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

J. Hunhevicz (✉) · D. M. Hall
ETH Zurich, Institute of Construction and Infrastructure Management, Chair of Innovative and Industrial Construction, Zurich, Switzerland
e-mail: hunhevicz@ibi.baug.ethz.ch

D. M. Hall
e-mail: hall@ibi.baug.ethz.ch

T. Dounas
Robert Gordon University, Aberdeen, Scotland
e-mail: t.dounas@rgu.ac.uk

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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.

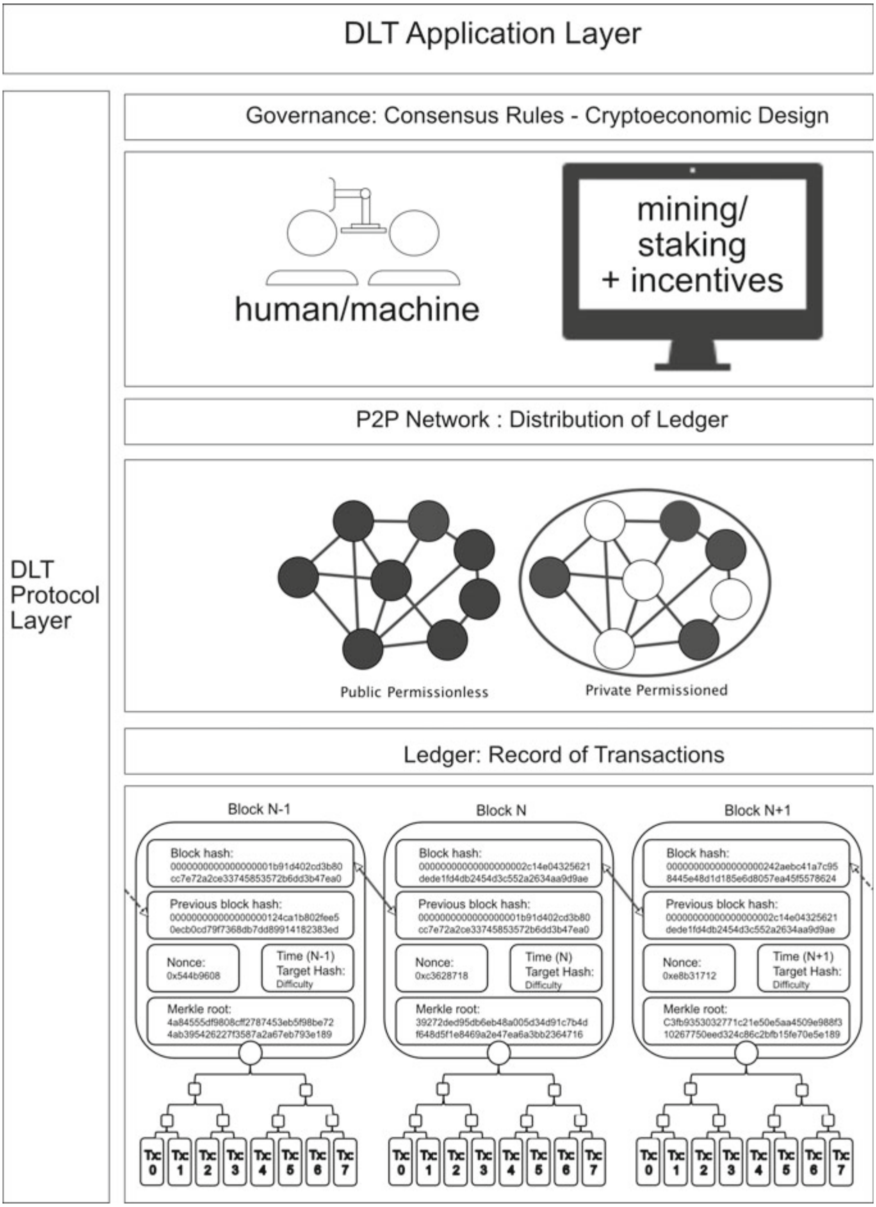

Fig. 1 The three technical layers of blockchain forming the protocol layer. P2P network figures adapted from Allessie et al. [10]

