Decentralized project delivery on the crypto commons
Conceptualization, governance mechanisms, and future research directions

Hunhevicz, Jens J.; Hall, Daniel M.; Brasey, Pierre-Antoine; Bonanomi, Marcella M.M.; Fischer, Martin

DOI
10.1016/j.plas.2024.100132

Publication date
2024

Document Version
Final published version

Published in
Project Leadership and Society

Project Leadership and Society 5 (2024) 100132

Contents lists available at ScienceDirect

Project Leadership and Society

journal homepage: www.sciencedirect.com/journal/project-leadership-and-society

Empirical Research Paper

Decentralized project delivery on the crypto commons: Conceptualization, governance mechanisms, and future research directions

Jens J. Hunhevicz [a,b,*], Daniel M. Hall [c], Pierre-Antoine Brasey [d], Marcella M.M. Bonanomi [e], Martin Fischer [f]

[a] ETH Zurich, Institute of Construction and Infrastructure Management, Zurich, Switzerland
[b] EMPA, Urban Energy Systems Lab, Dübendorf, Switzerland
[c] TU Delft, Department of Management in the Built Environment, Delft, Netherlands
[d] Dsp Ingenieure & Planer AG, Zurich, Switzerland
[e] Polis Lombardia, Milan, Italy
[f] Stanford University, Department of Civil and Environmental Engineering, Stanford, United States

ARTICLE INFO

Keywords:
Blockchain
Commons
Common pool resources
Integrated project delivery
Collaborative project delivery
Smart contracts
DAO

ABSTRACT

This paper presents a first conceptualization for decentralized project delivery through the combination of blockchain technology and common pool resource governance theory, also known as the ”crypto commons”. While previous literature on project delivery models identifies the use of decentralized governance, there is not yet a holistic conceptualization nor a specific overview of governance applications that can be applied. To develop the concept, we use a literature review to synthesize fourteen blockchain governance mechanisms useful for managing the crypto-commons. Subsequently, we use systematic combining to identify twenty-two specific applications for decentralized project delivery in the construction industry, one of the largest project-based industries. Each application is briefly reviewed, and examples of their relevance to realize decentralized project delivery models are provided. We discuss the potential for novel forms of project delivery, but also the need for future research on the applications, as well as on the system level implications, the system design challenges, and the implementation barriers in the specific context of the construction industry. Overall, the concepts and mechanisms presented provide a theoretical foundation upon which future researchers can use to design novel decentralized project delivery models.

1. Introduction

Complexity science suggests that bottom-up management and self-organization are better suited than hierarchical approaches to control and manage large and complex systems (Bertelsen and Koskela, 2004; Helbing and Lämmer, 2008; Filip and Leiviskä, 2023). Some recent project scholarship agrees, increasingly identifying the role of decentralized governance to manage system complexity (Gil and Pinto, 2018; Brunet and Cohendet, 2022), especially in pluralistic settings when the authority to make decisions is controlled by legally independent and heterogenous actors (Denis et al., 2001). Instead of a centralized organizational design where project managers attempt to ”command and control” stakeholders through project hierarchy (Levitt, 2011), project organizations can employ decentralized governance mechanisms that enable shared decision making, collective action, and polycentric behavior among multiple interdependent stakeholders (Henisz et al., 2012; Zavyalova et al., 2020; Gil, 2022; Brunet and Cohendet, 2022).

Decentralization can offer many potential benefits for the delivery of complex projects. Decentralized control has consistently been a choice for large-scale systems because it can address problems of dimensionality, uncertainty, information structure constraints, and time delays (Filip and Leiviskä, 2023). The advantages of cooperative control for systems of production includes ease of building and changing the control system, reliability, higher performance due to distributed execution of tasks, scalability and incremental design, and flexibility for heterogeneity within the project system. At the same time, there are disadvantages to centralized control such as communication overload, lack of data security, and decision paralysis among others (Monostori et al., 2014).

Although project scholars explore the topic of decentralization and

* Corresponding author. ETH Zurich, Institute of Construction and Infrastructure Management, Zurich, Switzerland.
E-mail address: jens.hunhevicz@empa.ch (J.J. Hunhevicz).

https://doi.org/10.1016/j.plas.2024.100132
Received 24 November 2023; Received in revised form 8 March 2024; Accepted 24 April 2024
Available online 1 May 2024

its potential advantages, we find very little work to date that investigates *how* to deliver decentralized projects. The project delivery model (PDM) is defined as the framework to explain how multiple parties involved in a project are organized and managed to create and capture value on a one-time basis, and then disbanded when the task is completed (Davies et al., 2019). It is easy to suggest that more decentralization can be good; it is much more difficult to provide a theoretical framework to help underpin the mechanisms needed to design a decentralized PDM. Therefore, this paper sets forth to answer the questions: (1) What could be the conceptual model for a decentralized project delivery? (2) What specific governance mechanisms and applications are needed to enable a decentralized governance system for projects?

To answer these research questions, we build upon two main ideas: 1) project delivery as a commons, and 2) blockchain as an economic governing technology.

The first idea is to understand decentralized project delivery as a "commons". When collaborative PDMs combine project resources, share decision-making rights, and distribute risk-and-reward among participants, the project resembles a Common Pool Resource (CPR) scenario (Hall and Bonanomi, 2021). Scholars have suggested that these collaborative projects resemble pluralistic (Tillmann et al., 2014) and heterarchic (Brunet and Cohendet, 2022) project ecologies. Project managers need a mindset shift of stewarding the project commons instead of commanding and controlling them (Ahola, 2023). To manage project commons effectively, the Ostrom Principles (OPs) - found to facilitate trust, reciprocity, and long-term collective action in CPR scenarios (Cox et al., 2010; Ostrom, 2015), can be adopted and reinterpreted as project governance principles (Hall and Bonanomi, 2021).

The second idea is to understand blockchain technology as a facilitator for a new type of economic governance. Blockchain is a decentralized and distributed system for peer-to-peer asset transactions. Blockchain offers increased productivity by reducing transaction costs through near costless verification and eliminating expensive intermediaries (Catalini and Gans, 2020). While blockchain has been touted as a solution for project management (Hewavitharana et al., 2019; Kim et al., 2020; Sonmez et al., 2021), we argue that current blockchain applications merely replicate existing economic coordination mechanisms. There is enormous potential to imagine how blockchain can be used as a novel governance technology to create new economic systems through the use of smart contracts (Davidson et al., 2018; Miscione et al., 2019; Voshmgir and Zargham, 2019).

This combination of blockchain and CPR scenarios is known as the "crypto commons." The crypto commons describes a set of blockchain-based market mechanisms and economic incentives aimed at rewarding contributions to the public good (Maples, 2018; Crypto Commons Association, 2021). Such an approach has been found to be promising for scaling real-world CPR scenarios (Fritsch et al., 2021; Rozas et al., 2021b, 2021a ; Papadimitropoulos, 2022). In this paper, we apply the idea of the crypto commons to project delivery. The crypto commons acts as the theoretical basis, upon which we develop our novel model for *decentralized project delivery*.

To better illustrate the concept, we specifically use the example of PDMs in the construction industry, one of the largest project-based industries. PDMs are often highly relevant to construction project management, because the delivery of large construction and infrastructure projects requires multiple organizations across various supply chains to deliver a complex product. The resulting project organization can be described as a loosely-coupled yet highly complex system (Gidado, 1996; Dubois and Gadde, 2002a; Bertelsen, 2003). Construction projects have recently experimented with more decentralized PDMs. One example is the recent development of Integrated Project Delivery (IPD) in North America. IPD often explicitly seeks out decentralized governance mechanisms such as joint decision making, shared risk-and-reward pools, and inter-organizational teams (Hall and Scott, 2019; Davies et al., 2019; Hall and Bonanomi, 2021). Early results have indicated that IPD has been a successful form of project governance for the delivery of large and complex construction projects (El Asmar et al., 2013; Cheng et al., 2016; Mesa et al., 2016; Franz et al., 2017; Ibrahim et al., 2020). Because of its decentralized characteristics, the example of IPD can be a helpful starting point to understand the shift towards decentralized project delivery in the construction industry (Hall and Bonanomi, 2021).

The paper is organized as follows. The first part of this paper establishes our conceptual framework, illustrating the compatibility between blockchain technologies and commons governance (Section 3). In the second part of the paper, we identify the specific blockchain-based governance mechanisms and applications that could be applied to govern and scale decentralized project delivery on the crypto commons (Sections 4). More information on the structure and research approach of this paper is given in Section 2. The paper concludes with a discussion of a systemic implementation and associated design challenges and industry barriers (Section 5). The discussion also gives direction for potential areas of future research to extend our conceptual work.

2. Methodology

This paper is separated methodologically into two distinct parts. In Part I, we seek to establish the concept of decentralized project delivery on the crypto commons. This includes the introduction of the conceptual linkages, a review of blockchain mechanisms aligned with the OPs, and a resulting framework for decentralized project delivery. In Part II, we seek to identify the specific blockchain applications as applied in our example case of construction project delivery models. To do this, we review existing blockchain applications in construction, evaluate them against previously identified blockchain mechanisms, and conclude with a list of specific applicaions that can be used to govern decentralized project delivery. Fig. 1 provides a summary of these methodological steps, and the following text describes each step in greater detail.

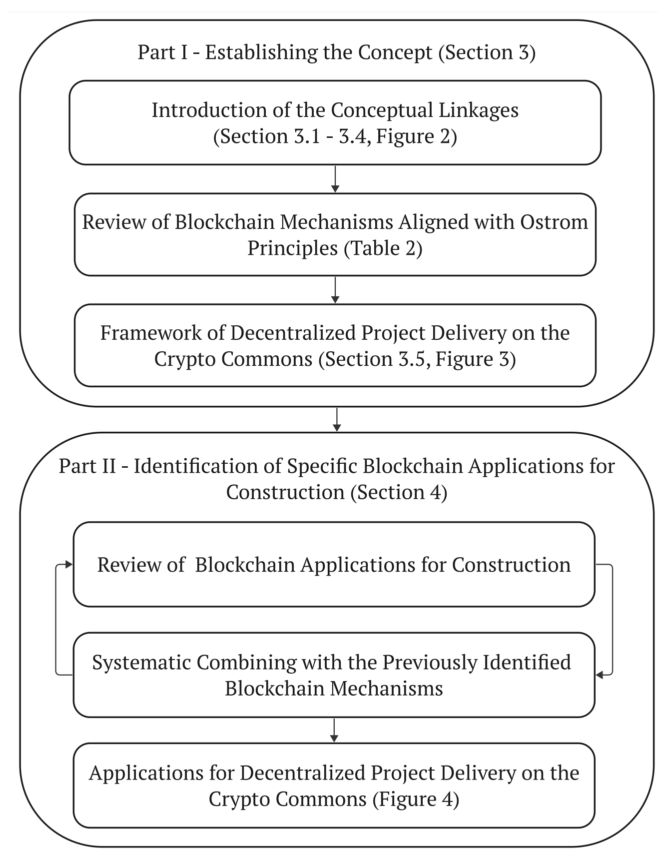

Fig. 1. The research approach and structure of this paper.

In part I, we develop three conceptual links between The Commons and Ostrom Principles, Governing Project Delivery on the Commons, and Blockchain for Economic Activity. The first two concepts are summarized from existing works. Section 3.1 introduces the Nobel-prize winning work of Elinor Ostrom, who developed the Ostrom Principles for managing common pool resources (CPR) scenarios. Section 3.2 summarizes recent work that finds parallels between CPR scenarios and the organization of collaborative construction project delivery models such as IPD. This section is based on the recent work of Hall and Bonanomi (2021) and supporting case studies by the same authors.

The third conceptual link, which connects blockchain governance mechanisms to the OPs, is not yet established in literature. While some literature on the topic is present, we find it scattered and unsuitable to build on for identifying and structuring further applications in Part II. Therefore, we conduct a literature review and clustering of proposed blockchain mechanisms aligned with the OPs, as shown in Table 2. Literature was identified through a search in Google Scholars with keywords including ”blockchain” and ”commons”, screened to assess the relevance of the content. Papers were included when they propose blockchain mechanisms consistent with the OPs. Due to the early and scarce nature of the sources, also gray literature from a traditional Google search was included when deemed helpful. In total, fourteen sources were considered. The results are presented in 3.4.

Section 3.5 then summarizes all three conceptual links as the foundation to propose our conceptual framework of ”decentralized project delivery” in Fig. 3.

In Part II (Section 4), we seek to identify specific applications of crypto common blockchain mechanisms and their interactions to enable decentralized project delivery (see Fig. 1, Part II). This supplements the first part of the paper that has not yet defined how specific blockchain governance mechanisms can be applied to project delivery (Fig. 2, dashed arrow). Because there is no work that explicitly addresses the relationships between project delivery and blockchain governance mechanisms for crypto commons, we take an approach inspired by ”theory matching” or ”systematic combining” grounded in an abductive logic (Dubois and Gadde, 2002b). Abduction can lead to a probable conclusion from what is known by systematically interpreting, matching, or recontextualizing existing phenomena within a conceptual framework (Kovács and Spens, 2005). Abduction is the only logical operation with the goal to introduce new ideas (Peirce, 1974) using systematized creativity and intuition to break through the limitations of deduction and induction (Andreewsky and Bourcier, 2000; Taylor et al., 2002; Kovács and Spens, 2005), which can lead to an intuitive leap of knowledge that emerges as a whole (Taylor et al., 2002). The resulting explanatory hypothesis then requires further confirmation with deductive and inductive study (Timmermans and Tavory, 2012). Overall, an abductive approach can be fruitful when the goal is to develop understanding of a new phenomenon or insight into existing phenomena by examining them from a new perspective (Dubois and Gadde, 2002b; Kovács and Spens, 2005).

