contacted before the delivery, according to agreement?

🟢 Check 2: Delivered at the right place?

🟢 Check 3: Are the labels and quantities correct?

Check 4: Is the

Fig. 7 Order processing 3 (supplier, transporter)



● Check 4: Is the packaging undamaged?

INVOICING

STATUS

● Upload invoice

● Accept invoice

for a tentative/unchecked clause, red for rejected clause. In the indicative screenshots (Figs. 5, 6 and 7), the three mandatory clauses are green, namely:

1. The acceptance of the order confirmation.
2. The acceptance of the delivery receipt.
3. The acceptance of the invoice, which was previously uploaded by the supplier.

When it comes to the optional checks, the following are shown:

3. Check 1 (red): Did the transporters notify the construction site of their arrival?
4. Check 2 (green): Were the orders delivered at the right place?
5. Check 3 (green): Were the deliveries' labels and quantities correct?
6. Check 4 (green): Was the deliveries' packaging undamaged?

It should be noted that the UI from the contractor's side is almost identical; however, all mandatory clauses have a 'Yes' and a 'No' button (by tapping them, the contractor signals a green or red notification, respectively), and all optional clauses have 'Yes', 'No' and 'No agreement' buttons, with the latter signaling a yellow notification.

Right after the first development iteration of BLogCHAIN, a series of in-house checks were conducted on the stability and utility of the alpha version. The developers created dummy contractor, supplier and transporter accounts and conducted test transactions. This process lasted for about a week, in which various minor bugs and UI issues were tackled. Afterward, a series of remote meetings were held with the actual testers, in order to introduce and train them in installing and using the application. In some cases, short subsequent meetings were held for clarifications.

Following was the first testing iteration, which consisted of transactions between the contractor and two out of the three suppliers that were contacted. One supplier was responsible for delivering concrete and aggregates of a varying granulometric gradation, and the other delivering an assortment of lighter materials (primarily wood). These transactions were infrequent and spread during the testing period of late November and into December 2020. As a result, only a handful of transactions were recorded on BLogCHAIN by the end of this testing period. This infrequency and sparseness had to do with the construction phase, which mostly entailed a few bulk deliveries of construction materials, as well as the COVID-19 pandemic crisis, which detained (to a certain degree) the supply chain and logistics processes.

The third supplier (delivering reinforcement steel) had been present in the preparatory stage and had also installed BLogCHAIN after its development, but they ended up not using the application at all. Shortly after the installation, this supplier informed us that their company already deployed an automated digital system for handling the flows between them and the contractor (e.g. issuing invoices). This system was deemed by the supplier to be as optimized as needed for the company's business model, and therefore the supplier declined participating in testing BLogCHAIN even in parallel to their established work practices.

It should be noted that during the tests, the developers maintained their dummy accounts within BLogCHAIN for technical and functional reasons. Moreover, several informal correspondences and communications were held with the testers, in order to monitor their testing attempts on a hands-on basis and offer continuous technical support.

After the completion of the first testing iteration, a series of semi-structured interviews were held with the testers, in order to record their experiences from implementing BLogCHAIN. The interviews covered issues of participating actors, aspects and processes of the test. The aspects included integration, efficiency, value creation, collaboration and work environment (including UI). By comparing their established supply chain and logistics practices to the test transactions conducted through BLogCHAIN in parallel, the interviewees indicated a number of envisioned benefits in the implementation of the application: tampering with past data was avoided; the integration of the logistics flows led to a streamlining of the process; and a somewhat higher degree of trust among the testers was fostered. However, the test did confirm the practitioners' almost absent previous engagement with blockchain, which made it more difficult for them to experience the technology's potential. Regardless, the interviewees provided proposals for improving BLogCHAIN, central among which were:

1. The re-involvement of the client and the logistics consultants, under the condition that they would have a strictly observatory role, i.e. not participating in the consensus checks, but having a full overview of all conducted transactions.
2. Deploying a notification function for the transporters as they approach the construction site, which was included in a smart contract clause (see Fig. 2).

3. Making provisions to accommodate the different roles of sales managers and invoice issuers within the same supplier company, which were facilitated through the integral functionality of MetaMask.

As can be understood, the accommodation of these three proposals updated the concept only slightly, and did not actually alter the process flow in Fig. 2. The proposals were of a rather functional nature. As such, there was no need to produce a third process flow diagram. Following this updated concept, the second development iteration was conducted between late December 2020 and late January 2021.

Following the second development iteration, the second (and final) testing iteration featured both more suppliers and more transactions than the first round. In particular, four suppliers now acted as testers (compared to the two suppliers in the first testing iteration), who conducted, in total, more than double the transactions. The tests were conducted during the two middle weeks of February 2021. The initial plan was to use only one week, but utilitarian issues forced some of the deliveries to be spread over a second week, so that was included in the testing period as well.

The feedback after the second testing iteration was acquired through one interview with each of the supplies, and one with the contractor's site management representatives. Overall, the feedback consisted of mainly positive and constructive comments. With regard to the positive comments, it was mentioned that BLogCHAIN creates a clear connection between the supplier and the contractor, while the confirmation function in the app allows this connection to be documented and available for different roles in the supply chain (and not just individuals). Moreover, its ability to bring together and connect the supply chain actors was highlighted as an improvement, as 'in current practices, e.g. e-mails between individuals, they cannot do the same thing, as the individual can disappear, and the information can disappear or get mixed up among different people, or it is even difficult to access/follow it up' (according to one interviewee). It can possibly be understood that this comment mainly referred to the information flow. Furthermore, BLogCHAIN creates a ready-made platform where everyone can join, as 'the key is that everyone in the industry must gather around a common interface' (according to one interviewee). It was also noted that even though there might be no major problems with invoices and approvals today, planned meetings for clarifications (e.g. at the end of the month) were needed—and the app, through the overview it offers, could potentially reduce the need for such meetings. Finally, the app was praised for making it possible to quickly satisfy requests of finding and showing the right order confirmation—through BLogCHAIN, it is possible to quickly get details out of the purchase, and know exactly what the customer previously bought (and of which they now want to buy more, or on which they now want to make a complaint).

When it comes to the constructive comments, it should be mentioned that we were not given a really critical feedback. However, not all testers felt that any substantial value was generated for them by using BLogCHAIN. Specifically, one company shared that they are in the process of developing a system with similar functions, although not based on blockchain; it remains to be seen how another base technology can lead to 'similar functions'. The benefits, costs and risks of handling payments via a common blockchain solution instead of the parties' current systems, were considered to be not self-evident and impossible to calculate. The cost of internal administration at each party is not clear and there are probably more aspects that need to be highlighted. Another supplier declared that apart from a visible approval of the order confirmation, no major benefit was generated for them, as they already have a functioning system. The same company highlights that there are different issues depending on the material to be delivered, and therefore the app is too generic to be of real interest. However, the same company highlighted that they distrust the industry's ability to adapt to new technologies (regardless of the type). This last comment can be interpreted as emanating mostly from a concern on the institutional aspects of the industry ('slow to adapt'), rather than the app in itself.

6 Results and Analysis

The results and analysis of this study are organized along the following: (1) The evaluation of the prototype's potential as a solution for construction logistics with integration flows within the Swedish context, according to five dimensions: integration, reduction of transactions, transparency, value creation, and implementation; (2) The sociomaterial understanding of the in-between professional relationships of the participating testing parties; (3) Considerations on the feedback given by the testers for the improvement of BLogCHAIN.

6.1 Evaluation

Regarding integration, the material flow is currently affected adversely by a lack of joint planning, a risk of parallel orders and other processes, and disorientation among actors active in the pursuit of integrating and defragmenting parallel material flows and logistics. The tests of the prototype showed the way a more integrated management of received goods can be done on-site, by using BLogCHAIN as a common tool. The tests also showed that stronger integration between, on the one hand, suppliers and their IT systems and, on the other hand, accountants and their ledger systems, is an attractive potential.

Taking the reduction of transactions into account, the information and economic flows nowadays require constant checking by a series of professionals. These checks thus imply constant human intermediation. As such, disintermediation (i.e. reducing human intervention), has a large potential for generating a surplus for the involved companies [20, 46]. However, our tests did not directly show a realization of this potential. BLogCHAIN operated as a stand-alone application, and as such, it increased rather than decreased the needed intermediation. Moreover, the longer-term possibilities of overseeing, e.g., monthly transactions, have not been tested.

Considering transparency, we characterize blockchain as a trust-based technology: it requires trust amongst the logistics actors but can also develop transparency-based trust. Public permissionless blockchains (such as the ones based on proof-of-work), do constitute open systems accessible to all. Such transparency is believed to be paired with the irreversibility of the conducted transactions, which is seen to assure that the system cannot be tampered with. However, BLogCHAIN is a permissioned system, only allowing actual members of the supply chain as users [28]. This type of limited trust, higher security and partial information privacy appears to have worked well in the tests and did not receive any negative comments. It actually seemed to have been taken for granted, as expected in blockchain applications [28]. Nonetheless, if blockchain is supposed to support a more client-oriented constellation, then it is more suitable in an atypical ('more egalitarian') constellation, e.g. a partnering project where mutual trust ('opening one's books') is declared.

For the dimension of value creation, we consider that presently, construction logistics are hampered by continuous tensions about deliveries and payments. In 2019, Swedish companies paid their bills on an average of 33 days after receiving them [44]—even if standard conditions clearly delimit this span to 28 days. Moreover, conscious late payment is viewed as accounting for 50% of the total payments. Therefore, the potential for agreeing on an automated payment is huge. The creditor can realize direct monetary advantages when receiving payment just 3–5 days earlier than the present average practice, and the debtor can avoid constant attention to paying at a late time, thus reducing human intermediation. Moreover, one can imagine rebates and other services included in agreements for the purchaser [9, 49]. It should therefore be possible to create a joint value creation—a win–win situation—with smart contracts.

In particular, smart contracts can support agreements specifying e.g. annual purchasing volumes, delivery, and quality conditions, and set prices. However, it is likely that the ability to deviate from the smart contracts at a later stage will be welcomed, as site managers are quite often able to negotiate better conditions than the initial (and by convention, immutable) clauses prescribed in a smart contract. In other words, there is a risk related to smart contracts, where they become a top-down instrument for management, to the detriment of the project constellation. As a case in point, we introduced optional checks as flexible clauses in BLogCHAIN. These were received well by the suppliers, but treated with some skepticism by the contractor's site managers. However, it remains to be seen if such simple solutions can account for a larger-scale implementation, where numerous conflicting flows and hundreds of transactions might have to be performed simultaneously.

Finally, the results on the dimension of implementation show that while substantial time and resources were invested in the initial concept of BLogCHAIN, updates and remarks that came later were also important—as those latter updates were very specific to the context of the construction site that served as the testing ground. Even little conceptual and preparatory changes had a far-reaching effect on the development process itself. Moreover, a set of interesting insights regarding late invoice payments and their possible amelioration through blockchain, emerged from the final round of interviews. Specifically, it was discussed that there are different driving forces for those delays, such as the client having difficulties paying due to financial problems, consciously paying late (either to make capital gains, or due to uncertainties about the deal), and even withholding the entire payment in case of ambiguity of parts of the delivery. Suppliers tend to avoid clients with financial difficulties, but the issue of consciously paying late appears mainly in 'serious' clients. There is a consensus among suppliers and clients that both parties contribute to this situation and it is not the respective company's internal payment routines per se that are the problem. As no interviewed party had a clear picture of the cost of internal administration of complaints/disputes regarding invoices, the actual problems seem to arise during the validation of the received goods and getting the correct information in the invoice. As such, late payments by 'serious' customers seem to be largely due to deficiencies in the contractor's delivery receipt control, which are only discovered when it is the time for the contractors to administer the payment.

6.2 Sociomaterial Understanding

The sociomaterial focus on the intertwinement of human and non-human elements frames a mutual interaction of artifacts with humans. However, the strong embedding of BLogCHAIN in human practice was prevented by its stand-alone character. BLogCHAIN would need several application programming interfaces (APIs) to become smoothly integrated into the IT setup, which is required to obtain reduced and/or changed human intermediation.

Nonetheless, both iterations of the development were sociomaterially informed by the in-between professional relationships of the participating testing parties. The resulting simplification of the concept, and as such the developmental process itself, led to the choice of widely used and relatively standard development tools in the field of blockchain and smart contracts (i.e. Hyperledger Besu, MetaMask, and Microsoft Azure). The absence of more 'exotic' choices did not harm the development of BLogCHAIN, but rather the opposite—it facilitated a streamlined process, and a relatively simple, understandable functionality and UI in the prototype itself, which helped the testers grasp it quicker. Streamlining, quickness and ease were essential for the testers, as this meant fewer disruptions in their normal day-to-day tasks. Such a reduced disruption was also facilitated by running the tests in parallel to (and not replacing) the business-as-usual transactions, after a bilateral agreement with the testers.

The sociomaterial perspective can also emphasize the way blockchain would be intertwined with changes in practices through implementation. In the current case, such an implementation encompassed preparatory interviews, introduction meetings when the prototype was ready for testing, and one-to-one sessions with each user setting up their account for BLogCHAIN. During the tests, a continuous online support was offered. The kickoff was a typical example of a common implementation process of digitalization—first-time users struggling with the basic function of the MetaMask shell and the entries in the blockchain itself. But these 'early symptoms' were overcome relatively quickly. A more thorough embedding would extend beyond the two testing periods, and a crucial moment for future adoption would be when the use of the system goes beyond a single case and becomes standard software for the central users.

As a future sociomaterial perspective, it is maintained that blockchain can bring about a complex sociomaterial system among actors, by digitizing the value chain, integrating various flows, shifting routines and capabilities, and reconfiguring existing infrastructure [18]. But this requires roughly at least five more years, as pointed out by Arup in their technology forecast for blockchain in the built environment [49, 50]. They predict that the period of 2023–2028 is needed for the emergence of a similar blockchain solution to the one described in this chapter.

6.3 Consideration on Test Feedback

For the future improvement of the app, it was highlighted that it needs to be integrated with the respective supplier's own ledger system, so that the order confirmations and invoices can enter the app automatically. Expansions in its utility, like the coupling with a scanning function upon receipt of incoming goods, enacting payments (probably requiring cryptocurrencies), connecting the information in the app with future additional sales from, e.g. the end customer, and using it as an interface between the parties' internal business systems for coherent information flows, were discussed. The future facilitation of partial invoice payments (e.g. when a defect is found in parts of the delivered goods), as well as regulating transactional disputes within the contractor firm itself, were suggested. Finally, a major proposal was the creation of an aftermarket case in the app; interestingly, to illustrate the need for this, a piece of the received feedback by an interviewee went thus: 'If a part of the invoice is questioned, the supplier can accept or reject the complaint; the contractor can then withhold payment for the disputed part—but pay the rest of the invoice. Today it is common for the contractor to withhold the entire amount. To make things clearer, let's say that a supplier delivers with a 30-day payment time. Receipt is approved. The material is assembled after 15 days, and after assembly a defect is found in the material. The contractor then withholds the entire invoice. It then becomes a dispute where the supplier must subsequently prove that the material now complained upon, was formerly received and approved by the contractor'.

7 Discussion

The discussion elaborates on the literature review, goes on with pointers regarding our choice of sociomateriality, deliberates the development, test and evaluation of BLogCHAIN, and concludes with insights on the system's evaluation.

Our literature review on blockchain for construction logistics shows that the core properties of blockchain, such as peer-to-peer transactions, record immutability and a degree of decentralization, are generally expected to generate the majority of the potential value-adding benefits—but few implementation experiences exist yet, as well as no actual business cases. Nonetheless, the associated research literature is growing quickly. However, this growth has to be coupled with more engagement with the technology within the construction supply chain and logistics context, and not only in regard to its functional aspects—but also its effect on work practices.

The choice of sociomateriality as our theoretical framework reflects not only our considerations on the way blockchain, a general-purpose technology, can be properly contextualized within Swedish construction supply chain and logistics setups—but also our empirical understanding of the real-life function of such setups. Rather than viewing the respective actions as technical choices among rationally discernible operational models (which is recurrent in the approaches of operations management and business economics), we interpret them as different solutions involving characteristic distributions of power. This evidently means that the investigated operational framework is not limited to knowledge exchange [51], but also constitutes a political game that is co-shaped along the utilized technological framework. Moreover, since large urban construction sites can suffer from theft and shrinkage in material supplies, at least internal trust among the actors in a (partially) decentralized blockchain network, should be cultivated. However, supporting an outright permissionless setup can be difficult. Thus, a permissioned private system (like BLogCHAIN) that can establish procedures to protect the blockchain network both from external threats and internal instabilities, is informed by existing sociomaterial conditions. Furthermore, deeply integrating the new technology evidently involves technical interoperability issues, as well as changes in the participating companies' work practices, social setups and organizational structure. Our sociomaterial understanding (also reflected in the testing of BLogCHAIN) places the blockchain solution in parallel or on top of an information infrastructure consisting of different accounting, project planning, site planning, quality control, and access control systems; then, the adoption of common standards for the structuring of ledgers should ensue.

The created value for the users and companies involved was limited in the tests, but nonetheless demonstrated the utility of blockchain in four dimensions: increasing integration, facilitating the opportunity of a reduced number of transactions, increasing transparency, and creating opportunities for future value creation. The integration occurred among members of site management supporting transparent coordination. Deficiencies in coordination are known to create quality defects, and transparency can help in amending those (e.g. more precise information on truck deliveries can reduce waiting times and on-site work interruptions). The opportunity for reduced transactions relates to the order and accounting processes in the participating companies, where a common ledger can lead to less human intermediation—which is currently substantial, if not voluminous. The prototype also highlighted the possibility of a more active and digitally supported role of the clients, despite not having included a client node in the distributed digital ledger of the 1st iteration. Enabling the online surveillance of the logistics flows (especially the economic flow) can provide the client with valuable knowledge, which could otherwise have been mostly accessed by the contractor, or indirectly through independent logistics consultants.

A dilemma of compulsory versus voluntary clauses within smart contracts in blockchain surfaced. Some users (e.g. site managers) requested making blockchain transactions obligatory, while others (e.g. suppliers) preferred a more flexible solution maintaining some transactions as voluntary. This is a dilemma for future development; however, it can already be considered that to avoid unnecessary bottlenecks in the process, it is maybe advisable to keep most steps voluntary. Nonetheless, it is possible that in the future, blockchain can support standardized processes involving obligatory steps.

System disintegration through APIs seems to be a major deficit in the operation of BLogCHAIN. Integration with other systems is crucial for the creation of value for the participating actors. Moreover, such value may be demarcated by the scope of this study; BLogCHAIN can be interpreted as positioning itself in a small niche, compared to the large number of articulated visions and prototypes of blockchain applications in the international construction context [51, 52]. It can be argued that the present ongoing differentiation of the industry into niches can be instrumental for moving the development and application of blockchain closer to actual use. However, it may also imply that this general-purpose technology is dispersed into a number of dissimilar applications, where construction logistics is only just one—and not widely researched yet. Thus, it should also be recognized that blockchain is a general-purpose technology in need of contextualization—in other words, an empty shell with wide application possibilities that need to be developed before any value creation really materializes.

The hindrances and barriers in adopting the solution, should also be contextualized and attributed to current issues that need to be overcome—such as data unavailability, relative lack of blockchain awareness, and the existing power balances within socio-material constellations. In the future, it would be interesting to also address the issues around payments. As mentioned above, if a blockchain- and smart contract-based solution can obtain payments just a few days quicker than the current practice, the business value potential is huge [9, 10, 50].

8 Conclusions

This study addresses the research question of what a solution for construction logistics (in which the information, material and economic flows are integrated in an event-driven way via a suitable technology), as well as the results of its conceptualization, development, implementation and testing in a context-conscious manner, could be—by proposing a blockchain solution.

Our literature review on, specifically, blockchain for construction supply chains and logistics, delineates a number of benefits emanating from core blockchain properties (e.g. the reduction of administrative and accounting rework, and a more efficient payment practice); however, the studies reflect a maturity level no higher than that of prototypes, and no solutions implemented into actual use cases have been found. Moreover, few studies have adopted a sociomaterial lens considering a strong embedding in practices.

The conceptual solution described in the current chapter, emerged into an event-driven, blockchain-induced flow integration across a segment of downstream logistics, i.e. from the issuing of purchasing orders until the completion of the on-site deliveries. The envisaged benefits of the solution included (among others) the streamlining, integration and transparency of logistics processes, and value creation. However, certain issues (mostly tied to the wider construction context) have to be addressed, so that the realization of such value will not be hindered; such issues include, among others, data unavailability, a relative lack of wide blockchain awareness, and the existing power balances within sociomaterial constellations.

The development, tests and evaluation of BLogCHAIN commenced with the prospective testers' experiences informing the development process itself, the evolution of the pilot's utility was informed by the way it was used during the tests, and the recommendations we got afterward were informed by the work practices in the supply chain and logistics constellation at the testing site. These have thus constituted a sociomaterial co-shaping of the digital technology with the related practices during testing, and with further implications for future implementation. Moreover, the sociomaterial approach considers the distribution of power within the logistics setup and leads to the understanding of mutual trust as a crucial issue in blockchain adoption. A permissioned private system can establish procedures to protect the blockchain network both from external and internal threats and/or abuse; in other words, supporting an outright permissionless system is here seen as an abstracted vision with little bearing. From a future perspective, integrating the new technology would change the work practices and social setups of the participating actors.

The created value for the users and companies involved was limited in the test, but nonetheless demonstrated the utility of blockchain in increasing integration, facilitating the opportunity of a reduced number of transactions, increasing transparency, and creating opportunities for future value creation. The integration and transparency occurred among members of site management supporting transparent coordination. The opportunity for reduced transactions and value creation remained mostly as future options, as the system was tested in a context-specific, stand-alone prototype. BLogCHAIN also highlighted the possibility of a more active and digitally supported client's role, by providing them with valuable knowledge through the online surveillance of logistics flows (especially the economic flow).

The limitations of this study include the choice of a particular context in a specific construction logistics setup, for which the presented blockchain solution was developed. The main downside of this choice is that the same conceptualization cannot be easily replicated for other contexts unless new context-specific analyses are first conducted. Moreover, it was planned from the outset to interact with a limited set of suppliers and transporters. The amount of such partners was further reduced when focusing on an early phase of a building project that served as the testing ground. This subsequently reduced the input concerning improvements for the app—making the number of participants and corresponding transactions more manageable, but also tending to simplify the test. An additional test iteration in a later (and more complex) phase of the building project was originally planned, but this proved impossible to follow through. Furthermore, due to the COVID-19 pandemic restrictions, the preparatory interviews and the follow-up evaluation interviews were carried out over virtual communication tools. The empirical material generated in this manner was interpreted as sufficient to fulfil the study's goals—but we believe that had we been able to be on-site during the preparatory work and the tests, it would have generated stronger research material. Additionally, it should be noted that the conceptual development, the prototype, and the testing, came to be focused on the logistics segment until delivery at the site gate, whereas processes inside the construction site were not prioritized. Finally, BLogCHAIN emerged as a stand-alone system that was tested in parallel to established work practices. This limits the test results, as a tighter integration with the ordering/accounting systems (and the respective flows) might have strengthened the test participants' understanding of the blockchain's potential.

Recommendations for future work include further sociomaterial field studies, the further updating of BLogCHAIN, and the testing of the latter in at least one construction site. This can be tied with a focus on horizontal integration in the logistics processes, thus tackling logistics processes within the site itself. Furthermore, a major proposal for future improvements has to do with the system checking the clients' creditworthiness on behalf of the suppliers.

As a concluding remark, blockchain has the potential to play a positive role in the ongoing digitalization within the construction industry (in general) and construction supply chains and logistics (in particular), and can complement well-established technologies such as BIM, and/or other currently investigated cutting-edge technologies, such as machine learning and IoT.

References

1. Palaneeswaran E, Kumaraswamy MM, Zhang XQ (2000) Reforging construction supply chains: a source selection perspective. Eur J Purchasing Supply Manag 7(3):165–178
2. Love PED, Irani Z, Cheng EDJ (2004) A seamless supply chain model for construction. Supply Chain Manag Int J 9(1):43–56
3. Titus S, Bröchner J (2005) Managing information flow in construction supply chains. Constr Innov 5:71–82
4. Panova Y, Hilletofth P (2018) Managing supply chain risks and delays in construction project. Ind Manag Data Syst 118(7):1413–1431
5. Pryke S (ed) (2009) Construction supply chain management. Wiley-Blackwell, Oxford
6. Lundesjö G (2015) Supply chain management and logistics in construction: delivering tomorrow's built environment. Kogan Page, London
7. O'Brien WJ, Formoso CT, Vrijhoef R, London KA (eds) (2009) Construction supply chain management handbook. CRC Press, Boca Raton

8. Kifokeris D, Koch C (2020) A conceptual digital business model for construction logistics consultants, featuring a sociomaterial blockchain solution for integrated economic, material and information flows. J Inf Technol Constr (ITcon) 25:500–521
9. ESCO (2020). Late payment in the construction sector: analytical Report. European Construction Sector Observatory (ESCO), Brussels
10. Nanayakkara S, Perera S, Senaratne S, Weerasuriya GT, Bandara HMND (2021) Blockchain and smart contracts: a solution for payment issues in construction supply chains. Informatics 8:36
11. Wang J, Wu P, Wang X, Shou W (2017) The outlook of blockchain technology for construction engineering management. Front Eng Manag 4(1):67–75
12. Kifokeris D, Koch C (2019a) Blockchain in construction logistics: state-of-art, constructability, and the advent of a new business model in Sweden. In: O'Donnell J, Chassiakos A, Rovas DV, Hall D (eds) Volume I—proceedings of the 2019 European conference on computing in construction. Chania: EC3, pp 332–340
13. Kifokeris D, Koch C (2019b) Blockchain in building logistics: emerging knowledge, and related actors in Sweden. In: Gorse C, Neilson CJ (eds) Proceedings of the 35th annual ARCOM conference. ARCOM, Leeds, pp 426–435
14. Kifokeris D, Koch C (2019c) Blockchain in construction—hype, hope, or harm? In: Kumar B, Rahimian FP, Greenwood D, Hartmann T (eds) Advances in ICT in design, construction and management in architecture, engineering, construction and operations (AECO): proceedings of the 36th CIB W78 2019 conference. University of Northumbria, Newcastle, pp 189–198
15. Orlikowski WJ, Scott SV (2008) Sociomateriality: challenging the separation of technology, work and organization. Acad Manag Ann 2(1):433–474
16. Orlikowski WJ, Scott SV (2016) Digital work: a research agenda. In: Czarniawska B (ed) A research agenda for management and organization studies. Edward Elgar Publishing, Northampton, pp 88–96
17. Moura EOD, Bispo MDS (2019) Sociomateriality: theories, methodology and practice. Can J Adm Sci 2019:1–16
18. Kohtamäki M, Parida V, Patel PC, Gebauer H (2020) The relationship between digitization and servitization: the role of servitization in capturing the financial potential of digitalization. Technol Forecast Soc Chang 151:119804
19. Barad K (2007) Meeting the Universe Halfway: quantum physics and the entanglement of matter and meaning. Duke University Press, Durham
20. Rossi M, Mueller-Bloch C, Thatcher JB, Beck R (2019) Blockchain research in information systems: current trends and an inclusive future research agenda. J Assoc Inf Syst 20(9):1390–1405
21. Bader V, Kaiser S (2017) Autonomy and control? How heterogeneous sociomaterial assemblages explain paradoxical rationalities in the digital workplace. Manag Revue 28(3):338–358
22. Andersen JV, Bogusz CI (2019) Self-organizing in blockchain infrastructures: generativity through shifting objectives and forking. J Assoc Inf Syst 20(9):1242–1273
23. Webster J, Watson RT (2002) Analyzing the past to prepare for the future: writing a literature review. MIS Q 26(2):xiii–xxiii
24. Bell E, Bryman A, Harley B (2019) Business research methods, 5th edn. Oxford University Press, Oxford
25. Greenhalgh T, Peacock R (2005) Effectiveness and efficiency of search methods in systematic reviews of complex evidence: audit of primary sources. BMJ 331:1064–1065
26. MacLure M (2005) 'Clarity bordering on stupidity': where's the quality in systematic review? J Educ Policy 20(4):393–416
27. Dundar Y, Fleeman N (2017) Applying inclusion and exclusion criteria. In: Boland A, Cherry G, Dickson R (eds) Doing a systematic review: a student's guide, 2nd edn. SAGE, London, pp 79–92
28. Pedersen AB, Risius M, Beck R (2019) A ten-step decision path to determine when to use blockchain technologies. MIS Q Exec 18(2):99–115

29. Xu Y, Chong HY, Chi M (2022) Blockchain in the AECO industry: current status, key topics, and future research agenda. Autom Constr 134:104101
30. Yoon JH, Pishdad-Bozorgi P (2022) State-of-the-art review of blockchain-enabled construction supply chain. J Constr Eng Manag 148(2):03121008
31. Cardeira H (2015) Smart contracts and possible applications to the construction industry. Rom Constr Law Rev 1(1):35–39
32. Wang Z, Wang T, Hu H, Cong J, Ren X, Xiao Q (2020) Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Autom Constr 111:103063
33. Nanayakkara S, Perera S, Senaratne S (2019) Stakeholders' perspective on blockchain and smart contract solutions for construction supply chains. CIB World Building Congress 2019: proceedings. CIB, Hong Kong, pp 3353–3363
34. Lanko A, Vatin N, Kaklauskas A (2018) Application of RFID combined with blockchain technology in logistics of construction materials. MATEC web of conferences, vol 170, pp 03032-1–03032-6
35. Penzes B (2018) Blockchain technology in the construction industry: digital transformation for high productivity. ICE Publications, London
36. Shemov G, Garcia de Soto B, Alkhzaimi H (2020) Blockchain applied to the construction supply chain: a case study with threat model. Front Eng Manag 1–14.https://doi.org/10.1007/s42524-020-0129-x
37. Scott DJ, Broyd T, Ma L (2021) Exploratory literature review of blockchain in the construction industry. Autom Constr 132:103914
38. Ma A (2020) Emerging legal issues in blockchain for construction supply chains. In: Proceedings 2020 2nd international workshop on big data and computing. ACM Digital Library, pp 1–7
39. Rodrigo MNN, Perera S, Senaratne S, Jin X (2020) Potential application of blockchain technology for embodied carbon estimating in construction supply chains. Buildings 10(8):140
40. Tezel A, Papadonikolaki E, Yitmen I, Hilletofth P (2020) Preparing construction supply chains for blockchain technology: an investigation of its potential and future directions. Front Eng Manag, 1–17.https://doi.org/10.1007/s42524-020-0110-8
41. Qian X, Papadonikolaki E (2020) Shifting trust in construction supply chains through blockchain technology. Eng Constr Archit Manag 28(2):582–602
42. Hamledari H, Fischer M (2021) The application of blockchain-based crypto assets for integrating the physical and financial supply chains in the construction & engineering industry. Autom Constr 127:103711
43. Hamledari H, Fischer M (2021) Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. Autom Constr 132:103926
44. Tezel A, Febrero P, Papadonikolaki E, Yitmen I (2021) Insights into blockchain implementation in construction: models for supply chain management. J Manag Eng 37(4):04021038
45. Lu W, Li X, Xue F, Zhao R, Wu L, Yeh AGO (2021) Exploring smart construction objects as blockchain oracles in construction supply chain management. Autom Constr 129:103816
46. Dounas T, Lombardi D, Jabi W (2021) Framework for decentralized architectural design BIM and blockchain integration. Int J Archit Comput 19(2):157–173
47. Suliyanti WN, Sari RF (2021) Blockchain-based implementation of building information modeling information using hyperledger composer. Sustainability 13(1):321
48. Chong AYL, Lim ETK, Hua X, Zheng S, Tan CW (2019) Business on chain: a comparative case study of five blockchain-inspired business models. J Assoc Inf Syst 20(9):1310–1339
49. Intrum (2019) European payment report 2019. Intrum, Stockholm
50. Gerber D, Nguyen B (2019) Blockchain technology timeline: case studies in the built environment. Arup, London
51. Nguyen B, Buscher V, Cavendish W, Gerber D, Leung S, Krzyzaniak A, Robinson R, Burgess J, Proctor M, O'Grady K, Flapper T (2019) Blockchain and the Built environment. Arup, London
52. Gustavsson TK (2018) Liminal roles in construction project practice: exploring change through the roles of partnering manager, building logistic specialist and BIM coordinator. Constr Manag Econ 36(11):599–610

Conceptual Model Utilizing Blockchain to Automate Project Bank Account (PBA) Payments in the Construction Industry

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Abstract The UK (United Kingdom) government published a guidance document in 2012 stipulating the use of project bank accounts (PBA) to promote fair and prompt payment practices in the construction industry. This article provides a high-level conceptual model utilising blockchain to automate project bank account payments. In PBA, project funds are partitioned in a separate bank account, like an escrow. Traditionally, before PBA, the main contractor would use the client's project payments to reinvest in new work, or strategically withhold supply chain payments to sustain positive cash flow. PBA revokes the main contractor as the sole recipient of the project budget and provides the client with transparency over project expenditures. The proposed conceptual model allows project participants to approve and execute automated payments through user dashboards. Part of the security of smart contracts is their unchangeable properties once deployed; however, this is problematic, as construction projects regularly undergo change orders and programme alterations. Furthermore, Ethereum-based smart contracts in the current environment are limited due to the costs associated with auditing and on-chain hosting fees. To mitigate this, transactions in the PBA blockchain model are instantiated through an off-chain application, which stores pre-executed transactions in the form of signed messages. These messages are pushed to the blockchain and converted to transactions once they are approved by validating authorities. The result is a strategy to achieve payment automation at a more economical cost. The proposed model illustrates a high-level amalgamation of PBA, blockchain, off-chain, and asset tokenization. A limitation of this article is that it does not include any programming and the ideas are presented in the form of a flowchart. Future work includes programming the solution.