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

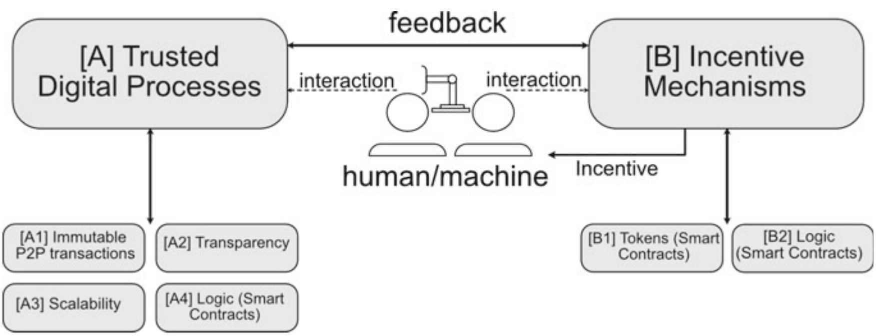

Fig. 2 Blockchain affordances allow to establish trusted digital processes (**a**) and incentive mechanisms (**b**) for decentralized governance mechanisms. Adapted from Hunhevicz et al. [13, 14]

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

[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

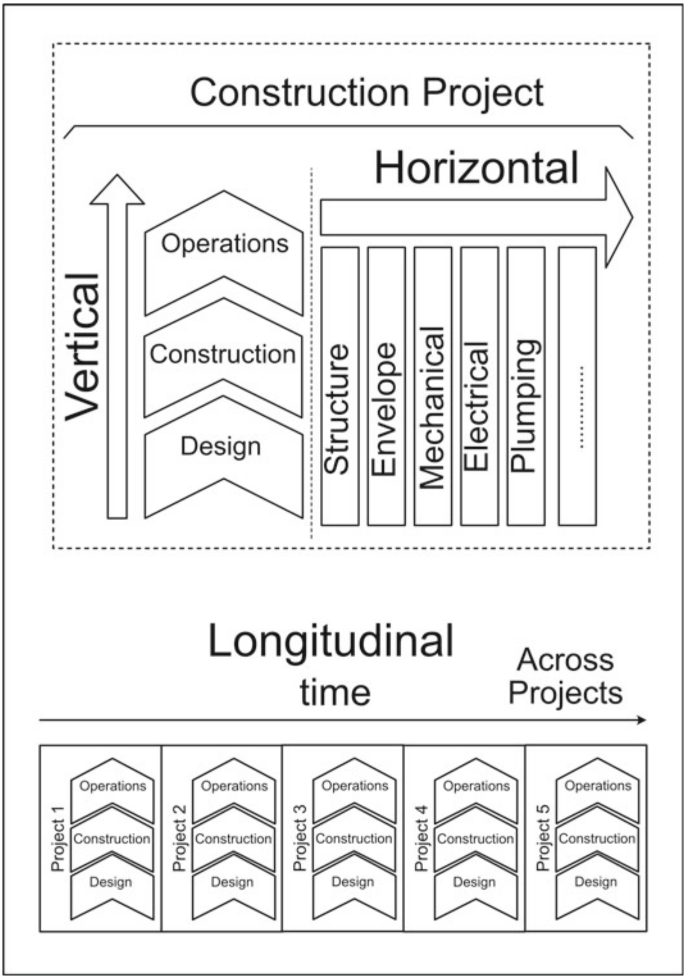

Fig. 3 Three degrees of fragmentation in the construction industry (adapted from Sheffer [43])

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.