Using abductive analysis, we conduct a second literature review, this time of existing blockchain applications. The scope of the review includes articles in leading journals, books, and other sources deemed relevant for identifying, establishing, and supporting potential applications. The starting point for identifying sources were reviews of blockchain applications in construction from 2019 to 2021 (Li et al., 2019; Perera et al., 2020; Li and Kassem, 2021; Scott et al., 2021). These were then continuously supplemented with new publications with the keywords ”blockchain” and ”construction” from the last three years. Articles were included if they were found to be consistent with the proposed mechanisms identified in Table 2. The applied systematic combination approach meant going back and forth between the new framework, the sources, and the analysis (Dubois and Gadde, 2002b), as indicated in Fig. 1. Thus, the emerging framework continuously informed the literature search, selection, and analysis over the course of three years in a dynamic process of logical inference to define reasonable application

Table 1
The eight Ostrom Principles and how they relate to IPD.

	Ostrom Principle (OP)	Description (Cox et al., 2010; Ostrom, 2015)	IPD Practices (Hall and Bonanomi, 2021)
1	Clearly Defined Boundaries for Users and Resources	Clear definition of users who have the right to withdraw resource units, as well as clear definition of the resources in question.	The firms jointly decide who is part of the multi-party contract, while the project sponsor and team collaborate to specify which project aspects and budget items are shared and which are not.
2	Local adaptation of rules for the management of resources	Rules should be established and enforced to ensure that resource allocation is congruent with local conditions. Moreover, users should reap benefits proportional to their input of labor, materials, or money.	Trade contractors, with their insight into local conditions such as labor availability and resource logistics, are brought in early. Their share of the risk/reward pool is determined by factors such as cost structure, duration of involvement, and impact on results.
3	Collective-choice arrangements	Involved or affected individuals should be able to participate in modifying the operating rules and resource management.	Firms that have signed the multi-party contract are entitled to participate in management group functions and vote on decisions that directly affect their work and area of expertise.
4	Monitoring	Active and transparent auditing of resources and user behavior to ensure that all parties are complying with agreed-upon rules.	Participants openly share resource, cost, profit, and performance data in big room meetings. They set cost targets, monitor resource usage for deviations (Target Value Design), and commit to completing work. The Planned Percent Completed (PPC) metric publicly reports the percentage of last week's commitments fulfilled.
5	Graduated sanctions	Resource appropriators are subject to increasingly severe penalties for breaking the rules, depending on the severity and context of the offense.	Sanctions may be increased as a result of persistent non-compliance or underperformance of the PPC, and may result in the removal of individual participants and/or companies.
6	Conflict-resolution mechanisms	Affordable procedures and fast access to local arenas should be available to resolve disputes as they arise.	Project participants develop conflict resolution mechanisms that include clear dispute resolution strategies to avoid costly litigation.
7	Minimal recognition of rights to organize	Ensure that external authorities respect the community's right to establish its own rules for self-governance.	Project participants can make collective decisions, including procedures for the team to override the wishes of the project sponsor.
8	Nested enterprises	For larger systems, governance should be organized at multiple levels to ensure that decisions are made at the appropriate level.	Governance activities of collaborative construction projects are organized into multiple layers of hierarchy using a nested enterprise design.

Table 2
Fourteen identified categories of blockchain mechanisms for the crypto commons.

Mechanism	OP	Summary	Sources
M1 - Identity and rights based on addresses and tokens	1	Blockchain addresses and tokens can be used to identify users and assign ownership and access rights to govern the boundaries of a CPR. This can be done through smart contract logic or utility tokens, enabling easily defined and revocable ownership and access rights.	Rozas et al. (2021a,b); Dao (2018); Xiao (2019); Malafosse et al. (2022); van Vulpen and Jansen (2023); Papadimitropoulos (2022)
M2 - Tokenization of resources	1	Tokenization can represent resource boundaries in CPRs through asset-backed currencies or commodity tokens. Bonding curves increase token price with supply to incentivize early protectors of CPR scenarios, creating a system that is less susceptible to speculation and manipulation.	Fritsch et al. (2021); Malafosse et al. (2022); van Vulpen and Jansen (2023); Decoodt (2019); Emmett (2019a); de la Rouviere (2018)
M3 - Decentralized markets tailored to local conditions	2	Decentralized markets facilitated by smart contracts can be employed to match local needs and conditions for unrestricted investment and trading while complying with formalized appropriation rules.	Xiao (2019); Papadimitropoulos (2022); Decoodt (2019); Emmett (2019a); de la Rouviere (2018)
M4 - Smart contracts formalize appropriation and provisions rules	2	Smart contracts can formalize CPR appropriation and provision rules with benefits proportional to the required inputs. Transparent and automated rules foster community discussions on value and enable collective decision-making on contributions and appropriation rules.	Rozas et al. (2021a,b); Dao (2018); Malafosse et al. (2022); van Vulpen and Jansen (2023)
M5 - Decentralized proposal and voting platforms	3	Decentralized proposal and voting platforms can be used to ensure individuals can be involved in modifying operational rules. Tokens can grant decision-making rights based on equal power distribution, contribution, or reputation.	Fritsch et al. (2021); Rozas et al. (2021a,b); Dao (2018); Xiao (2019); Papadimitropoulos (2022); Emmett (2019a,b)
M6 - Decentralized prediction markets	3	Decentralized prediction markets implemented with smart contracts create a betting platform to establish a trusted knowledge base by making well-informed predictions on future outcomes.	Dao (2018); Papadimitropoulos (2022)
M7 - Transparent record of transactions	4	Monitors ensure compliance by auditing CPR conditions and appropriator behavior. Blockchain enables transparent transaction records of user behavior and resource flows, improving compliance of community members when interacting with the CPR scenario.	Rozas et al. (2021a,b); Xiao (2019); Malafosse et al. (2022); van Vulpen and Jansen (2023); Papadimitropoulos (2022); Emmett (2019a); Poux et al. (2021)
M8 - Transaction signatures for tamper-proof commitments	4	Monitors and users of CPR must be accountable, and blockchain transaction signatures ensure accountability through transparency and verifiability.	Rozas et al. (2021a,b); Dao (2018)
M9 - Tokenization of reputation	4	Reputation tokens can provide a measure of accountability through representing the value of contributions earned through compliance with CPR rules.	Xiao (2019); Papadimitropoulos (2022); Pazaitis et al. (2017)
M10 - Decentralized peer-review mechanisms	4	Decentralized peer-review mechanisms using smart contracts can be used to review the status of work or the perceived value of contributions when automatic checking is not possible.	Rozas et al. (2021a,b); Pazaitis et al. (2017)
M11 - Smart contracts for transparent and self-enforcing sanctions	5	Smart contracts allow for transparent and self-enforcing graduated sanctions based on the severity and context of operational rule violations. Sanctions can include loss or value decrease of financial or reputation tokens.	Rozas et al. (2021a,b); Dao (2018); Xiao (2019); van Vulpen and Jansen (2023); Papadimitropoulos (2022); Emmett (2019a)
M12 - Decentralized jurisdiction systems	6	Blockchain can facilitate faster conflict resolution with decentralized jurisdiction systems and token-based incentives to provide low-cost local arenas for conflict resolution among appropriators and officials.	Rozas et al. (2021a,b); Dao (2018); Xiao (2019); Papadimitropoulos (2022); Emmett (2019a)
M13 - Smart contracts ensure decisions are made by affected parties	7	Smart contracts ensure affected parties make decisions and external authorities do not interfere with the rights of appropriators. They enforce local community rules locally.	Rozas et al. (2021a,b); Papadimitropoulos (2022)

(continued on next page)

Table 2 (*continued*)

Mechanism	OP	Summary	Sources
M14 - Smart contracts facilitate bottom-up coordination	8	Smart contracts can facilitate coordination across nested enterprises, allowing participants at various hierarchical levels to organize appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities in the best interest of the commons.	Rozas et al. (2021a,b); Dao (2018); Xiao (2019); Malafosse et al. (2022); Papadimitropoulos (2022); Emmett (2019a)

categories. Fig. 3 provides an overview of the final identified application categories and the 72 sources that were included to support them.

3. Conceptual linkages for decentralized project delivery on the crypto commons

3.1. The Commons and Ostrom Principles

Common pool resources (CPRs) are resources that are freely shared among multiple users (Ostrom, 1990). CPRs can include natural resources such as forests, pastures, and fishing grounds. They can also be man-made physical resources such as parking lots (Epstein, 2002) or digital resources such as open data (Linåker and Runeson, 2022). An economic good can be considered a common pool resource when it displays two primary characteristics: 1) the resource is rivalrous in consumption, meaning its use by someone means that others cannot use it, and 2) the resource is non-excludable, meaning it is very difficult to keep others from using the resource (Ostrom, 1990).

Overuse of these resources can lead to depletion (Hardin, 1968), also known as *the tragedy of the commons*. For decades, scholars and game theorists argued that centralized control was the only way to avoid the tragedy of the commons. However, research led by Elinor Ostrom (Gardner et al., 1990; Ostrom et al., 1994; Ostrom, 2010, 2015) used extensive case study research to show that local actors are much more successful when using self-organization to sustain the commons. Ostrom identified eight design principles (OPs) to guide effective bottom-up governance of the commons (Fig. 2, IIA). Bottom-up or peer-to-peer coordination based on Ostrom's principles have successfully created systems of peer production based on sharing, openness, co-creation, self-governance, and equitable distribution of value (Bauwens et al., 2019). However, a limitation remains the scaling of community governance to larger and more complex systems (Ostrom et al., 1999; Stern, 2011). Table 1 lists and describes briefly the eight OPs to understand the first conceptual link (see Fig. 2).

3.2. Governing project delivery on the commons

Traditional project delivery models organize the supply chain using a tiered hierarchy of contracts between the owner, general contractor, subcontractors, and suppliers. The delivery model is designed and developed at the start of the project. This is referred to as the front-end planning phase when the sponsor and client define the overall strategic objectives or vision, shape the governance structure, secure financing, and prepare the contracting and procurement approach (Davies et al., 2019). Next, the execution phase occurs when the project receives approval to proceed. At this stage, the selected contractors deliver the project using the allocated resources, including the required tasks of design, construction, integration, fit out, testing, and operational

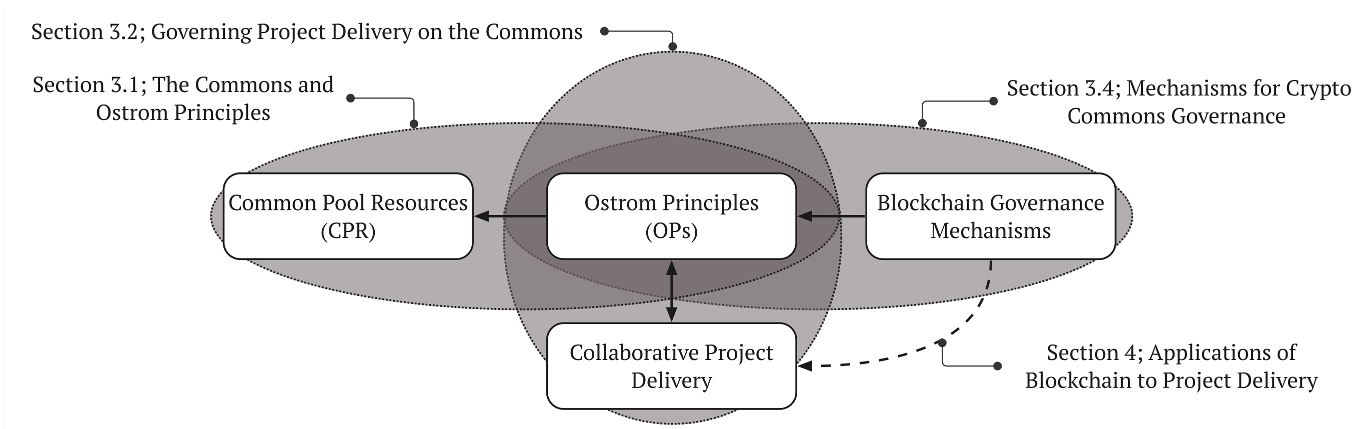

Fig. 2. The three conceptual linkages for decentralized project delivery on the crypto commons, as described in Section 3.