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1 Introduction

The construction industry is known for having bad payment practices like overextended periods of delayed payments [1]. Furthermore, the industry is still recuperating from the pertaining effects of the 2008 financial crisis, which left many construction companies with elevated capital expenditure, increased competition, and greater exposure to financial uncertainty [2]. Commercial solutions to mitigate this include parent company guarantees, collateral warranties, and counterparty risk assessments [3]. However, these do not address the primary concern of reducing delayed payments. Solving this problem would increase the stability of the industry by improving liquidity and reducing supply chain insolvencies, which leads to increased trust and reduced project risk [4]. Data from the UK National Office of statistics in 2019 suggested that for every large company in the construction industry, there are on average 1000 small and medium enterprises [5]. This imbalance creates over-competition and forces subcontractors to accept unfair contractual conditions, such as high-risk work for less pay [6].

The construction and civil engineering industry is known for being risk-averse. From a structural perspective, the risk of collapse is linked to public safety; therefore, by default, safety standards are high [7]. From a financial perspective, innovation is challenging due to low margins, which results in the overuse of legacy systems [8]. Lack of innovation in technology systems is the principal contributor to poor productivity, adversarial supply chain relationships, and negative workflow fragmentation [9]. Neighbouring industries such as manufacturing have managed to increase efficiencies annually throughout many generations, resulting in progressive productivity year after year [10]. Due to a lack of innovation, infrastructure projects are on average 80% over budget and 20% behind schedule; furthermore, productivity has been declining since 1990 [11]. Construction also suffers from a lack of transparency in company reports, whereby, stakeholders are subjected to inaccurate feedback on the state of a project [12].

The increasing global population has put additional pressure on the construction industry to build more with less, whilst in a skills shortage [13]. Additionally, the industry is facing pressure to incorporate smart technologies and decarbonization solutions throughout the lifecycle of built assets [14]. The demand for digital reform is required to meet the industrial dependencies of the modern economy [15]. Blockchain includes the potential to increase efficiencies in multiple areas, such as payments, data management, automation, and systems integration [16]. However, blockchain alone cannot be relied upon to drive the digital revolution. It is one of many components that need to work in harmony as part of an ecosystem of technology services.

The first documented use of a project bank account (PBA) on a construction project was in 2005, through a joint venture between the UK Ministry of Defence (MOD) and the main contractor, which was created to ensure the auditability of government funds throughout an entire project [17]. The UK government PBA guidance document was published in 2012, which discussed the partitioning of the project account away from the contractor to mitigate against cash farming and cascading payments down each tier of the supply chain [18]. Cash farming is when a contractor unfairly withholds payments to their supply chain to improve internal cash flow.

This article presents a conceptual model that amalgamates blockchain with PBA to automate the processing of supply chain payments, without having to use an intermediary to manage the PBA. In the proposed model, the partitioned account is represented by an off-chain database that controls the release of funds from the client to the supply chain. The PBA blockchain model attempts to bypass hosting on-chain (on the blockchain) smart contracts to mitigate transaction fees, development costs, and recoding when projects undergo change orders. The off-chain database is used to store pre-executed transactions that covert to transactions at a later point in time. This article provided a high-level process flow of the PBA blockchain model and the responsibilities of each transacting party.

2 Literature Review

The detrimental effects of delayed payments in the UK construction industry were documented in the 1964 Banwell Report [19], authored by Sir Harold Banwell, who was tasked with documenting the state of the industry. The construction industry is a large contributor to global GDP (Gross Domestic Product); however, it can increase its contribution further through innovating longstanding and outdated processes [20]. The industry is particularly known for having a lack of trust caused by poor procurement practices, cash flow, and lack of collaboration [21]. As a result, clients are hesitant to take on new work due to undisclosed risks and tight margins, which results in projects being selected based on low cost rather than long-term value [22]. Innovation remains a perpetuating problem despite advancements in digital solutions such as building information modelling (BIM) [23].

The supply chain in the construction industry transacts and communicates through fragmented systems that do not integrate efficiently [24]. These systems make it difficult to accurately report the state of a project with transparency and traceability [24]. Despite this, the industry is pushing towards greater standardisation to increase productivity through bodies such as the International Standard Organisation (ISO), Industry Foundation Class (IFC) by building Smart, and governmental mandates that support digital tools such as BIM [25].

The construction industry is dominated by a small selection of main contractors who provide work for many small and medium enterprises (SMEs), which causes over-competition amongst SMEs and provides main contractors with controlling authority over the supply chain [26]. SMEs are forced to accept unfair contractual conditions with overextended payment terms due to the hierarchical nature of the industry; whereby, contractors exercise *cash farming* techniques and *pay when paid* clauses [4]. Cash farming is a strategy implemented by contractors to improve internal cash flow at the cost of delayed payments to their supply chain, furthermore, it allows the project budget to be used for investing in new work rather than paying outstanding debts [27]. Despite the benefits of cash farming to contractors, it is the primary cause of SME insolvencies [28]. Data from the Office of National Statistics suggest that the average quantity of individual insolvencies in the UK construction industry is recorded at 2595 cases annually, which accounts for 18% of the overall insolvent population in the UK and is the highest across all other industries [29]. The danger of bad cash flow management is exemplified by the insolvency of Carillion, who in 2017 was the second-largest construction company in the UK (based on turnover); however, at the time of liquidation in 2018, it owed GBP 1.3 billion worth of unpaid liabilities to SMEs [30]. From 2009 to 2018, Carillion's debt increased from GBP 242 million to GBP 1.3 billion; furthermore, they imposed payment terms of 120 days to SMEs, which is four times the duration of what is typically agreed in construction contracts in the UK [31].

Dispute resolution in the construction industry is typically managed through mediation, which is a lightweight process that involves an impartial third party to manage and settle the dispute; however, large companies can enforce costlier methods against unsatisfactory settling, through methods such as litigation [32]. This places SMEs at a disadvantage because payments to the supply chain are withheld until a court settlement takes place, which can take over 12 months to process [32]. Countries such as France and Australia include regulations that allow SMEs to request overdue payments directly from the client; furthermore, Japan includes severe governmentally enforced penalties on construction companies that impose unfair payment terms [33].

2.1 UK Government Fair Payment Legislations

This section provides a brief overview of the UK legislation documents that promote fair payment practices. A common trend in this includes how to protect small and medium enterprises (SMEs) from unfair contract conditions, through the incorporation of reduced payment terms and requesting that contractors provide promissory notes as proof of goodwill to their supply chain. These legislations are variants of the same solution, as the payment problem remains unsolved and different approaches are incorporated. The UK Government has requested that some of these listed legislations be compulsory; however, construction companies in the UK continue to treat these as advisory documents due to a lack of governmental oversight. The following is an overview of several payment legislations that are currently active in the UK.

2021: Prompt Payment Code (originally published 2008): The *Department for Business, Energy & Industrial Strategy* revised their legislation to reduce payment terms to SMEs from 60 to 30 days [34]. Non-compliance from contractors includes membership suspension that requires a compulsory reinstatement program to retain status [35].

2014: Construction Supply Chain Payment Charter: The *Construction Leadership Council* requests that all contractors provide a signed commitment to fair payment terms, which provides clients and their supply chain with the assurance of good cash flow management [36]. The charter stipulates a maximum payment term of 30 days and advises the use of project bank accounts (PBA) in public sector work; furthermore, the charter enforces periodic checks on key performance indicators to ensure adherence by contractors [37].

2013: The Revised Late Payment of Commercial Debts Regulations (originally 1998): Published by the *Department for Business, Innovation and Skills* [38]. This legislation allows the supply chain to charge 8.5% statutory interest on invoices that have been left unpaid for 30 days [39]. However, this does not include a 30-day checking period, therefore, contractors can strategically delay payments for up to 60-days before interest is charged (30 days to check works and 30 days post-approval of works) [40].

2012: Project bank account (PBA) guidance document: Published by the UK Government *Cabinet Office*, PBA utilises a project-specific bank account that is partitioned away from the main contractor's bank account, which provides the client with full auditability of project expenditures throughout the entire construction stage of a project. All payments to the supply chain would be executed directly from the PBA, which mitigates the risk of contractors performing cash farming [18].

2012: Supply Chain Finance Scheme: Established in 2012 by the UK government to support SMEs in obtaining supply chain finance, it encourages banks to supply low-interest loans to the construction supply chain based on invoices that have been approved by clients [41].

2011: Part 2 of the Housing Grants Construction and Regeneration Act 1996: This legislation was put forward by the UK parliament in conjunction with the *Department for Business, Energy & Industrial Strategy* [42, 43]. The act allows the supply chain to legally withdraw from continuing with works in the event of non-payment from their employer; furthermore, it requests that employers provide signed proof of their obligation to make fair payments to their supply within the contractually agreed payment terms [44].

2.2 Project Bank Accounts (PBA)

The first recorded use of a project bank account (PBA) in a construction project was in 2005, through a joint venture between a public sector client (UK Defence Estates) and a main contractor; furthermore, the PBA was set up due to the adversarial nature of the construction industry and the client having a trusted relationship with their SMEs [17]. The result was successful, with the PBA managing all payments to subcontractors on time and within the agreed budget; furthermore, all expenditures were openly auditable throughout the entire construction process [17]. According to the UK Office of Government Commerce report on PBA implementation, clients can save up to 2.5% on public sector projects [45]. PBA was trialed in the public sector between 2012 and 2015 and was used to manage over GBP 4 billion worth of work

[18]. In 2013, the Northern Ireland government has mandated PBA in construction projects worth over GBP 1 million GBP; similarly, in the same year, Wales mandated the use of PBA in projects worth over GBP 2 million [46].

In a typical construction contract, main contractors customise contract clauses to protect themselves against legal disputes [47]. A barrier to SMEs requesting PBA in contracts is the fear of potential reprisal from main contractors, which may include exclusion from future work [48]. In a questionnaire conducted by PhD researchers Rachel Griffiths and Wayne Lord from Loughborough University on the topic of PBA adoption, consisting of a total sample of 58 respondents from the construction supply chain, 42% voted *fear of reprisal* as the principal factor preventing the adoption of PBA, followed by 34% *legal expenses*, and 25% *culture of the industry* [49]. Additionally, standard forms of contracts include various certifications, valuations, and compliance checks that require amending to suit the implementation of PBA; however, the interviewees suggested these as non-technical barriers [49]. Furthermore, the UK governmental department Cabinet Office asserted that PBA would not cause interference with contract valuations and certifications [50].

Removing the risk of main contractors performing cash farming promotes responsible working practices [50]. Progress on the uptake of PBA in existing contracts such as NEC, JCT, and FIDIC has steadily increased; however, PBA is challenging to enforce across all built environment contracts due to the diverse and bespoke nature of construction projects [51]. A similar variant to PBA emerged in Canada, called the Ontario Construction Lien Act, which discussed using a multi-project bank account [52]. Whereby, a partitioned bank account is used for executing payments across multiple projects [53]. The payment duration for this is 28 days from the client to the contractor and seven days from the contractor to the subcontractors; however, it permits a *paid when paid* clause, thus is prone to delays caused by cascading payments down the supply chain [54]. Furthermore, it suffers from liability and trust issues regarding the appointment of an account manager that can oversee private/sensitive data across multiple projects.

Blockchain includes the potential to integrate with PBA by linking payments directly to signed approvals, through smart contracts that automate the release of payments to the supply chain [55]. Benefits include reduced delays caused by administrative processing, and increased transaction traceability [56]. Payments can be automated through preprogrammed functions that control the execution of transactions; furthermore, these codified instructions can be audited by regulatory controls to ensure compliance with government-enforced legislation [57]. The inbuilt properties of blockchain, such as immutability and data trust, make it a suitable medium for value transfer, which provides a reliable data trail in the event of dispute resolution [58]. Data stored on the blockchain can be relayed into enterprise systems through an application programming interface (API) that integrates blockchain with legacy systems [59]. For example, services that are typically managed across various IT systems such as asset ownership certificates, accounting data, and signed contract agreements can potentially be integrated through a blockchain-based system [60].

2.3 Cryptography and Encryption

Blockchain incorporates asymmetric encryption (synonymously called public-key cryptography), which comprises the use of a public–private key pair [61]. These keys serve two main functions, encryption, and signatures [62]. The public key is the digital address that is used for receiving funds (like the account number written on a person's bank card), while the private key provides the authority to execute transactions from a user's wallet (like a person's card number on their bank card) [63]. Due to asymmetric encryption, public keys can be shared openly without the risk of revealing their associated private key [64]. It was invented in 1976 and is the evolution of symmetric encryption [65]. Symmetric encryption uses only one key to encrypt and decrypt data, while asymmetric encryption uses two keys, a public–private key pair [66].

Additionally, asymmetric keys are also used to provide encryption when sending data across a peer-to-peer network, which allows users to provide signed proof that a particular piece of data was not manipulated or changed [67]. Asymmetric encryption also plays a fundamental role in internet security, by allowing computers to exchange data online with privacy, such as with internet banking, e-commerce, email, and any other online data exchange system [68].

2.4 Off-Chain Messages

Asymmetric keys are not a product of the blockchain, despite their vital role in its functionality [69]. Asymmetric keys are produced through the Elliptic Curve Digital Signature Algorithm (ECDSA), which is available in most programming languages [70]. Because of this, public–private key pairs can be created whilst disconnected from the internet to increase security [71].

A blockchain transaction can also be instantiated off-chain (off the blockchain) by storing a signed message that states the intention to send a transaction at a future point in time, this can be incorporated as part of a payment application to automate payments for delivered works [123]. An example of an off-chain application that is used ubiquitously across blockchain is a decentralised exchange (DEX), which allows users to trade currencies peer-to-peer without a centralised exchange. Decentralised applications such as DEXs mitigate against hacks, provide lower transaction fees, and allows users to trade peer-to-peer [122]. DEXs include a unique property, whereby, the public keys of transacting parties are not required to perform the trade, therefore, swaps take place anonymously [124]. The off-chain features of a DEX are adapted and implemented into the PBA blockchain model.

2.5 Smart Contracts

Currently, smart contracts are costly to build due to the auditing, development, and on-chain deployment fees [72]. The estimated cost for outsourcing a smart contract can range from USD 7000 to 100,000 each, depending on the complexity of its business logic [73]. However, outsourcing a smart contract is only part of the equation, it must also be audited, which can range from USD 4000 to 100,000 each [74]. The number of smart contracts required to fully automate payments in a construction project can realistically reach thousands, due to the volume of participants and activities involved in a typical project. Additionally, including more technical features into a smart contract simultaneously increases its cost, thus there is a level of diminishing returns that applies to smart contracts as they increase in complexity [75].

The technical functions of the PBA blockchain model derive its ideation from a decentralised application (dApp) with off-chain functionalities. A blockchain transaction is a signed message which states the intention to send cryptocurrency from one person to another [76]. However, this intent can be stored off-chain and is the basis of the proposed dApp. The rules that permit the release of messages to the blockchain would be governed by conditions pre-programmed into an off-chain database. The conditions would be openly auditable for all users to verify its terms and conditions before entering blockchain-based agreements. A downside to using off-chain as opposed to on-chain is the higher rate of centralization [77]. To increase security, the PBA dApp would need to be hosted by many nodes to revoke any one party from having controlling authority over the dApp. The most practical selection of participants would be the ones directly involved in the project, such as the client and the supply chain. External participants of the dApp could include banks, governmental authorities, and standards organizations.

3 Methodology

The research topic was selected through an investigation of the longstanding detrimental payment practices of the construction industry, which are caused by delayed payments and unfair contract conditions that are enforced by upper-tier contractors. From 1998 to 2008, the average rate of individual insolvencies in the UK construction industry totalled 2145 cases annually, at 14% of the UK insolvent population, which is the highest amongst all other industries [28]. Furthermore, more recent figures from the Office of National Statistics based on 2018 to 2020, displayed an average of 2595 recorded cases annually, accounting for 18% of the UK insolvent population [29]. This article provides a conceptual model that discusses how blockchain can potentially be incorporated as part of a payment system to automate PBA transactions.

The proposed PBA blockchain model was conceptualised through a compilation of ideas adapted from existing literature [78]. This included reviewing governmental payment strategies and existing blockchain applications. Of these, the UK governmental guidance document on project bank accounts (PBA) was selected as a viable strategy that can benefit from the inclusion of blockchain [79]. The ideation of the PBA blockchain application was derived from a decentralised off-chain payment application that allows users to predefine transaction conditions without having to use a smart contract [80].

4 Conceptual Model

The conceptual model uses three flowchart diagrams to explain the functionalities of how the blockchain-based off-chain application operates. Figure 1 explains the core functions of message signing, Fig. 2 provides a holistic view of how transactions are processed through the PBA blockchain application, and Fig. 3 discusses how project participants set up contract agreements through the proposed system.

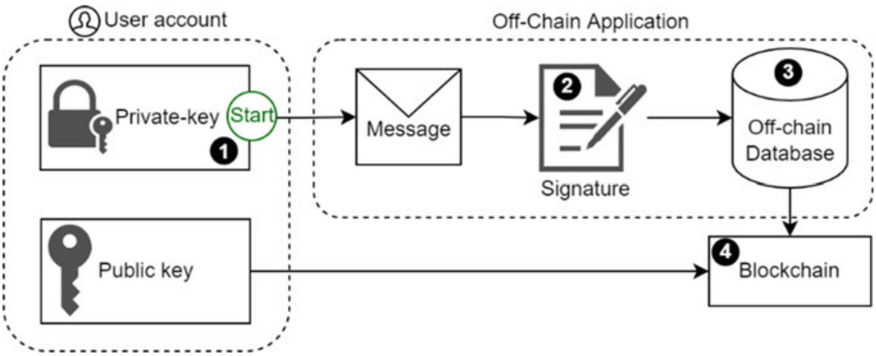

Fig. 1 Off-chain message signing

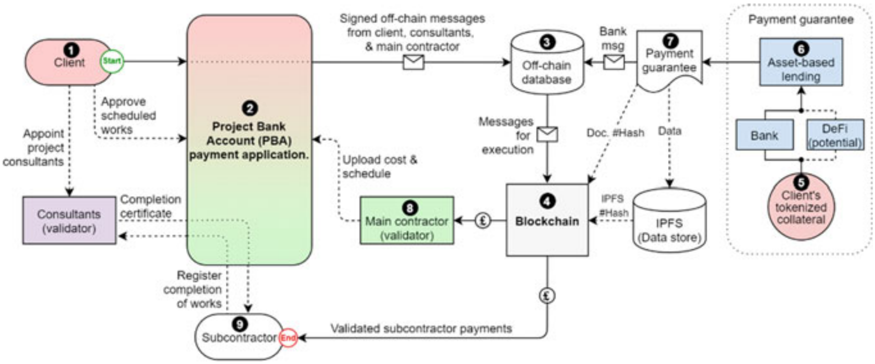

Fig. 2 PBA blockchain model process flow

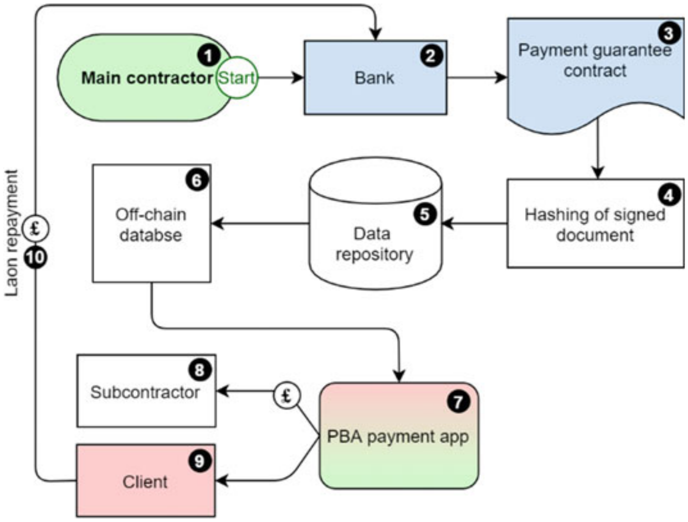

Fig. 3 Payment guarantee process flow

4.1 Message Signing

Blockchain transactions are signed messages that provide cryptographic proof that a payer wishes to send cryptocurrency from their wallet to a recipient. However, these messages can be instantiated and managed off-chain, which is the purpose of the proposed application. The intention is to use signed messages that include instructions to execute project payments to the supply chain participants upon validated completion of works. Each message would be signed with the account holder's private key, which provides the authorization for the message to convert to a transaction when it is uploaded to the blockchain [81]. Furthermore, signed messages can be used in conjunction with a promissory note, which provides evidence of the client's intention to make fair payments. The message signing process is displayed in Fig. 1 and is numerically annotated to discuss the sequential steps of the message signing function.

1. **Private key**: This is primarily used to authorize blockchain transactions that can be instantiated off-chain through a cryptographic signature. The private key can also be used to encrypt/decrypt data. For example, a file can be encrypted with a user's public key that allows only the corresponding private key to decrypt the data.
2. **Signed messages**: This can only be conducted using an account holder's private key. Each message is signed to ensure its authenticity and provide proof that it has not been tampered with. The algorithm used to sign these messages is the Elliptic Curve Digital Signature Algorithm (ECDSA), which is supported in most programming languages and allows the signing process to take place

whilst disconnected from the internet or off-chain [82]. Blockchain transactions also include the ability to store short strings of text in their data input field, which can be used to store reference codes or repository links that are stored in the form of a data hash [83].

3. **Off-chain database**: This is a repository for storing signed messages. An off-chain database can host its own IF/THEN statements that can be used to control the release of messages to the blockchain [84]. A front-end application would allow users to perform the message signing process with their blockchain wallet address without requiring any coding knowledge. A Public-key Recovery algorithm (PKR) exists for public blockchains that allow users to sign off-chain messages anonymously without revealing their public key, thus increasing the security of off-chain applications [85]. Public blockchains such as Ethereum include PKR built into their protocol, thus when messages are uploaded on-chain, the sender's public key is autonomously generated, and the transactions can execute [86]. Because of PKR, the digital keys of the payment participants in an off-chain application are not required to be disclosed, thus mitigating data privacy risks.
4. **Blockchain**: This is used to process signed messages received from the off-chain database. As soon as messages are pushed from the off-chain database to the blockchain, the transaction would execute provided that the sender has enough funds in their wallet. Blockchain wallets cannot go overdrawn. Therefore, a blockchain-based payment guarantee would be required to cover any missing liabilities. More on this will be discussed in a later section.

4.2 Project Bank Account (PBA) Blockchain Model

Figure 2 flowchart is numerically annotated displaying the sequential steps of the envisioned PBA blockchain model. It discusses the responsibilities of each actor and process flow. The PBA blockchain application would utilise various interfaces that interoperate to control the flow of messages from the off-chain database to the blockchain. Off-chain would be used for data storage, management, and computational processing, while the blockchain is used for payment executions and indexing of hashes.

1. **Client**: This user is responsible for approving the project budget through the PBA application. Approval is conducted through signed messages that state the intention to make payments to the supply chain upon validated completion of works. Appointed project validators, such as the main contractor and consultants, would be provided with the authority to control the release of signed messages from the off-chain database to the blockchain.
2. **Project Bank Account (PBA) payment application**: This is the front-end interface that allows users to instantiate signed messages, input project data, validate works, and provide completion certificates. Primary actors of the PBA

blockchain model would include the client, bank, main contractor, consultants, and subcontractor.

3. **Off-chain database**: This is used to represent the partitioned PBA account. Off-chain applications include greater modularity in allowing its governing council (such as client, contractor, and bank) to select the level of scalability (measured in transactions per second) and privacy that is suitable for the project [87].
4. **Blockchain**: This would autonomously and periodically receive signed messages from the off-chain database for transaction execution. The data input field of on-chain transactions can be used to store validation signatures that were instantiated off-chain, such as hashed completion of works signatures [83]. This data can interoperate with enterprise systems through the integration of an application programming interface that filters and relays relevant blockchain data through user dashboards [88].

   Steps five to seven include the process of obtaining project finance if the client is unable to pay liabilities at project milestones. This process is automated through a financial authority (such as a bank) that signs a message stating its intention to cover unpaid liabilities. The message is stored in the off-chain database and would execute autonomously when the non-payment event is triggered.
5. **Tokenised collateral**: This can potentially provide liquidity in the event of non-payment from the client, through a blockchain-based tokenised securities service provided by a financial institution [89]. Whereby, a financial provider such as a bank can potentially supply project finance in exchange for the client's tokenised collateral. Despite this being a nascent aspect of blockchain, major banks such as HSBC, JP Morgan, Bank of China, China Construction Bank, and Santander have been tokenising securities since 2019, each migrating billions of US dollars' worth of assets to blockchain securities [90]. Alternatively, decentralised finance (DeFi) is another nascent blockchain-based service that emerged in 2020, which introduced collateralised peer-to-peer lending through a decentralised network [91]. However, in the current environment, DeFi has not matured enough to extend its services to business-to-business or peer-to-business lending, as DeFi for businesses is more burdensome with regulatory compliance, and regulation is one of blockchain's biggest challenges.
6. **Asset-based lending**: This is an existing financial service offered by banks to provide compensation to the client in the event of non-delivery from the contractor, similarly, contractors also obtain payment guarantees to insure against non-payment from their client [92]. Both compensation events are typically implemented in construction contracts to hedge against risk, however, this process also increases the project budget due to the bank charging high fees for their services [93]. Stock Exchange Group, IBM, and Borsa Italiana have collaborated to develop an asset exchange platform hosted on the blockchain, that allows enterprises to tokenise securities without having to use the services of a bank [94]. These tokens include the potential to be utilised in conjunction with decentralised finance.