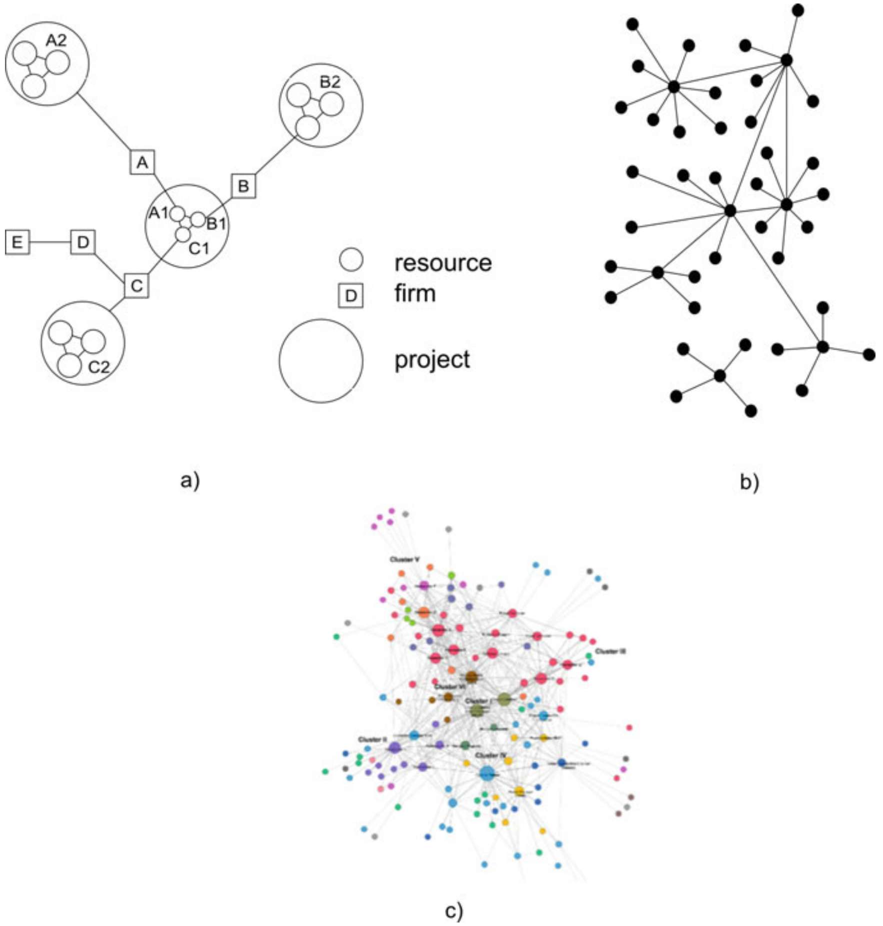

Fig. 4 The construction industry as decentralized collaboration network. *Sources* **a** Dubois and Gadde [47] **b** Baran [80] **c** Graser et al. [81]

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.

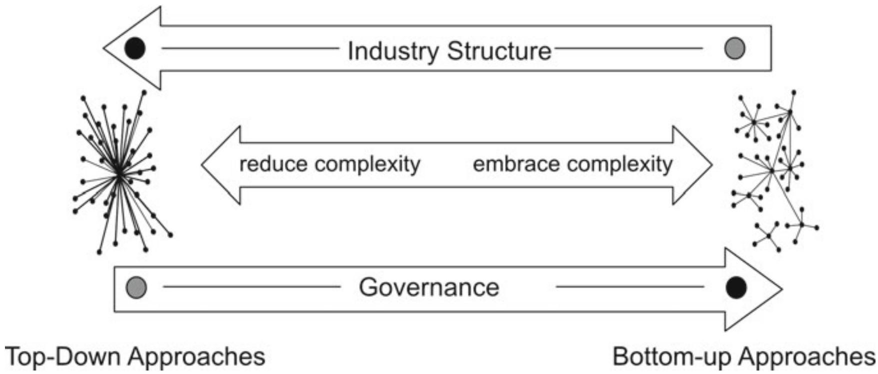

Fig. 5 Approaches to deal with complexity in construction. Light gray dots: the predominant situation today—a misalignment between top-down management and decentralized project organization (loosely coupled networks). The organization can either be adapted towards vertical integration (reducing complexity),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

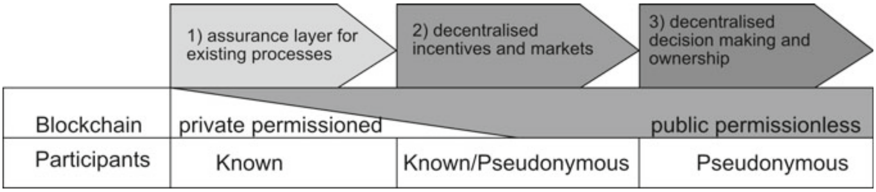

Fig. 6 Three steps of blockchain adoption through a blockchain-based governance lens

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

[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