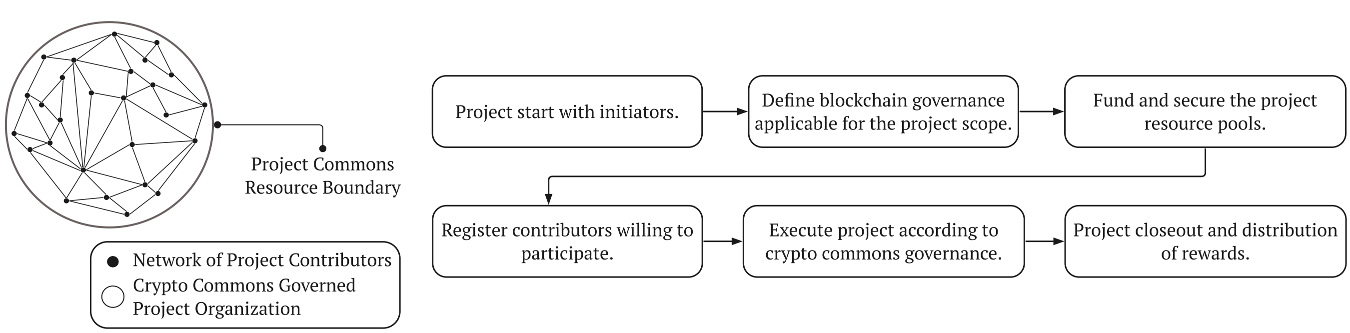

Fig. 3. High-level framework of decentralized project delivery on the crypto commons.

handover (Davies et al., 2019).

However, the limitations of the traditional, hierarchical approach based on lowest-price bidding, fixed-price contracts, and the transfer of risk down the supply chain have led to experimentation with new forms of PDM (Henisz et al., 2012; Hall and Scott, 2019). One specific example is the recent development of Integrated Project Delivery (IPD). IPD aligns multiple, independent firms to share financial risks and rewards during the design and construction of a facility (Lahdenperä, 2012). As a governance system, IPD projects involve multiple formal and informal practices (Bygballe et al., 2015; Hall and Scott, 2019) including early stakeholder involvement, shared risk and reward mechanisms, joint project control, and collective decision making (Cheng et al., 2016; Hall et al., 2018).

IPD differs from the traditional project delivery model in three significant ways (Hall and Bonanomi, 2021). First, IPD creates a common pool of financial resources that is contractually available to all project parties. Second, IPD promotes shared governance, with mechanisms that empower all project participants to make decisions. Decision making is no longer centralized. Third, IPD suggests the project teams should self-organize to decide on the shared financial risks and rewards of the project, ensuring agreement on how positive project outcomes are distributed among the participants (Hall and Scott, 2019; Rodrigues and Lindhard, 2021; Rankohi et al., 2022).

When PDMs have the above three characteristics, Hall and Bonanomi (2021) suggest the project resembles a CPR scenario instead of a project hierarchy. The project budget and schedule might be subject to "overdrawal" by the project participants, leading to a downward spiral of resource availability and the eventual "tragedy of the project." Instead, participants establish self-governance structures to manage the shared resource pool. Many of these governance structures share characteristics with the OPs. Recent empirical (Bonanomi et al., 2019, 2020) and positional work (Brunet and Cohendet, 2022) has supported and extended this conceptualization of governing project delivery on the commons. Example practices for each of the eight OPs, as identified by Hall and Bonanomi (2021), are listed for an overview in the last column of Table 1. This forms the second conceptual linkage for decentralized project delivery (see Fig. 2).

3.3. Blockchain for Economic Activity

Before introducing the last conceptual building block, it is important to understand the rationale behind blockchain's potential to govern economic activity trough its decentralized technology stack.

Blockchain is a specific type of distributed ledger technology (DLT) that enables direct peer-to-peer (P2P) transactions of value without the need for trusted intermediaries (Tasca and Tessone, 2019). The first blockchain was Bitcoin (Nakamoto, 2008), and since then many new blockchains have been created to enable novel features and infrastructure (Spychiger et al., 2021). Most relevant to this work, the Ethereum blockchain pioneered the execution of smart contracts (Buterin, 2014). Smart contracts allow the encoding of rules of interaction with blockchain transaction, which enables the execution and coordination of economic activity without traditional intermediaries (e.g., banks to facilitate payments). In addition, smart contracts can encode tokens, which are value containers representing, for example, currencies, securities, or utilities (Ballandies et al., 2021b). These tokens can be transferred between blockchain users.

The main reason why blockchain is interesting for decentralized governance of economic coordination is its innovation to use cryptoeconomic mechanisms to achieve shared consensus for P2P transaction without centralized trust, but instead building confidence in the underlying decentralized technical infrastructure (De Filippi et al., 2020). While blockchain can increase productivity of existing economic processes by reducing transaction costs through a negligible cost of verification and the elimination of intermediaries (Catalini and Gans, 2020), scholars argue that the real potential of blockchain lies in its ability to create new forms of institutional organization and governance that can disrupt existing economic coordination (Davidson et al., 2016, 2018; Beck et al., 2018; Miscione et al., 2019; Schmidt and Wagner, 2019; Jacobo-Romero and Freitas, 2021; Petersen, 2022).

Such cryptoeconomic systems can leverage smart contracts to build new forms of economic activity on top of blockchains. As a result, these applications can provide a decentralized institutional infrastructure that facilitates a wide range of socio-economic interactions to regulate the distribution of effort, goods, and services in new digital economies (Voshmgir and Zargham, 2019; Brekke and Alsindi, 2021). There is ongoing research into what forms of organization and governance can be supported or replaced by blockchain (Petersen, 2022). For example, the emerging organizational form of a decentralized autonomous organization (DAO) allows people to coordinate themselves, mediated by a set of self-executing rules deployed on a blockchain, and whose governance is decentralized (Hassan and De Filippi, 2021; Santana and Albareda, 2022).

3.4. Mechanisms for crypto commons governance

Given the potential of blockchain for innovative forms of economic governance, several studies have explored the linkage of this technology with the commons and Ostrom principles. Blockchain networks themselves can resemble a form of the commons, demonstrating successes in coordinating actors according to CPR theory through the application of cryptoeconomics (Red, 2019; Shackelford and Myers, 2016; Werbach, 2020; Machart and Samadi, 2020). These networks incentivize collaboration around a shared ledger to maintain security, leverage network effects, and preserve the perceived value of their cryptocurrency (Red, 2019). Therefore, blockchain's cryptoeconomic incentive systems, when applied to the digital governance of commons-oriented economies, have the potential to address limitations of the commons, such as coordination problems, funding limitations, mismanagement, and unacknowledged labor (Papadimitropoulos, 2022).

Several scholars propose how blockchain can be applied to commons governance. Rozas et al. (2021a) evaluated the relationship between blockchain-based mechanisms and the eight OPs to facilitate the peer production of real-world commons. Subsequently, Rozas et al. (2021b) have explored how encoding the OPs can improve CPR governance for global software commons and address some of the challenges of scaling to large systems (Stern, 2011). Fritsch et al. (2021) explore how blockchain can help scale the commons not only for digital but also physical production of common value by exploring three exemplary cases. Papadimitropoulos (2022) examines the relation of blockchain mechanisms to the commons by illustrating the case study of the Commons Stack. Furthermore, van Vulpen and Jansen (2023) research the application of commons governance to DAOs to help foster digitally-enabled collective action. Additional academic works (Malafosse et al., 2022; Poux et al., 2021; Pazaitis et al., 2017) and informal articles (Dao, 2018; Xiao, 2019; Decoodt, 2019; de la Rouviere, 2018; Emmett, 2019b) have proposed approaches for governing different types of digital and real-world commons using blockchain-based mechanisms.

Because blockchain mechanisms for the OPs is the third conceptual linkage (see Fig. 2), we synthesized fourteen categories of mechanisms proposed to govern the crypto commons through a review of the above literature (see Section 2 for more information). In Table 2, we provide an overview and definition of these categories. For now, the categories are generalized to be applicable to all crypto commons scenarios. Later, in Section 4 of this paper, we will elaborate on each category in our specific context of decentralized project implementation.

3.5. Summary and promise of the conceptualization

Given the established links as shown in Fig. 2 between the OPs and CPRs (see 3.1), the OPs and collaborative project delivery (see 3.2), and the OPs and blockchain governance mechanisms (see 3.4), we believe that blockchain is the appropriate technology for economic coordination of decentralized project delivery. This would involve forming an organization on the crypto commons around a shared resource pool represented on the blockchain, governed and coordinated by selected cryptoeconomic mechanisms, as illustrated in Fig. 3. Specifically, to facilitate decentralized project delivery on the crypto commons, the initial actors need to create effective bottom-up governance rules for decentralized peer production of the network. They then fund and secure the resource pool on the blockchain, setting up the project as a common, and invite or accept contributors to the project who are willing to abide by the governance structure. Finally, the project is executed and rewards are distributed.

In summary, the authors propose the use of the identified blockchain governance mechanisms aligned with the OPs (Table 2) to establish a governance system for decentralized project delivery on the crypto commons. As discussed in the introduction, collaborative decentralized approaches to construction project delivery, such as IPD, have been shown to be effective for the fragmented (Levitt, 2011) and loosely coupled (Dubois and Gadde, 2002a) structures present in construction projects. A more decentralized approach to project delivery could create effective peer-to-peer governance approaches (Bauwens et al., 2019) to managing the complex aspects of the industry (Hunhevicz et al., 2022a). And even when applied to existing relational contracting approaches of collaborative project delivery, blockchain-based governance could enhance or replace both contractual and relational approaches in business networks (Petersen, 2022), mitigating various costs such as reduced competition or extended decision-making processes (Henisz et al., 2012). Ultimately, crypto commons' *"networked governance [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"* (Maples, 2018).

4. Findings: Identified applications

Through the abductive analysis process, we identify 22 blockchain application categories that could be used to build the above described decentralized project delivery (see Section 2 for more information on the research approach). The findings of these applications are described below. To organize the applications, we use the previously identified fourteen crypto commons mechanisms in Table 2, structured according to the corresponding OPs (see Table 1). A graphical overview is given in Fig. 4, showing the applications, the crypto commons mechanisms, and the corresponding OPs.

4.1. OP1 - define boundaries for resources and users

CPR scenarios require clear definition of resource withdrawal rights (Ostrom, 2015; Cox et al., 2010). For example, in IPD, this includes identification of who is part of the multiparty contract (Cheng et al., 2016; Hall and Bonanomi, 2021). In addition, clear definition of resource boundaries in CPR scenarios is critical (Cox et al., 2010; Ostrom, 2015).

4.1.1. M1 - Assign identity and rights based on addresses and tokens

Blockchain enables identification of actors through addresses or tokens, improving the definition, propagation and revocation of rights in CPR scenarios (see Table 2). Smart contract logic then ensures that authorized participants can perform specific actions based on their addresses or token ownership.

Scalable, real-world identity management will be important for the proposed decentralized project delivery. Decentralized identity management using blockchain has received increasing attention (Dunphy and Petitcolas, 2018), and could be also used to **manage stakeholder identities and project rights** in decentralized project delivery (see Fig. 4, purple boxes). Although address-based user identification is used in blockchain applications in the built environment, explicit identity management and related rights and ownership are less explored. For data access to material passport information, address-based rights management has been explored using both role-based and token-based smart contracts (Hunhevicz et al., 2023). The token-based mechanism allows rights to be traded by transferring tokens between addresses, while address-based roles remain with the address until revoked. In a prototype of a design DAO, non-fungible tokens are issued to grant access (Dounas et al., 2022a, 2022b). However, further research is needed to evaluate blockchain-managed rights in the context of multi-party contracts, considering factors such as profit distribution, liability, and incentive systems. In addition, the exploration of blockchain-based ownership, such as for property rights, requires further investigation (Wang et al., 2022).

In addition, blockchain **allows for machine participation in projects** (see Fig. 4, purple boxes). Blockchain does not distinguish who controls an address as long as the terms of the transaction are valid (Wang et al., 2022; Nabben, 2021). This could allow machines to participate in various project tasks, such as bidding, signing off on work packages, accessing resources, and being compensated for their work. For example, researchers have explored the use of blockchain to allow robots to receive incremental payments for work performed (Lee et al., 2021). In addition, a self-owned house has been developed to receive and spend funds for maintenance and operations (Hunhevicz et al., 2021). Other work suggests that artificial intelligence applications in construction could operate machines more transparently and trustworthily based on the available transaction data (Adel et al., 2022). Further research is needed to explore the socio-technical implications and feasibility of machine participation in project delivery.

4.1.2. M2 - Tokenize resources

Tokenization using asset-backed currencies or commodity tokens to represent resources, goods, or services in the crypto commons can help achieve well-defined resource boundaries (see Table 2). Tokenization of project resources can enable **transparent representation of project resource pools**, allowing more accessible and shared ownership, exchange and trading, as well as digital management of one or even multiple resource pools with distinct appropriation and payoff functions (see Fig. 4, purple boxes).

The definition of monetary resources in construction projects on the blockchain has been proposed with blockchain-based project bank accounts (Li et al., 2019; Tezel et al., 2021; Scott et al., 2022). In addition, tokenization of data has been proposed to represent it as a resource in projects and the built asset lifecycle that can be owned and traded (Venugopalan and Aydt, 2023; Teisserenc and Sepasgozar, 2022; Wu et al., 2023b). Currently, there is no research on the tokenization of physical resources in the construction industry, but early studies have explored how crypto assets can integrate physical and financial supply chains (Hamledari and Fischer, 2021a), and non-fungible tokens can digitally represent building components (Dounas et al., 2021), but without a link to the actual physical components.