7. **Payment guarantee**: This is currently an administratively time-consuming task to process, as it requires the bank to refamiliarise themselves with agreements that were signed many months before the payment guarantee pay-out request, causing unnecessary data reprocessing and delays [92]. This can be mitigated through the bank storing signed blockchain messages which state the intention to execute compensations according to the liability amount owed by the client. These messages would be stored in the PBA off-chain database and released autonomously based on the trigger of a non-payment event.
8. **Main contractor**: This party is relieved of their responsibility as sole proprietor of the project budget; however, they play a vital role in validating subcontractor works through the PBA-blockchain application. The contractor is responsible for validating the percentage of works completed, while consultants are responsible for ensuring works are delivered to the agreed standard. Validations are performed through signed blockchain messages conducted through the PBA front-end application. Successful validations permit the flow of messages from the off-chain database to the blockchain. The contractor's role also includes uploading project cost and schedule data through the PBA front-end for signed approval by the client. The client would approve these through signed blockchain messages that instruct the transfer of funds from their wallet to the supply chain.
9. **Subcontractors**: These parties have sustained longstanding detrimental payment conditions in the construction industry for many generations. Statistics from the UK's leading retail payment authority suggest that 78% of small and medium enterprises are forced to wait 30 days or longer beyond agreed payment terms [95]. Once a subcontractor registers completion of works through the PBA application, this autonomously notifies validators of their responsibility to approve works. Once approved, an automated payment would execute according to the project's milestone schedule. The release of payments from the off-chain database would be controlled by a predefined IF/THEN statement that is codified into the application. To protect against negligence from validating parties, an automated reward/penalty system can be embedded into the PBA blockchain application.

5 Payment Guarantee

Figure 3 displays a high-level process flow of the documentation, storage, and execution of the payment guarantee.

1. **Main contractor**: This party can obtain payment guarantees from multiple banks through a syndicate finance approach, whereby several banks can aggregate their services to mitigate short-term variance like high-value payouts [96]. Syndicate finance is a service that is typically requested by the payment guarantee recipient; however, it can also be offered by the bank. The first syndicate loan delivered through blockchain was in 2018, valued at USD 150 million, which comprised of a joint venture between three banks, these were

Banco Bilbao Vizcaya Argentaria (BBVA), Mitsubishi UFJ Financial Group (MUFG), and Banque Nationale de Paris (BNP) [97].

2. **Banks**: This party is the current supplier of payment guarantees in construction projects [98]. Their involvement in the PBA blockchain model is crucial, and they would need incentivising to integrate their services with it. However, the architecture of this is beyond the scope of this article to investigation. An entirely separate article can be written on whether banks would be willing to provide blockchain-based finance to construction projects.
3. **Payment guarantee contracts**: This guarantee is implemented in existing construction agreements to provide financial security to investors, stakeholders, and the supply chain, because construction projects have a long-standing reputation of being elevated risk and low reward [98]. This payment guarantee is a complicated service provided by banks, thus high fees are charged for it, which contributes to reducing project margin [92]. The automated and traceable features of blockchain make it a suitable technology for the reliable dissemination of payment guarantees without incurring excessive intermediary fees and processing delays.
4. **Hashing of signed documents**: This is a way to generate a unique identifier for any given digital file [99]. Hashes can be algorithmically produced using any computer; therefore, it is universally acceptable and mathematically accurate without having to rely on a trusted third *party* to generate the hash [100]. Websites such as this: https://emn178.github.io/online-tools/sha256_checksum.html allow users to test the hashing function by uploading a file to it, which autonomously generates a unique hash for the file.
5. **Data repository**: This is a mandatory requirement if the intention is to link documents to the blockchain, as the blockchain can only be used for storing short strings of text such as hashes. Decentralised storage providers such as IPFS integrate with blockchain to add an extra layer of security when storing data in a decentralised repository, as centralised storage is at greater risk of being hacked and at the mercy of data mining from service providers [101]. The digital keys used for signing messages on the blockchain can also be used for encrypting and decrypting files, whereby, a sender can encrypt a file with the recipient's public key, which allows only the recipient to decrypt the file with their private key. This allows documents to be stored and exchanged safely in a public domain without the risk of data privacy breaches. However, should the file need to be stored without encryption while simultaneously allowing the public to verify its authenticity, then this can be achieved by the sender hashing the file, encrypting this hash with their private key, and storing the encrypted hash with their public key in a publicly accessible folder, thereby, allowing anyone to decrypt the file's hash with the sender's public-key to verify its authenticity [102]. This allows documents to be stored publicly while allowing all parties to verify their authenticity without having to rely on trust.
6. **PBA payment application**: The front-end of this application allows the bank to sign a blockchain message stating the intention to guarantee the client's project payments up to an agreed sum, this message later transpires into a

transaction when it is pushed to the blockchain. Data such as payment codes can be stored in the data input field of each blockchain transaction, which allows for the referencing of off-chain data on the blockchain [83].

7. **Off-chain database**: This stores the bank's signed blockchain messages which are ready for deployment when a compensation event is triggered. Due to asymmetric encryption, signed messages cannot be falsified because each message is signed with the account holder's private key.
8. **Subcontractor**: This party would register the completion of their work through the PBA blockchain application, which would simultaneously notify validators of their responsibility to approve completed works. If the client is insufficient with funds on the payment due date, then the subcontractor would receive an automated compensation payment from the bank at the sum owed by the client. It is typical for payment guarantees to only cover a fraction of the client's overall budget. However, all supply chain parties would be made aware of this through a contractual agreement that they would sign beforehand. To reassure the subcontractors, the proposed PBA application would provide a tally of the bank's pending compensation payments that would be verifiably through an application programming interface (API).
9. **Client**: This party would autonomously receive a notification regarding their obligation to repay the payment guarantee loan through the PBA application. Privacy of the loan repayment can be maintained through zero-knowledge proofs, which is a cryptographic mechanism that allows private transactions to occur on a public blockchain [103]. Alternatively, the client can repay the bank by manually sending them a blockchain transaction of the amount owed.
10. **Loan repayment**: This activity would be conducted through the PBA blockchain application. This allows reference codes to be managed autonomously (through APIs) to reduce data entry errors. The APIs can also be designed to integrate with existing legacy enterprise systems.

6 Discussions

The 1964 Banwell report, titled The Placing and Management of Contracts for Building and Civil Engineering Work, discussed the importance of change in the payment culture of the construction industry and outlined the importance of collaborative contracts; however, 50 + years later, the same problems are still existent [19]. This was reiterated in the 1994 Latham report [104], and the 1998 Construction Task Force Egan report [105]. Furthermore, across 25-years, spanning from 1996 to 2021, the UK government published six major legislation documents regarding sustainable payment practices in the construction industry. Despite this, from 2008 to 2013, the duration of overdue payments increased by 22%, while bank lending for construction projects decreased by 38% [106]. This places small and medium enterprises (SMEs) under increasing pressure to sustain financial adversity, due to banks increasingly refusing to provide financial support and construction contracts that allow for unsupportive payment conditions. For example, unfairly withholding supply chain payments (cash farming) and unnecessary processing delays caused by cascading payments down each tier of the supply chain.

Building information modelling (BIM) did not provide the digital reform that was expected of it, which is due to many factors that are beyond the scope of this article to investigate; however, some of these include the culture of the industry to resist change, skills shortage, and cost of the technology [107]. Additionally, many of the expectations of BIM were overinflated and based on premature forecasting. While BIM is a construction industry-focused innovation, blockchain includes substantial development in other industries, which includes solutions adaptable to the construction industry [108]. Technology leaders such as Facebook, Amazon, Microsoft, Google, and Apple, (FAMGA) are providing blockchain-based services for enterprises and consumers to integrate with existing IT systems [109]. Due to blockchain being a multi-industry innovation, it includes greater contribution and development from a wider community, unlike BIM, which is a construction industry-centred innovation.

Project bank account (PBA) shares several principal characteristics with blockchains, such as transparency, auditability, and disintermediation, through creating a partitioned bank account that is co-managed by project participants. The ideation of the PBA blockchain model is taken from a decentralised application. It includes payment conditions preprogrammed into a blockchain application to automate the execution of payments to the supply chain. The proposed PBA blockchain model assumes that banks have adopted blockchain and can offer payment guarantees through tokenised collateral; however, the readiness of banks to provide blockchain services to the construction industry requires further research [110]. If banks are reluctant to assist in providing guarantees, opportunities exist with decentralised finance (DeFi), and asset tokenisation through collateral-backed lending [111]. However, the technical aspect of DeFi for enterprise is in the conceptualisation and testing stage and requires regulatory maturity. Furthermore, insuring against blockchain-related risks is difficult to forecast in the current environment due to the nascency of the technology. This disincentivizes an already risk-averse construction industry. DeFi came into fruition in 2020, and in the same year, a USD 25 million USD hack of a DeFi platform took place, which was untraceable due to the pseudonymous nature of public blockchains [112]. Collateral lending through DeFi is currently only available for peer-to-peer borrowing/lending, which is unsuitable for DeFi-based peer-to-business or business-to-business finance [113].

When the client approves the project budget through a signed blockchain message instantiated through the PBA application, this can be used as part of a promissory note that guarantees a level of financial certainty to the supply chain. It is envisaged that the client's signed message could integrate as part of a formal digital document to provide legal assurance of the intention to provide good payment practices. Since the PBA application is off-chain, it can adapt more easily to contract-specific alterations or new regulations that may be imposed by GDPR. This can be achieved without having to obtain consensus from a large public blockchain network since the application is off-chain. Some of the primary risks associated with blockchain include incorrectly written code and hacks. If the project funds are stolen due to a hack, they will be almost impossible to retrieve due to the pseudonymous nature of user wallets on the blockchain.

The proposed PBA blockchain model imposes automated loans to the client based on their unpaid liabilities; however, clients are likely to dispute this, as they are not typically penalised for overdue payments. To combat this, a small percentage of the project budget can be pooled to cover any overdue payment fees. If the client does not incur any late fees, then they would receive reimbursement at the handover stage. Incentives for the client to use the PBA blockchain application include the ability to provide payment guarantees to the supply chain, payment automation, and mathematical proof of good payment practices.

The cost of developing the PBA blockchain application was not investigated quantitatively; however, the incorporation of an off-chain application provides a more economical alternative than having to deploy smart contracts directly on the blockchain. These overheads are reduced though diverting computational processing off-chain [114]. Since the proposed application is off-chain, privacy features are easier to incorporate and customise; however, increased modularity is exchanged for a greater centralization; therefore, this tradeoff is important to consider when designing the security aspects of the off-chain application and the governance team that will be appointed to manage it.

The proposed PBA blockchain model bypasses having to use smart contracts. This mitigates costs associated with their development, auditing, and on-chain hosting fees. According to Andrew Zapotochnyi, CEO of Block Geeks, which is a smart contract auditing and education company, the estimated cost for auditing a smart contract can range from USD 4000 to 100,000 each, depending on how advanced the coding is [74]. While iOlite, a non-profit organisation for smart contract technologies, estimated that the cost of developing a smart contract can range from USD 7000 to 100,000 each, based on the complexity of its business logic [73]. Furthermore, deploying smart contracts directly on the blockchain incurs hosting fees that need to be considered. Despite the generalised nature of these costs, even the lowest spectrum is uneconomically feasible, as potentially thousands of smart contracts would be required to fully automate payments in a construction project, due to the volume of participants and activities that occur in a typical project. Despite this, as blockchain and smart contracts mature, it is likely to become exponentially more affordable. Until then, other options such as off-chain must be explored.

Due to the volatility of cryptocurrencies, payments would need to be conducted through stablecoins or central bank digital currencies (CBDC). CBDCs are a digital reproduction of a national currency, issued and managed by the government; however, it is currently in the testing stage, with China being the first to conduct a full-scale pilot in 2021 [115]. The Bank of England and HM Treasury created the CBDC taskforce in 2021 to further explore its viability as legal tender [116]. Stablecoins are like CBDCs in that they are cryptocurrencies pegged at a one-to-one ratio with a national currency, such as the US dollar or Euro; however, they are not minted or controlled by a central bank [117]. Adoption of the PBA blockchain model is dependent on the host country having a stablecoin or CBDC in their national currency. Many major currencies such as USD, Euro, and GBP include a stablecoin variant; however, these stablecoins have a limited circulating supply, they also lack government regulation, and it is difficult for liquidity providers instantaneously converted them back into national currencies at a large scale.

A survey conducted by the Construction Industry Training Board (CITB) and Construction Skills Certification Scheme (CSCS), of 419 certificate verifiers in the construction industry, revealed that 18% of the verifiers encountered at least one counterfeit certificate being used on projects within the past 12 months [118]. The British Standards Institute (BSI) has partnered up with the OriginTrail blockchain application to store certificate verifications on the Ethereum blockchain. This allows subcontractors to append QR codes onto certificates that link directly to the blockchain to provide proof of compliance with standards [119]. This is a prime example of a private enterprise application hosted on a public blockchain platform. Most of the innovations in blockchain emerge from public platforms due to their permissionless nature, which provides free protocol infrastructure and unrestricted access for developers to test and build applications, without incurring fees or having to request permission from the platform [120].

7 Conclusion

From 1996 to 2021, six major UK governmental legislative documents were published to address the payment problem in the construction industry. From these, the project bank account (PBA) strategy was identified as an area that could benefit from the integration of blockchain. Despite its nascency, blockchain is rapidly evolving and changing the outlook of how businesses, people, and services operate. In a report which discusses the potential impact of blockchain, it was identified as potentially transforming 58 industries globally, which includes the construction industry [121]. The proposed PBA blockchain model provides a high-level overview of how project participants could interact with a blockchain application to upload payment activities, validate works, and automate the execution of liabilities to the supply chain. The PBA model also discussed potential blockchain solutions regarding how to mitigate the risk of non-payment from the client, through tokenised collateral that can be used as a medium of exchange with a bank, thereby allowing the bank to automate the execution of overdue payments in exchange for collateral.

The values of PBA and blockchain harmonise across several key attributes such as transparency, auditability, and disintermediation. However, this study requires further investigation through developing and codifying the proposed PBA blockchain application and simulating its process flows. Additionally, interviews with industry practitioners knowledgeable in PBA would provide constructive criticism on areas within the proposed model that were overlooked, such as formal decision processes that are required in setting up the PBA.

References

1. Noushad, Naseem A, Ali NA (2006) A construction industry payment and adjudication act: reducing payment-default and increasing dispute resolution efficiency in construction. Master Build 4–6. http://www.cicqs.my/main/files/PaymentAct_Article_Part1%5B1%5D.pdf
2. Purnus A, Bodea C (2016) Multi-criteria cash flow analysis in construction projects. Proc Eng 164:98–105
3. Cheng T, Soo G, Kumaraswamy M, Jin W (2010) Security of payment for Hong Kong construction industry. Proc Inst Civ Eng Manage Procurement Law 163(1):17–28. https://doi.org/10.1680/mpal.2010.163.1.17
4. Kenley R (2003) Financing construction: cash flows and cash farming. Routledge. ISBN: 1134573480. https://books.google.co.uk/books?hl=en&lr=&id=daGBAgAAQBAJ&oi=fnd&pg=PP1&dq=construction+cash+flow&ots=saPc2rbzRI&sig=hATMEAGZHaRSC97le1eqL2XXLoI&redir_esc=y#v=onepage&q&f=false
5. Office_for_National_Statistics, SME by size and section (2019). https://www.ons.gov.uk/businessindustryandtrade/business/activitysizeandlocation/adhocs/10412smebysizeandsection. Accessed 14 April 2021
6. Gruneberg SL, Ive GJ (2000) The economics of the modern construction firm. Macmillan Press Ltd, Hampshire, UK. ISBN: 978-0-230-51043-2. https://doi.org/10.1057/9780230510432
7. Broyd T (2017) Engineering a digital future. Proc Inst Civ Eng Civ Eng 170:3–8. https://doi.org/10.1680/jcien.2017.170.1.3
8. Oesterreich TD, Teuteberg F (2016) Understanding the implications of digitisation and automation in the context of industry 4.0: a triangulation approach and elements of a research agenda for the construction industry. Comput Ind 83:121–139. https://doi.org/10.1016/j.compind.2016.09.006
9. Ive G, Murray A (2013) Trade credit in the UK construction industry: an empirical analysis of construction contractor financial positioning and performance. Crown Copyright. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/210964/bis-13-956-trade_credit-in-uk-construction-industry-analysis.pdf
10. Farmer M (2016) The farmer review of the UK construction labour model. http://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2016/10/Farmer-Review.pdf
11. Agarwal R, Chandrasekaran S, Sridhar M (2016) Imagining construction's digital future. https://www.mckinsey.com/industries/capital-projects-and-infrastructure/our-insights/imagining-constructions-digital-future
12. Haffar N, Houalla M, Palk W, Simkova M, McColl C, Mitchel SA, Wood T, Jatain S, Talwalker C, Majid M, Suri R (2019) Perspectives on government services, cities and technology. https://assets.kpmg/content/dam/kpmg/ae/pdf/wgs-kpmg-2019-.pdf
13. Woodhead R, Stephenson P, Morrey D (2018) Digital construction: from point solutions to IoT ecosystem. Autom Constr 93:35–46. https://doi.org/10.1016/j.autcon.2018.05.004
14. Hua W, Jiang J, Sun H, Wu J (2020) A blockchain based peer-to-peer trading framework integrating energy and carbon markets. Appl Energy 279. https://doi.org/10.1016/j.apenergy.2020.115539
15. Kypriotaki K, Zamani E, Giaglis G (2015) From bitcoin to decentralized autonomous corporations—extending the application scope of decentralized peer-to-peer networks and blockchains. Enterprise Information Systems, 3, Barcelona, Spain, pp 284–290. https://doi.org/10.5220/0005378402840290
16. Mathews M, Robles D, Bowe B (2017) BIM+Blockchain: a solution to the trust problem in collaboration? CITA BIM Gathering 2017
17. National Audit Office (2005) Improving public services through better construction. https://www.nao.org.uk/wp-content/uploads/2005/03/0405364.pdf
18. Cabinet Office (2012) Project bank accounts—briefing document UK government. London

19. Banwell H (1964) The placing and management of contracts for building and civil engineering work: report of the committee [on the placing and management of contracts for building and civil engineering work]. HM Stationery Office
20. Wu J, Kumaraswamy M, Soo G (2008) Payment problems and regulatory responses in the construction industry: Mainland China perspective. J Prof Issues Eng Educ Pract 134(4):399–407. https://doi.org/10.1061/(ASCE)1052-3928(2008)134:4(399)
21. Tai S, Sun C, Zhang S (2016) Exploring factors affecting owners' trust of contractors in construction projects: a case of China. Springerplus 5(1):1783–1783. https://doi.org/10.1186/s40064-016-3393-9
22. McDermott P, Khalfan M, Swan W (2005) Trust in construction projects. J Financ Manage Property Constr. http://alliancecontractingelectroniclawjournal.com/wp-content/uploads/2017/04/McDermott-P.-Khalfan-M.-and-Swan-W.-2005-%E2%80%98Trust-in-Construction-Projects%E2%80%99.pdf
23. Xu J (2019) The value of trust in construction supply chains. PhD Thesis, UCL University College London
24. Safa M, Baeza S, Weeks K (2019) Incorporating blockchain technology in construction management. Strateg Dir 35(10):1–3. https://doi.org/10.1108/SD-03-2019-0062
25. Hargaden V, Papakostas N, Newell A, Khavia A, Scanlon A (2019) The role of blockchain technologies in construction engineering project management. In: 2019 IEEE international conference on engineering, technology and innovation (ICE/ITMC). Institute of Electrical and Electronics Engineers, pp 1–6. https://doi.org/10.1109/ICE.2019.8792582
26. Cui Q, Hastak M, Halpin D (2010) Systems analysis of project cash flow management strategies. Constr Manag Econ 28(4):361–376. https://doi.org/10.1080/01446191003702484
27. Gyles RV, Yeldham DA, Holland KJ (1992) Reports of hearings, royal commission into productivity in the building industry in New South, Wales 3
28. Lowe JG, Moroke E (2010) Insolvency in the UK construction sector. In: Proceedings 26th annual ARCOM conference, pp 6–8
29. HM_Government (2021) Monthly insolvency service statistics. Crown, London
30. Thurley D, Mor F, Booth L, Conway L (2018) The collapse of Carillion. https://commonslibrary.parliament.uk/research-briefings/cbp-8206/
31. Hajikazemi S, Aaltonen K, Ahola T, Aarseth W, Andersen B (2020) Normalising deviance in construction project organizations: a case study on the collapse of Carillion. Constr Manag Econ 38(12):1122–1138. https://doi.org/10.1080/01446193.2020.1804069
32. Goodman Derrick_LLP (2016) Different methods of dispute resolution in construction disputes. https://www.gdlaw.co.uk/site/blog/sectors-blog/construction-blog/different-methods-of-dispute-resolution-in-construction-disputes
33. Greenwood D (2020) Digital processes can reform payment practices in UK construction. https://www.pinsentmasons.com/out-law/analysis/digital-processes-payment-practices-construction
34. Gov_UK (2021) Government tackles late payments to small firms to protect jobs. https://www.gov.uk/government/news/government-tackles-late-payments-to-small-firms-to-protect-jobs. Accessed 1 April 2021
35. CICM (2008) Prompt payment code, The Chartered Institute of Credit Management. The Chartered Institute of Credit Management
36. BuildUK (2017) Implementing the construction supply chain payment charter. http://builduk.org/wp-content/uploads/2017/01/Implementing-the-Construction-Supply-Chain-Payment-Charter-Guidance-Note.pdf
37. Const Leader Council (2018) Construction supply chain payment charter construction leadership council. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/541454/construction-supply-chain-payment-charter.pdf
38. GovUK (1998) Late payment of commercial debts act. UK Government, London
39. GovUK (2013) Late payment of commercial debts regulations (Amended from 1998) UK Gov. Department for Business, Innovation and Skills London

40. Jones E (2013) Late payment of commercial debts. https://www.osborneclarke.com/media/filer_public/19/8e/198e3129-4118-45fa-9801-eb34d34204e2/late-payments-of-commercial-debts.pdf
41. GovUK SC (2012) Finance initiative 2012. Crown, London
42. GovUK (1996) Housing grants construction and regeneration act. UK Government, London
43. GovUK (2021) Part 2 of the housing grants, construction and regeneration act 1996. In: E.I.S. Department for Business (Ed.), Crown, London
44. Claremont T (2011) Housing grants, construction and regeneration act 1996 changes—10 things you need to know. https://www.brownejacobson.com/training-and-resources/resources/legal-updates/2011/07/housing-grants-construction-and-regeneration-act-1996-changes-10-things-you-need-to-know
45. OfficeGovCommerceUK (2007) Guide to best 'fair payment' practices UK office of Government Commerce, Office of HM Treasury
46. Hooks N (2019) Project bank accounts—is 2019 the year they are finally adopted? https://medium.com/@neal.hooks.zuuse/project-bank-accounts-is-2019-the-year-they-are-finally-adopted-c65f7251bd75
47. Theodore J (2009) Risk management. https://www.sciencedirect.com/topics/engineering/subcontractor
48. Brand MC, Uher T (2010) Follow-up empirical study of the performance of the New South Wales construction industry security of payment legislation. Int J Law Built Environ. https://doi.org/10.1108/17561451011036496
49. Griffiths R, Lord W, Coggins J (2017) Project bank accounts: the second wave of security of payment? J Financ Manag Prop Constr 22(3):322–338. https://doi.org/10.1108/JFMPC-04-2017-0011
50. CabinetOffice (2012) A guide to the implementation of project bank accounts (PBAs) in construction for government clients UK Government. London, pp 1–45
51. Penzes B (2018) Blockchain technology in the construction industry: digital transformation for high productivity. Institution of Civil Engineers. https://www.ice.org.uk/ICEDevelopmentWebPortal/media/Documents/News/Blog/Blockchain-technology-in-Construction-2018-12-17.pdf
52. Gowling WLG (2017) It's finally here! Ontario reforms the construction lien act. https://gowlingwlg.com/en/insights-resources/articles/2017/ontario-reforms-the-construction-lien-act/
53. Reynolds B, Vogel S (2016) Striking the balance: expert review of Ontario's construction lien act. Ministry of the Attorney General and the Ministry of Economic Development, Employment and Infrastructure, Ontario
54. Thomas G, Heintzman OC, Mamedova M (2011) The trust fund provisions of the construction lien act (Ontario): new developments relating to suppliers and third parties. http://www.constructionlawcanada.com/construction-and-builders-liens/442/
55. Li J, Kassem M (2018) Blockchain and construction: opportunities and challenges. http://www.bimplus.co.uk/explainers/blockchain-and-construction-opportunities-challeng/
56. Wang J, Wu P, Wang X, Shou W (2017) The outlook of blockchain technology for construction engineering management. Front Eng Manage 4:67–75. https://doi.org/10.15302/J-FEM-2017006
57. Cohn A, West T, Parker C (2017) Smart after all: blockchain, smart contracts, parametric insurance, and smart energy grids. Georgetown Law Technol Rev 1:273–304, https://georgetownlawtechreview.org/smart-after-all-blockchain-smart-contracts-parametric-insurance-and-smart-energy-grids/GLTR-04-2017/
58. Shumsky P (2019) Blockchain use cases for banks in 2020. https://www.finextra.com/blogposting/17857/blockchain-use-cases-for-banks-in-2020
59. Shojaei A (2019) Exploring applications of blockchain technology in the construction industry. Interdependence Between Structural Engineering and Construction Management, ISEC Press Chicago
60. Higginson M, Hilal A, Yugac E (2019) Blockchain and retail banking: making the connection. https://www.mckinsey.com/industries/financial-services/our-insights/blockchain-and-retail-banking-making-the-connection

61. Ray S (2017) Cryptographic hashing. https://medium.com/hackernoon/cryptographic-hashing-c25da23609c3
62. Agrawal R (2018) Digital signature from blockchain context. https://medium.com/@xragrawal/digital-signature-from-blockchain-context-cedcd563eee5
63. Pal O, Alam B, Thakur V, Singh S (2019) Key management for blockchain technology. JCT Express. https://doi.org/10.1016/j.icte.2019.08.002
64. Bhakhra S (2020) Public key encryption. https://www.geeksforgeeks.org/public-key-encryption/
65. Simmons GJ (1979) Symmetric and asymmetric encryption. ACM Comput Surv (CSUR) 11(4):305–330. https://doi.org/10.1145/356789.356793
66. Zhang ZY, Yuan ZM, Ni GD, Lin H, Lu YJ (2020) The quality traceability system for prefabricated buildings using blockchain: an integrated framework. Front Eng Manage 7(4):528–546. https://doi.org/10.1007/s42524-020-0127-z
67. Wong A (2019) Signing a message and encryption. https://itnext.io/signing-a-message-e303c2954499
68. Mousavi SK, Ghaffari A, Besharat S, Afshari H (2021) Security of internet of things based on cryptographic algorithms: a survey. Wireless Netw 27(2):1515–1555. https://doi.org/10.1007/s11276-020-02535-5
69. Wirdum AV (2019) Statechains: sending keys, not coins, to scale bitcoin off-chain. https://bitcoinmagazine.com/articles/statechains-sending-keys-not-coins-to-scale-bitcoin-off-chain
70. Marx S (2018) Signing and verifying messages in ethereum. https://programtheblockchain.com/posts/2018/02/17/signing-and-verifying-messages-in-ethereum/
71. Asolo B (2019) Blockchain public key & private key: a detailed guide. https://www.mycryptopedia.com/public-key-private-key-explained/
72. Igbojekwe C (2019) How to create an ethereum automated smart contract auditor for the web. https://medium.com/swlh/how-to-create-an-ethereum-automated-smart-contract-auditor-for-the-web-e0ac5c9dfa77
73. iOlite (2018) Problems & costs of smart contract development. https://medium.com/@iolite/problems-costs-of-smart-contract-development-649d88eedd1f#:~:text=A%20simple%20smart%20contract%20with,contract%20on%20the%20main%20net. Accessed 8 April 2021
74. Zapotochny A (2018) Why are smart contract security audits so important? https://blockgeeks.com/smart-contract-security-audits/. Accessed 5 May 2021
75. Levi SD, Lipton AB (2018) An introduction to smart contracts and their potential and inherent limitations. https://corpgov.law.harvard.edu/2018/05/26/an-introduction-to-smart-contracts-and-their-potential-and-inherent-limitations/. Accessed 10 June 2021
76. Scott DJ, Broyd T, Ma L (2021) Exploratory literature review of blockchain in the construction industry. Autom Constr 132:103914. https://doi.org/10.1016/j.autcon.2021.103914
77. Scott DJ, Broyd T, Ma L (2020) Archival study of blockchain applications in the construction industry from literature published in 2019 and 2020, Exploring the mutual role of BIM, Blockchain and IoT in changing the design, construction and operation of built assets. Association of Researchers in Construction Mangament (ARCOM). https://itc.scix.net/paper/ADW-2020-05
78. Adom D, Hussein EK, Agyem JA (2018) Theoretical and conceptual framework: mandatory ingredients of a quality research. Int J Sci Res 7(1):438–441. https://www.researchgate.net/publication/322204158_THEORETICAL_AND_CONCEPTUAL_FRAMEWORK_MANDATORY_INGREDIENTS_OF_A_QUALITY_RESEARCH
79. Li J, Greenwood D, Kassem M (2019) Blockchain in the built environment and construction industry: a systematic review, conceptual models and practical use cases. Autom Constr 102:288–307. https://doi.org/10.1016/j.autcon.2019.02.005
80. Lin LX (2019) Deconstructing decentralized exchanges. Stanford J Blockchain Law Policy. https://stanford-jblp.pubpub.org/pub/deconstructing-dex
81. Walker H (2016) How digital signatures and blockchains can work together. https://www.cryptomathic.com/news-events/blog/how-digital-signatures-and-blockchains-can-work-together. Accessed 27 April 2021