Further inspiration for tokenizing physical resources could be found in the asset-backed tokenization of Holochain's Commons Engine or the commodity tokens of the Economic Space Agency (Fritsch et al., 2021). More research should also investigate how tokenization can represent project resources beyond monetary or physical resources, such as for example carbon emissions or community values. Examples could include carbon credits (Woo et al., 2021) and the issuance of new currencies representing community-defined values (De Filippi, 2015), as explored by the Finance4.0 project for sustainability (Ballandies et al., 2021a).

4.2. OP 2 - Devise rules congruent with local conditions

CPR scenarios must ensure transparency and clarity in the logic of access and usage of shared resources, and the benefits that users derive should be directly proportional to the amount of inputs required in the

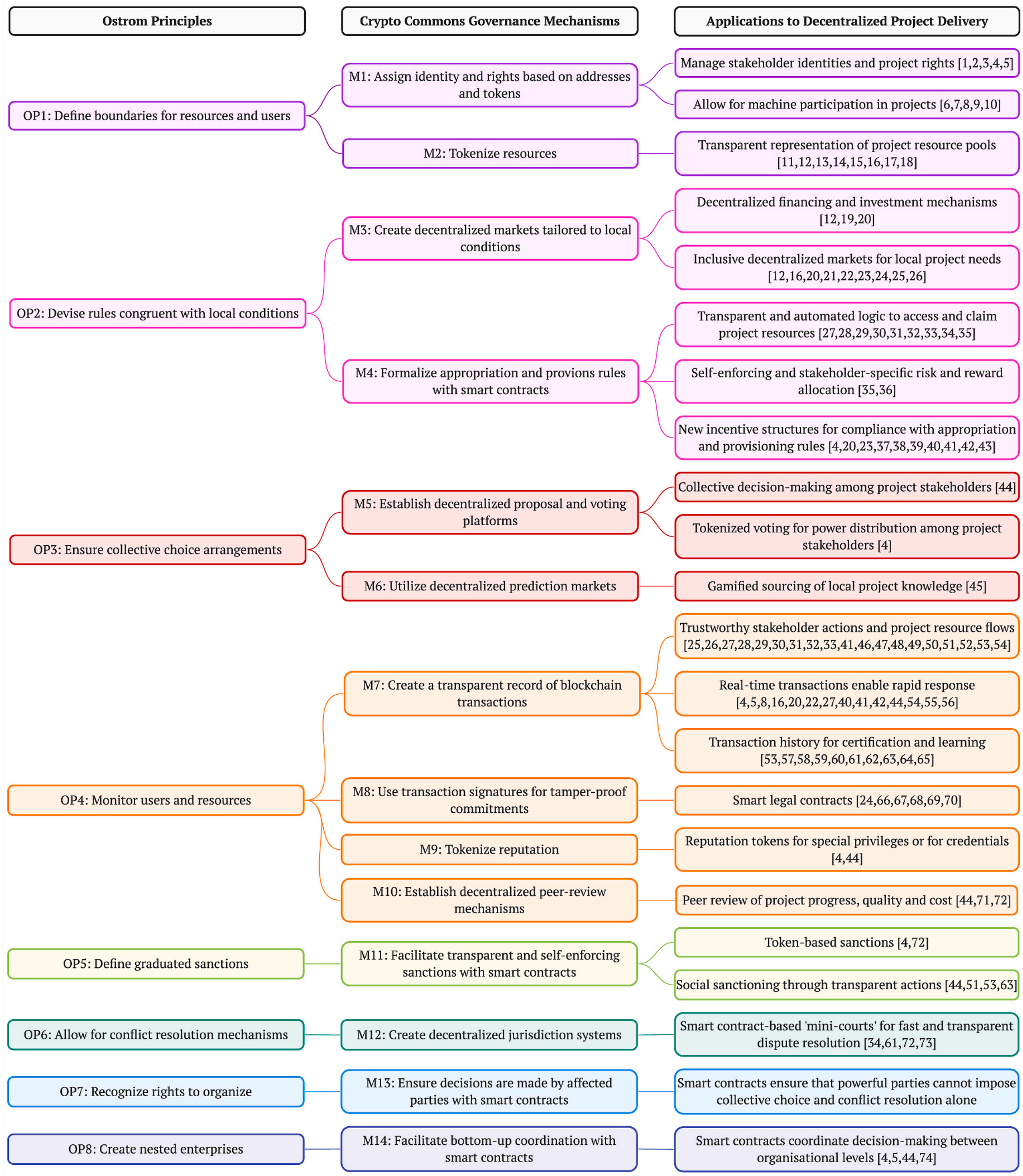

Fig. 4. Summary of the 14 crypto commons governance mechanisms based on the OPs (see Tables 1 and 2), as well as the 22 identified applications for the governance of decentralized project delivery. Sources: [1] Pazaitis et al. (2017), [2] Dunphy and Petitcolas (2018), [3] Hunhevicz et al. (2023), [4] Dounas et al. (2022a), [5] Dounas et al. (2022b), [6] Wang et al. (2022), [7] Nabben (2021), [8] Lee et al. (2021), [9] Hunhevicz et al. (2021), [10] Adel et al. (2022), [11] Li et al. (2019), [12] Tezel et al. (2021), [13] Scott et al. (2022), [14] Venugopalan and Aydt (2023), [15] Teisserenc and Sepasgozar (2022), [16] Wu et al. (2023b), [17] Hamledari and Fischer (2021a), [18] Dounas et al. (2021), [19] Tian et al. (2020), [20] Akbarieh et al. (2022), [21] Gunasekara et al. (2022), [22] Ahmadisheykhsarmast et al. (2023), [23] Dounas et al. (2020), [24] Gupta and Jha (2023), [25] Venugopalan and Aydt (2023), [26] Ahmadisheykhsarmast and Sonmez (2020), [27] Torkanfar et al. (2023), [28] Chong and Diamantopoulos (2020), [29] Hamledari and Fischer (2021c), [30] Nanayakkara et al. (2021), [31] Ye and König (2021), [32] Bolton et al. (2022), [33] Elghaish et al. (2022), [34] Cheng et al. (2023), [35] Elghaish et al. (2020), [36] Chen et al. (2023b), [37] Mathews et al. (2017), [38] Hunhevicz et al. (2020), [39] O'Reilly and Mathews (2019), [40] Hunhevicz et al. (2022b), [41] Chen et al. (2023a), [42] Naderi et al. (2023), [43] Bao et al. (2024) [44] Lombardi et al. (2020), [45] Peterson et al. (2022), [46] Wahab et al. (2022), [47] Das et al. (2020), [48] Watson et al. (2019), [49] Kifokeris and Koch (2020), [50] Wang et al. (2020), [51] Li et al. (2021b), [52] Brandín and Abrishami (2021), [53] Wu et al. (2022), [54] Wu et al. (2023a), [55] Niavis et al. (2022), [56] Hamledari and Fischer (2021b), [57] Weerasuriya et al. (2023), [58] Sheng et al. (2020), [59] Erri Pradeep et al. (2021), [60] Wu et al. (2021), [61] Kim et al. (2022), [62] Celik et al. (2023), [63] Li et al. (2021a), [64] Rodrigo et al. (2020), [65] Shojaei et al. (2021), [66] Shojaei et al. (2020), [67] Allen and Hunn (2022), [68] Mason (2017), [69] McNamara and Sepasgozar (2021), [70] Msawil et al. (2022), [71] Dietsch et al. (2018), [72] Son and Lien (2022), [73] Saygili et al. (2021), [74] Lombardi and Dounas (2022).

form of labor, materials, or money (Cox et al., 2010; Ostrom, 2015). Similarly, IPD projects use different practices and rules to determine who can access resources and for what purpose (Hall and Bonanomi, 2021).

4.2.1. M3 - Create decentralized markets tailored to local conditions

The crypto commons can use decentralized markets tailored to local needs and conditions (see Table 2). Smart contracts can encode market rules, allowing unrestricted reciprocal trading without intermediaries while adhering to formalized appropriation rules. With resource tokenization, decentralized funding and investment mechanisms based on cryptoeconomic mechanisms can be used to crowdfund protection of the commons by incentivizing early protectors to invest (see Table 2). For example, a bonding curve (Balasanov, 2018) is a type of cryptoeconomic mechanism to allow investors to buy a resource token by locking in their investment and then sell it back at a later point according to the new price determined by the bonding curve. Bonding curves can be extended to augmented bonding curves, so they act as a means of continuous funding, liquidity provider, and market maker at the same time, while the tokens issued represent access or voting rights to the resource or future revenue (Titcomb, 2019; Favre, 2019; Zargham et al., 2020).

New **decentralized financing and investment mechanisms**, such as augmented bonding curves, could also expand market structures in decentralized project delivery by providing additional financial benefits to both the project and invested stakeholders (see Fig. 4, pink boxes). Research already mentions tokenized investments to finance construction projects (Tezel et al., 2021; Tian et al., 2020) or proposes the use of new financial revenue mechanisms to return the salvage value of recycled materials to invested shareholders (Akbarieh et al., 2022). Further work could investigate how to adapt decentralized financing mechanisms (Schär, 2020) or other cryptoeconomic incentive mechanisms for decentralized project delivery, possibly taking into account differences from CPR scenarios, such as an owner typically paying for the project, and management of resources being determined by the respective project roles, not the timing of their investment.

In the context of project delivery, **inclusive decentralized markets for local project needs** can relate to different resources such as project budget, collective tools or machines, or physical working space (see Fig. 4, pink boxes). Current proposed applications of blockchain-based markets for materials include waste trading (Wu et al., 2023b) and recyclable materials (Akbarieh et al., 2022). Research also explored market mechanisms for project contributors, e.g. for procurement of facility management (Gunasekara et al., 2022), transparent project tendering (Ahmadisheykhsarmast et al., 2023; Torkanfar et al., 2023), a reverse auction-based bidding mechanism (Tezel et al., 2021), a decentralized design competition (Dounas et al., 2020), or automated contracting (Gupta and Jha, 2023). Finally, a decentralized data marketplace was proposed for project related data assets (Venugopalan and Aydt, 2023).

Further research should explore the potential of decentralized markets for project delivery to create inclusive markets that include not only human actors, but also autonomous machine agents. In addition, these markets could encode market rules that are adapted to the specific needs and constraints of local projects, benefiting both the actors involved in the project and those affected by it, such as residents and the natural environment.

4.2.2. M4 - Formalize appropriation and provision rules with smart contracts

Smart contracts could encode selection criteria and market mechanisms for resource appropriation and access, making formalized rules automated and visible to all (see Table 2). In the same way, smart contracts can potentially manage the shared resource pools of decentralized project delivery through **transparent and automated logic to access and claim project resources** (see Fig. 4, pink boxes), if the resources in question are represented on the blockchain (see 4.1.2). To our knowledge, research is currently mostly focusing on smart contract logic to manage financial resources in construction projects (Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020; Hamledari and Fischer, 2021c; Nanayakkara et al., 2021; Ye and König, 2021; Bolton et al., 2022; Elghaish et al., 2022; Cheng et al., 2023), of which only Elghaish et al. (2020) focus on collaborative project delivery. Further research is needed to explore the use of smart contracts to coordinate both financial and non-financial resources such as materials, labor, and time, in the context of decentralized project delivery.

In the IPD model, the risk and reward pool is used to balance firms' participation and potential rewards, taking into account their cost structure, accounting practices, project involvement, and impact on outcomes (Cheng et al., 2016). In decentralized project delivery, smart contracts have the potential to establish **self-enforcing and stakeholder-specific risk and reward allocation** (see Fig. 4, pink boxes). An exemplary smart contract mechanism for financial rewards has already been prototyped for IPD projects (Elghaish et al., 2020). Furthermore, Chen et al. (2023b) developed Shapley value-based smart contracts to automatically assign fair rewards/penalties to motivate task-level collaboration.

Finally, cryptoeconomic mechanisms enabled by smart contracts and tokens have the potential to expand the incentive structures for decentralized project delivery beyond current approaches to risk and reward contracts with **new incentive structures for compliance with appropriation and provisioning rules** (see Fig. 4, pink boxes). For example, mechanisms could include non-monetary reputation tokens (see 4.4.3), or access tokens to decentralized markets (see 4.2.1) and decision-making processes (see 4.3.1). Such non-monetary tokens can be way to activate trust and community similar to the approach of relational contracts. In addition, token-based rewards and sanctions could be implemented at the individual or corporate level (see 4.5.1). Although blockchain-based incentives have not been widely explored in the construction literature, some studies have suggested their use. For example, smart contracts and tokens have been proposed to reward parties for maintaining and improving BIM databases (Mathews et al., 2017) or, more generally, high-quality data sets (Hunhevicz et al., 2020). Performance-based incentives can improve the performance of modular construction (Chen et al., 2023a), and applied across life cycle phases could lead to design and construction for the best possible energy performance (O'Reilly and Mathews, 2019; Hunhevicz et al., 2022b). Similarly, strategic allocation of funds or rewards can incentivize better design according to targets such as productivity, carbon and waste reduction (Dounas et al., 2020, 2022a) or material recycling (Akbarieh et al., 2022). Finally, tokens are proposed to incentivize compliance with construction safety practices (Naderi et al., 2023; Bao et al., 2024).

4.3. OP 3 - ensure collective choice arrangements

Stakeholders in decentralized projects affected by operational rules should be allowed to participate in changing them (Cox et al., 2010; Ostrom, 2015). In IPD, firms that have signed the multi-party contract are entitled to participate in management group functions and vote on decisions that directly affect their work and area of expertise (Hall and Bonanomi, 2021).

4.3.1. M5 - Establish decentralized proposal and voting platforms

Decentralized decision making and voting are widely discussed in the context of governing blockchain networks and decentralized applications. As such, decentralized proposal and voting platforms based on smart contracts have been proposed as a mechanism to govern real-world commons (see Table 2).

Decentralized proposal and voting platforms could improve **collective decision-making among project stakeholders** in decentralized project delivery to gather opinions and define proposals for using the pooled resources (see Fig. 4, red boxes). Stakeholders can vote on proposals to make quick decisions across organizational levels, e.g., to collectively decide on resource allocation and provisioning rules. If the project uses a tokenized resource pool or rewards, approved funds or resources could be automatically released upon approval. While only Lombardi et al. (2020) have prototyped a DAO voting platform for approving or rejecting design proposals related to construction, several blockchain-based decision-making mechanisms have been implemented. For example, Token Curated Registries (TCRs) can manage the validity and functionality of tokens (Asgaonkar and Krishnamachari, 2018; Wang and Krishnamachari, 2019), while Politeia (Decred, 2023b) and Aragon Voice (Aragon, 2023a) are just two out of many examples of decentralized decision-making platforms for DAOs that allow stakeholders to propose and vote on governance changes and financial expenditures.

Tokens can grant decision-making rights, either to ensure an equal distribution of power by design (Rozas et al., 2021a; Red, 2019) or based on the contribution and reputation of parties (Emmett, 2019a; Xiao, 2019). In the context of decentralized project delivery, appropriate voting forms and decision-making mechanisms need to be explored e.g. with such **tokenized voting for power distribution among project stakeholders** (see Fig. 4, red boxes). With the exception of one study that explores a weighted tokenized voting mechanism through a governance token (Dounas et al., 2022a), there is very little research using token-based voting in a construction industry context.

In the blockchain space, there are various proposed voting mechanisms that could inspire new ways of voting in decentralized project delivery. For example, in Decred (2023a) , holders have one vote per token, which is pooled into larger amounts and locked for an uncertain period of time. This approach is anonymous and may be better suited to decentralized project delivery than where voters must be identifiable for 1 vote per person, as in existing democratic systems. Other proposed voting mechanisms that could be relevant to decentralized project delivery include quadratic coin-lock voting (Buterin, 2016) as a token-based variant of quadratic voting (Weyl and Lalley, 2017). The weight of votes is discounted by an exponential function to give more weight to minority opinions (Fritsch et al., 2021). Finally, in conviction voting, stakeholders continuously allocate votes in the form of tokens to different options, which slowly decay if not renewed (Emmett, 2019b). This allows user preferences to be tracked over long periods of time and prevents last-minute vote swings by large token holders (Fritsch et al., 2021).

4.3.2. M6 - Utilize decentralized prediction markets

Decentralized prediction markets have been proposed as a means of building a trusted knowledge base (see Table 2). Prediction markets were first introduced by Hanson (2013) as a way to get a more representative picture of future outcomes by creating a betting platform. The idea is that predictions made by people willing to risk a loss are more likely to be well-informed. Such decentralized prediction markets could be used as a **gamified sourcing of local project knowledge** from project stakeholders or other local actors (see Fig. 4, red boxes). However, to our knowledge, no such mechanisms have been explored for project delivery. Augur is probably the most common blockchain-based implementation of a prediction market that could be used also in a construction context (Peterson et al., 2022). Research could further explore the potential usefulness of prediction markets for decentralized project delivery, such as a betting platform to estimate the expected cost of the project or to identify risks that only local residents would know about. This could be an incentive for knowledgeable but unknown actors to participate, as they would be rewarded if their prediction was correct.

4.4. OP 4 - monitor users and resouces

Active monitoring of both the conditions of common resource and project stakeholder behavior is necessary to ensure compliance with agreed-upon tasks (Cox et al., 2010; Ostrom, 2015). In collaborative projects, stakeholders openly share resource, cost, profit, and performance data in big room meetings (Hall and Bonanomi, 2021).

4.4.1. M7 - Create a transparent record of blockchain transactions

Blockchain technology provides a transparent transaction record of users' actions by tracking transactions associated with their addresses, which are visible to all members of the community (see Table 2). Blockchain has been shown to increase trust by tracking information in construction supply chains (Qian and Papadonikolaki, 2020; Wahab et al., 2022), and could also ensure **trustworthy stakeholder actions and project resource flows** in decentralized project delivery by tracking transactions related to their addresses (see Fig. 4, orange boxes). Without stakeholders having access to trusted information about project performance, decentralized governance is not possible, e.g. for collective management of project resources (see 4.2.2) or collective voting (see 4.3.1). Substantial research is already focused on making construction project finances more trustworthy and transparent (Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020; Das et al., 2020; Elghaish et al., 2020, 2022; Hamledari and Fischer, 2021c; Nanayakkara et al., 2021; Ye and König, 2021; Bolton et al., 2022; Cheng et al., 2023). In many cases, the use of blockchain would inherently ensure open-book project finances. Similarly, tracking information and materials in the supply chain and throughout the lifecycle of assets with blockchain creates a trusted knowledge base of project progress (Kifokeris and Koch, 2020; Li et al., 2021b; Wang et al., 2020; Watson et al., 2019; Brandín and Abrishami, 2021; Wu et al., 2022, 2023a; Chen et al., 2023a).

Bottom-up coordination is essential for the management of decentralized systems (see 4.8.1). Decentralized project delivery will require that participants openly and transparently share information about resources, costs, profits, and performance. **Real-time transactions enable rapid response** of both project progress and resource unit withdrawals (see Fig. 4, orange boxes). Similar as weekly withdrawal of resource units is tracked through the "Planned Percent Complete" (PPC) metric in IPD to monitor deviations from the target value design process (Thomsen et al., 2009), the analysis of the constant flow of blockchain transactions can allow stakeholders to quickly respond to project events in a decentralized environment even with potentially unknown stakeholders. Proposed decentralized applications related to construction project delivery rely on real-time transactional feedback, often coupled with data from real-world events. For example, decentralized design competitions (Dounas et al., 2020) and design DAOs (Dounas et al., 2022a, 2022b) require feedback on the current design state. Performance-based smart contracts act on transaction data from digital twins (Hunhevicz et al., 2022b; Niavis et al., 2022), while automated payments and incentives rely on feedback from humans (Wahab et al., 2022), sensors (Chong and Diamantopoulos, 2020), robots (Lee et al., 2021), or reality capture technology providing images or videos (Hamledari and Fischer, 2021b; Naderi et al., 2023; Cheng et al., 2023; Wu et al., 2023a). Market mechanisms such as waste trading (Wu et al., 2023b) or recyclable materials (Akbarieh et al., 2022) also require constant real-time transaction feedback on available resources and recent trades.

Learning can be challenging in project-based organizations (Taylor et al., 2009; Lampel and Shamsie, 2003). The availability of a holistic project **transaction history for certification and learning** can help to comply with project terms or system boundaries, and create reliable feedback loops for improvement in decentralized project settings (see Fig. 4, orange boxes). Proposed blockchain applications for construction projects include trusted and traceable certification (Weerasuriya et al., 2023), focusing on quality information (Sheng et al., 2020), design liability control (Erri Pradeep et al., 2021), field work quality (Wu et al., 2021), document authenticity (Kim et al., 2022), or BIM data provenance (Celik et al., 2023). In addition, certification of compliance with local conditions, such as ethical sourcing or sustainability, can be automatically issued or obtained with less effort, e.g. by tracking prefabricated housing (Li et al., 2021a), estimating embodied carbon

(Rodrigo et al., 2020), tokenizing energy emission data (Niavis et al., 2022), or tracking material and energy for recycling and reuse (Shojaei et al., 2021).

4.4.2. M8 - Use transaction signatures for tamper-proof commitments

Decentralized projects, like other CPR scenarios, require stakeholder accountability (Cox et al., 2010; Ostrom, 2015). The immutability and censorship resistance of blockchain ensures that all decisions and transactions are transparent and verifiable (see Table 2). Each transaction on the blockchain is signed by a valid private key, generating digital signatures that guarantee tamper-proof commitments. This mechanism can be used to digitally commit to work packages by signing **smart legal contracts**, ensuring accountability in decentralized project delivery (see Fig. 4, orange boxes). Since machines can also hold addresses, they could participate in intelligent legal contracts and commit to work packages. The construction literature has explored the use of smart legal contracts (Shojaei et al., 2020; Allen and Hunn, 2022), also referred to as intelligent contracts (Mason, 2017; McNamara and Sepasgozar, 2021), to automatically execute encoded conditions for contract administration (Msawil et al., 2022) or automated contracting (Gupta and Jha, 2023).

4.4.3. M9 - Tokenize reputation

Pazaitis et al. (2017) proposed a system of reputation tokens to represent the value of contributions in blockchain applications. Earning reputation tokens by following the rules of the CPR scenario can be an additional measure of accountability (Xiao, 2019; Papadimitropoulos, 2022). The idea of using **reputation tokens for special privileges or for credentials** is also a potential approach to incentivize honest participation in decentralized project delivery (see Fig. 4, orange boxes). Reputation tokens may be superior to monetary rewards for some use case scenarios (Ballandies, 2022). They can be used to grant access to advanced governance features or be used as credentials for markets or future projects. In Dounas et al. (2022a), access to the design DAO is provided via a non-fungible token that also records each stakeholder's skills and track record. And although not tokenized, reputation-based voting was used in another prototype to evaluate proposed architectural designs (Lombardi et al., 2020).

4.4.4. M10 - Establish decentralized peer-review mechanisms

Decentralized projects cannot rely on the face-to-face "big room" meetings found in IPD, where they use a shared physical spaces for peer review of project activities and budgets (Hall and Bonanomi, 2021). However, decentralized peer review mechanisms using smart contracts have been proposed to assess work progress and contribution value (see Table 2). Blockchain-based **peer review of project progress, quality and cost** could be used to create a digital "big room platform" for accountability and evaluation of appropriate rewards and sanctions related to project progress, quality, and cost (see Fig. 4, orange boxes). The Covee protocol is an example of a blockchain-based peer review system that could be used to evaluate work and ensure fair distribution of benefits for decentralized collaborative teams (Dietsch et al., 2018). Anonymous contributors can receive cryptocurrency rewards based on their peer review scores. Peer review of transaction data can be an interesting alternative when automated and algorithmic verification is difficult to implement. Although not as extensive as Covee's peer review process, peer review of design (Lombardi et al., 2020) or the crowd-sourced arbitration process (Son and Lien, 2022) are early implementations of peer review in construction.

4.5. OP 5 - define graduated sanctions

In CPR scenarios, appropriators who violate operational rules should be subject to graduated sanctions based on the severity and context of the violation (Cox et al., 2010; Ostrom, 2015). Graduated sanctions are often not explicitly implemented in collaborative project deliveries (Bonanomi et al., 2019; Hall and Bonanomi, 2021), but in the case of persistent non-compliance or underperformance, removal of individual participants or companies is sometimes necessary (Cheng et al., 2016). Moreover, the weekly public reporting of the PPC metric serves as a means of social sanctioning (Hall and Bonanomi, 2021).

4.5.1. M11 - Facilitate transparent and self-enforcing sanctions with smart contracts

Blockchain enables transparent and self-enforcing token-based sanctions (see Table 2). This could be through the loss of either financial or reputational tokens (Dao, 2018; Emmett, 2019a; Xiao, 2019), or a decrease in the value of tokens (Xiao, 2019). **Token-based sanctions** can provide an opportunity to reimagine and improve graduated sanctions for decentralized project delivery through the self-enforcing loss of access tokens, loss of reputation tokens, or reduction in the value of monetary tokens (see Fig. 4, light green boxes). For example, a construction arbitration process implements monetary penalties (Son and Lien, 2022). Staking, or "locking" tokens for a period of time, has also been proposed to ensure "skin in the game" (Xiao, 2019). In case of non-compliance with the rules or the decision, the staked tokens can be penalized. One example is implementation of a staking mechanism used to participate in the DAO design competition of Dounas et al. (2022a).

Moreover, blockchain creates **social sanctioning through transparent actions** by making wrong actions automatically visible to the community (see Fig. 4, light green boxes). Underperformance in the project is visible to all, which could lead to even more efficient social sanctioning than current PPC practices. This may be sufficient to ensure accountability in many cases, but it could be reinforced by the loss of tokens described above. Examples proposed for construction project delivery include a reputation-based design mechanism to avoid poor design (Lombardi et al., 2020), transparent sustainability metrics of a prefabricated housing system (Li et al., 2021a), a supervision model for modular housing (Li et al., 2021b), or supervision of cross-border logistics (Wu et al., 2022).

4.6. OP 6 - allow for conflict resolution mechanisms

In CPR scenarios, it is important to have access to low-cost local arenas for conflict resolution among stakeholders (Cox et al., 2010; Ostrom, 2015). To avoid costly litigation in collaborative project delivery, project decision protocols (Ashcraft, 2011) and liability waivers (Sive and Hays, 2009) often include clear dispute resolution strategies.