82. Griffith AT (2018) Ethereum meta transactions. https://medium.com/@austin_48503/ethereum-meta-transactions-90ccf0859e84
83. Davies E, Kirby N, Bond J, Grogan T, Moore A, Roche N, Rose A, Tasca P, Vadgama N (2020) Towards a distributed ledger of residential title deeds in the UK: It's business. But it's personal. https://www.mishcon.com/news/hm-land-registry-towards-a-distributed-ledger-of-residential-title-deeds-in-the-uk
84. Sklaroff J (2017) Smart contracts and the cost of inflexibility. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3008899
85. Wuille P (2018) How is public key extracted from (message, digital signature, address). https://bitcoin.stackexchange.com/questions/81232/how-is-public-key-extracted-from-message-digital-signature-address#:~:text=An%20algorithm%20called%20Public%20Key,and%20signature%20would%20be%20valid.&text=This%20technique%20is%20used%20in,rather%20than%20a%20public%20key. Accessed 6 April 2021
86. Zuidhoorn M (2020) The magic of digital signatures on ethereum. https://medium.com/mycrypto/the-magic-of-digital-signatures-on-ethereum-98fe184dc9c7. Accessed 10 June 2021
87. Bai L, Hu M, Liu M, Wang J (2019) BPIIOT: a light-weighted blockchain-based platform for industrial IoT. Inst Electr Electron Eng (IEEE) 7:58381–58393. https://doi.org/10.1109/ACCESS.2019.2914223
88. Tempesta S (2019) Blockchain API for the enterprise. https://www.apiscene.io/api-business-models/blockchain-api-for-the-enterprise/. Accessed 12 May 2021
89. Shen C, Pena-Mora F (2018) Blockchain for cities—a systematic literature review. IEEE Access 6:76787–76819. https://doi.org/10.1109/ACCESS.2018.2880744
90. Security_Token_Advisors (2020) Biggest banks in the world working on security tokens & blockchain. https://blog.stomarket.com/biggest-banks-in-the-world-working-on-security-tokens-blockchain-9c25daa2f439. Accessed 6 May 2021
91. Mitra R (2019) DeFi—what in the world is decentralized finance? The most comprehensive guide. https://blockgeeks.com/guides/demystifying-defi-ultimate-guide/. Accessed 13 March 2020
92. Chovancova J, Krejza Z, Vankova L (2019) Bank guarantees of construction projects, their concept in management accounting and role in regional development. IOP Conf Ser Mater Sci Eng 471:022017. https://doi.org/10.1088/1757-899X/471/2/022017
93. Maritz T (2011) Doubts raised on the validity of construction and payment guarantees. Acta Structilia 18(1):1–26. https://cdn.ymaws.com/www.sacqsp.org.za/resource/collection/876D0B9A-72A3-4AA9-B6F8-1BD0B2760F04/E-version_Acta_Structilia_18(1).pdf
94. Biedrzycki N (2019) Will blockchain transform the stock market? https://www.datadriveninvestor.com/2019/04/09/will-blockchain-transform-the-stock-market/. Accessed 11 March 2020
95. Pay.UK (2019) UK SMEs face debt burden of £23.4 billion. https://www.wearepay.uk/uk-smes-face-debt-burden-of-23-4-billion/
96. Lin C, Ma Y, Malatesta P, Xuan Y (2012) Corporate ownership structure and bank loan syndicate structure. J Financ Econ 104(1):1–22. https://doi.org/10.1016/j.jfineco.2011.10.006
97. Noonan L (2018) Banks complete first syndicated loan on blockchain. https://www.ft.com/content/2b12d338-e1d1-11e8-a6e5-792428919cee. Accessed 7 April 2021
98. Barru DJ (2005) How to guarantee contractor performance on international construction projects: comparing surety bonds with bank guarantees and standby letters of credit. Geo Wash Int Law Rev 37:51. https://heinonline.org/HOL/Page?handle=hein.journals/gwilr37&id=61&collection=journals&index=
99. Sheng D, Ding L, Zhong B, Love PED, Luo H, Chen J (2020) Construction quality information management with blockchains. Autom Constr 120. https://doi.org/10.1016/j.autcon.2020.103373
100. Dakhli Z, Lafhaj Z, Mossman A (2019) The potential of blockchain in building construction. Buildings 9(4). https://doi.org/10.3390/buildings9040077
101. Terado T (2018) What is decentralized storage? (IPFS, FileCoin, Sia, Storj & Swarm). https://medium.com/bitfwd/what-is-decentralised-storage-ipfs-filecoin-sia-storj-swarm-5509e476995f

102. OpenLearn (2020) Digital signatures and certificates. https://www.open.edu/openlearn/ocw/mod/oucontent/view.php?id=48322&section=3.2. Accessed 7 April 2021
103. Banerjee A, Clear M, Tewari H (2020) Demystifying the role of zk-SNARKs in Zcash. In: 2020 IEEE conference on application, information and network security (AINS). Institute of Electrical and Electronics Engineers Inc., Kota Kinabalu, Malaysia, pp 12–19. https://doi.org/10.1109/AINS50155.2020.9315064
104. Latham M (1994) Constructing the team: final report of the government/industry review of procurement and contractual arrangements in the UK construction industry, Crown copyright. https://constructingexcellence.org.uk/wp-content/uploads/2014/10/Constructing-the-team-The-Latham-Report.pdf
105. Egan J (1998) Rethinking construction, Department of Trade and Industry. https://constructingexcellence.org.uk/wp-content/uploads/2014/10/rethinking_construction_report.pdf
106. ConstructingExcellence (2019) The payments minefield. https://constructingexcellence.org.uk/wp-content/uploads/2016/07/Payments-Minefield-%E2%80%93-A-review-of-payment-practices-within-the-UK-Construction-industry.pdf
107. Tulubas Gokuc Y, Arditi D (2017) Adoption of BIM in architectural design firms. Architect Sci Rev 60(6):483–492. https://doi.org/10.1080/00038628.2017.1383228
108. Di Giuda GM, Pattini G, Seghezzi E, Schievano M, Paleari F (2020) Digital transformation of the design, construction and management processes of the built environment. Springer, pp 27–36, ISBN: 21987300. https://doi.org/10.1007/978-3-030-33570-0_3
109. Liang Y, Qin Y (2020) Cross-lingual public opinion tracing based on blockchain technology. In: International conference on web information systems and applications. Springer, pp 607–617. https://doi.org/10.1007/978-3-030-60029-7_54
110. McNamara AJ, Sepasgozar SME (2021) Intelligent contract adoption in the construction industry: concept development. Autom Constr 122. https://doi.org/10.1016/j.autcon.2020.103452
111. Hobbs D, Moll RD, Griswold D (2018) Crunch time IV blockchain for finance. https://www2.deloitte.com/content/dam/Deloitte/sg/Documents/finance-transformation/sea-ft-crunch-time-iv-blockchain.pdf
112. Chong N (2020) Deal with the devil: ethereum DeFi protocol negotiates with hacker of $25 million. https://cryptoslate.com/deal-with-the-devil-ethereum-defi-protocol-negotiates-with-hacker-of-25-million/
113. Salami I (2020) Decentralised finance: the case for a holistic approach to regulating the crypto industry. J Int Banking Financ Law 35(7):496–499. https://doi.org/10.2139/ssrn.3733647
114. Hepp T, Sharinghousen M, Ehret P, Schoenhals A, Gipp B (2018) On-chain versus off-chain storage for supply-and blockchain integration. Inf Technol 60(5–6):283–291. https://doi.org/10.1515/itit-2018-0019
115. Becky (2021) The rise of crypto: countries with their own CBDCs. https://www.coininsider.com/the-rise-of-crypto-countries-with-their-own-cbdcs/#:~:text=Since%20China%20announced%20the%20pilot,Japan%2C%20Turkey%2C%20and%20Switzerland. Accessed 27 April 2021
116. Bank Of England (2021) Bank of England statement on Central Bank Digital Currency. https://www.bankofengland.co.uk/news/2021/april/bank-of-england-statement-on-central-bank-digital-currency. Accessed 27 April 2021
117. Calle G, Zalles DB (2019) Will businesses ever use stablecoins? http://www.r3.com/wp-content/uploads/2019/03/R3_Stablecoin_Mar2019-New.pdf
118. CITB_CSCS (2015) Card fraud and onsite card checking survey, Ask for Research Limited. https://www.cscs.uk.com/wp-content/uploads/2015/06/card-fraud-and-onsite-card-checking-survey-report.pdf
119. TraceLabs (2020) British standards institution releases white paper on use of origintrail decentralised network. https://medium.com/origintrail/british-standards-institution-releases-white-paper-on-use-of-origintrail-decentralised-network-b8c32937ea39. Accessed 21 April 2021
120. Yang R, Wakefield R, Lyu S, Jayasuriya S, Han F, Yi X, Yang X, Amarasinghe G, Chen S (2020) Public and private blockchain in construction business process and information integration. Autom Constr 118. https://doi.org/10.1016/j.autcon.2020.103276

121. CB_Insights (2021) Banking is only the beginning: 58 big industries blockchain could transform. https://www.cbinsights.com/research/industries-disrupted-blockchain/. Accessed 4 May 2021
122. https://yos.io/2019/12/08/decentralized-finance-explained/
123. On or Off the Blockchain? Insights on Off-Chaining Computation and Data
124. Ter Heide, Dominiek (2018). Understanding Decentralized Exchanges. https://hackernoon.com/understanding-decentralized-exchanges-51b70ed3fe67 Retrieved 12 April 2019

Smart Contracts and Payment in the UK Construction: The Legal Framework

David S. Christie and Joseph Mante

Abstract This chapter critically evaluates the way in which the existing United Kingdom (UK) construction payment regime will function with—and assist—payment mechanisms which utilise smart contracts. Blockchain is one of several new developments in the increasingly technologically developing UK construction industry. Whilst the law translates real-world actions into legal obligations to pay and then assists in turning those obligations into payment, the blockchain with smart contract mechanisms will automate that process, providing security and removing any intermediation which could stop or slow the process down illegitimately. Coupled with the use of smart contracts, therefore, blockchain technology has the potential to facilitate a solution to the payment and cash flow issues in the UK construction industry. To achieve the added functionality described and thereby make it a useful tool for payment in construction, however, these developments would need to coexist with the existing legal framework. There are important points in the detail that should be more fully understood by users of the blockchain/smart contract systems, and which are explored in this chapter.

Keywords Blockchain · Smart contracts · Payment · Law · Housing Grants Construction and Regeneration Act 1996 · Legal frameworks · Oracle problem

1 Introduction

For lawyers, blockchain technology represents an opportunity—but it remains somewhat unknown (see e.g., Low and Mik [11]). For the construction industry, the practice of combining human ingenuity and technology has a long history. The desire to achieve efficiency in the industry has led to a call to embrace recent and emerging technological developments. Blockchain is the latest of these. The UK Government's

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recent guidance on sourcing and contracting public works, projects and programme (the Construction Playbook) published in December 2020 has a whole chapter addressing modern methods of construction. A recent report by McKinsey and Co identifies several areas of construction technology ripe for growth in the industry [14]. These include BIM and Electronic management, robotics and technology infrastructure (such as wireless connectivity, construction drones, electric vehicle docking areas, etc.). These opportunities provide ways to gather, assess and present the information at the core of construction management. Nevertheless, longstanding issues remain; in particular, the problem of cash flow.

The problem of facilitating cash flow has been in the industry for decades and it is rightly the focus of work done by the Construction Blockchain Consortium to see how technology can facilitate it [3]. The interaction of that technology with the legislative solution is identified within the CBC white paper on construction cash flow. The white paper concludes at para 4.4.1 on this point that:

> Strict application of legal concepts will prevent, or at least reduce, improper implementation and inadequate execution of those concepts and process failures, e.g., failure to issue pay less notices on time will prevent inappropriate withholding or deduction at the time payment is due.

It is therefore helpful to explore how the regime imposed by law will interact with a smart contract that facilitates payment. Whilst ‘strict application’ is required, this does not necessarily mean that the system is rigid. A more general observation of the white paper is that it takes a very cautious approach to what could be achieved by deploying blockchain technology with a smart contract to aid the payment process, soon. This hesitation can be gleaned from the description of what is possible in the short term—automation of interparty payments, acceleration of payment and automation of the accounting process—and what is not. There is a sense in which this perspective of the white paper is connected to the very definition of ‘smart contracts’ adopted ([3], p. 17).

In this chapter, we take the view that both at this nascent stage of development or in future, the ‘smart contract’ will likely have legal implications for the parties involved in construction transactions and therefore should be conceptualised as such. Conceiving the ‘smart contract’ as more than just an ‘application’ (see [3], p. 17), will allow for a discussion of content and how that is ‘translated’ into computer codes for the purposes of the operation of the smart contract.

There is scope for scepticism about the application of legal rules and indeed much of the discussion of smart contracts has, rightfully, focussed on the revolutionary possibilities of the decentralised nature of the information held. However, there is a key distinction relevant to construction where—if the smart contract (or system of smart contracts) operates as it should—then there is a mark and impact on the physical world. No matter how distributed and decentralised the activity on the blockchain is, the outcome will end up in one actual place where the construction has happened. The legal framework therefore provides some certainty to the sort of questions that lawyers will set out to their clients to quantify and manage risk.

One of the challenges of implementation in smart contracts is the so-called ‘oracle problem’ where the quality of the inputs into the blockchain from the outside world drive the acceptability of the outputs generated through the smart contract process ([11], p. 26), “garbage in/garbage out” being the axiom (see e.g., the discussion with industry in Mason ([13] p. 16). That is also significant in terms of the process of changing work done into an obligation to pay, and then into actual payment. The UK payment legislation discussed below can help in understanding that process.

2 Methodology

Using payment legislation, relevant case law and academic literature, a legal doctrinal research approach is used to critically examine the extent to which the combination of smart contract and blockchain technologies on one hand and the existing statutory payment system in the UK construction industry on the other can facilitate and indeed address some of the bottlenecks around that process. The basic tenets of this methodology have been described in detail elsewhere [12]. Also identified are ways in which the legal framework is relevant to the payment issues in construction contracts—both in terms of how it might create obligatory force and in terms of the sort of issues that might need to be determined in setting up the contract.

The chapter begins by identifying the emerging legal context of smart contracts and related issues. From this legal perspective, discussions around the introduction of new technologies such as smart contracts will involve what they are, the extent to which such technologies will comply, or indeed conform to, the existing legal framework or operate around it. Then there is the question of how the use of the technology will interact with various aspects of the law. The origins and the importance of the underlying policy surrounding the legal framework for payment in the UK are identified. The relevance of this approach is to underscore the need to maintain the logic underpinning the legal policy even when the ‘form’ of the payment arrangement is facilitated by technology. Finally, the chapter attempts to examine how the current legal framework would apply to the processes and operation of a smart contract for payment in a construction contract (as at the time of writing in 2021). This will focus on how the framework would apply to smart contract payment mechanisms for work done and highlight possible issues which the use of the technology might give rise to.

3 Legal Framework and Issues

The combined features of the blockchain and smart contracts (with the ability to self-execute agreements when certain agreed conditions are met [4]) have made these technologies potentially effective substitutes for interventions by human experts. The idea of the smart contract is viewed differently by different people. Three dominant views are gleanable from the literature.

The first set of definitions conceptualise smart contracts by their form and function. An example of this category of definitions is seen on page 17 of the CBC Whitepaper. Citing the Ethereum Foundation [5]. The report describes smart contracts as 'applications that run exactly as programmed without any possibility of downtime, censorship, fraud or third-party interference'. Missing from this definition is any reference to a contract. This definition, like others in the same category, emphasises the form of the concept (computer programme, application, computer code, etc.), the absence of human intervention and the self-executing elements of smart contracts. The input is often viewed as a set of instructions, and conditions; not necessarily as something legal.

The second set of definitions leaves readers with no doubt that the smart contract is a legal instrument. The English Law Commission's perspective falls under this category. It defines smart contract as 'a legally binding contract in which some or all of the contractual obligations are recorded in or performed automatically by a computer programme deployed on a distributed ledger' [10]. This definition, like many others, highlights the legally binding nature of smart contracts and the contractual obligations they embody [17].

There are other definitions that straddle the two categories of definitions described above. Temte [18] defines smart contracts as "a set of promises, specified in digital form, including protocols within which the parties perform on these promises." Ng defines smart contracts as self-executing contracts the terms of which are directly written into a line of code [15].[1]

The last set of definitions highlights the nature, creation (reducing the terms into a computer code) and the execution of the contract [19]. Ng's definition notes that once terms are incorporated into lines of code, the terms of the contract are automatically executed by computer transaction protocols based on conditions agreed by consensus and incorporated into the computer programme. These are referred to as "oracles," mutually agreed real-time data providers used to confirm triggering events [2].[2] There is a need for agreement on what these oracles will be since one of the key parts ensuring the smart contract's credible operation is an agreement (a contract) between those who are using it. It is the mutual agreement that gives force to the oracle—taking the 'real world' information 'into' the smart contract operation.

The implication of the above views on the smart contract is significant. Those of the view that smart contracts are not necessarily equivalent to legal contracts tend to play down discussions about the validity or otherwise of smart contracts within the context of the legal system. That way, the argument as to the legal status of the contracts is reduced to general compliance with the wider legal framework and not the

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[1] Tsui S. Ng, 'Blockchain and Beyond: Smart Contracts,' Bus. L. Today (September 2017) (Am. Bar Assoc.)). This definition was endorsed in the American case Rensel v. Centra Tech Inc., 17–24,500-CIV, 2018 WL 4,410,110, at 10 (S. D. Fla. June 14, 2018). See also Kevin Werbach & Nicolas Cornell, Contracts Ex Machina, 67 Duke L. J. 313, 319 (2017).

[2] 'A Primer on Smart Contracts,' U.S. Commodity Futures Trading Commission, Lab CFTC, Nov. 27, 2018, available at cftc.gov/PressRoom/PressReleases/7847-18.

legal status of the terms themselves. In this chapter, it is argued that given the role that smart contracts may play in the short and medium term in the construction industry, it is vital that they are conceptualised from the onset as legal agreements to allow for a thorough examination of their legal status. This will also encourage conversation around how *legal* language in the form of a contract in a *natural* language may be translated into a computer code language.

If the 'smart contracts' are legal agreements in substance, then there are a number of questions that need to be addressed. Some of these are highlighted in Table 1, along with some observations which flow generally from the literature.

For the construction lawyer, the issues in the table will not be the only legal issues that need attention. For those engaged in the actual design and construction work, the key question is: 'when will I get paid?'

4 Cash Flow Is the Lifeblood of the Industry

The background to the current UK legal position in terms of construction cash flow is well known and the importance is acknowledged in exercises such as the CBC white paper. It is not proposed to reiterate that here beyond setting out the necessary information for what follows: the origin and reasons for the legal framework for construction payment in the UK are important in understanding how it might operate on or alongside a smart contract.

The need for reform to promote cash flow was recognised by Sir Michael Latham [9] and others who produced several reports on the state of the UK construction industry in the early to mid-1990s. These reports were produced as joint efforts of the industry and government. At the core of the problems underlying, the industry was said to be an adversarial culture. This exacerbated structural problems where lack of cash flow was a major issue in the industry (although that diagnosis goes back decades with the phrase 'cashflow is the lifeblood of the industry' being immortalised in construction law by Lord Denning in the early 1970s.[3])

The recommendations in the reports became the basis of a legislative response culminating in the passing of the Housing Grants, Construction and Regeneration Act 1996, later amended by the Local Democracy, Economic Development and Construction Act 2009. Part II of the 1996 Act (as amended) responded directly to the two key challenges facing the industry, namely costly dispute resolution and cashflow problems. The first saw the emergence of the process of construction adjudication, which has now become the primary means of speedy resolution of construction disputes in the UK. The second set of rules established a statutory payment system. This essentially set the standard for payment for construction works falling under the Act and also provides default rules—the Scheme for Construction Contracts[4]—which

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[3] Gilbert-Ash (Northern) Ltd v Modern Engineering (Bristol) Ltd (1973) 71 L. G. R. 162, 167.

[4] The Scheme for Construction Contracts (England and Wales) Regulations 1998/649 (there is an equivalent set for Scotland).

Table 1 Summary of issues from interaction of contract law with smart contracts

Stage of contracting process	Questions	Problems	Challenges	Examples of solutions
Agreement of contract	• When is the smart contract agreed? • How does it interact with the broader concept of agreement in law? • How is consideration (where relevant) conceptualised? • What type of contract are they? For example are they unilateral? • Is acceptance by performance/conduct only?	• There are traditionally considered to be essentials of a contract, offer/acceptance, and relevant intention to create a legal relationship. These might not exist in the smart contract. • There needs to be parties to the contract who have legal capacity to enter into a contract.	• There are issues with anonymity of parties in the blockchain and a full understanding of the subject matter of the contract will need to be conveyed	• There are existing rules for the giving of legal personality to incorporeal entities, such as the creation of limited companies. Alternatively, certain individuals need to be given delegated authority
Form of contract	• Is the smart contract distinct from the traditional written contract, or part of it? • How are implied terms of performance incorporated? • What provisions and protocols govern the use of the smart contract?	• The Law Commission of England and Wales envisages that smart contracts may take on at least three different forms—it may be a normal contract in a written human language with automated performance; it may be a hybrid or a fully/completely coded contract. The emphasis on payment is an example of an instance where only an element of the contract may be coded	• Smart contracts are seen as automated and self-executing therefore distinct from the parties' agreement. That means that there is no questioning of the contents or context	• It is important to be clear on the distinction between the traditional contract and the smart contract and the means of interactions between them. There is no reason to consider them separately however, they should be seen as part of the same 'contract'—with the smart contract being the more prescriptively operation part

(continued)

Table 1 (continued)

Stage of contracting process	Questions	Problems	Challenges	Examples of solutions
Operation of contracts	• What values apply to the interpretation of the underlying code of a smart contract? • How are errors dealt with? • What happens if the smart contract facilitates a breach of contract? • How are security breaches occasioned by third parties addressed? • How are variations to be handled?	• The automation of the contract should in theory prevent breaches but that is only as good as the performance specifications put in the contract and the nature of the real-world inputs made	• The 'oracle problem' is an issue: 'garbage in/garbage out' as discussed elsewhere in the paper • The transparency of the blockchain as a means of storing information is helpful but it can mean that it requires technical specialism to work out from where a problem has arisen	• This clearly points to the need for pre-planning and certainty at the outset • Mechanisms should be put in place to deal with change and to change the operation of the smart contract • Dispute and conflict resolution mechanisms are important but need to be something which the parties accept
Termination of contract	• How is a smart contract brought to an end? • What are the consequences of this and how are they quantified?	• An end date ought to be easy enough to code into a smart contract. However, if there is an unexpected ending to a project as a result of changing circumstances this can be difficult to unwind. In particular, even if provision is made for unwinding, it may not always be done in a way which satisfies the parties at the time	• The automation of the smart contract means that issues can arise without necessarily being highlighted to the users (an inversion of the traditional 'transparency' feature of the blockchain). This can make unwinding errors difficult • Kill mechanisms need to be considered carefully—the interaction of their use with rules around repudiatory breach should be done with care	Planning needs to be undertaken to anticipate these issues

(continued)

Table 1 (continued)

Stage of contracting process	Questions	Problems	Challenges	Examples of solutions
Enforcement of obligations	• How are smart contracts enforced? • What rules of private international law apply?	• The decentralised nature of the blockchain may mean that there are issues with the identification of parties and assets which presents a challenge to the ultimate enforcement of these obligations	• The credibility of the process is important in achieving engagement with by both parties. That should include safeguards in terms of enforcement—such as access to insurance or other 'real world' protections	• Alternative means of assurance to traditional mechanisms for payment might be required • Alternatively, parties may assume the risk in return for other benefits of the blockchain • As noted above, the dispute resolution process should be clear and accepted

apply in situations where the parties fail to agree on a payment arrangement that is compliant with the Act. The Act sets the scope of its application by defining 'construction contracts' and 'construction operations' and specifically excludes certain types of contracts from its purview (Sections. 104–106).

On payment, the Act establishes entitlement to instalment, stage, or other periodic payments for works that take over 45 days (Section 109). The literature tends to emphasise instalment payments specifically, but it is clear from the language of the Act, as applied, that the law envisages a flexible system where parties can agree different periodic payment arrangements.

Section 109(2) provides that the parties are free to agree: (i) the amounts of the payments; (ii) the intervals at which they become due and (iii) the circumstances in which they become due. The start of the payment period is marked by an established 'due date.' This sets a baseline of 5 days for the provision of a notice by the payer of what is considered due. If the payer fails to do so, then there is a provision that an earlier application for payment by the payee can stand in its stead. There is then an obligation on the payee to pay the sum in the payment notice by the final date for payment (contractually agreed) unless they serve a further notice within a time from that final date.

The parties can—by agreement—make provision for the detail within this mechanism, but it must be an 'adequate mechanism'.[5] The Act provides for a further consequence of non-payment, which is allowing for the suspension of works by the

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[5] S110(1).

contractor if they are not paid. The Act also provides that if the relevant notices are not served then payment of the amounts set out in the notices should be made.[6] This means that if a payer does not engage in the process, they suffer the consequence of having to pay a sum claimed, even if it is not an accurate reflection of the work done (and then having to undertake further proceedings to correct any inaccuracies, without the benefit of holding onto the cash).

The operation of these provisions is to highlight issues quickly and then allow for their resolution—potentially by construction adjudication if not capable of amicable negotiation. The notices serve in a way as 'oracles' into the parties' decision-making processes: setting out and explaining the inputs for decision making. The process has fall-back options if a party does not comply: it continues without their input.

The processes imposed by the 1996 Act are generally considered to have been successful and this can be seen from the fact that:

(i) they have remained in place for over twenty years;
(ii) the key concepts underpinning the process have remained largely unchanged in spite of the opportunity for reform in 2009;
(iii) the solution adopted in the 1996 Act has been the foundation for reforms that are at least similar in structure in other jurisdictions.[7]

On the basis of the above, it can be said that these rules are accepted by the industry and treated seriously. However, some of the challenges the payment system was created to address still remain.

In terms of the interaction of this framework with smart contracts, the first point of significance to note is that this solution is not prescriptive. It would have been possible for the Act to mandate specific processes or outcomes (such as is seen in the building regulations) or to prescribe more flexible duties on the parties—but in further detail (as in the Construction, Design and Management regulations 2015).[8] However, for payment, the solution is not a wholly regulatory one. Rather than prescribe specific processes, the Act preserves some freedom of contract for the parties and allows them to decide how to implement the requirements. In introducing the Bill which became the Act, the Minister speaking explained the aims as follows:

> There is a multiplicity of possible payment arrangements for construction contracts. It is not for Government to decide that one is better than another ….
>
> However, Parliament can legislate to ensure that contracts are clear about what payments become due and when. We can ensure that information about payment is available to the payee. We can agree arrangements which expose unreasonable grounds for withholding

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[6] S110B and the subject of a number of cases on the 'smash and grab' adjudications which arise as a result.

[7] The operation of these different systems is set out well in Pickavance [16], part II (albeit it needs an update).

[8] The distinction was discussed, albeit in a different context by Judith Hackitt in her review of the Building Regulations following the Grenfell Tower fire [8] pp 6–8).

> payment and which can be challenged before an adjudicator. That is the basis of what we propose.[9]

The legislative regime is flexible in allowing parties to work out the detail of what they propose within constraints and in allowing the approach to evolve as the industry and technology evolve. The framework is therefore potentially operable with a smart contract mechanism. As noted above, the CBC considers compliance with the legal framework will be beneficial.

The operationalisation of that aim is worth considering both in terms of understanding these benefits and—through that understanding—gaining insights into how the smart contract may be operated within the legal framework.

5 Does the 1996 Act Apply to Smart Contracts in Construction?

Even while maintaining contractual agreements, there is scope for parties to agree to be bound by the law of any jurisdiction—and to cherry-pick particular legal rules for particular contractual issues. Indeed, since smart contracts can provide significant gains in contract management and efficiency, they may even facilitate this sort of segmentation (different rules for different parts of an arrangement) in the future. In theory, therefore, what is to prevent parties from simply disapplying of the Act by agreeing that their contract and smart contract will be governed by the law of another jurisdiction?

In answering this question, the starting point is whether (or in what circumstances) the 1996 Act is at all relevant for governing smart contracts (as envisaged here). The legal answer is clear. It is the parties cannot decide that the Act does not apply by agreeing that a contract should be bound by the laws of a different legal system. In *Motacus Constructions Ltd v Paolo Castelli SpA*,[10] there was an argument about whether the Act applied to a contract for construction works in England, but under a contract that was said to be governed by the law of France. In reaching their decision, the court was keen to ensure that the policy of ensuring a quick adjudication decision and the ensuing cash flow could not be thwarted by a party simply agreeing to contract under the law of a different jurisdiction. It is suggested that the reasoning on that point would apply equally to the payment provisions (although there are some interesting questions around how valuation might work in different jurisdictions). The courts held that the Act governed ‘construction operations’ in the UK. They noted that the legislation is itself clear that the scope of the Act is over *all* works in the UK—not just those which have an agreement to be governed by the law of one of the UK jurisdictions (see Section 107(4) of the Act). Rather than looking at the abstract agreement of the parties as to the ‘location’ of the contract, the court looked

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[9] Housing Grants, Construction and Regeneration Bill [Lords] HC Deb 07 May 1996 vol 277 cc45-122 at col. 53.

[10] [2021] EWHC 356 (TCC) (22 February 2021).

at where the work was actually being done. That real-world impact was in the UK and so it was the UK framework that applied.

This demonstrates the point made above; at the point of delivery, a construction project needs to be about the creation of a physical thing and that will be in a physical place. The process of creation will also have to happen in that place for at least some of that period (albeit modular construction techniques may decrease the length of time in which that is to happen). Without getting too metaphysical and conceptual on the way in which laws apply, the country or region which governs the site where the project is being built will have an interest in it. The general laws of that state will apply to that building and the people who are working there. The question is how the particular features of the more complex regime of the 1996 Act will apply as it sits—consciously—on the border between regulation and freedom of contract.

The Act defines when these features will apply. Not all activity carried out by a smart contract will necessarily be caught, but some will. Payment for *design* work (which falls within the definition of 'construction operations' in the Act) can happen without being in any particular 'place' and so poses a particular test for the application of the Act. For payment, there is a significant issue that payment or value can be automatically transferred anywhere (or indeed to some sort of conception of 'nowhere') and more generally, the generation of intellectual property, such as design can occur virtually anywhere (although then the question becomes one of how it is protected—an issue for others to consider).