4.6.1. M12 - Create decentralized jurisdiction systems

Blockchain technology can facilitate faster conflict resolution through decentralized jurisdictional systems compatible with existing legal and regulatory frameworks (see Table 2). Such **smart contract-based 'mini-courts' for fast and transparent dispute resolution** could be established during decentralized project delivery (see Fig. 4, dark green box). An existing example of dispute resolution in DAOs is the Aragon Court (Aragon, 2023b), which has implemented a decentralized judicial system with a network of guardians to arbitrate subjective disputes that cannot be resolved by smart contract logic alone. In construction, Saygili et al. (2021) have proposed a decentralized blockchain-based online dispute resolution platform specifically for construction disputes. Rather than a full platform, other dispute resolution-related proposals include a blockchain crowdsourced arbitration platform for resolving construction project delays (Son and Lien, 2022), a construction document tracking system for claims and dispute support (Kim et al., 2022), and an accountable cost search for resolving construction disputes (Cheng et al., 2023).

4.7. OP 7 - recognize rights to organize

The rights of the stakeholders to design their own institutions should not be challenged by external authorities (Ostrom, 2015; Cox et al., 2010). In collaborative project delivery, project sponsors trade decision-making autonomy for consensus mechanisms among project team members (Hall and Bonanomi, 2021).

4.7.1. M13 - Ensure decisions are made by affected parties with smart contracts

Within crypto-commons, smart contract mechanisms have been proposed to ensure that decisions are made by the affected parties (see Table 2). In other words, decentralized projects need to have a sponsor, but these project sponsors delegate authority to project participants to self-organize and self-govern the project. Once the decentralized sponsor has set up the project resource pool, they must recognize they no longer have full control over the project resources. Therefore, **smart contracts ensure that powerful parties cannot impose collective choice and conflict resolution alone** but by the relevant stakeholder group (see Fig. 4, light blue box), identified either on an individual address basis or by holding governance tokens. None of the reviewed articles mention this application specifically, but it is important for identified applications of decision making (see 4.3.1 and dispute resolution (see 4.6.1).

4.8. OP 8 - create nested enterprises

Appropriation, provision, monitoring, enforcement, conflict resolution, and governance rules and activities need to be coordinated across multiple layers of nested entities (Cox et al., 2010; Ostrom, 2015). Currently, large collaborative construction projects require multiple levels of management, including a senior management team for executive leadership, a cross-functional project management team for coordination, and functional teams for direct work execution and organization (Ashcraft, 2011; Laurent and Leicht, 2019).

4.8.1. M14 - Facilitate bottom-up coordination with smart contracts

Smart contracts can help coordinate different hierarchical levels of participants to achieve common goals that benefit the commons (see Table 2). For decentralized project delivery on the crypto commons, **smart contracts must coordinate decision-making between organisational levels** (see Fig. 4, dark blue box), either by adapting to existing hierarchical structures of collaborative project delivery, or by creating new organizational forms that can respond more quickly to local events and propagate information bottom-up to ensure maximum decentralization. Some of the early DAO experiments in construction prototype such decentralized coordination and consensus mechanisms between stakeholders (Lombardi et al., 2020; Lombardi and Dounas, 2022; Dounas et al., 2022b, 2022a).

5. Discussion

To provide a holistic basis for future research on decentralized project delivery, we discuss the proposed applications in terms of their potential impact at a systemic level, challenges related to system design,

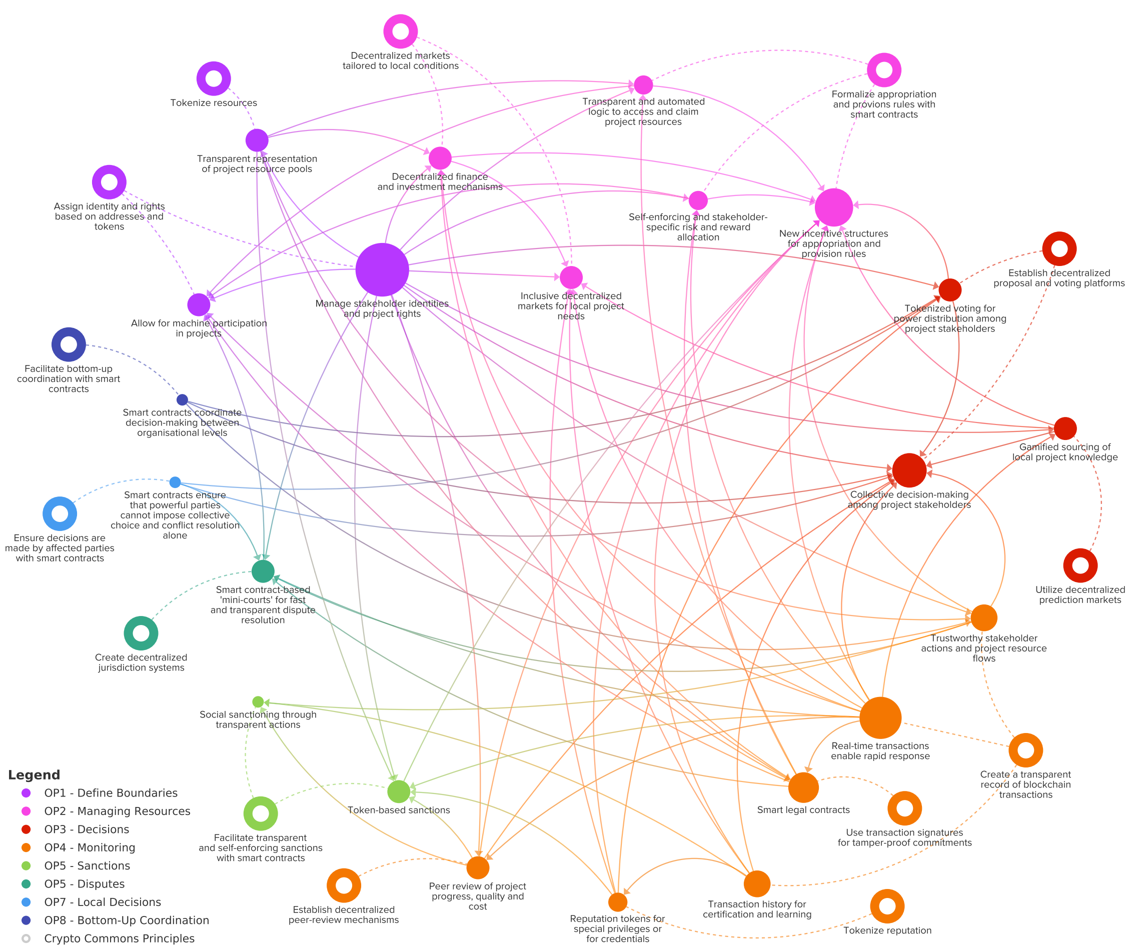

Fig. 5. The blockchain applications are interdependent and could form a system that aligns with CPR management principles to facilitate decentralized project delivery.

challenges specific to the construction industry context, and implications for project management research.

5.1. The value of a systemic implementation

While some of the identified applications can be used independently to support project delivery, they are likely to facilitate decentralized project delivery only in conjunction with each other through systemic implementation. To better illustrate this, Fig. 5 shows interdependencies between the different identified applications. The Figure is also accessible online, allowing for interactive exploration of the relationships.[1] The figure was created by going through all the combinations of applications identified in section 3 and asking whether they either depend on or enable another application. Adding directional arrows between these applications in the appropriate direction created the network shown. The applications were colored according to the color code used in Fig. 4 and scaled according to the number of connections. It is important to note that some relationships may not have been identified, and further research may reveal additional interactions between applications. The goal was to give the reader an idea how the individual application connect towards a more systemic view of decentralized project delivery. Below we describe some early but notable observations related to the interdependency of different applications.

Applications that are essential for facilitating decentralized project delivery have a high number of outbound connections. For example, "manage stakeholder identities and project rights" is necessary for identifying users through blockchain addresses for almost all other applications. Similarly, "transparent representation of project resource pools" and "real-time transactions enable rapid response" are critical to facilitate numerous other applications. As a result, these applications should be implemented first as a foundation for decentralized project delivery.

It is also noteworthy that these applications are consistent with the fundamental affordances of blockchain, underscoring the importance of the underlying technical system to ensure these properties (Xu et al., 2017; Hunhevicz and Hall, 2020; De Filippi et al., 2020). Therefore, future research should also explore the appropriate technical infrastructure for implementing the proposed blockchain governance applications in line with the desired properties of decentralized project delivery.

Most applications are interdependent and form system loops with other applications. For example, "smart legal contracts" depends on "manage stakeholder identities and project rights" and "real-time transactions enable rapid response" to execute automated contract terms, but in turn is a prerequisite for applications such as "decentralized financing and investment mechanisms", "transparent and automated logic to access and claim project resources", or "self-enforcing and stakeholder-specific risk and reward allocation".

Finally, certain applications are the result of a systemic implementation of applications, indicated by the many inbound connections in Fig. 5. These include "allow for machine participation in projects", "new incentive structures for compliance with appropriation and provisioning rules", and "collective decision-making among project stakeholders". These applications are not just standalone, but are the result of a systemic implementation of all other applications proposed for decentralized project delivery.

Therefore, the degree of decentralized project delivery can vary from individual use of identified applications to systemic implementation. High decentralization is consistent with the recommended bottom-up coordination approach to complex systems management, and potentially represents an alternative approach for future construction project delivery compared to currently explored vertical supply chain integration efforts (Hunhevicz et al., 2022a). Decentralized project delivery could build on existing models such as IPD and evolve towards theoretically proposed delivery systems such as IPD 4.0 (Hall et al., 2022), which provides an early vision for collective commons organizational structure, a value-based operating system, and micro-exchange commercial terms.

In addition, there is a connection between the concepts and the emerging field of DAOs in the blockchain space. Emerging DAO frameworks show similarities to the governance mechanisms of decentralized project delivery identified in this paper (van Vulpen and Jansen, 2023; Faqir-Rhazoui et al., 2021), and a recent study empirically investigated the use of a DAO for traditional project management tasks (Spychiger et al., 2023). The use of blockchain to create DAO-like organizations in the architecture, engineering, and construction (AEC) industry has been conceptually proposed (Sreckovic and Windsperger, 2020; Lombardi and Dounas, 2022) and prototyped in a DAO for the decentralized coordination of the design process (Lombardi et al., 2020; Dounas et al., 2022b). Therefore, further research should explore the relationships between the concepts of decentralized project delivery and DAOs. Emerging studies on metaverse and DAO governance (e.g., van Vulpen and Jansen (2023); Goldberg and Schär (2023)) could provide valuable insights for the further development of decentralized project delivery.

5.2. System Design challenges

Designing new blockchain-based governance systems for decentralized project delivery presents several challenges. To guide future research on potential difficulties in implementing blockchain governance, we discuss design challenges for decentralized project delivery. The section is organized according to the challenges identified by Cila et al. (2020) for monitoring, coding, and negotiating (see Table 3).

5.2.1. Monitor

Decentralized project delivery on the crypto commons presents new challenges in terms of privacy and transparency. While transparency is critical for effective system monitoring, it can also raise privacy concerns for stakeholders sharing their data on the blockchain (Cila et al., 2020). This is particularly challenging in public permissionless blockchain systems (Hunhevicz and Hall, 2020), where traditional privacy solutions may not be effective. To address this challenge, future research should carefully consider what data needs to be stored transparently to enable governance for decentralized project delivery, and how stakeholders perceive the implications of sharing this data.

In addition, potential measures to maintain an appropriate level of privacy without impeding monitoring should be explored. The

Table 3
Governance design challenges for crypto commons (Cila et al., 2020).

Design Challenges	Type	Description
Transparency vs. Privacy	Monitor	Crypto Commons must be monitored, but transparent tracking could lead to privacy concerns.
Economic vs. Social Values Quantified vs. Qualified Values	Code	Values of the Crypto Commons must be encoded in a representative way. This can be especially challenging for social or qualified values.
Incentivisation vs. Manipulation	Code	Crypto Commons must encode incentives without causing manipulation and unjustified exclusion of stakeholders.
Private vs. Collective Interests	Code	Encoding rules for Crypto Commons must weigh individual gains of stakeholders against the greater good of the community.
Human vs. Algorithmic Governance	Negotiate	Crypto commons must preserve human reasoning and debate in a system of formalized and algorithmic logic.

[1] https://embed.kumu.io/731342b14f9c54691a396e3852c52eff.

technological guarantees of blockchain technology, in terms of ex-ante automation and ex-post verification, could even replace the traditional requirements of monitoring and sanctioning in commons (Poux et al., 2021). Overall, striking a balance between transparency and privacy is critical to the successful implementation of blockchain governance mechanisms in decentralized project delivery.

5.2.2. Code

A major challenge in designing artificial commons is to decide, represent, and encode values in the system while maintaining a balance between individual gains and the greater good of the community (De Filippi, 2015; Cila et al., 2020).

For now, cryptoeconomic governance often focuses on monetary incentives, where feedback loops between wealth and power often spiral into plutocratic outcomes, human needs and wants beyond monetary ones are crowded out, and unwanted externalities such as environmental costs are discounted (Schneider, 2021). While economic and quantifiable values are easier to encode in blockchain systems through market pricing mechanisms, non-monetary values such as reputation play a critical role in commons (Fritsch et al., 2021). In the context of decentralized project delivery, both quantitative and informal systems can be used to incentivize behavior. Therefore, future research should investigate value flows in decentralized project delivery and explore ways to encode them into incentive systems, both monetary or non-monetary, that support bottom-up organization towards value creation (De Filippi, 2015). However, incentives can have downsides such as forced conformity and unforeseen negative secondary effects (Cila et al., 2020). Decentralized project delivery on the crypto commons must encode incentives without causing manipulation and unjustified exclusion of stakeholders. In addition, there is a need for a careful balance between incentivizing behaviors and preserving creativity and teamwork.

While natural commons are renewable and have an infinite lifespan, construction projects have a finite lifespan and their resources are intentionally consumed over time. The project is usually owned by the project sponsor, which also differs from natural commons. To design effective mechanisms for decentralized project delivery, it is important to thoroughly understand its peculiarities and complex nature in different project settings. Game theory, agent-based simulations, and mechanism design have been used in previous research to evaluate and design new incentive structures for project delivery (Teng et al., 2019; Jung et al., 2012; Son and Rojas, 2011; Han et al., 2019; Eissa et al., 2021).

5.2.3. Negotiate

Finally, preserving human reasoning and debate is difficult in a system based on formalized and algorithmic logic (Cila et al., 2020). This issue is also relevant to decentralized project delivery, where the ex-ante design of smart contracts is fraught with risk, as system engineers must anticipate all possible scenarios. Therefore, the governance system must be able to adapt to exceptions and design errors through community input. In addition to the governance structure and the enabling technology, community governance is an important part of cryptoeconomic governance (van Vulpen and Jansen, 2023). However, even with embedded governance processes to adjust algorithmic logic, the system may only respond to problems after the first failure has occurred. And once implemented, algorithmic processes may get stuck in the predefined cryptoeconomic processes even as the interests of participants change (Schneider, 2021). Therefore, careful and incremental adoption, coupled with extensive testing, is necessary to ensure successful implementation of such systems.

5.3. Challenges related to the construction context

The construction industry is known for its inherent barriers, which can pose significant challenges for the adoption of emerging technologies such as blockchain. Prior research has examined barriers and socio-technical challenges in applying blockchain to this domain (Li et al., 2019, 2023; Singh et al., 2023). Here, we only highlight some of the key challenges to implement new forms of project delivery relying on cryptoeconomic governance mechanisms for new incentives and coordination.

Unlike other industries that can be shifted to a mostly digital environment, the construction industry will always rely on the production of physical assets. Therefore, ensuring the integration of the physical and digital realms and the interconnection of existing software stacks is essential. This requires the collection of project-related data that reflects the physical state of the project and asset to be governed. Emerging technologies such as sensors, vision-based capturing technologies, and digital twins are crucial to achieving this integration (Hamledari and Fischer, 2021c; Hunhevicz et al., 2022b; Lee et al., 2021; Naderi et al., 2023; Dounas et al., 2023b). Nevertheless, there remain many unanswered questions concerning the effective connection and use of available blockchain technologies with real-world data sources (Al-Breiki et al., 2020; Dounas et al., 2023a).

Furthermore, the level of digitization in the construction industry remains low (Agarwal et al., 2016; Barbosa et al., 2017). This can hinder the adoption of digital project delivery models, including the here proposed blockchain-based decentralized project delivery, that require extensive project-related data. As long as this data remains unavailable, the proposed mechanisms cannot be used to manage construction projects. However, there are indications that the level of digitalization in the industry is rapidly increasing. This new reality has already necessitated changes in project delivery models (Whyte, 2019) and project management (Levitt, 2011), as will be discussed further below.

Finally, researchers need to address challenges related to legal implications arising from these solutions. Specifically, there is a need to explore how smart contract code can comply with relevant legal and regulatory frameworks (De Filippi and Hassan, 2016).

5.4. Implications for project management research

Although the proposed conceptualization has been motivated by construction project delivery models, we suggest that decentralized project delivery could be applicable to the delivery of many other types of projects. We expect that the same governance mechanisms would be applicable in many other situations.

From the perspective of project management research, conceptualizing the project as a commons also enables further connection between project delivery models and the application of stewardship theory in the project management domain (Ahola, 2023). Stewardship theory proposes that the behavior of individuals in organizations is aligned and supportive to organizational and collective goals, rather than individualistic and self-serving goals (Davis et al., 1997). The application of stewardship theory to projects suggests that project stakeholders are empowered and jointly incentivized to maximize utility for the good of the overall project (Ahola, 2023; Biesenthal and Wilden, 2014). This aligns closely with the guiding incentives of stakeholders that steward the commons (Ostrom, 2015).

Future research directions could seek to understand how and why project stewards might select and implement some of the proposed mechanisms to govern their decentralized projects. Examining the role of these stewards might provide insight into the future of project management. In the past, scholars identified how shifts in digital technologies have influenced project management (Marnewick and Marnewick, 2022), such as how the introduction of real-time, synchronous data exchange overturned long-held assumptions (e.g., centralized planning and control) of classical project management (Levitt, 2011). In the same way, future research could investigate how the nature of blockchain technology, when applied to decentralized project delivery, might also overturn current assumptions of project management and require new skills and proficiency from the project steward. Such observations might act as a basis for study towards understanding "Project Management 3.0."

6. Conclusion

This paper conceptualizes *decentralized project delivery on the crypto commons*. The paper reviewed 14 blockchain mechanisms for governing CPR scenarios in line with the eight Ostrom Principles (OPs), and subsequently identified 22 applications to decentralized project delivery, which are routed in individually proposed and reviewed use cases of blockchain to construction as a project-based industry. In doing so, we contribute to the emerging scholarship on blockchain's potential to disrupt economic systems. The conceptualization acts as a basis which can encourage project management scholars to explore new project delivery models that are consistent with the principles of decentralized organization on the crypto commons.

The proposed applications could be combined in different system combinations, and with that promotes thinking about how project stewards could select from the possible proposed applications as needed on a specific project basis. This could potentially lead to the next generation of project delivery models which are delivered in a decentralized and collective manner on the crypto commons. Overall, this paper argues that blockchain-based governance mechanisms hold the promise of facilitating trusted, scalable, and efficient bottom-up coordination mechanisms that can handle the complexity of construction projects. They also offer new opportunities to improve coordination, participation, and decision-making by both humans and machines.

While the paper presents a coherent conceptualization for blockchain-based decentralized project delivery, it builds on the presented conceptual linkages and needs to be revised in case of new insights. Moreover, the paper encourages more research on both the individual application mechanisms, especially for applications only supported by a small number of publications. The paper further discusses the need for more interdisciplinary research efforts regarding the challenges associated with implementing of combined applications into a system, the difficulties in designing blockchain-based governance systems, and the industry-related challenges to be overcome. Validation through proof-of-concepts to explore the feasibility of individual and combined applications will be important. Selection and implementation of successful approaches could be further inspired and supported by current experimentation in DAOs, as many of the proposed application mechanisms seem to align.

The paper primarily targets construction as a project-based industry, but the identified blockchain governance mechanisms and applications could eventually be applied to other projects and cases of digital or real-world commons. Overall, this paper provides a starting point for future research to explore the potential of blockchain in transforming digital project delivery in the construction industry and beyond.

CRediT authorship contribution statement

Jens J. Hunhevicz: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Daniel M. Hall:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Conceptualization. **Pierre-Antoine Brasey:** Investigation, Conceptualization, Writing – review & editing. **Marcella M.M. Bonanomi:** Writing – review & editing, Supervision, Conceptualization. **Martin Fischer:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

References

Adel, K., Elhakeem, A., Marzouk, M., 2022. Decentralizing construction AI applications using blockchain technology. Expert Syst. Appl. 194, 116548 https://doi.org/10.1016/j.eswa.2022.116548.

Agarwal, R., Chandrasekaran, S., Sridhar, M., 2016. Imagining Construction's Digital Future. Technical Report. McKinsey & Company.

Ahmadisheykhsarmast, S., Senji, S.G., Sonmez, R., 2023. Decentralized tendering of construction projects using blockchain-based smart contracts and storage systems. Autom. ConStruct. 151, 104900 https://doi.org/10.1016/j.autcon.2023.104900.

Ahmadisheykhsarmast, S., Sonmez, R., 2020. A smart contract system for security of payment of construction contracts. Autom. ConStruct. 120, 103401 https://doi.org/10.1016/j.autcon.2020.103401.

Ahola, T., 2023. Classic perspectives on project governance: transaction cost economics, agency theory, and stewardship theory. Chapters 31–41.

Akbarieh, A., Carbone, W., Schäfer, M., Waldmann, D., Teferle, F.N., 2022. An Adaptive Conceptual Framework for Smart Management of Recyclable Construction Materials by Leveraging the Salvage Value through Blockchain and Building Information Modelling-Compliant Material Banks.

Al-Breiki, H., Rehman, M.H.U., Salah, K., Svetinovic, D., 2020. Trustworthy blockchain oracles: review, comparison, and open research challenges. IEEE Access 8, 85675–85685. https://doi.org/10.1109/ACCESS.2020.2992698.

Allen, J., Hunn, P. (Eds.), 2022. Smart Legal Contracts: Computable Law in Theory and Practice, 1 ed. Oxford University Press. https://doi.org/10.1093/oso/9780192858467.001.0001.

Andreewsky, E., Bourcier, D., 2000. Abduction in language interpretation and law making. Kybernetes 29, 836–845.

Aragon, 2023a. Aragon Voice. https://voice.aragon.org/.

Aragon, 2023b. Aragon Whitepaper. https://github.com/aragon/whitepaper.

Asgaonkar, A., Krishnamachari, B., 2018. Token Curated Registries - A Game Theoretic Approach.

Ashcraft, H.W.J., 2011. Negotiating an integrated project delivery agreement. Construct. Lawyer 31 (17–34), 49–50.

Balasanov, S., 2018. Bonding Curves in Depth : Intuition & Parametrization.

Ballandies, M.C., 2022. To incentivize or not: impact of blockchain-based cryptoeconomic tokens on human information sharing behavior. IEEE Access 10, 74111–74130.

Ballandies, M.C., Dapp, M.M., Degenhart, B.A., Helbing, D., 2021a. Finance 4.0: Design Principles for a Value-Sensitive Cryptoecnomic System to Address Sustainability.

Ballandies, M.C., Dapp, M.M., Pournaras, E., 2021b. Decrypting distributed ledger design—taxonomy, classification and blockchain community evaluation. Cluster Comput. 1–22. https://doi.org/10.1007/s10586-021-03256-w.

Bao, Q.L., Tran, S.V.T., Yang, J., Pedro, A., Pham, H.C., Park, C., 2024. Token incentive framework for virtual-reality-based construction safety training. Autom. ConStruct. 158, 105167 https://doi.org/10.1016/j.autcon.2023.105167.

Barbosa, F., Woetzel, J., Mischke, J., Ribeirinho, M.J., Sridhar, M., Parsons, M., Bertram, N., Brown, S., 2017. Reinventing Construction: A Route to Higher Productivity. McKinsey & Company.

Bauwens, M., Kostakis, V., Pazaitis, A., 2019. Peer to Peer: the Commons Manifesto. University of Westminster Press. https://doi.org/10.16997/book33.

Beck, R., Müller-Bloch, C., King, J., 2018. Governance in the blockchain economy: a framework and research agenda. J. Assoc. Inf. Syst. Online 19.

Bertelsen, S., 2003. Complexity - a new way of understanding construction. Proceedings of the Thirteen Annual Conference of the International Group for Lean Construction, IGLC- 13, 1–13.

Bertelsen, S., Koskela, L., 2004. Construction beyond lean: a new understanding of construction management. \ldots the International Group for Lean Construction 1–11.

Biesenthal, C., Wilden, R., 2014. Multi-level project governance: trends and opportunities. Int. J. Proj. Manag. 32, 1291–1308. https://doi.org/10.1016/j.ijproman.2014.06.005.

Bolton, S., Wedawatta, G., Wanigarathna, N., Malalgoda, C., 2022. Late payment to subcontractors in the construction industry. J. Leg. Aff. Dispute Resolut. Eng. Constr. 14, 04522018 https://doi.org/10.1061/(ASCE)LA.1943-4170.0000552.

Bonanomi, M., Fischer, S., Hall, D.M., 2019. Identifying project management practices for the multi-party construction commons. In: 17th Annual Engineering Porject Organization Conference (EPOC).

Bonanomi, M.M., Hall, D.M., Staub-french, S., 2020. Governing integrated project delivery as a common pool resource scenario: what management practices and impact on project participants?. In: 18th Annual Engineering Project Organization Conference (EPOC).

Brandín, R., Abrishami, S., 2021. Information traceability platforms for asset data lifecycle: blockchain-based technologies. Smart and Sustainable Built Environment 10, 364–386. https://doi.org/10.1108/SASBE-03-2021-0042.