5.1 Court's Approach

The courts in the UK[11] way, justified have tended to approach the assessment of when the Act applies in an expansive way ,justified by reference to the clear policy aims of the 1996 Act. The technical term for this is to take a 'purposive' approach[12] to interpretation: that is to read the language of the legislation in the context of what purpose the legislation is trying to achieve. So, for example, The House of Lords[13] Judicial Committee criticized 'over literal'[14] attempts to interpret the legislation in *Melville Dundas v Wimpey Homes*—and said that the Act 'was intended to have practical application to a wide variety of contractual relationships.'[15]

In the case of the 1996 Act, that clarity of purpose has translated into a clear idea of how the legislation should operate. Going back to the initial cases on the Act, the courts have been less concerned about the formal detail of the way the process works,

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[11] That is, of the three jurisdictions: Scotland, Northern Ireland and England and Wales which make it up.

[12] see e.g., S&T v Grove Developments Ltd 2018 EWCA 2448 at para 108 per Jackson LJ.

[13] then the UK's highest court.

[14] Melville Dundas Limited (in receivership) and others (Respondents) v. George Wimpey UK Limited and others (Appellants) (Scotland) 2007 UKHL 18 Para 9.

[15] Ibid.

in favour of what is referred to as ‘rough justice’[16] and a spirit that the ethos of the Act is to get parties to ‘pay now, argue later’.[17] The need for cash flow is paramount. While many of the discussions have focused specifically on the adjudication process (the ‘argue later’ part of the equation); the ‘pay now’ part is integral to the conception of the law. This means that even novel approaches such as those facilitated by smart contracts are likely to be approached in the same way—where they can be said to fall under the Act.

5.2 Definition of Construction Contract

The Act applies to ‘construction contracts’. These are widely defined (with some exceptions) to mean contracts for the ‘carrying out of construction operations’[18] or arranging for others to do those. As noted above, these operations must happen in the UK.

This clearly locates the subject matter of the contract in the physical realm—and therefore subject to the law. However, the Act also makes clear that more intellectual work such as design, surveying and advice on building, engineering or decoration are also ‘construction contracts’, where this is in ‘relation to’ construction operations.[19]

This then means that even activities on the intellectual plane are caught where they ‘relate to’ physical works. In terms of what the ‘relationship’ must be, there does not appear to be any specific case law on this provision. However, it has been said (in a more general way than construction specific) that

> the words ‘in relation to’ invariably are words of connection. But there can, in my opinion, be no set meaning as to the ambit and reach of that phrase. It will depend on the particular context, be it statutory or contractual, in which those words appear. As always, context is all[20]

Applying this to the 1996 Act and the wider interpretation given by the courts to its application, it is difficult to identify design work that would be sufficiently closely linked to a particular construction project such that payment might be made but not somehow ‘relate to’ it. Therefore, it should be considered that design work for at least an identifiable construction project would likely be considered to ‘relate to’ it and to fall within the Act.

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[16] See, for example, Pentland Investments Ltd v Aitken Turnbull Architects Ltd 2018 SLT (Sh Ct) 284 at para. 36 (although the origins of the phrase in the context of adjudication go back to Lord Howie in the debates on the then Bill in Parliament, and beyond).

[17] Commonly referred to in case law, the phrase appears to have been coined by Robert Fenwick Elliott see Fenwick Elliot [6].

[18] S105 of the 1996 Act.

[19] S104(2).

[20] Re National Crime Agency [2020] EWHC 268 (Admin) at para 50.

6 Applying the Act to Smart Contracts

If the Act applies, then the way in which a smart contract might operate along with it are discussed as follows.

6.1 Instalment Payments?

The Act prescribes payment in stages where work is done over a period of more than 45 days.[21]

This is a sensible approach to take and ensures cash flow. In terms of the intellectual work being done in contract management and the contractual arrangements, there may be some scope for doubt about the extent of work being done by particular smart contracts if that has led to segmentation of tasks into smaller components. It may be that this provision does not apply and this might cause a potential problem. However, the courts are likely to look at the arrangement as a whole to see what is being done and achieved. It would be analogous to the existing approach taken for framework agreements. In that case, each 'call off' is treated as a separate contract. It might be that a similar approach is taken for the sort of use of smart contracts envisaged—each segment of work is treated differently. That might mean that even if the Act applies—there is no right to installment payments. That gives rise to three observations.

1. If payment is made automatically for each 'micro task' then there is no need for installments.
2. Payment not being made for each microtask might give rise to the courts interpreting a broader set of micro-arrangements as one 'contract'. Again, the fixed physical location of the works can anchor the otherwise distributed work and smart contractual arrangements
3. More philosophically, the policy goal of payment by instalments is enshrined in legislation. The lesson of this is the 'good' that this approach has. One reason to have the lower time limit is/was to avoid the administrative difficulty of processing multiple payments. Smart contracts allow for that more detailed, granular approach.

6.2 Payment Cycle

Even if there is no right to installment payments, the Act still makes provisions for a payment process.[22]

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[21] S109(1).

[22] Sections 109 to 114.

There are three key parts to this. There is the need, firstly, for a process that is intelligible (an 'adequate mechanism' in the legislation[23]); secondly, there is detail on how the information is to be presented and thirdly, that there are remedies if the process is not followed.

6.2.1 Adequate Mechanism

The Act provides for an adequate mechanism for payment to be agreed upon by the parties.[24] The precise latitude given for this mechanism is unclear. If the model in the Scheme is taken as indicative,[25] then significant detail is required. However, the courts have been seemingly happy to leave this to the parties. To some extent, this is in line with the general freedom of contract approach facilitated by the Act. The principal guidance can be seen in the case of *Bennett (Construction) Limited v CIMC MBS Limited (formerly Verbus Systems Ltd)*[26] which said:

> As previously noted, in relation to payment provisions, the purpose of the Act was to provide for certain minimum, mandatory standards so as to achieve certainty and regular cash flow. Save in perhaps exceptional circumstances, it was not designed to delete a workable payment regime which the parties had agreed and replace it with an entirely different payment regime based on a radically changed set of parameters. It seems to me that that could only happen where the regime which had been agreed was so deficient that wholesale replacement was the only viable option. That is plainly not this case.

So, it appears that 'adequate' is broadly synonymous with 'workable' in this situation. It had been made clear in *Maxi Construction v Morton Rolls* that the mechanism had to both specify what was due, and when it was due.[27]

The main challenge for smart contracts, therefore, is having a sufficiently certain and clear process that can be explained to a judge or other decision-maker satisfactorily. Beyond that, there is significant latitude. More broadly, the process is important as a means of ensuring transparency and mandating communication on this point. This is done through the notice provisions.

6.2.2 Notice Provisions

The sequence of notices is set out above. The requirements for the notices are that those who are seeking payment need to set out:

1. The sum due and
2. The basis on which that sum is calculated.[28]

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[23] S110(1).

[24] Ibid.

[25] See n. 4 above.

[26] 2019 EWCA Civ 1515.

[27] [2001] ScotCS 199, discussed in paras. 20–30.

[28] S110A (2).

If a lesser sum is to be paid, the notice must provide information as to the grounds on which that deduction is based, and the basis for calculation.

These provisions are important as they indicate the nature of the notices as being somewhat analogous to the ‘oracles’ in a smart contract: they take the situation on site and turn it into a legal obligation to pay. In this context, it is notable that the judge who gave the lead judgement in *S&T v Grove* compared one of the key sections on this point to a ‘philosopher’s stone’ (albeit unfavourably)[29]—the echoes of the oracle problem are within that framing—what is the alchemy which leads from construction operations to payment?

In terms of translating those requirements into action, there are various legal issues. These include understanding what constitutes a notice (what form does it take, whether and how documents can be incorporated into it and so on) and about how clear it should be. The bottom line comes from the Court of Appeal decision in *S&T v Grove*. In that case, an earlier decision of the UK House of Lords about the interpretation of documents[30] was applied and the key question was said to be ‘how a reasonable recipient would have understood the notice.’[31]

These provisions, therefore, operate in the following way:

Firstly, they show the need for clarity. It is necessary to assess understanding on an objective basis, rather than making assumptions about what parties understand. Some degree of empathy is needed. This helps with building trust. It builds on the opportunity of the blockchain in building trust between parties: fostering the transparency which is critical to it.

That need for objective clarity also helps with assuring the credibility of the process—and of the relationship. This can be seen in the following example: one of the opportunities of blockchain technology is that participants can potentially remain anonymous, or at least have their identities shielded behind another entity. This could limit the confidence that others might have in contracting with that party. However, in many cases, the confidence which is needed to contract is not over the identity of the other as such, but confidence that they will do what they should. This transparency over payment is a good way of building this trust. To a significant extent, it does not matter who is carrying out an obligation; as long as they are. Thus, the payment mechanism provides a useful means of demonstrating how some of the flexibility of blockchains and smart contracts can be enhanced.

6.2.3 Remedies

Rights under the payment provisions of the Act would, of course, have less benefit if they could not be enforced. The concerns about moving the legal framework away from the UK, and of anonymity, or small work package sizes will tend to be judged in

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[29] S&T v Grove Developments Ltd 2018 EWCA 2448 at Para 92.

[30] *Mannai Investment Co Ltd v Eagle Star Life Assurance Co Ltd [1997] AC 749 (in particular 768 A–D).*

[31] S&T v Grove Developments Ltd 2018 EWCA at para 50.

the context of both parties needing to be reasonably confident that they will achieve what they want from the contract. One outcome might be the provision of some form of assurance, such as payment deposits or bonds, or so on (see Bailey [1]). These all have a cost.

The Act provides two routes that assist in addressing this challenge by providing some level of assurance as a baseline, which acts to enforce the obligation to pay which arises as set out above.

These routes are:

(i) A fast-track dispute resolution process, construction adjudication. A detailed examination of this point is beyond the scope of this chapter. It suffices to state that this engagement with a third party to verify the information is a useful step in meeting the oracle problem and that the blockchain more generally may provide useful opportunities in developing and supporting construction dispute resolution. As with the payment provisions discussed, the adjudication process has a degree of flexibility built in and so could be adapted to deal with disputes arising from smart contract operation.
(ii) The second remedy is the right to suspend works where a party is not paid, under s112 of the Act. This is essentially, a self-help remedy. Combined with the right to instalment payments it provides a real-world, factual remedy if there is non-payment. This right is enshrined in the 1996 Act (and it might be that similar rights exist in Scots law, as a matter of course).[32]

The right to suspend works—with consequences for not doing so and rights to claim the costs of this is often overlooked and subject to relatively little discussion in the case law.[33] That might be because the other remedies for enforcing payment operate effectively within the current regime. However, this may be an important tool to complement smart contracts as it has a real-world consequence to non-payment, whether that is a party ‘downing tools’ on-site—or simply withdrawing their intellectual engagement. It may prove difficult—on occasion—to enforce some rights against parties sitting on a blockchain: but the self-help real world remedy of suspension takes some of the power away from them. If that were combined with an effective form of adjudication, there would be teeth to the ability to recover payment.

This remedy also aligns with the likely incentives for the delivery of a construction project. The paying party is most likely to be the one who wishes to avoid their obligation (that is, to pay)—but they are also the party who has the greatest interest in the real-world outcome of the successful delivery of the project. Suspension can prevent that outcome—and so encourages payment to facilitate it.

The provision of these remedies—and the mechanisms to reach these remedies—provides parties with an incentive to comply. It shifts the balance of power somewhat by making it easier to enforce and to do so in the real world where the enforcement

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[32] Scottish Law Commission (2018) Report on Review of Contract Law: Formation, Interpretation, Remedies for Breach, and Penalty Clauses, Ch. 11.

[33] COD Hyde Limited v Space Change Management Limited [2016] EWHC 820 (Ch) is a rare example—and see discussion in paras. 43 to 51.

has consequences. By way of example, it is entirely possible for the parties who intend to use the blockchain and smart contract to facilitate payment to incorporate a process that incentivises early or timely payment. This could be in the form of a built-in discount system that rewards a conscientious payer and discourages any behaviour that frustrates the smooth running of the automated payment system. In other words, there could be further research into how smart contracts and blockchains could drive an incentive system that promotes desired behaviour and entrenches trust. Another example would be the use of the smart contract to adjust the payment process to make timely payment a default position provided agreed criteria are met and against which non-payment is to be justified rather than payment actively claimed.

7 Conclusion

The Act is likely to be applied to some construction operations facilitated by smart contracts—if not all. That means that steps should be taken, when designing and writing a smart contract, to ensure that there is payment by instalments, and that the mechanism by which payment is made is clear, sufficient, and operational—within the confines of adequacy under the Act—and that notifications are generated which are intelligible and which provide for the level of detail needed by the Act.

Doing so is a formal requirement and a strength. The process reinforces the aims of transparency and trust which are so important to the blockchain being taken up as a useful tool. That is done because it focuses on construction operations—actions in a physical, centralised place—and builds from there. By creating a mechanism that is intelligible to the parties involved, it allows for understanding and transparency—assuring the credibility of the payment mechanism. By providing for means of enforcement, which again operate in terms of a particular place, it means that there is a reason to comply: which reinforces the whole edifice. The incentives of the contract shift by requiring the parties to consider and justify their decisions. That brings benefits to the whole project—and helps facilitate the use of the smart contract.

References

1. Bailey J (2014) Money is the lifeblood of construction: securing payments in English law. Int Constr Law Rev 520
2. Commodity Futures Trading Commission (USA) (2018) A primer on smart contracts. Lab CFTC. Available at https://cftc.gov/PressRoom/PressReleases/7847-18 (Copy on file)
3. Construction Blockchain Consortium Financing and Procurement Working Group (2020) White paper on blockchain and construction cashflow (Rev 1)
4. Cuccuru P (2017) Beyond bitcoin: an early overview on smart contracts. Int J Law Inf Technol 25(179):184–186
5. Ethereum Foundation (2018) Ethereum project available at https://ethereum.org/en/foundation/

6. Fenwick Elliott R (2016) Pay now, argue later. https://feconslaw.wpcomstaging.com/2016/01/15/pay-now-argue-later/. Accessed 16 June 2021
7. HM Government (2020) The construction playbook (Cabinet Office)
8. Hackitt J (2017) Building a safer future. Independent review of building regulations and fire safety: final report Cm 9607
9. Latham M (1994) Constructing the team: final report of the government/industry. Review of procurement and contractual arrangements in the UK construction industry HMSO
10. Law Commission (2020) Smart contracts: call for evidence
11. Low KFK, Mik E (2020) Pause the blockchain legal revolution. Int Comp Law Q 69(1):135–175
12. Mante J (2021) Understanding legal research in the built environment. In: Manu E, Akotia J (eds) Secondary research methods in the built environment. Routledge, Abingdon [online], chapter 8
13. Mason J (2017) Intelligent contracts and the construction industry. J Leg Aff Dispute Resolut Eng Constr (worktribe.com)
14. McKinsey and Co (2020) Rise of the platform Era: the next chapter in construction technology available at <www.mckinsey.com/industries/private-equity-and-principal-investors/our-insights/rise-of-the-platform-era-the-next-chapter-in-construction-technology>
15. Ng TS (2017) Blockchain and beyond: smart contracts. Bus Law Today (Am Bar Assoc)
16. Pickavance J (2015) A practical guide to construction adjudication
17. Raskin M (2017) The law and legality of smart contracts. Geo Law Tech Rev 1:305–306
18. Temte M (2019) Blockchain challenges traditional contract law: just how smart are smart contracts? Wyoming Law Rev 19:87
19. Werbach K, Cornell N (2017) Contracts ex machina. Duke Law J 67:313

Private Distributed Ledger for Indoor Scene Annotation

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Abstract Visualization of annotation recording using a digital indoor model (e.g., point clouds, 3D models, 2D floorplans) allows stakeholders to see exactly how, e.g., furniture items or machinery have been moved from one location in a building to another. The recording of such actions is vital for record keeping and future decision-making within the realm of facility management (FM), and especially concerning operations and maintenance (O&M) procedures. The use of a digital ledger enables immutable recording of attributes associated with a given indoor representation, e.g., recording of stakeholder annotations onto a point cloud representation. We present a conceptual approach based on blockchain technology (BT) for annotation of indoor scenes, with a focus on point cloud representations of such scenes. We present a case study describing the design and implementation of a private distributed ledger (PDL) as a service-oriented software (SOS) component—where any user annotations are recorded and verified, for proof of immutability for enhancing decision-making among FM stakeholders. We implement the visualization component using a Web3D-based client-side viewer and interface. Our approach sets the foundation for a development of a PDL-based system for indoor scene annotation, with potential to be further integrated into digital twin (DT) platforms.

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1 Introduction

Digital representation of indoor environments plays a critical role in modern facility management (FM), especially with adaptation of building information modeling (BIM) practices [1]. Digital representations of indoor environment can make use of existing 2D or 3D floorplans, BIM and CAD data, as well point clouds.

Point clouds allow the capture and representation of the current physical state of the built environment, with enormous potential for further analysis and decision-making [2]. Point clouds are also very useful for visualization and analysis applications within built environment and geospatial domains [3], being able to capture the current physical state of an environment as a “digital snapshot”. Methods for indoor capture rely on using either photogrammetry or light detection and ranging (LiDAR) systems (e.g., terrestrial laser scanning (TLS)) as well modern commodity mobile devices that include integrated LiDAR sensors. The captured point clouds include the spatial representation in 3D space, along with color and/or intensity attributes.

Using such a representation of indoor environments, FM personnel is able to assess the indoor environments current state, and make decisions concerning operation and maintenance (O&M) procedures, e.g., the generation of inventory for items such as a furniture or machinery, which can be detected in the point cloud using deep learning [4]. Being able to record any changes and user annotations, using a physically accurate representation of indoor environments provided by point clouds, allows users to make decisions with enhanced spatial context for an for a particular point in time. The use of annotation is an important tool for establishing an ontology for FM decision-making concerning indoor environments, as it adds semantics to otherwise possibly ambiguous point cloud representations of real-world environments [5]. Any such annotation recording can then be stored as textual and/or numeric data that is associated with a particular digital representation (in this case being point clouds).

This has additional important implications in various architecture, engineering, construction, owner, and occupant (AECOO) domains for generation of immutable digital documentation (e.g., tracking of construction site progress, recording of annotations during renovations/retrofitting of buildings, etc.). This digital documentation can then be used for further analysis, review of decisions or even as proof of contractual obligations with third parties.

1.1 Motivation and Contributions

Annotation recording based on a digital representation and in an non-modifiable manner requires the use of a specific data structure that ensure immutability between current and previously recorded data segments. The use of a private distributed ledger (PDL), based on *blockchain technology* (BT) principals, allows for immutable recording of such *transaction* data. The immutably recorded data can be based on, e.g., user annotations of common office furniture and areas using a point cloud (Fig. 1).

Fig. 1 Example of annotations of an indoor point cloud using the prototypical implementation of a PDL. In this case, a new proposed location for a sofa object is recorded, along with an annotation of an arbitrary distance measurement. All of the blocks within the private ledger are immutably recorded, based on the users interactions with the point cloud scene, and presented using a Web3D-based software component

While such data could be stored and queried using a database management system (DBMS), there is a need for a lightweight software component implementation, especially for use within a service-oriented system (SOS). The use of SOSs allows for decoupling of hardware requirements between the client and the server and enables flexible computation and streaming of result to various client configurations [6].

While a common shortcoming with public blockchains is that they are expected to be ever increasing in size, for private distributed ledgers, it may be the case that for each new scenario, a new blockchain is generated and used—after which, e.g., it can be securely archived and kept on the server for future reference. Another possibility would be to use a "master PDL" for each stakeholder group, which would be updated for every new O&M scenario that is shared, annotated, and reviewed by stakeholders.

Such a SOS software component should not require the overhead of implementing and maintaining a traditional database and should be suitable for securely recording transactions between involved stakeholders, with validation of each new transaction being accepted by a consensus of trusted stakeholders. This is also important for integration with digital twin (DT) platforms, as such platforms attempt to combine multiple data sources of the built environment in order to create a cyberphysical counterpart and often require inputs and decision-making from multiple stakeholders as well [7].

We present a conceptual approach, system design, and prototypical implementation of a PDL. We present and discuss a case study where we implement and test a prototypical PDL as a SOS component for recording of user annotations using indoor point clouds. A Web3D-based client-side software component is used for visualization of the point clouds and user-driven interaction, specifically for annotation recording within an 3D scene via the client Web-browser (Fig. 2).

Fig. 2 Example of user-based annotations of an indoor point cloud. These annotation operations are recorded as blockchain data in the presented case study, using the prototypical PDL software component

2 Related Work

2.1 *Blockchain Technology for AECOO Applications*

BT is based on a decentralized and distributed collection of ever-growing records, where the validity of each new added record is computed using a specified consensus algorithm, thus ensuring immutable digital record keeping. BT first appeared with the introduction of Bitcoin [8], as has since been adapted in various domains, with more recent adaptations focusing on use cases for smart cities [9], and the digital built environment representations [10]. A blockchain data structure is an example of a Merkle tree [11], allowing for immutable record keeping by using a hash verification mechanism. The decoupling of BT from cryptocurrency, and its subsequent use for various real-world applications, has led the development of Blockchain 2.0, and related distributed ladger technologies (DLT) based on the key concepts of BT [12].

A distributed ledger is a system where each record in a digital ledger is kept distributed and synchronized across all involved stakeholders, and any additions to it require the computation of the validity of all previous records in order to ensure immutability (e.g., that no previous records have been tampered with). This has significant applications for AECOO and related domains, e.g., BIM-based and smart building domains [10, 13, 14], digital twins (DTs) [15, 16], and smart cities [9, 17, 18]—since any changes made to, e.g., BIM or a point cloud representation, can be recorded immutably and used as potential legal and contractual documentation. Another comprehensive review of applications of DLTs for AECOO is provided by [19].

As noted by Turk and Klinc, the most notable difference between document-based and current BIM-based practices is that any legally binding documentation was previously kept in physical form where it would pass through different level of bureaucracy [20]. Research by Gunasekara et al. advocates the use of BT, DLT, and smart contracts for replacing current procurement practices in FM, by providing a conceptual framework that aims to digitize each of the main bottleneck processes in the pre-tendering, tendering, and post-award phases [21].

With the use of BIM practices, particularly with the use of the common data environments (CDEs) concept, sharing of digital data used for all representational aspects of a building poses particular challenges concerning its ownership [1]. Research by Suliyanti and Sari presents a prototypical implementation of a BT-based multi-party BIM-management platform, where the aim is to allow multiple parties to record important transactions concerning the whole building lifecycle using a permissioned blockchain [22]. The authors take note that a single “network admin” is still required to oversee the maintenance and integrity of the blockchain through fully granted access permissions using creating, reading, updating, and deleting (CRUD) operations on assets that represent the key phases of a buildings lifecycle.

While the use of DLTs based on BT are still new to the AECOO industry, their use has already been researched for various BIM-related applications. Dounas and Lombardi investigate the use and multi-level integration of BT with CAD and BIM applications, particularly for tracking any changes and annotations to the BIMs, as well as CAD models [23]. Lemeš and Lemeš discuss the potential use of BT for use distributed CAD and BIM software environments [24]. Hargaden et al. discuss the benefits and challenges of using BT for construction progress monitoring, and the feasibility of integrating such systems with existing BIM practices [25].

DLTs based on BT can either be public consortium-based or private [26]. For example, a private DLTs, referred to as a PDL in this research, are commonly found in organizations where there is a high level of trust between all users. Thus, the PDL can be used without needing to compute any proof-of-work results when adding new records—but the validity of the records in the ledger is still ensured using the same method as in public and consortium-based blockchains (e.g., the ledger is distributed to trusted clients who form a consensus for any new data that is added). The use of PDLs are therefore suitable for integration into BIM and DT platforms [12, 27].

2.2 Point Cloud-Based Annotation Recording

Point clouds can provide 3D and textured up-to-date physical representations of the built environment up to high resolutions (millions of points per square meter), and featuring intricate details [28]. According to Richter, point clouds can *“represent almost any type of physical object, site, landscape, geographic region, or infrastructure … at all scales and with any precision”* [29]. The processes of capture, post-processing, and semantic enrichment are all required before the point cloud be analyzed and/or visualized [5]. The final output of a semantically-enriched or processed point cloud can provide great benefit to AECOO practitioners and stakeholders such as FM operators who want a deeper insight into the current state of the built environment [30].

The use of point clouds representations of the built environment for annotation recording is thus a natural extension of their use, as frequently captured point clouds of of the same area can be compared for spatial deviations and changes over time [31]. For indoor environments, point clouds provide a good source for generation of semantically-enriched representations, especially those used to represent complex indoor spaces such a university campuses and offices [32]. Semantic enrichment of point clouds using annotations added by users, or as results of various semantic enrichment processes (e.g., semantic segmentation using deep learning approaches [33]), can further engage stakeholders, especially using Web-based visualization where multiple users are able to inspect the same point cloud scene [34].

While domain expertise is usually required for reviewing and decision-making based on BIM [35], the use of point clouds provides a more intuitive way for inspecting the physical representation of the *as-is* built environment. By capturing the physical state of objects such as furniture and equipment, including their spatial attributes at the time of the scan, point clouds can capture physical features that are otherwise often omitted or difficult to model using high-level geometric representations typically found in as-designed/as-built BIMs [36]. Any changes made by users reviewing a point cloud can thus be based on the real-world representation rather than an *as-designed* or *as-built* BIM.

3 Approach

The presented PDL software component is based on BT principals, except that it does not use any proof-of-work mechanism. Rather, any changes such as spatial and/or user annotations are recorded within an block with a unique hash code, and this block is added by a trusted user upon theoretical agreement between all stakeholders (e.g., a PDL "administrator" or multiple stakeholders with specific permissions). As such, all of the stakeholders are able to inspect and view the current scene with the annotations via the Web3D-based client-side user interface. This way, any changes can be communicated by stakeholders and referenced as immutable documentation.

3.1 System Design and Implementation

The prototypical PDL is implemented within a service-oriented paradigm, with decoupling between client and server processing tasks (Fig. 3). The blockchain component of the PDL is implemented as a server-side software component using Node.js, and it is responsible for creating and maintaining the blockchain. The blockchain is updated with specific attributes after the user records any changes or annotations made to the point cloud (Sect. 3.3). Three different servers are also implemented, one for sending data updates to the blockchain, one for updating the blockchain, and one for updating the blockchain across all connected stakeholders.

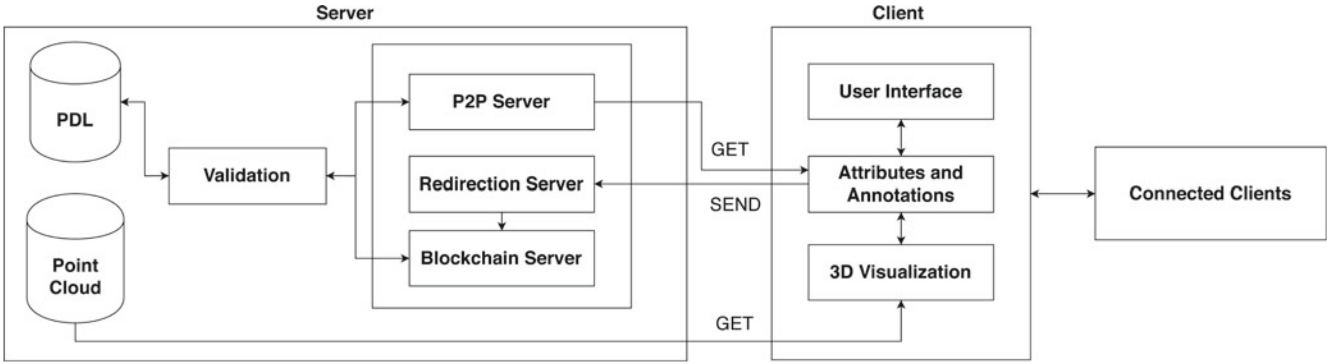

Fig. 3 A high-level system design of the prototypical PDL implementation, along with the proposed data flow between the client and server components

3.2 Servers Design and Implementation

The primary server dealing with updating the blockchain is implemented as an express server,[1] using the Sockets.io framework to enable bi-directional communication between the client and the server. The server is REST-based and utilizes HTTP POST and GET commands in order to add new blocks to the blockchain, as well as to send back the current contents of the blockchain. The secondary server is a re-direction server, which is also an express server that runs simultaneously alongside the main server, and passes the recorded annotations and scene changes from the client-side as HTML 5 hidden attribute form data. This server redirects the HTML 5 hidden form-data attributes to the HTTP server port running on the main express server, where a POST operation is triggered—thus creating a new block with the parsed form attributes and broadcasting a message to all connected peers that a new block has been added to the blockchain.

In order to allow more than one trusted stakeholder access to the blockchain, and to implement a basic conflict resolution mechanism, a third peer-to-peer (P2P) server architecture is implemented using WebSockets. The P2P server listens simultaneously at the same time as the HTPP server, except that instead of updating the blockchain from input by the client-side interface, it checks which peers have connected to the server and sends them a copy of the blockchain. The P2P server also constantly checks that each of the connected peers has the most recent version of the blockchain, and synchronizes it with the most recent version by updating the blockchain with the latest transactions, or replaces the current blockchain of a peer that is not up-to-date with the longest (and most recent) blockchain. The updating frequency of the blockchain implemented by the P2P server can be set to check, e.g., every couple of seconds, or can be triggered by a certain action, e.g., a specific stakeholder adds an annotation to the active scene. Finally, the P2P server can also add new blocks to the current blockchain by validating the hash of the last block in the current chain with the hash of the latest block received from any of the connected peers (Sect. 3.4). This way for every new block that is added by the user, the block chain can be synchronized across all connected peers.

3.3 Block Structure

The blockchain records specific attributes of an indoor environment, using its point cloud representation, at a particular point in time. These attributes provide an example of attributes that could be important for forming O&M decisions (a comprehensive list of attributes relative to FM is discussed by [37]). The block structure used to store the transactions for the ledger is composed of the following data members:

- *Index*: The index of the current block in the chain.

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[1] Express: https://expressjs.com/.

- *Previous Hash*: The unique hash of the previous block.
- *Timestamp*: The timestamp of the current block.
- *User ID*: The ID or name of the current user making annotations to the scene.
- *Scene Comments*: User annotations of the current point cloud scene.
- *Scene Objects*: The current point cloud clusters in the scene.
- *Selected Objects*: The selected point cloud clusters.
- *Selected Objects Position*: The position of the selected point cloud clusters.
- *Current Hash*: The computed hash of the current block.

The blockchain is first formed using an initial block, called the *genesis block*, which is set with default values. This genesis block is then used as the foundation block for computing the subsequent hash values of the next blocks that are added to the blockchain. The most notable data member of the block is the current hash, which is computed using all of the current data members. This unique hash value is computed as a 32 byte random character string using the SHA-256 pseudo-random number generator (PRNG) [38], which is provided using the CryptoJS library.[2]

Once the new block has been added with all of the data members set, and with a unique hash code based on the hash of the previous block, it is added to a global block array that is initiated and used during the run-time of the application. For the prototypical implementation, we used an in-memory approach for accessing and updating the blockchain. This blockchain array is shared and synchronized with all connected peers as well.

Since we are using a "trusted ledger" approach, we do not compute any proof of work when accepting a new block to be added to the blockchain. A trusted ledger is intended to be used internally by trusted stakeholders, where there is no need to for any of the stakeholders to "mine" any of the blocks, as everyone who is generating and adding new blocks is known to all other stakeholders using the blockchain. Mining of the blocks usually requires spending vast amounts of computational power in order to generate a valid signature based on the computed hash value that meets certain requirements (e.g., having a certain number of zeros as the first characters of the signature) and is common in public and decentralized ledgers and blockchain implementations.

3.4 Blockchain Validation

A blockchain has the ability to immutably record transactions. The meaning of immutability in this sense means that the validity of the entire blockchain structure is based on the computed hash values of the sequential blocks containing previously recorded attributes and unique hash values (Fig. 4). As such, assurance against tempering with previously inserted blocks can be obtained by validating the hash values of the current and the previous block in the blockchain and comparing them. If the

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[2] CryptoJS: https://cryptojs.gitbook.io/.

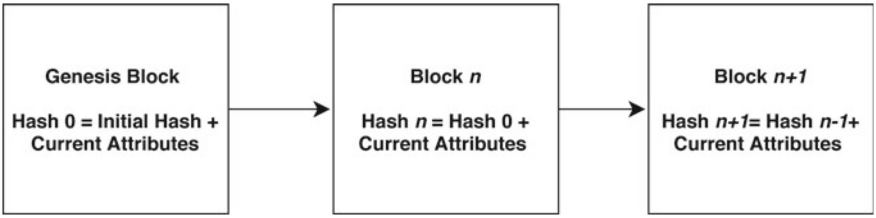

Fig. 4 Example generation of blockchain data, where each new block contains a hash code generated from the current block attributes and the hash of the previous block

hash value of current block, which was computed based on the hash value of the previous block along with any of its current attributes, is the same as the previous block hash value, then we can be certain that the these blocks contain attributes that were not tempered in any way.

If transaction values within any of the inserted blocks in the blockchain were tempered with, the generated hash of the new block will be different than that of the same block in the copies of the blockchain used by other stakeholders. As all of the blocks are known to the stakeholders, it will be visible which blocks contain attributes that were tampered with. In essence, this process assumes that the blockchain is shared between trusted stakeholders, and as such each stakeholder has a copy of the blockchain that is updated and synchronized with other stakeholders.

In the prototypical PDL implementation, we have implemented three different blockchain validation methods, namely (1) index validation of the current and the previous block, (2) validation of the hash of the previous block, and (3) validation of the hash of the current block. Additionally, these three validation methods are used to validate the consensus blockchain once it has been synchronized across all connected peers.

4 Client Design and Implementation

4.1 Web3D-Based Visualization and Scene Interaction

The client-side implementation makes use of HTML 5 and Three.js for the main visualization and user input tasks.[3] Via the web-based user interface, users are able to load in a point cloud and add in any annotations, which are recorded in the PDL.

The visualization component is able to display the complete point cloud of a indoor scene (typically of about 100,000 points per 20 m^2). The current limit for visualizing a number of points per scene is approximately four million points (due to the use of non-optimized point cloud rendering). The use of Three.js enables the rendering of other useful visualization idioms [39], e.g., billboard sprite rendering

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[3] Three.js: https://threejs.org/.

(used for displaying text), and various shading operations that can be performed on the point cloud via the programmable graphics pipeline (e.g., changing of color of a point cluster or its opacity).

A user is able to add annotations to the 3D point cloud scene, either for the entire scene or for specifically selected point clusters. Currently, this includes textual annotation and distance and area measurements (Fig. 2). For annotation generation purposes, a portion of the original point cloud, used for generating annotations, can be copied without modifying the original data (Sect. 6.1). Apart from textual annotations, the user can also select given cluster and transform its position and rotation in the 3D scene. Both the annotation and transformation actions can be captured as updated scene attributes that are sent to the server as a new block update. Each stakeholder can add blocks without explicit permission, due to the trusted nature of the PDL.

4.2 Stakeholder Block Update Consensus

If some of the stakeholders are required to add annotations that need to be approved by other stakeholders, an consensus-based approach is required. We propose an approach for such a situation: Once the annotations have been made, the user who made the changes can send a preview of the scene and changes as an image and textual description to all involved stakeholders. The connected stakeholders can then approve or reject the changes. If the majority of stakeholders approve the changes, the user who made the suggested changes is then able to upload the proposed changes as a new block to the blockchain.

5 Case Study

We present an experimental case study where we made use of point cloud representations of typical office environment. The office environment was captured using a commodity mobile device and presents an open office area of approximately 15 m^2, along with common office furniture (e.g., chairs, sofas, tables). The point cloud contains 318,589 points, featuring spatial, and RGB color attributes. We performed both annotation and transformation tasks, where we annotated common office furniture and transformed the segmented point clusters to new locations in the scene. These changes were then recorded in the blockchain and updated to all connected peers. We assessed the integrity of the blockchain after it has been updated, using three different validation techniques (index, previous, and current hash validation).

5.1 Annotation and Transformation Task

The annotation and transformation task present a typical scenario in FM, where furniture has to be moved from one location to another by the O&M personnel, with instructions and result inspections carried out the O&M manager (Fig. 5). This scenario is broken down into six different tasks, with tasks 1–3 illustrated in result Fig. 6, and showing the transaction results of recorded annotations between the three involved stakeholders. Once the task has been completed by the O&M employee in this scenario, the physical result of the task can be compared by the O&M Manager with the version of the point cloud scene that contains the annotated and agreed instructions of where to move the chairs. If the task is carried out to the satisfaction of the O&M manager, both the O&M employee and building manager would receive notification of a successfully completed task and this would be recorded as well in the PDL.

5.2 Blockchain Computation Performance

We further provide preliminary results in terms of computational performance of key block creation and validation methods (Table 1), which are implemented and executed server-side using Node.js. The server used for testing is a commodity desktop PC, with an Intel Core i5-6500 CPU at 3.2 GHz with 8 GB RAM, using Node.js version 14.0.0.

Each performance attribute measures the average time taken to complete a specific blockchain operation. The average time taken was measured using 15 consecutively recorded samples for each operation. The selected performance attributes are split up into three different types of operations: (1) block creation, (2) validation, and (3) retrieval. We used a blockchain with 15 different block elements.

The block creation attributes include time taken to generate a new block, and the time taken to compute a unique hash for the new block. The validation attributes include validation of the current block index, and the validation of the previous and current hashes of two consecutive blocks. The validation of the complete block chain is performed using all three validation methods (index, current, and previous hash validation). The retrieval performance attributes were used to evaluate the time taken to retrieve the first block in the blockchain (the *genesis block*), and well as the time taken select and retrieve a random block from the complete blockchain.

6 Discussion

The presented case study demonstrates the feasibility of our approach of tracking of spatial and user-annotated changed within a point cloud scene using a PDL. The use of a PDL based on BT principals offers promising alternative for storing of immutable

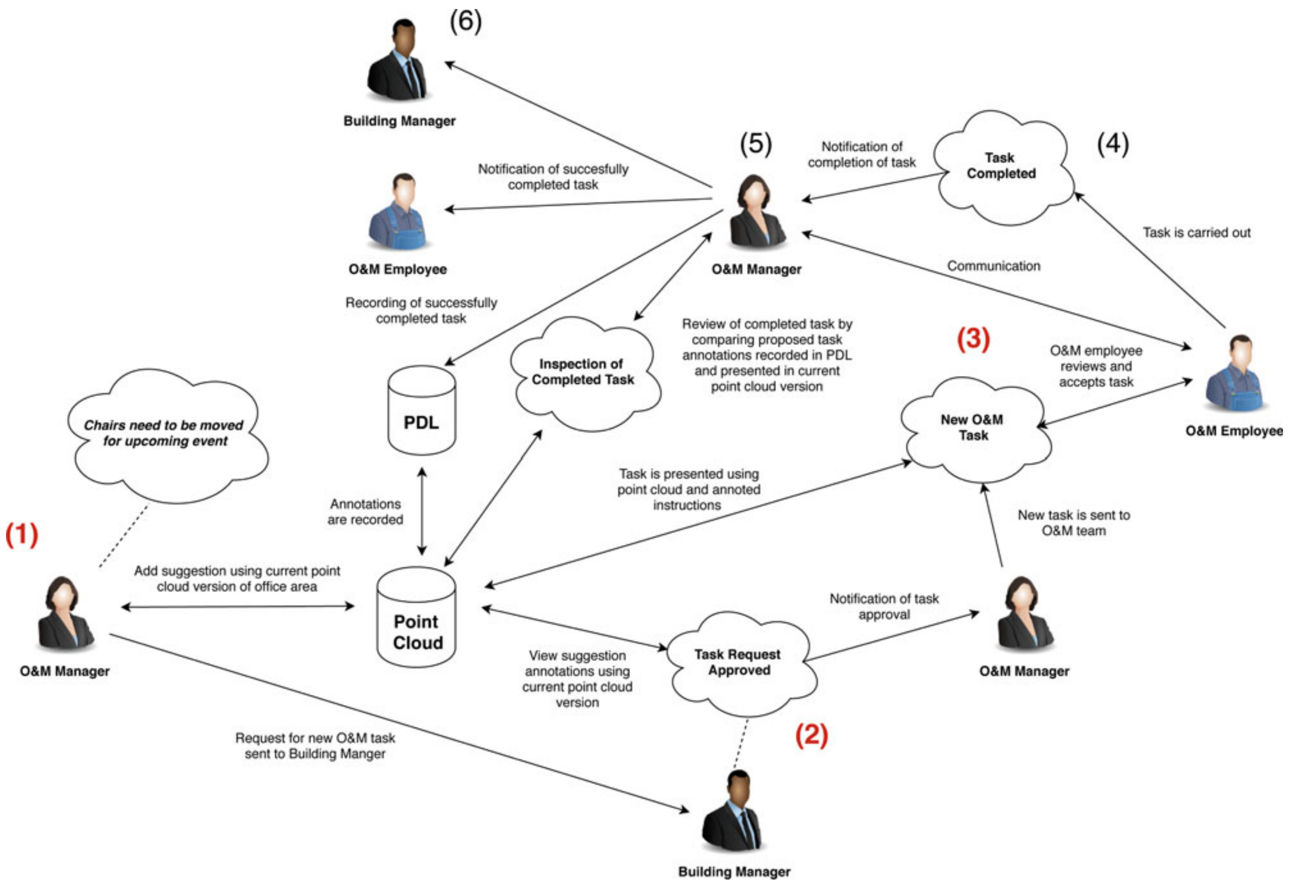

Fig. 5 Illustration of the proposed annotation and transformation task, broken down into six different steps, and involving three different stakeholders

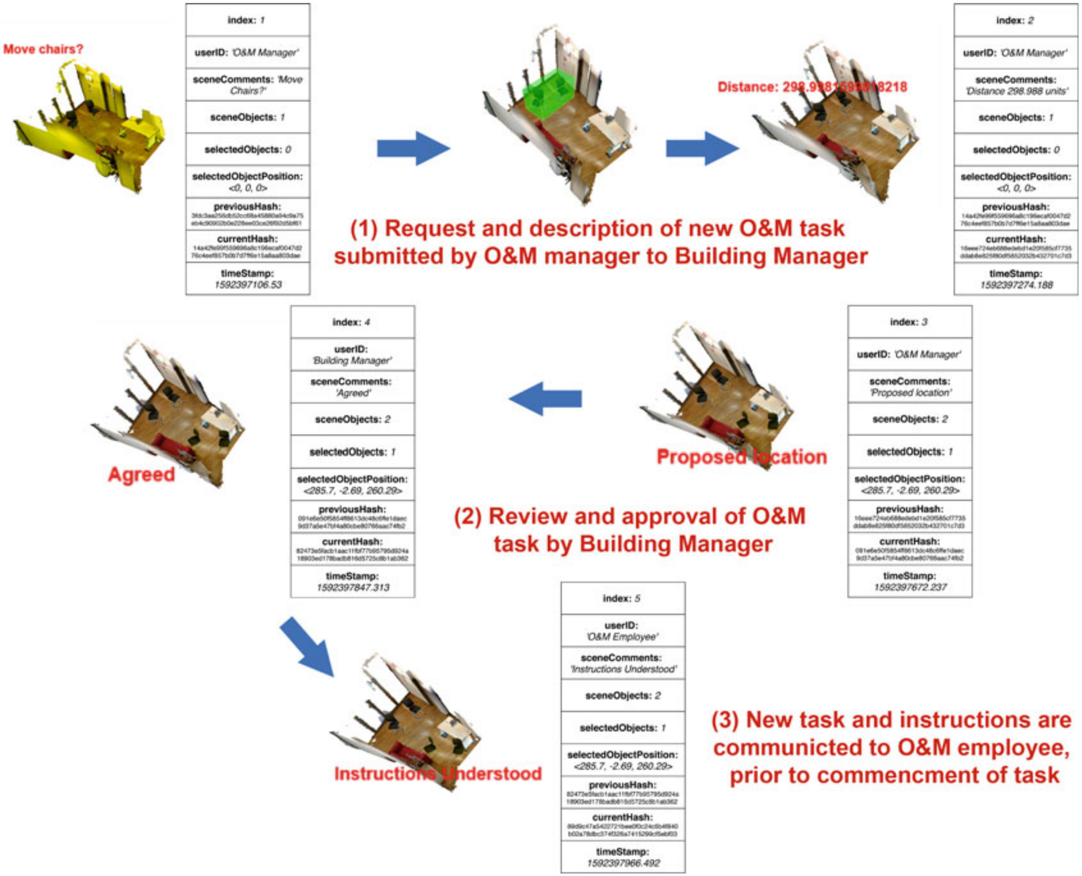

Fig. 6 Result of the case study where the first three steps of the task generation and communication process are recorded in the PDL, visualized using the point cloud representation of the office area, and communicated to all involved stakeholders

Table 1 Preliminary evaluation of the PDL in terms of performance of key block creation and validation methods

Performance attribute	Time (ms)
Block creation	5.608
Block hash computation	0.306
Block index validation	1.072
Previous block hash validation	1.031
Current block hash validation	1.278
Complete chain validation	62.431
Genesis block retrieval	7.810
Random block retrieval	7.744

data related to decision-making within the realm of FM, and integration with DT platforms. However, there are additional important points to take into account when considering the use of a PDL for FM-related-decision making tasks.

6.1 Data Transfer and Storage Considerations

In the presented case study, we focus on simple annotations (e.g., measuring distances between two points or adding simple work order instructions), though the number of attributes recorded by each block for each transaction could increase to include many more details e.g., complete scene editing or selected object transformation history. This would also inevitably increase the processing overhead of the block hashing, synchronization, and validation operations.

The presented approach does not explicitly store any point cloud data within the blockchain, but rather attributes associated with a given point cloud. As such, it is assumed that all stakeholders have access to the same and most recent version of the point cloud. Since point clouds tend to be very large (potentially millions or billions of points with gigabytes in size), their transmission, and storage remains impractical, especially using SOS implementations.

Due to this presumably large size of point clouds, it is more practical to identify and make use of *metadata* of point clouds when using them for versioning and decision-making within a PDL. This can include timestamps of when the point cloud was created, number of points, size on hard disk, etc., and more importantly, the point cloud that is used can be stored on a secure server that provides read-only access to it for PDL-based versioning. This way all of the of the stakeholders can use the same and unmodified version of the point cloud for recording of user annotations, with the annotations becoming *proposed* changes that can be implemented in the updated version of the point cloud once a consensus has been reached.

However, in order to prove that the stakeholders are using the original version of the point cloud, an initial verification step can be implemented using the actual point cloud data. A hash of the complete point cloud can be computed using SHA-256 as the main PRNG component. This hash value can then be compared and verified prior to any further stakeholder use and annotation of the point cloud, thus ensuring that the original and non-modified version of the point cloud is being used.

It should also be noted that while the validity of the blockchain is ensured, the actual point cloud data should be treated as read-only data, so that it cannot be modified by any of the stakeholders. A portion of the original point cloud used for annotation purposes can be copied and stored temporarily (e.g., either in system memory or a DBMS), and this copied portion can be used for making any changes that enable the illustration of important scene changes for communication with stakeholders (e.g., showing where to move machinery or furniture items within a room).

Furthermore, the annotations and illustrations made using the temporary point cloud portion can be transmitted to other stakeholders as e.g., image-based annotations. This way, a single and valid version of the point cloud is used between all stakeholders, on to which the various annotations are projected, and images are captured and shared for decision-making—without the original point cloud being modified.

6.2 *Potential Stakeholder Use Cases*

A notable use case of the blockchain-based scene annotation would be integration into DT platforms for FM. As mentioned, it is impractical to include actual point cloud data in the blockchain, therefore criteria for inclusion of useful metadata would need to be investigated. The selection of appropriate metadata becomes particularly important for DT systems that integrate various data sources (e.g., BIM, CAD, floorplan, digital documents, sensor data—all in addition to point cloud data). For example, in a hypothetical DT platform, a BIM model would form only one of the key "base-data" sources. The combined use of multiple historic, current, and real-time digital data related to the operational lifecycle of a building can be merged together to form an "asset information model" (AIM), which is essentially what the DT platform uses and maintains [40]. Additionally, a DT would be implemented within a digital twin environment (DTE), where the use of service-oriented architecture and system implementation could be benefit the integration of various processing components [41].

This is in contrast with current AECOO practices, where a BIM model and associated digital documentation are generated, shared and maintained using a common data environment (CDE)—usually with proprietary BIM software. Stakeholders can view the BIM model within a static state (e.g., not usually dynamically updated), where time, cost, and spatial clash detection properties can be computed using a given level-of-detail (LOD) BIM representation [1, 42].

An AIM can be made up of a number of different file formats that facilitate capture, semantic enrichment, and exchange of information between stakeholders. Common file formats for such data exchange include IFC,[4] CoBIE,[5] and the BIM collaborative format.[6] BCF is of notable interest due to the design of its API that enables sharing of important of BIM data, based on the IFC model, through a REST-based API that enables integration into a SOS. BCF is also a good potential candidate for use in a PDL since it is designed to share the metadata of an IFC model, instead of the IFC model itself. A possible use case scenario for a PDL could be to keep track of any changes to the IFC model via the specification of the BCF format, where each of the defined block datatypes and attributes correspond to their counterparts in the BCF specification.

An alternative would be to use the model view definition (MVD)[7] for selecting specific attributes, using a subset of the IFC specification to define the block structure of the blockchain based on the pre-defined usage requirements (e.g., usage for mechanical, electrical, and plumbing (MEP) components tracking versus spatial change tracking that can be captured at a LOD-300 IFC specification).

Scenarios where the use of BT would benefit stakeholders could include, e.g., managing payments to third parties for maintenance of a building. This could further be extended with the use of *smart contracts*, where a transaction can trigger a scripted mechanism within the blockchain once a certain transaction is recorded [43]. Stakeholders could also use a point cloud representation of an indoor environment to agree with responsible parties what changes need to be made by spatially selecting an area of interest and annotating it. As this is recorded immutably once all parties agree, it could be used for tracking of various building inventory tasks, e.g., movement of furniture or machinery from one specific location to another.

Using the presented approach, the level of stakeholder interaction and annotation using the point cloud representation at minimum requires that the user selects a point cluster and annotates it by adding a textual note associated with it. This enables fast and easy overview and annotation, and potentially enhanced decision-making using the *as-is* point cloud representation of the built environment. While the the use of point clouds is advocated as the preferred means to convey key geometrical representation of the built environment, the presented approach of using PDL-based annotation can be applied to other geometric representations (e.g., triangulated meshes, boundary representations, 2D floorplans, etc.).

Furthermore, building managers and sub-contractors could use the blockchain to track changes such as on-going renovation and retrofitting work, e.g., multiple point clouds of an area that is being renovated could be captured, along with relevant documentation, and stored as metadata where a unique hash is associated with a given point cloud captured at a particular time. This way the involved stakeholders could use BT to track changes and monitor progress for such renovation or retrofitting work.

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[4] https://www.iso.org/standard/70303.html.

[5] https://www.nibs.org/page/bsa_cobie.

[6] https://technical.buildingsmart.org/standards/bcf/.

[7] https://technical.buildingsmart.org/standards/mvd/.

6.3 Comparison with DBMSs

A PDL can be thought of as a database in the sense that it is able to record, retrieve, and verify information in block-based data structures using BT APIs or protocols. However, a traditional database is designed to store data that cannot only be retrieved, but also modified (i.e., CRUD operations). A DBMS is usually installed on a single server, and copies of it are not intended to be distributed among users—unless they have special database administrator privileges. Since the blockchain is distributed, it has better fault tolerance than a traditional DBMS as all connected stakeholders have a copy of it, where as a DBMS usually has limited copies with privileged access rights.

Additionally, DBMSs are designed to hold any kind of data, including very large spatial datasets such as point clouds, images, CAD models, and associated digital data. The speed of retrieval of such data in specialized DBMSs is also critical, and thus, they are designed around advanced data retrieval algorithms, e.g., spatial hash indexing for use in GIS [44]. In comparison, a blockchain is designed to hold "lightweight" data—mostly textual and numerical data associated with transactions or metadata related to larger datasets that may be kept on a database or remote server. In terms of storage requirements, the average size of our PDL for a single scenario with 10 elements is 5.69 kb—using the specified block attributes stored and parsed in the JSON data format (Sect. 3.3).

DBMS are also designed to deal with data types that can change based on use cases and data storage requirements. A blockchain block has hard-coded data types and attributes, and these cannot be changed unless a new blockchain is implemented from scratch. A PDL also does not have the same kind of flexibility as a non-relational DBMS for dealing with unstructured data, nor data whose attributes change once it is in use. Therefore, it is a requirement to decide among stakeholders which data attributes need to be included in the initial block design prior to deploying and using a PDL.

In terms of security, a PDL can be thought as always being secure—as all involved stakeholders have a copy of it, and in a trusted setting only blocks that have been approved by a majority of stakeholders or an appointed admin can be added to the blockchain. A DBMS usually requires one or more administrators to control who has access to and to grant required credentials to users to have specified access to complete or select parts of it when creating or modifying data. Therefore, the security and maintenance overhead of using a DBMS also tend to be higher in comparison with using a PDL.

6.4 Attack Possibilities on the Blockchain

A notable hypothetical weakness of public blockchains that they are susceptible to the "51%" or "double spending" attack [45]. In the classic decentralized blockchain architecture, if the attacker manages to mine more blocks (51% more than the rest of the users), all of the connected users of the blockchain would use the attackers version of the blockchain since it would be the "consensus" or most up-to-date version. The attacker could then invalidate or modify any previously recorded transactions with their copy of the blockchain, which all other peers would be using.

This is mainly a problem in decentralized and public blockchains, where there are many anonymous users and proof of work is required prior to adding each new block. For PDLs, each of the blocks would usually be validated and added by a trusted person or party—and be dependant on social control rather than technical protection. The trusted stakeholders responsible for validation could, e.g., form a consensus when attempting or rejecting to add each new block with recorded transactions (Sect. 4.2). This prevents the copying of the blockchain and adding blocks to it unless this was performed by a trusted client or group.

Another possibility for preventing modification of the PDL would be to create snapshots of it and back these up on a secure server with strong encryption. The snaphsots could be generated after each, e.g., important meeting between stakeholders, where the PDL and point cloud scene are used to annotate agreed items of discussion that may, e.g., form a part of a contractual obligation. Such a mechanism would reduce the possibility for any of the parties to claim that a tampered PDL is a valid one (if the valid one is stored safely as a snapshot and can be produced as evidence when required).

7 Conclusions and Outlook

In this paper, we have described a conceptual approach for tracking of user annotations of indoor point clouds for FM applications using a prototypical PDL software component. The provided experimental results demonstrate the feasibility of our approach, and we demonstrated its use in a typical O&M scenario. We have also discussed potential use of the blockchain for FM-related use by taking into account the kind of data types and attributes such a system would need to record immutably for O&M related tasks, and how stakeholders would be able to interact with it by viewing or adding new data using a Web3D-based user interface and visualization. The case study results also show that the prototypical PDL is able to record stakeholder annotations immutably, and that the validity of the blockchain cannot be compromised undetected. Furthermore, the preliminary performance results demonstrate the feasibility of the PDL as a lightweight SOS component that is able to perform key blockchain computations efficiently. Furthermore, the presented approach is not explicitly tied to using point clouds for representation and can be used for all scenarios using digital representations of various environments requiring immutable user annotations (e.g., city planning using CityGML-based representations).

For the prototypical PDL implementation, the point cloud is kept on the server and loaded by the client user interface (copied into the clients system memory). A more efficient streaming-based method that provides read-only access to the point cloud that is stored securely on the server will be investigated. We have also proposed an approach for stakeholder consensus for adding new data to the blockchain, which we aim to implement and test for future work. Finally, we plan to expand the attributes of the blockchain to match those of the BCF specification, and test this approach using multiple stakeholders.

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References

1. Teicholz P et al (2013) BIM for facility managers. Wiley
2. Qu T, Coco J, Rönnäng M, Sun W (2014) Challenges and trends of implementation of 3D point cloud technologies in building information modeling (BIM): case studies. Comput Civ Build Eng 2014:809–816
3. Döllner J (2020) Geospatial artificial intelligence: potentials of machine learning for 3D point clouds and geospatial digital twins. PFG–J Photogramm Remote Sens Geoinf Sci 1–10
4. Stojanovic V, Trapp M, Döllner J, Richter R (2019) Classification of indoor point clouds using multiviews. In: The 24th international conference on 3D web technology, pp 1–9
5. Stojanovic V, Trapp M, Richter R, Döllner J (2019) Service-oriented semantic enrichment of indoor point clouds using octree-based multiview classification. Graph Models 105:101039
6. Döllner J, Hagedorn B, Klimke J (2012) Server-based rendering of large 3D scenes for mobile devices using G-buffer cube maps. In: Proceedings of the 17th international conference on 3D web technology. ACM, pp 97–100
7. Qiuchen Lu V, Parlikad AK, Woodall P, Ranasinghe GD, Heaton J (2019) Developing a dynamic digital twin at a building level: using Cambridge campus as case study. In: International conference on smart infrastructure and construction 2019 (ICSIC) driving data-informed decision-making. ICE Publishing, pp 67–75
8. Nakamoto S et al (2008) Bitcoin: a peer-to-peer electronic cash system
9. Chaturvedi K, Matheus A, Nguyen SH, Kolbe TH (2018) Securing spatial data infrastructures in the context of smart cities. In: 2018 international conference on cyberworlds (CW). IEEE, pp 403–408
10. Nawari NO, Ravindran S (2019) Blockchain and the built environment: potentials and limitations. J Build Eng 100832
11. Merkle RC (1987) A digital signature based on a conventional encryption function. In: Conference on the theory and application of cryptographic techniques. Springer, pp 369–378
12. Li J, Greenwood D, Kassem M (2018) Blockchain in the built environment: analysing current applications and developing an emergent framework. Diamond Congress Ltd
13. Li J, Kassem M, Ciribini A, Bolpagni M (2019) A proposed approach integrating DLT, BIM, IoT and smart contracts: demonstration using a simulated installation task. In: International conference on smart infrastructure and construction 2019 (ICSIC) driving data-informed decision-making. ICE Publishing, pp 275–282

14. Siountri K, Skondras E, Vergados DD (2019) Towards a smart museum using BIM, IoT, blockchain and advanced digital technologies. In: Proceedings of the 3rd international conference on vision, image and signal processing, pp 1–6
15. Yaqoob I, Salah K, Uddin M, Jayaraman R, Omar M, Imran M (2020) Blockchain for digital twins: recent advances and future research challenges. IEEE Netw
16. Dietz M, Putz B, Pernul G (2019) A distributed ledger approach to digital twin secure data sharing. In: IFIP annual conference on data and applications security and privacy. Springer, pp 281–300
17. Liu Z, Chi Z, Osmani M, Demian P (2021) Blockchain and building information management (BIM) for sustainable building development within the context of smart cities. Sustainability 13(4):2090
18. Melhem A, AlZoubi O, Mardini W, Yassein MB (2019) Applications of blockchain in smart cities. In: Proceedings of the second international conference on data science, E-learning and information systems, pp 1–7
19. Li J, Kassem M (2021) Applications of distributed ledger technology (DLT) and blockchain-enabled smart contracts in construction. Autom Constr 132:103955
20. Turk Ž, Klinc R (2017) Potentials of blockchain technology for construction management. Procedia Eng 196:638–645
21. Gunasekara HG, Sridarran P, Rajaratnam D (2021) Effective use of blockchain technology for facilities management procurement process. J Facil Manag 1–17
22. Suliyanti WN, Sari RF (2021) Blockchain-based implementation of building information modeling information using hyperledger composer. Sustainability 13(1):321
23. Dounas T, Lombardi D (2018) A cad-blockchain integration strategy for distributed validated digital design. In: eCAADe 2018: computing for a better tomorrow
24. Lemeš S, Lemeš L (2019) Blockchain in distributed cad environments. In: International conference "new technologies, development and applications". Springer, pp 25–32
25. Hargaden V, Papakostas N, Newell A, Khavia A, Scanlon A (2019) The role of blockchain technologies in construction engineering project management. In: 2019 IEEE international conference on engineering, technology and innovation (ICE/ITMC). IEEE, pp 1–6
26. Zheng R, Jiang J, Hao X, Ren W, Xiong F, Ren Y (2019) bcBIM: a blockchain-based big data model for BIM modification audit and provenance in mobile cloud. Math Probl Eng 2019
27. Lee D, Lee SH, Masoud N, Krishnan M, Li VC (2021) Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. Autom Constr 127:103688
28. Discher S, Richter R, Trapp M, Döllner J (2019) Service-oriented processing and analysis of massive point clouds in geoinformation management. In: Service-oriented mapping. Springer, pp 43–61
29. Richter R (2018) Concepts and techniques for processing and rendering of massive 3D point clouds
30. Qu T, Sun W (2015) Usage of 3D point cloud data in BIM (building information modelling): current applications and challenges. J Civ Eng Archit 9(11):1269–1278
31. Xiao W, Vallet B, Paparoditis N (2013) Change detection in 3D point clouds acquired by a mobile mapping system. ISPRS Ann Photogramm Remote Sens Spatial Inf Sci 1(2):331–336
32. Armeni I, Sener O, Zamir AR, Jiang H, Brilakis I, Fischer M, Savarese S (2016) 3D semantic parsing of large-scale indoor spaces. In: Proceedings of the IEEE conference on computer vision and pattern recognition, pp 1534–1543
33. Zhang J, Zhao X, Chen Z, Lu Z (2019) A review of deep learning-based semantic segmentation for point cloud. IEEE Access 7:179118–179133
34. Discher S, Richter R, Döllner J (2018) A scalable webGL-based approach for visualizing massive 3D point clouds using semantics-dependent rendering techniques. In: Proceedings of the 23rd international ACM conference on 3D web technology, ser. Web3D '18. ACM, pp 19:1–19:9
35. Volk R, Stengel J, Schultmann F (2014) Building information modeling (BIM) for existing buildings-literature review and future needs. Autom Constr 38:109–127

36. Anil EB, Akinci B, Huber D (2011) Representation requirements of as-is building information models generated from laser scanned point cloud data. In: Proceedings of the international symposium on automation and robotics in construction (ISARC), Seoul, Korea, vol 29. Citeseer
37. Dias PDR, Ergan S (2020) Owner requirements in as-built BIM deliverables and a system architecture for FM-specific BIM representation. Can J Civ Eng 47(2):215–227
38. Gilbert H, Handschuh H (2003) Security analysis of SHA-256 and sisters. In: International workshop on selected areas in cryptography. Springer, pp 175–193
39. Haber RB, McNabb DA (1990) Visualization idioms: a conceptual model for scientific visualization systems. Vis Sci Comput 74:93
40. Loscos E, Xie H, Koppelaar R (2020) Digital twin definitions for buildings—how to move digital twin environments to the AECOO sector. SPHERE Project
41. Stojanovic V, Trapp M, Hagedorn B, Klimke J, Richter R, Döllner J (2019) Sensor data visualization for indoor point clouds. In: Advances in cartography and GIScience of the ICA, vol 2
42. Sacks R, Eastman C, Lee G, Teicholz P (2018) BIM handbook: a guide to building information modeling for owners, designers, engineers, contractors, and facility managers. Wiley. ISBN: 9781119287544
43. Lamb K (2018) Blockchain and smart contracts: what the AEC sector needs to know
44. Bartoszewski D, Piorkowski A, Lupa M (2019) The comparison of processing efficiency of spatial data for PostGIS and MongoDB databases. In: International conference: beyond databases, architectures and structures. Springer, pp 291–302
45. Sayeed S, Marco-Gisbert H (2019) Assessing blockchain consensus and security mechanisms against the 51% attack. Appl Sci 9(9):1788

Collective Digital Factories for Buildings: Stigmergic Collaboration Through Cryptoeconomics

Theodoros Dounas, Davide Lombardi, and Wassim Jabi

Abstract The chapter describes conceptually how a blockchain (BC), through smart contracts (SC) and tokenisation, can act as a stigmergic information layer for the creation of collective digital factories in construction. The chapter focuses on the orchestration of a series of design agents and tools in the design of buildings; however, the presented framework can be extended to the whole lifecycle of the AEC industry. Furthermore, a cryptoeconomics-like strategy for the AEC industry is explored, based on smart contracts, having the potential to operationalise the stigmergic coordination via token incentive mechanisms. We expect that stigmergic coordination through cryptoeconomic incentives on the blockchain is a better fit for the fragmented nature of the construction industry, compared to current modes of organisation; consequently, the scope for presenting this strategy is threefold: the incentives mechanism can lead to an increase in productivity, a reduction in both whole-lifecycle carbon and waste, and a decentralised governance through smart contracts. While blockchain and decentralised ledger technologies have proven to have the potential to be embedded deeply as an information governance layer in many industries, the scope within the paper is limited to the digital aspects of the AEC industry, forming what we call "collective digital factories". An engagement strategy of the manufacturing sector of the AEC industry is presented with arising open questions discussed at the end.

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1 Introduction

Value in Architectural design is a controversial subject, as it normally is related to the cost of a building rather than the value of the act of design. Academic and professional sources that reference value in architectural design tend to come from allied disciplines in evaluating costs of design, for example, quantity surveying [RICS source] or specifiers [7, 15].

Value is also ascribed to the level of control an individual or group has over the design of a building [15], where a sense of ownership for the design will develop in the designer, by having a high degree of autonomy and control in making decisions. Architectural design, however, is not a solitary act. It involves a variety of stakeholders, and in most cases encompasses groups of architectural designers working together to achieve a common goal. Design Value is the value attached to the design specification in relation to cost. In that sense, value management or value engineering exercises are driven towards cost reduction against a requirement specification for the client. As such, architects have surrogated value and the discussion around value to other professions, whether these are specifiers or quantity surveyors or construction managers, that value and cost estimate the physical object of the building. In a similar manner, the Target Value Design process structures design processes that work towards the budget the client has available, instead of designing, then evaluating the design, and then optimising the existing design to fit the available budget. Target Value Design "relies on clusters of collaboration organised by systems (e.g. envelopes, structures, mechanical)" [38]. Tillman et al. [40] have found that costs in TVD appearing in three categories, (a) product design (b) process design, and (c) service design. Product design affects the design and costs associated with the building itself, process design impacts the costs of the building production system, and service design affects the service and maintenance of the building. Design activity however is when the true value gets created [3] as the designer brings the process of physical resources together in a coordinated manner. These value judgements by the designer are executed according to Broadbent, via the comparison and relative performance of parameters and conflicting factors that are inherent into the design process. In a sense, value in the design arises from the act of prioritising one parameter over another.

Within the chapter, we develop a strategy that allows architectural designers to do just that, and as an operational example, we present how our strategy can be used to prioritise the performance of designs in terms of carbon and waste impact (where the designs minimise them) and productivity in design (where the designs maximise it).

Our strategy employs blockchain and a schema of tokens implemented unto smart contracts. The schema of tokens binds the designers and the digital tools they use in what we call collective digital factories for the design of buildings.

To help the reader, the chapter structure is presented thus: First, some definitions are briefly introduced on BC, SC, tokens and DAOs, then secondly a discussion on productivity, carbon and waste impact of the AEC industry is briefly discussed, to explain why we have chosen these parameters to embed value. Thirdly, stigmergic collaboration is discussed as applied to the design process of a building, and fourthly our BC/SC framework is presented that creates the collective digital factories for buildings, using cryptoeconomic incentives to address issues of productivity, carbon, waste.

2 Blockchain and Decentralised Ledger Technologies

Blockchain in the context of this paper is meant as a decentralised ledger, hosted in a distributed nodes network where each node retains a copy of the ledger and has an algorithmic mean to arrive at a consensus. This does not prejudice specific algorithms over others, as long as they are reliable and elect to record the truth. Transactions or changes on the network are batch-recorded cryptographically into blocks of information, where each block contains the cryptographic hash of the previous block. As such blockchains are very difficult to tamper with their data but also impossible to erase entries on them in the past [33].

3 Smart Contracts: Tokens and Incentives

The blockchain is essentially a distributed state machine that records its current state, but also has the means to change it. To do so a virtual machine is introduced, run by all nodes on the network, so that the machine runs software codes to effect change, called "Smart Contracts". Smart Contracts are the equivalent of a software vending machine: with the introduction of a token the machine executes an action automatically and reliably. This allows us to encapsulate relationships, rules, incentives, and other functions on the blockchain. Within a smart contract, developers can encode tokens and incentive systems that can enable a particular behaviour or shape collective efforts towards a desirable goal in the ecosystem the smart contract is operating within. As such, Smart Contracts can be also used to produce work. Tokens, encoded within smart contracts, are used as proxies for the value and functionality of the system.

Within the tokenisation analysis, we examine here, there are three types of tokens that are used in the system we describe: Utility Tokens, used to access functionality, Security tokens which represent the value in an underlying asset, and Payment Tokens used to pay in transactions. Each token can integrate more than one type of function. All these can be either Fungible or Non-Fungible: Fungible tokens, are used when we need to create tokens that are interchangeable, with each other, Non-Fungible Tokens, are used to denote a unique digital asset—and if a trustworthy bridge exists, a unique physical entity.

4 Decentralised Autonomous Organisations (DAOs)

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5 Methodology

The chapter uses hybrid methods to develop: Literature review has helped extract the key knowledge for each section of the chapter, while a combination of design research and software conceptual prototyping has been applied for the latter parts of the chapter. The literature review provided secondary data while the conceptual prototyping and the design research provided primary data to inform the strategy discussed in the end. To be able to address issues of carbon, waste and productivity we propose the integration of early architectural design tools (including capabilities for simulation and validation) with the governance of the project via blockchain smart contracts, where the decrease in carbon impact and waste and the increase in productivity are coupled with economic incentives on the smart contracts. The description of this coupling takes place through the lens of Stigmergic collaboration. Stigmergic collaboration provides the coordination mechanism within the context of the AEC industry. The mechanisms we are proposing can be framed as collective design processes, rather than as a single sequence of authoritative design processes by a single person, even though they can be used for that as well.

6 Productivity

Construction in the past two decades has underperformed, as it has shown only a 1% productivity growth, while it represents a 13% of the global industrial base. Hasan et al. [23], in a 30 years systematic review of the factors impeding productivity in construction, mention the scarcity or "non-availability of materials, inadequate supervision, skills shortage, lack of proper tools and equipment and incomplete drawings and specification". At the same time, they mention that researchers have not examined processes in construction and project culture along with the implications of technology in productivity [8]. Loosemore [31] examines the often-neglected point of view of subcontractors in construction productivity; furthermore, the studies find that productivity from the subcontractors' point of view is framed on the quality of the relationships with the principal contractors, the opportunity for early involvement in design transparent tender practices, document control and design management, along with planning, scheduling, coordination and risk management.

In 2015, the Farmer review [18] found that non only the construction industry was not productive, but also that the level of profits did not warrant a further investment in innovation and productivity improvements, which along with a chronic skills shortage created a vicious cycle [28]. Within that framework, Heiskanen [24] mentions innovative, socio-technical mechanisms leading to explosive advances in capability and productivity, by doing three things at once: engender trust between stakeholders, standardise essential information, and rationalise the cost of production.

7 Supply Chain Integration in the AEC Industry

The impact of organisational structures on productivity can not be addressed without discussing the structure of supply chains. These structures in sequence have a deep impact on the value chain of the AEC industry, and due to the low productivity of the construction industry globally [32] they are subject to disruption by new organisational structures and models. The shifts taking place though in sustainability requirements, costs, skills scarcity [18], materials and industrial approaches [41], digitisation [11] and the emergence of a new class of industrial competitors in the face of digital companies entering the construction industry, are set to transform the production of the value chain. Some of the future trends predicted by the McKinsey report "the new normal" in construction include Value-Chain Control and integration with industrial-grade supply chains, consolidation, and sustainability. Within the emergence of industrial-grade supply chains, the importance lies within modularisation and off-site production, and the shift of the construction supply chain towards a product and assembly-based approach. This industrial shift, coupled with digitisation of products and services, leads to various strategies where companies attempt to integrate design with the value chain [30] by harnessing the collaborative power of Building Information Modelling, shifting crucial decision-making early in the design and construction process rather than have construction and design run in parallel modes. The employment of BIM, and the incorporation of scheduling and cost as additional information layers, along with automated parametric design and the use of blockchain technologies have the potential to radically transform construction.

8 Carbon Impact

Low carbon materials and efficiencies in the operation of buildings are considered two of the mitigation solutions to the emissions of greenhouse gases that contribute to climate change. (IPCC report, [4] Chap. 4). "Built environment is responsible for significant use of energy (62%) and is a major source of greenhouse emissions (55%) [2] Embodied carbon and carbon from operational use are the dominant factors in the environmental impact of a built asset, with the construction phase surprisingly contributing only 2%. Embodied carbon and operational carbon are interrelated: decreasing one, increases the other. Significant gains in both are possible with optimised architectural designs. In parallel, carbon efficiencies are interconnected with supply chain structure, which in turn is integral to the social and economic aspects of the Architecture-Engineering-Construction (AEC) industry, making the carbon impact of the built environment a difficult problem to solve. As such an interdisciplinary collaboration framework that allows AEC stakeholders to create improved carbon mitigation and adaptation strategies is needed [35]. Such a collaboration framework may be thought to exist within Building Information Modelling (BIM) paradigm, however, the paradigm has so far not delivered radical improvements in carbon reductions due to the complexity of the models being used, lack of interdependence, and data on supply chains, lack of stakeholders' engagement, and non-availability of carbon performance data in the full life-cycle analysis.

9 Policy and Carbon Incentives in the AEC Industry

The AEC industry is a fragmented industry with various stakeholders having friction in collaboration due to misaligned incentives in the delivery of projects. This leads to reduced productivity, increased waste, and conflicting economic and environmental scopes and targets that have an impact on carbon-equivalent emissions. In parallel, the reduction of embodied carbon and operational carbon emissions are not aggressively scoped into legislation as they are perceived to create an economic performance deficit for the industry. Economic decisions are taken by building users and industry stakeholders affect the environmental outcome of the design and construction of buildings, embedding chronic issues with little momentum for change, despite the various government's efforts to introduce Building Information Modelling in the industry to address this.

Others such as Stadel et al. [39] propose to tackle the carbon issues faced by the industry via integration of carbon accounting with Building Information Modelling. Within this integration, it becomes apparent that certain BIM tools (aggregate the lifecycle assessment information for many off the building components in their database and as such the designer/researcher needs to disaggregate the data from the components. This leads to a need for a better, more accurate and well accounted process for accounting for embodied carbon in the design process. Certain practices in the UK for an example, also believe in the same processes resulting in the creation of dedicated embodied carbon accounting plugins [37]. Fenner et al. [20] take a holistic look at the Lifecycle assessment of the buildings and focus on which parts of the lifecycle should most mitigate actions. They find great discrepancies in the measurement of carbon emissions amongst the literature. The result is that the construction part of an asset does not account for much in the Lifecycle Carbon Assessment process, however the production phase of the asset and the operational phase account for the majority of emissions. The paper also calls for the creation of a benchmark system that can be used to compare carbon intensities among buildings and help inform policy and design. Within this policy envelope, Evans et al. [16] call for the forging of an environmental governance, where the management of carbon emissions is transformed into an issue of carbon governance, executed in parallel with a transition to a low carbon economy. They identify then three types of experimental governance: policy, technology, and urban laboratories. The latter is a type of experimental governance project, a policy envelope where decarbonisation is married with economic development. These projects are normally run with a heavy research university involvement and develop an integration with their urban context to avoid a kind of "island" effect in their relationship with the city. Within the example they provide in the Manchester's Oxford corridor, they mention that the pooling of resources of a range of stakeholders, can result in reducing ecological impact and increasing economic growth, if the stakeholders orchestrate the resource utilisation in a coordinated manner. Within the Oxford Road experiment, they describe the use of embedded IoT sensors to examine and test not only the carbon performance but also the ecological performance of various materials in an urban setting. They use then the data to inform policy of where to plant trees, resulting in an ever-optimised recursive cycle, as the planting of trees will in turn inform the data in the future. We can reflect though that the governance of this type of projects focuses on quantitative measurements in a wider technocratisation of decision-making approaches, which are not always easy for the public, non-expert stakeholders to participate in [16].

We can understand from all this that carbon reduction in the built environment extends beyond simple technical decisions in the design and construction of the building but extend to the supply chain and its integration with the design process. Subsequently, policy, governance and technical decisions need to be orchestrated in a socio-technical framework that is both informed by data also in such a manner where data and evidence from it are applied in a recursive manner of continuous improvement, both in the same project but also globally from project to project. The challenge thus is to conceive and maintain methods of project governance that optimise and reduce carbon, with the most important areas of focus being embodied and operational, but also do it via collective governance.

10 Stigmergy and Coordination

While we might be able to look at Common Pool resources problems and Ostrom Design Principles [27, 34] to be able to structure the boundaries of the local environment where design collaboration might occur [22], the structure and mechanisms of the collaboration still remain a question. For this, we turn to stigmergy.

Grassé [21] created the term Stigmergy (stigmergie in the original French), combining the Greek words stigma (meaning sign) and ergo (meaning work), signalling that previous work signals and triggers new building actions in ant colonies. His was essentially a decentralised informational infrastructure used by social insects like ants to build their lairs. A variant of stigmergy where the building is the medium that carries information is through pheromones, biological material that insects leave behind to signal the importance of a path to other insects.

Cybernetician Heylighten [25] discusses stigmergy as a universal coordination mechanism, analysing its basic components and dimensions. Within Heylighten's analysis stigmergy is presented as an example of self-organisation, a mechanism to provide spontaneous ordering. Delving within the mechanisms that structure stigmergy, Heylghten discusses stigmergy as a state machine with production rules, where the rules affect and change the state, and the state provides feedback and direction on where the rules need to be applied within a body of "work". Forming this parallel, Heylighten frames condition as the antecedent of the state and action as the consequence of the state, where the condition is the current state of the world, and action changes that state to form a new condition (Fig. 1).

Heylighten's definition of stigmergy does not need or necessitate the concept of the agent as a decision-maker, instead, stigmergy is defined with ignorance on the agent level, with agent-less process, for example, physical events or processes. This in effect makes stigmergy as a concept compatible with the notion of creating collaborative work using the blockchain, as within the blockchain automation actions change

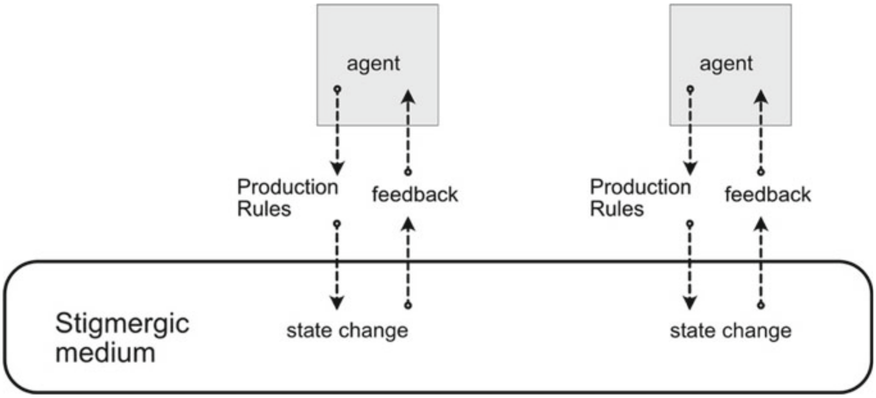


Fig. 1 Stigmergy Medium and production rules, drawn by the first author

the current state to a new one. Agents do participate in the system, but only when defined as external to the blockchain actor. Additionally, the medium of stigmergy, for example, lumps of muds for termites, is forming the state itself, and undergoes changes through actions, whose states are sensed as conditions for other subsequent actions. Hence the medium, in our case the blockchain, carries the communication between subsequent actions, and coordinates indirectly the agents that act stigmergically. Constructed within the medium, the overall goal of the system is encoded. To provide an example, Heylighten describes the problems of coordination in construction, that arise from planning and from its contingencies and structural interconnectedness and points to well-established issues of coordination in construction. With this description, a proposal is made for a website where all construction actions and states are recorded by construction workers so that everyone has the most up-to-date, current state of affairs in their hands, a description that sounds accurately like a decentralised ledger that records all action.

Stigmergic coordination in construction is also analysed by Christensen [6], in an effort to provide a self-organised, emerging framework for collaboration in construction. Initially, Christensen compares and contrasts Stigmergy with other coordination and collaboration concepts. Specifically, stigmergy is compared to articulation, awareness, feedthrough. With all three concepts, stigmergy is unique in the sense that it differs from having to develop the work and an articulation about the work (articulation) nor is it needed to develop awareness for certain activities for certain workers (awareness) as stigmergic means already plays that role globally for the system of work, while also it differs from a conduit metaphor, where workers communicate through the feeding information through artefacts, as actors engaged in Stigmergy have a different basis for their actions than telementation. Still construction workers pay heed to the material evidence of work previously executed, while performing their own tasks, a very strong indication that construction activities are stigmergic. This incorporates the idea that workers coordinating through the material field of work are mindful of the material work that needs to be developed by others in the future, rather than just paying heed to work accomplished in the past.

Similarly, architectural design is coordinated by the virtue of actors paying heed to the material evidence of work previously accomplished by others while performing their own tasks, and concurrently, design is paying heed to the tasks that need to be done in the future as part of a larger AEC project. Within that, design agents can be configured to collaborate using blockchain smart contracts [10–13] in a transparent, agile, stigmergic manner, where the material artefact of the blockchain is integrated with the digital tools the architects use [9]. Additionally, framing this stigmergic design collaboration is the common pool resource problem of minimising carbon impact, waste and increasing productivity while integrating the design system with the supply chain information of the AEC project.

Albrecht discusses decentralised supply chain planning along with coordination mechanisms for supply chain planning, which for construction would contribute towards a solution. Albrecht discusses the lack of coordination in decentralised planning of supply chains and sets forward the need for collaborative planning and the need to motivate or incentivise coordination. Notably he writes this in 2009, just before the first blockchain appears. Within decentralised planning, he notes that without a system-wide optimum, the profits are generated mainly for the large players within the system, and to counter that argues for optimal coordination. This then introduces the understanding of a coordination system: “A coordination scheme is a set of rules specifying actions whose implementation by decentralized parties potentially coordinates a system” [1].

Which then is upgraded into a coordination mechanism: “A coordination mechanism is a mechanism for which the implementation of the optimal strategies by decentralized, self-interested parties may lead to a coordinated outcome and neither violates the individual rationality of the participating parties nor the budget balance of the system.” Within decentralised planning as such Albrecht identifies information asymmetry as one of the main reasons why decentralised planning might fail: i.e. not all participants have the best information possible. The alternative, of sharing private data with everybody, is identified as problematic, as it might lead to the loss of a competitive advantage. As such the mathematical models developed up until then discuss only the planning that one participant in the supply chain will execute not the decentralised planning as a whole supply chain, coordinating every aspect of supply. Albrecht provides examples of early or late decentralised supply chains that result in suboptimal execution, even if all parties agree to upstream planning, i.e. planning with the needs of the buyer in mind, and proposes “collaborative” planning as the solution to the sub-optimisation of supply chains.

11 Stigmergy and Coordination

The mechanism that we propose uses stigmergy, realised through cryptoeconomic incentives, to integrate digital design tools with smart contracts, so that the carbon impact, waste reduction and productivity increase in AEC can be achieved.

Architectural design has a large impact on the carbon, waste and productivity performance of an AEC project as already discussed previously. Still, this impact can be managed strategically in an improved manner if the value in the design shifts from optimising impact to directly addressing it. For carbon, the material and supply chains choices in the design stage affect the embodied carbon impact of the project, while the whole design and its operation has a direct impact on the operational energy use of the building, hence its carbon footprint during operations. Waste, is also part of the equation here, as the architectural design can via elegantly constructed geometry, supply chain choices and strategic choices of methods of construction embedded within design, directly increase and decrease waste. Productivity in the AEC sector, more so in construction, also firstly is affected by design choices and the complexity with which one develops a design.

Additionally to these, Building Performance is of course directly affected by design choices and as such forms part of the goal and part of the incentives’ scheme. Beyond the design phase the operational framework we present forms a smaller part of a larger ecosystem which is designed to incentivise the same behaviour in all other phases of a project (construction and assembly, operations and then decommissioning). The mechanism that we propose for design works best then as part of a larger cryptoeconomic shift in the manner in which AEC projects are run.

12 Smart Contracts Architecture and Project Lifecycle

We propose this to introduce collective digital factories for buildings, a form of Decentralised Autonomous Organisation (DAO), the collective digital factories for buildings, that tackles through cryptoeconomics issues of waste, carbon, performance, and productivity.

The collective factories for architectural design consist of a series of design agents (Fig. 2) that collaborate in assuming an architectural design work, four smart contracts that regulate the "factory" and three tokens that are used for incentivising

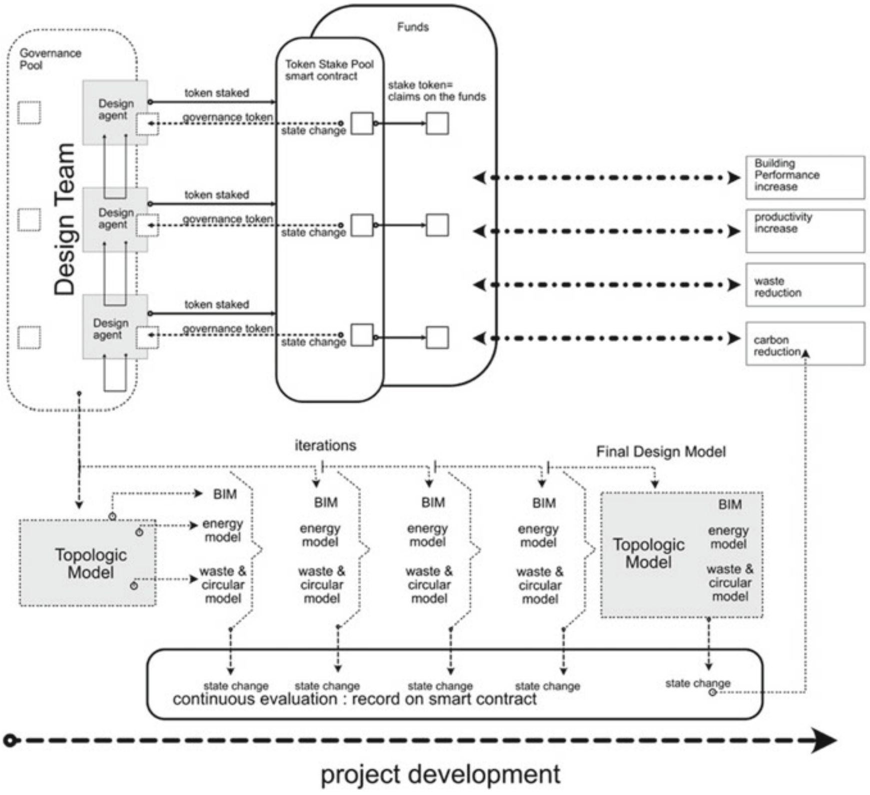


Fig. 2 Collective digital factories for architectural design, drawn by the first author

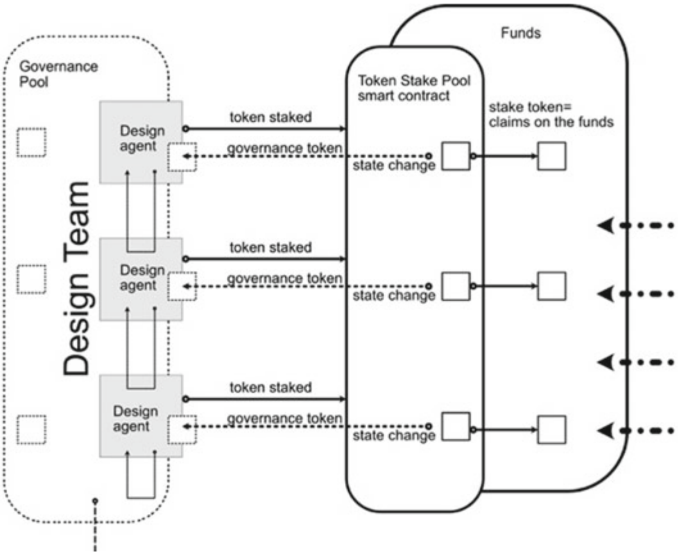


Fig. 3 Stake, governance and funds token setup, connected with the design agents and the performance targets, drawn by the first author

work towards carbon and waste reduction, increase in productivity and building performance (Fig. 3).

The design agent each "lock" their tokens A on the smart contract that regulates participation, by staking them. This acts both as a declaration that they are working on the problem and also as claims function on the larger pot of funds that is funding the project. The staked tokens have a claim on the funds smart contract that funds the project.

Each design agent then receives a proportion of governance tokens G, in exchange for their stake in the project. The governance tokens are used for voting on design proposals, or as utility tokens to be able to write in the smart contracts that measure/validate design performance (Fig. 4).

Access to the DAO is provided via a Non-Fungible Token contract that plays the role of an ID system, that also records each agent's abilities and track record. We use a modified ERC721 contract to represent these abilities, within a struct, i.e. with an on-chain information rather than with referencing metadata. The NFT also contains a state function that activates it by requiring validation by other agents-members of the DAO, acting hence as an onboarding mechanism [17] (Fig. 5).

The Staking contract uses a modified ERC20 fungible smart contract code with special functions on adding an agent as a stakeholder, creating stakes and rewards and functions that connect the staking with the rewards. For security purposes the rewards are not automatic, but use a push–pull mechanism, i.e. the agent needs to activate the reward [14]. This protects against spoofing attacks on the staking contract, where attackers might trigger mechanisms through which funds are sent automatically to

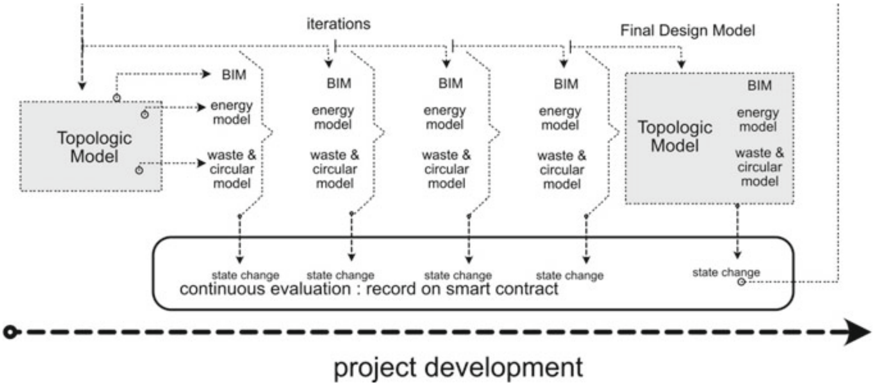
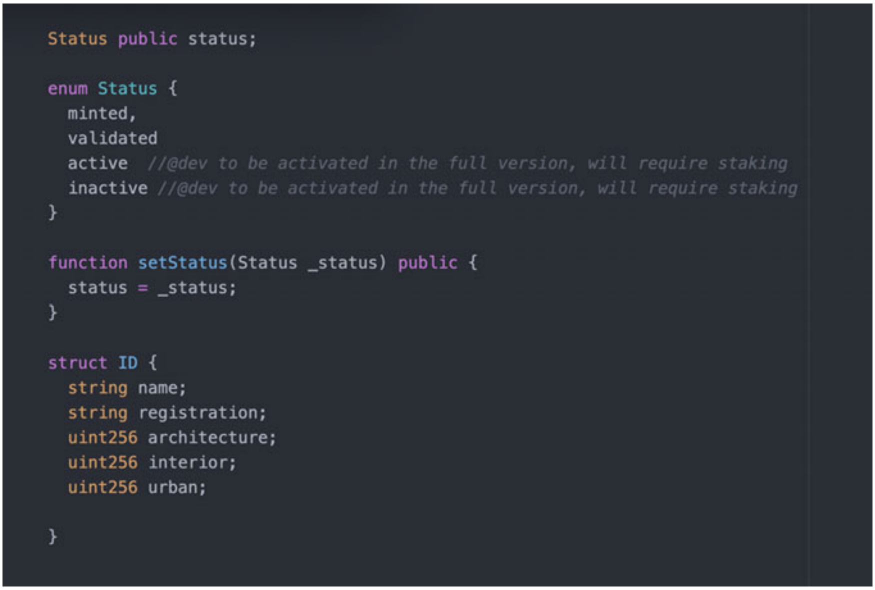


Fig. 4 Iterative design connected with a smart contract on the blockchain, drawn by the first author



```
Status public status;

enum Status {
  minted,
  validated
  active  //@dev to be activated in the full version, will require staking
  inactive //@dev to be activated in the full version, will require staking
}

function setStatus(Status _status) public {
  status = _status;
}

struct ID {
  string name;
  string registration;
  uint256 architecture;
  uint256 interior;
  uint256 urban;

}
```

Fig. 5 Modified ERC721 solidity smart contract code. The rest of the contract uses the OpenZeppelin ERC721 template, code written by the first author

an unauthorised account. The push–pull mechanism prevents that (Figs. 6, 7, 8 and 9).

For the governance tokens, we use a standard OpenZeppelin template with governance functionality added. While there are many alternative governance models, for example, from lazy consensus, where voting is not required but there are dispute mechanisms to stop undesirable actions by certain agents, within our present example we use a voting system that allows agents to only record solutions that have clear

```
//@dev staking mechanisms start below.
address[] internal stakeholders;

function isStakeholder(address _address)
       public
       view
       returns(bool, uint256)
   {
       for (uint256 s = 0; s < stakeholders.length; s += 1){
           if (_address == stakeholders[s]) return (true, s);
       }
       return (false, 0);
   }

   /**
    * @dev A method to add a stakeholder.
    * @param _stakeholder The stakeholder to add.
    */
   function addStakeholder(address _stakeholder)
       public
   {
       (bool _isStakeholder, ) = isStakeholder(_stakeholder);
       if(!_isStakeholder) stakeholders.push(_stakeholder);
   }

   /**
    * @dev A method to remove a stakeholder.
    * @param _stakeholder The stakeholder to remove.
    */
   function removeStakeholder(address _stakeholder)
       public
   {
       (bool _isStakeholder, uint256 s) = isStakeholder(_stakeholder);
       if(_isStakeholder){
           stakeholders[s] = stakeholders[stakeholders.length - 1];
           stakeholders.pop();
       }
   }
```

Fig. 6 Modified ERC20 staking smart contract, code written by the first author, on a solution by Alberto Cuesta Cañada

collective benefits. A DAO can always decide to modify its governance model and this will be reflected in the on-chain/off-chain mechanisms (Fig. 10).

13 Digital Design Tools: Topologic

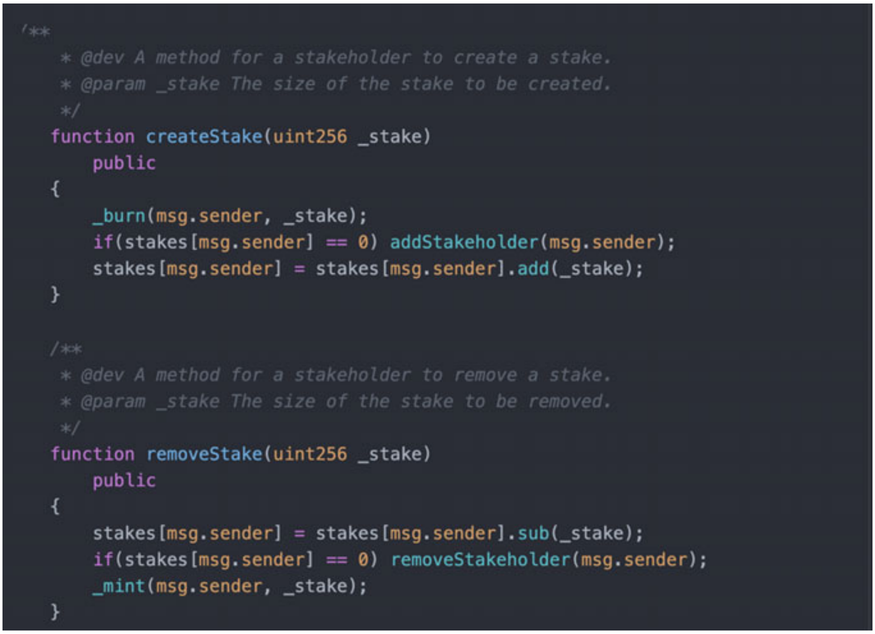
The tools the digital factories use are shaped for integration with smart contracts and a web3 approach. Within our paradigm presented here, the digital factories use Topologic as the main digital tool for design [29].

Topologic is a software system that supports the creation of succinct spatial models that encode new layers of information and enable deeper analysis. Topologic uses

```
// @dev the stakes for each stakeholder

mapping(address => uint256) internal stakes;

/**
    * @notice A method to retrieve the stake for a stakeholder.
    * @param _stakeholder The stakeholder to retrieve the stake for.
    * @return uint256 The amount of wei staked.
    */
   function stakeOf(address _stakeholder)
       public
       view
       returns(uint256)
   {
       return stakes[_stakeholder];
   }

   /**
    * @notice A method to the aggregated stakes from all stakeholders.
    * @return uint256 The aggregated stakes from all stakeholders.
    */
   function totalStakes()
       public
       view
       returns(uint256)
   {
       uint256 _totalStakes = 0;
       for (uint256 s = 0; s < stakeholders.length; s += 1){
           _totalStakes = _totalStakes.add(stakes[stakeholders[s]]);
       }
       return _totalStakes;
   }
```

Fig. 7 Modified ERC20 staking smart contract showing stakes, code written by the first author, on a solution by Alberto Cuesta Cañada

boundary representation (brep) as the basis of its models. Objects in Topologic are represented by one or more Vertices, Edges, Wires, Faces, Shells, Cells, CellComplexes, and Clusters. A Vertex represents a location in space stored as three coordinates (X, Y, Z). An Edge is a line in space represented by its start Vertex and end Vertex. A Wire is represented by a set of connected Edges in any configuration. Edges in a Wire must connect through shared Vertices. A Face is a surface that is represented by one external boundary (a closed Wire) and a set of internal boundaries (a set of closed Wires) that represent holes in the Face. A Shell is represented by a set of connected Faces in any configuration. Faces in a Shell must connect through shared Edges. A Cell is a volume of space that is represented by an external boundary (a closed Shell) and a set of internal boundaries (a set of closed Shells) that represent voids in the Cell. A CellComplex is represented by a set of connected Cells in any configuration. The Cells in a CellComplex must connect through shared Faces. Lastly, a Cluster is represented as an ad-hoc group of objects in any configuration.



```
/**
 * @dev A method for a stakeholder to create a stake.
 * @param _stake The size of the stake to be created.
 */
function createStake(uint256 _stake)
    public
{
    _burn(msg.sender, _stake);
    if(stakes[msg.sender] == 0) addStakeholder(msg.sender);
    stakes[msg.sender] = stakes[msg.sender].add(_stake);
}

/**
 * @dev A method for a stakeholder to remove a stake.
 * @param _stake The size of the stake to be removed.
 */
function removeStake(uint256 _stake)
    public
{
    stakes[msg.sender] = stakes[msg.sender].sub(_stake);
    if(stakes[msg.sender] == 0) removeStakeholder(msg.sender);
    _mint(msg.sender, _stake);
}
```

Fig. 8 Modified ERC20 staking smart contract creating and removing stakes, code written by the first author, on a solution by Alberto Cuesta Cañada

The aforementioned objects are hierarchically connected which allows the user to deconstruct any object into its constituent sub-topologies. For example, a CellComplex can be decomposed into its constituent Cells which in turn can be decomposed into Faces, Edges, and Vertices. This hierarchical connection is bi-directional which means that lower-dimensional entities can be queried for the higher dimensional parents of which they are a member. It is important to note that objects in Topologic are spatially resolved which means that overlapping entities do not exist. For example, if we ask a Cube (Cell) for its number of Faces, Edges, and Vertices, the answer will be six (6), twelve (12), and eight (8), respectively. There is no need in Topologic to check for overlapping entities and to remove redundant shapes.

In addition to bi-directional hierarchical connectivity, Topologic supports bi-directional lateral connectivity. This means that you can query a Topologic entity for any of its adjacent entities. For example, you can ask a Cell in a CellComplex for its adjacent Cells (neighbours) that share a Face with it. You can also ask two entities to return any shared entities between them (e.g. ask two Cells in a CellComplex to return the face that they share).

More formally, one can implement the above as a topological graph made of vertices and edges where a vertex (V) represents any entity in a Topologic model, and an edge (E). In fact, Topologic implements a Graph class that can convert any Topologic model into a graph. This allows the user to apply graph theory to analyse the

```
/**
 * @dev A simple method that calculates the rewards for each stakeholder.
 * @param _stakeholder The stakeholder to calculate rewards for.
 */
function calculateReward(address _stakeholder)
    public
    view
    returns(uint256)
{
    return stakes[_stakeholder] / 100;
}
 //@dev A method to distribute rewards to all stakeholders.
function distributeRewards()
    public
    onlyOwner
{
    for (uint256 s = 0; s < stakeholders.length; s += 1){
        address stakeholder = stakeholders[s];
        uint256 reward = calculateReward(stakeholder);
        rewards[stakeholder] = rewards[stakeholder].add(reward);
    }
}
/**
 * @notice A method to allow a stakeholder to withdraw his rewards.
 */
function withdrawReward()
    public
{
    uint256 reward = rewards[msg.sender];
    rewards[msg.sender] = 0;
    _mint(msg.sender, reward);
}
```

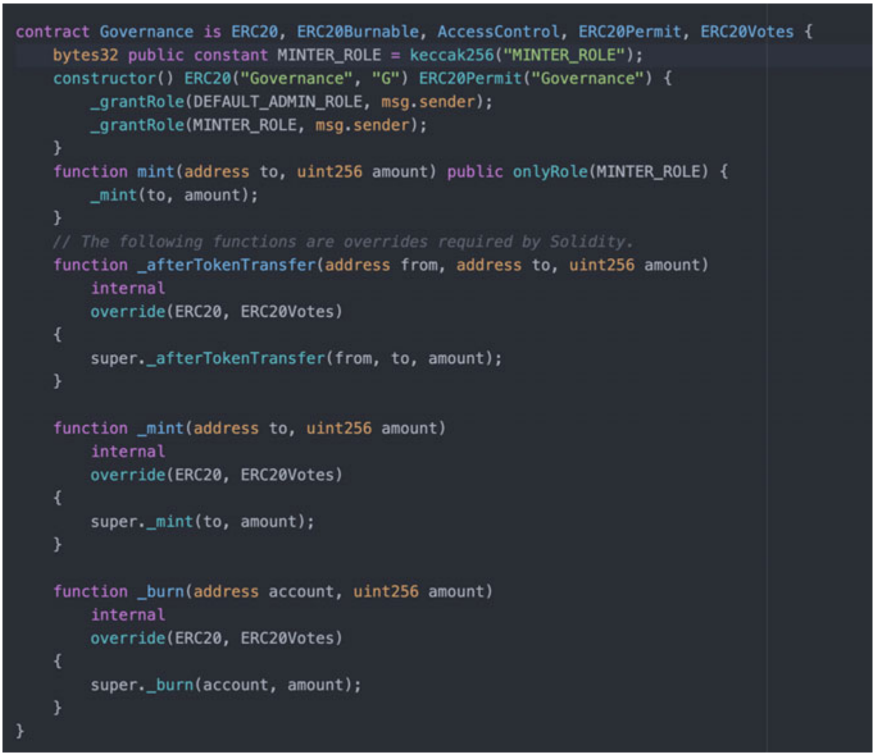
Fig. 9 Modified ERC20 staking smart contract showing rewards, code written by the first author, on a solution by Alberto Cuesta Cañada

model including computing the shortest distance between elements and measuring the centrality of vertices in a graph among others.

Topologic also allows the user to store ad hoc entities within other entities in the model using a Content/Context mechanism. This type of relationship is many-to-many in that an object can exist as the content within more than one entity and thus it can exist in more than one Context. For example, a window entity can be stored in the contents of the wall to which it belongs, but also in the contents of the room to which it also belongs. In this case, one can say that the window exists in the two contexts: The context of the wall, and the context of the room.

Topologic allows the user to modify entities and build more complex entities according to constructive solid geometry (CSG) rules.

Beyond geometry and topology, Topologic supports the encoding of semantic information through the creation of dictionaries. A dictionary stores an ad hoc set



```
contract Governance is ERC20, ERC20Burnable, AccessControl, ERC20Permit, ERC20Votes {
    bytes32 public constant MINTER_ROLE = keccak256("MINTER_ROLE");
    constructor() ERC20("Governance", "G") ERC20Permit("Governance") {
        _grantRole(DEFAULT_ADMIN_ROLE, msg.sender);
        _grantRole(MINTER_ROLE, msg.sender);
    }
    function mint(address to, uint256 amount) public onlyRole(MINTER_ROLE) {
        _mint(to, amount);
    }
    // The following functions are overrides required by Solidity.
    function _afterTokenTransfer(address from, address to, uint256 amount)
        internal
        override(ERC20, ERC20Votes)
    {
        super._afterTokenTransfer(from, to, amount);
    }

    function _mint(address to, uint256 amount)
        internal
        override(ERC20, ERC20Votes)
    {
        super._mint(to, amount);
    }

    function _burn(address account, uint256 amount)
        internal
        override(ERC20, ERC20Votes)
    {
        super._burn(account, amount);
    }
}
```

Fig. 10 Modified ERC20 governance smart contract G code written by the first author based on the ERC20 OpenZeppelin

of keys and values. Dictionaries can be associated with an entity as well as with its sub-topologies. For example, a Cell can have a dictionary describing its attributes. In addition, the Cell's Faces can each have their own dictionaries, their Edges, and Vertices can also each have their own dictionaries. This allows for granular and hierarchical encoding of information in a Topologic model. Dictionaries can affect and be affected by geometric Boolean operations. New entities that emerge for such operations can inherit and merge the dictionaries of their parents. For example, if a Cell named "*A*" is merged with another Cell named "*B*" the resulting intersection will automatically inherit and merge the dictionaries of the parent cells resulting in its name being listed as (*A*, *B*). Lastly, values in dictionaries can be retrieved at any point and used to affect the outcome of any geometric operation using pre-specified rules.

Through the extensive and unique features of Topologic, it has found several applications in the Architecture, Construction, and Engineering sector. Topologic has been used in the conceptual design phase to analyse a project before the complexity of building information modelling (BIM) sets in. Calculations of areas, volumes, centrality, congestion, and fit to adjacency requirements can all be conducted at an early stage in the design process. Topologic models with their inherent connectivity are also highly compatible with the input requirements of energy and structural analysis engines. One of the early applications of Topologic is Topologic Energy, which converts a Topologic model into a Building Energy Model (BEM) for analysis in openstudio/EnergyPlus [5].

Given the consistent, hierarchical, and connected nature of Topologic models have a consistent, hierarchical and connected nature, allowing shape grammar rules to be applied to the models to convert them into fully detailed BIM models ready for the design development stage. One such effort converted Topologic models (derived from Test Fit models) into Autodesk Revit models and a second effort converted Topologic models into highly detailed IFC models with embedded energy and structural models [36].

Topologic helps the designers build lightweight models with a spatial-information first approach, on top of which other information is overlayed, whether this is for energy usage, structural analysis or other. This makes Topologic highly useful in our model of collective digital factories for buildings as compared to a full BIM approach it allows the use of JSON files which are highly compatible with SC/BC, but also from an information data-wrangling perspective makes the development of variants of architectural design solutions more elegant than full BIM model approaches.

14 Design Tool Integration with Smart Contracts

Within the Collective Digital Factories, the agents apply iterative design through Topologic, to develop simple spatial models that organise the core of the AEC project. With each iteration, the Topologic diagram produces three different outputs: a BIM model, an energy model and a waste and circular economy model. Key parameters of performance of these models are measured and recorded on a "continuous evaluation" smart contract. To develop the next design decisions, the design agents use the governance tokens to participate in voting rounds for which model to develop next, but also their governance tokens identify them to the "continuous evaluation" smart contract of the system.

Through the state changes in the "continuous evaluation" smart contract, one can have a stigmergic understanding of where the project lies in terms of performance, through a situation dashboard that all project agents use to display the achieved performance of their proposal. This reflects exactly the mechanisms that Heylighten predicts in his example of stigmergy in construction.

The state changes in the contract are then able to be reflected against specific targets for the AEC project in terms of carbon, waste productivity, and overall quality in regards to the performance of the building. Topologic can write directly to the smart contracts via simple scripting mechanisms written on python [43].

The cryptoeconomic loop closes then by increasing the value of the fund contract, allowing essentially the design agents to earn a higher value of the fund against their proportion of the staked tokens. To retrieve the funds, the designers need to run the process in reverse, by returning the staked tokens, which then can be swapped with the proportion of the funds that they can claim.

The structure of the tokens is developed as thus: the funds' tokens are fungible ERC20 tokens [42] that are used as a payment and funding mechanism. The governance tokens are fungible ERC20 tokens [17] that represent the design agent's their governance rights. A Non-Fungible ERC721 token represents the identity, competence and track record of the agent. This last part of the track record needs to be a dynamic part of the NFT, including the potential to be used in many other parts of the decision-making framework. The continuous evaluation smart contract records and activates via the governance tokens, in our case a weighted voting system. The state change of the continuous evaluation changes then the overall performance indices for carbon, waste, building performance and productivity.

15 Conclusions: Strategy and Constraints

We developed an incentives cryptoeconomics mechanism for Architectural Design teams in the AEC industry, that operates through stigmergic coordination, directly connecting the value of architectural design with carbon and waste reduction and productivity increase. The tight integration between tools such as Topologic and SC on a blockchain is key for our mechanisms, while the novelty lies in not only connecting carbon and waste reduction and increase in productivity with value in name only but directly through cryptoeconomics. The use of Topologic instead of a full BIM solution, allows for the creation of nimble, fast, accurate design iterations early in the design phase of the building, minimising the investment in time and effort that is frequently needed for developing full BIM models to test design solutions [26]. Further, our solution can be expanded to the whole lifecycle of a building incentivising full AEC teams for a particular performance, and shifting the value from immediate task-based gains to a better performance of the design and built asset. The intricacies of the mechanisms involved in the token design, have been modelled and proof-tested already in decentralised finance applications, however, the capital and entrenched structure of AEC projects make it difficult to test the mechanisms in a real project. Still our model, we posit, provides another step forward in proofing the validity of using cryptoeconomics in incentivising a better-built environment.

References

1. Albrecht M (2009) Supply chain coordination mechanisms: new approaches for collaborative planning. Springer Science & Business Media
2. Anderson JE, Wulfhorst G, Lang W (2015) Energy analysis of the built environment—a review and outlook. Renew Sustain Energy Rev 44(April):149–158. https://doi.org/10.1016/j.rser.2014.12.027
3. Broadbent G (1966) Design method in architecture. Architects' J 144:679–685

4. Chapter 4—Global warming of 1.5 °C (n.d.). https://www.ipcc.ch/sr15/chapter/chapter-4/. Accessed 17 Jan 2022
5. Chatzivasileiadi A, Lila AAM, Lannon S, Jabi W (2018) The effect of reducing geometry complexity on energy simulation results. In: eCAADe 2018: 36th annual conference, Lodz, Poland. https://orca.cardiff.ac.uk/111727/
6. Christensen L (2013) Stigmergy in human practice: coordination in construction work. Cogn Syst Res 21:40–51. https://doi.org/10.1016/j.cogsys.2012.06.004
7. Churcher D (2017) Value management and value engineering. RICS guidance note, UK. RICS
8. Dounas T, Laing R (2021) Programme for excellence for ICT skills in the AEC industry in Scotland. Zero-waste Scotland and Construction Scotland Innovation Centre
9. Dounas T, Lombardi D, Jabi W (2021) Framework for decentralised architectural design BIM and blockchain integration. https://doi.org/10.1177/1478077120963376
10. Dounas T (2019) Towards blockchains for architectural design—consensus mechanisms for collaboration in BIM'. In: Sousa JP, Xavier JP, Castro Henriques G (eds) Architecture in the age of the 4th industrial revolution—proceedings of the 37th ECAADe and 23rd SIGraDi conference, vol 1. University of Porto, Porto, Portugal, pp 267–274
11. Dounas T (2020) Smart contracts for decentralised building information modelling. In: Werner L, Koering D (eds) Anthropologic: architecture and fabrication in the cognitive age—proceedings of the 38th ECAADe conference, vol 2. TU Berlin, Berlin, Germany, pp 565–574
12. Dounas T (2021) Topology generated non-fungible tokens—blockchain as infrastructure for a circular economy in architectural design. In: Globa A, van Ameijde J, Fingrut A, Kim N, Lo TTS (eds) PROJECTIONS—proceedings of the 26th CAADRIA conference, vol 2. The Chinese University of Hong Kong and Online, Hong Kong, pp 151–160
13. Dounas T, Lombardi (2019) Blockchain grammars—designing with DAOs—the blockchain as a design platform for shape grammarists' decentralised collaboration. In: Haeusler M, Schnabel MA, Fukuda T (eds) Intelligent & informed—proceedings of the 24th CAADRIA conference, pp 293–302
14. ERC-20 Token Standard (n.d.) Ethereum.Org. Accessed 17 Jan 2022. https://ethereum.org.
15. Emmitt S, Yeomans D (2008) Specifying buildings a design management perspective, 2nd edn. Butterworth-Heinemann (Elsevier), Oxford
16. Enriken W, Shirley D, Evans J, Sachs N (n.d.) EIP-721: non-fungible token standard. Ethereum improvement proposals. https://eips.ethereum.org/EIPS/eip-721. Accessed 17 Jan 2022
17. Entriken W, Shirley D, Evans J, Sachs N (2018) EIP-721: non-fungible token standard [WWW Document], (n.d.). Ethereum improvement proposals. https://eips.ethereum.org/EIPS/eip-721 (Accessed 7.19.22)
18. Farmer-Review.Pdf (n.d.). https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2016/10/Farmer-Review.pdf. Accessed 17 Jan 2022
19. Farmer M (2016) The farmer review of the UK construction labour model. Construction leadership council. https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2016/10/Farmer-Review.pdf
20. Fenner AE, Kibert C, Woo J, Morque S, Razkenari M, Hakim H, Lü X (2018) The carbon footprint of buildings: a review of methodologies and applications. Renew Sustain Energy Rev 94:1142–1152. https://doi.org/10.1016/j.rser.2018.07.012
21. Grasse PP (1959) La theorie de la stigmergie: essai d'interpretation du comportement des termites constructeurs. Insectes Sociaux
22. Hall DM, Bonanomi MM (2021) Governing collaborative project delivery as a common-pool resource scenario. Proj Manage J 52:250–263. https://doi.org/10.1177/8756972820982442
23. Hasan A, Baroudi B, Elmualim A, Rameezdeen R (2018) Factors affecting construction productivity: a 30 year systematic review. Eng Constr Archit Manag 25(7):916–937. https://doi.org/10.1108/ECAM-02-2017-0035
24. Heiskanen A (2017) The technology of trust: how the internet of things and blockchain could usher in a new era of construction productivity. Constr Res Innov 8(2):66–70. https://doi.org/10.1080/20450249.2017.1337349

25. Heylighten F (2015) Stigmergy as a universal coordination mechanism: components, varieties and applications. Hum Stigmergy: Theor Dev New Appl. Springer
26. Holzer D (2011) BIM's seven deadly sins. Int J Archit Comput 9(4):463–480. https://doi.org/10.1260/1478-0771.9.4.463
27. Hunhevicz JJ, Brasey PA, Bonanomi M, Hall DM (2020) Blockchain and smart contracts for integrated project delivery: inspiration from the commons. In: EPOC 2020 working paper proceedings. Engineering Project Organization Society (EPOS). https://doi.org/10.3929/ethz-b-000452056
28. Industrial Strategy Government and Industry in Pa.Pdf (n.d.). https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/bis-13-955-construction-2025-industrial-strategy.pdf. Accessed 17 Jan 2022
29. Jabi W, Chatzivasileiadi A (2021) Topologic: exploring spatial reasoning through geometry, topology, and semantics. In: Eloy S, Viana DL, Morais F, Vaz JV (eds) Formal methods in architecture. Advances in science, technology & innovation. Springer International Publishing, Cham, pp 277–285. https://doi.org/10.1007/978-3-030-57509-0_25
30. Kedir F, Hall DM (2021) Resource efficiency in industrialized housing construction—a systematic review of current performance and future opportunities. J Clean Prod 286:125443. https://doi.org/10.1016/j.jclepro.2020.125443
31. Loosemore M (2014) Improving construction productivity: a subcontractor's perspective. Eng Constr Archit Manag 21(3):245–260. https://doi.org/10.1108/ECAM-05-2013-0043
32. McKinsey (2020) The next normal in construction: how disruption is reshaping the world's largest ecosystem. Ribeirinho MJ, Strube G, Sjödin E, Blancko J, Palter P, Biorck J, Rockhill D, Anderson T, McKinsey Report
33. Nakamoto—Bitcoin A Peer-to-Peer Electronic Cash System.Pdf (n.d.). https://www.ussc.gov/sites/default/files/pdf/training/annual-national-training-seminar/2018/Emerging_Tech_Bitcoin_Crypto.pdf. Accessed 17 Jan 2022
34. Ostrom E (2015) Governing the commons: the evolution of institutions for collective action, canto classics. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781316423936
35. Pomponi F, Moncaster A (2016) Embodied carbon mitigation and reduction in the built environment—what does the evidence say? J Environ Manage 181:687–700. https://doi.org/10.1016/j.jenvman.2016.08.036
36. Postle B (2021) 2022 Homemaker add-on. Python. https://github.com/brunopostle/homemaker-addon
37. Schwartz Y, Eleftheriadis S, Raslan R, Mumovic D (2016) Semantically enriched BIM life cycle assessment to enhance buildings' environmental performance
38. Silveira SS, Thais DC, Alves L (2018) Target value design inspired practices to deliver sustainable buildings. Buildings 8(9):116. https://doi.org/10.3390/buildings8090116
39. Stadel A, Eboli J, Ryberg A, Mitchell J, Spatari S (2011) Intelligent sustainable design: integration of carbon accounting and building information modeling. J Prof Issues Eng Educ Pract 137(2):51–54
40. Tillmann PA, Do D, Ballard G (2017) A case study on the success factors of target value design, pp 563–570. https://iglc.net/Papers/Details/1421
41. UK Government (n.d.) Industrial strategy: government and industry in partnership, p 78
42. Vogelsteller F, Butterin V (n.d.) EIP-20: token standard—ERC20: a standard interface for tokens. EIP: ethereum improvement proposals. https://eips.ethereum.org/EIPS/eip-20. Accessed 17 Jan 2022

Code

43. Dounas T, Jabi W, Lombardi D (n.d.) Archchain.Cc Github code repository. https://github.com/bimblockchain/dbim