Brekke, J.K., Alsindi, W.Z., 2021. Cryptoeconomics. Internet Policy Review 10. https://doi.org/10.14763/2021.2.1553.

Brunet, M., Cohendet, P., 2022. Transforming construction: heterarchical megaproject ecologies and the management of innovation. Construct. Manag. Econ. 40, 973–986. https://doi.org/10.1080/01446193.2021.1983851.

Buterin, V., 2014. Ethereum: A Next-Generation Smart Contract and Decentralized Application Platform.
Buterin, V., 2016. On Coin-lock Voting, Futarchy and Optimal Decentralized Governance : Ethereum.
Bygballe, L.E., Dewulf, G., Levitt, R.E., 2015. The interplay between formal and informal contracting in integrated project delivery. Eng. Proj. Organ. J. 5, 22–35. https://doi.org/10.1080/21573727.2014.992014.
Catalini, C., Gans, J.S., 2020. Some simple economics of the blockchain. Commun. ACM 63, 80–90. https://doi.org/10.1145/3359552.
Celik, Y., Petri, I., Barati, M., 2023. Blockchain supported BIM data provenance for construction projects. Comput. Ind. 144, 103768 https://doi.org/10.1016/j.compind.2022.103768.
Chen, G., Li, H., Liu, M., Hsiang, S.M., Jarvamardi, A., 2023a. Knowing what is going on—a smart contract for modular construction. Can. J. Civ. Eng. 50, 210–223. https://doi.org/10.1139/cjce-2021-0649.
Chen, G., Liu, M., Li, H., Hsiang, S.M., Jarvamard, A., 2023b. Motivating reliable collaboration for modular construction: Shapley value–based smart contract. J. Manag. Eng. 39, 04023042 https://doi.org/10.1061/JMENEA.MEENG-5428.
Cheng, J.C.P., Liu, H., Gan, V.J.L., Das, M., Tao, X., Zhou, S., 2023. Construction cost management using blockchain and encryption. Autom. ConStruct. 152, 104841 https://doi.org/10.1016/j.autcon.2023.104841.
Cheng, R., Allison, M., Sturts-Dossick, C., Monson, C., Staub-French, S., Poirier, E., 2016. Motivation and Means: How and Why IPD and Lean Lead to Success. Technical Report. University of Minnesota; University of Washington; University of British Columbia; Scan Consulting.
Chong, H.Y.Y., Diamantopoulos, A., 2020. Integrating advanced technologies to uphold security of payment: data flow diagram. Autom. ConStruct. 114, 103158 https://doi.org/10.1016/j.autcon.2020.103158.
Cila, N., Ferri, G., de Waal, M., Gloerich, I., Karpinski, T., 2020. The blockchain and the commons: dilemmas in the design of local platforms. In: Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems. ACM, New York, NY, USA, pp. 1–14. https://doi.org/10.1145/3313831.3376660.
Cox, M., Arnold, G., Tomás, S.V., Villamayor Tomás, S., 2010. A review of design principles for community-based natural resource management. Ecol. Soc. 15, art38 https://doi.org/10.5751/ES-03704-150438.
Crypto Commons Association, 2021. Crypto Commons.
Dao, D., 2018. Decentralized Sustainability.
Das, M., Luo, H., Cheng, J.C., 2020. Securing interim payments in construction projects through a blockchain-based framework. Autom. ConStruct. 118, 103284 https://doi.org/10.1016/j.autcon.2020.103284.
Davidson, S., De Filippi, P., Potts, J., 2016. Disrupting governance: the new institutional economics of distributed ledger technology. SSRN Electron. J. https://doi.org/10.2139/ssrn.2811995.
Davidson, S., De Filippi, P., Potts, J., 2018. Blockchains and the economic institutions of capitalism. J. Inst. Econ. 14, 639–658. https://doi.org/10.1017/S1744137417000200.
Davies, A., MacAulay, S.C., Brady, T., 2019. Delivery model innovation: insights from infrastructure projects. Proj. Manag. J. 50, 119–127. https://doi.org/10.1177/8756972819831145.
Davis, J.H., Schoorman, F.D., Donaldson, L., 1997. Toward a stewardship theory of management. Acad. Manag. Rev. 22, 20–47. https://doi.org/10.2307/259223 arXiv:259223.
De Filippi, P., 2015. Translating commons-based peer production values into metrics: toward commons-based cryptocurrencies. In: Handbook of Digital Currency. Elsevier, pp. 463–483.
De Filippi, P., Hassan, S., 2016. Blockchain technology as a regulatory technology: from code is law to law is code. Clin. Hemorheol. and Microcirc. 21 https://doi.org/10.5210/fm.v21i12.7113.
De Filippi, P., Mannan, M., Reijers, W., 2020. Blockchain as a confidence machine: the problem of trust & challenges of governance. Technol. Soc. 62, 101284 https://doi.org/10.1016/j.techsoc.2020.101284.
de la Rouviere, S., 2018. Saving the Planet: Making it Profitable to Protect the Commons.
Decoodt, K., 2019. The Commons Stack: Scaling the Commons to Re-prioritize People and the Planet.
Decred, 2023a. Introduction to decred governance. https://docs.decred.org/.
Decred, 2023b. Politea. https://docs.decred.org/.
Denis, J.L., Lamothe, L., Langley, A., 2001. The dynamics of collective leadership and strategic change in pluralistic organizations. Acad. Manag. J. 44, 809–837. https://doi.org/10.2307/3069417 arXiv:3069417.
Dietsch, M., Krause, J., Nax, H.H., Omeru, J., Schoettler, R., Seuken, S., 2018. Covee Protocol.
Dounas, T., Hunhevicz, J., Byers, B., 2023a. Design dimensions for blockchain oracles in the AEC industry. In: 2023 European Conference on Computing in Construction and the 40th International CIB W78 Conference. https://doi.org/10.35490/EC3.2023.297.
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, T.T.S. (Eds.), PROJECTIONS - Proceedings of the 26th CAADRIA Conference - Volume 2. The Chinese University of Hong Kong and Online, Hong Kong, pp. 151–160, 29 March - 1 April 2021.
Dounas, T., Lombardi, D., Jabi, W., 2020. Framework for decentralised architectural design BIM and Blockchain integration. Int. J. Architect. Comput. https://doi.org/10.1177/1478077120963376.
Dounas, T., Lombardi, D., Jabi, W., 2022a. Collective digital factories for buildings: stigmergic collaboration through cryptoeconomics. In: Dounas, T., Lombardi, D. (Eds.), Blockchain for Construction. Springer Nature. Blockchain Technologies, Singapore, pp. 207–228. https://doi.org/10.1007/978-981-19-3759-0_11.
Dounas, T., Lombardi, D., Vele, J., Prokop, S., 2023b. A crypto-twin framework for the AEC industry - enabling digital twins with blockchain technologies. Architecture and Planning Journal (APJ) 28. https://doi.org/10.54729/2789-8547.1215.
Dounas, T., Voeller, E., Prokop, S., Vele, J., 2022b. The Architecture Decentralised Autonomous Organisation - a stigmergic exploration in architectural collaboration. In: eCAADe 2022: Co-creating the Future - Inclusion in and through Design, pp. 567–576. https://doi.org/10.52842/conf.ecaade.2022.1.567. Ghent, Belgium.
Dubois, A., Gadde, L.E., 2002a. The construction industry as a loosely coupled system: implications for productivity and innovation. Construct. Manag. Econ. 20, 621–631. https://doi.org/10.1080/01446190210163543.
Dubois, A., Gadde, L.E., 2002b. Systematic combining: an abductive approach to case research. J. Bus. Res. 55, 553–560. https://doi.org/10.1016/S0148-2963(00)00195-8.
Dunphy, P., Petitcolas, F.A., 2018. A first look at identity management schemes on the blockchain. IEEE Security & Privacy 16, 20–29. https://doi.org/10.1109/MSP.2018.3111247.
Eissa, R., Eid, M.S., Elbeltagi, E., 2021. Current applications of game theory in construction engineering and management research: a social network analysis approach. J. Construct. Eng. Manag. 147, 04021066 https://doi.org/10.1061/(ASCE)CO.1943-7862.0002085.
El Asmar, M., Hanna, A.S., Loh, W.Y., 2013. Quantifying performance for the integrated project delivery system as compared to established delivery systems. J. Construct. Eng. Manag. 139, 04013012 https://doi.org/10.1061/(ASCE)CO.1943-7862.0000744.
Elghaish, F., Abrishami, S., Hosseini, M.R., 2020. Integrated project delivery with blockchain: an automated financial system. Autom. ConStruct. 114, 103182 https://doi.org/10.1016/j.autcon.2020.103182.
Elghaish, F., Pour Rahimian, F., Hosseini, M.R., Edwards, D., Shelbourn, M., 2022. Financial management of construction projects: hyperledger fabric and chaincode solutions. Autom. ConStruct. 137, 104185 https://doi.org/10.1016/j.autcon.2022.104185.
Emmett, J., 2019a. Automating Ostrom for Effective DAO Management.
Emmett, J., 2019b. Conviction Voting: A Novel Continuous Decision Making Alternative to Governance.
Epstein, R.A., 2002. The allocation of the commons: parking on public roads. J. Leg. Stud. 31, S515–S544. https://doi.org/10.1086/342023.
Erri Pradeep, A.S., Yiu, T.W., Zou, Y., Amor, R., 2021. Blockchain-aided information exchange records for design liability control and improved security. Autom. ConStruct. 126, 103667 https://doi.org/10.1016/j.autcon.2021.103667.
Faqir-Rhazoui, Y., Arroyo, J., Hassan, S., 2021. A comparative analysis of the platforms for decentralized autonomous organizations in the Ethereum blockchain. Journal of Internet Services and Applications 12, 9. https://doi.org/10.1186/s13174-021-00139-6.
Favre, T., 2019. Continuous Organizations.
Filip, F.G., Leiviskä, K., 2023. Infrastructure and complex systems automation. In: Nof, S. Y. (Ed.), Springer Handbook of Automation. Springer International Publishing, Cham, pp. 617–640. https://doi.org/10.1007/978-3-030-96729-1_27. Springer Handbooks.
Franz, B., Leicht, R., Molenaar, K., Messner, J., 2017. Impact of team integration and group cohesion on project delivery performance. J. Construct. Eng. Manag. 143, 04016088 https://doi.org/10.1061/(ASCE)CO.1943-7862.0001219.
Fritsch, F., Emmett, J., Friedman, E., Kranjc, R., Manski, S., Zargham, M., Bauwens, M., 2021. Challenges and approaches to scaling the global commons. Frontiers in Blockchain 4, 1–16. https://doi.org/10.3389/fbloc.2021.578721.
Gardner, R., Ostrom, E., Walker, J.M., Wilson, D.B., 1990. The nature of common-pool resource problems. Ration. Soc. 2, 335–358.
Gidado, K.I., 1996. Project complexity: the focal point of construction production planning. Construct. Manag. Econ. 14, 213–225. https://doi.org/10.1080/014461996373476.
Gil, N., 2022. Megaprojects: a meandering journey towards a theory of purpose, value creation and value distribution. Construct. Manag. Econ. 40, 562–584. https://doi.org/10.1080/01446193.2021.1946832.
Gil, N., Pinto, J.K., 2018. Polycentric organizing and performance: a contingency model and evidence from megaproject planning in the UK. Res. Pol. 47, 717–734. https://doi.org/10.1016/j.respol.2018.02.001.
Goldberg, M., Schär, F., 2023. Metaverse governance: an empirical analysis of voting within Decentralized Autonomous Organizations. J. Bus. Res. 160, 113764 https://doi.org/10.1016/j.jbusres.2023.113764.
Gunasekara, H.G., Sridarran, P., Rajaratnam, D., 2022. Effective use of blockchain technology for facilities management procurement process. J. Facil. Manag. 20, 452–468. https://doi.org/10.1108/JFM-10-2020-0077.
Gupta, P., Jha, K.N., 2023. A decentralized and automated contracting system using a blockchain-enabled network of stakeholders in construction megaprojects. J. Manag. Eng. 39, 04023021 https://doi.org/10.1061/JMENEA.MEENG-5366.
Hall, D.M., Algiers, A., Levitt, R.E., 2018. Identifying the role of supply chain integration practices in the adoption of systemic innovations. J. Manag. Eng. 34, 04018030 https://doi.org/10.1061/(ASCE)ME.1943-5479.0000640.
Hall, D.M., Bonanomi, M.M., 2021. Governing collaborative project delivery as a common-pool resource scenario. Proj. Manag. J. https://doi.org/10.1177/8756972820982442.
Hall, D.M., Hunhevicz, J., Bonanomi, M.M.M., 2022. Blockchain Governance for Integrated Project Delivery 4.0, 1 ed. Routledge, London, pp. 288–305. https://doi.org/10.1201/9781003150930-23.

Hall, D.M., Scott, W.R., 2019. Early stages in the institutionalization of integrated project delivery. Proj. Manag. J. 50, 875697281881991 https://doi.org/10.1177/8756972818819915.
Hamledari, H., Fischer, M., 2021a. The application of blockchain-based crypto assets for integrating the physical and financial supply chains in the construction & engineering industry. Autom. ConStruct. 127, 103711 https://doi.org/10.1016/j.autcon.2021.103711.
Hamledari, H., Fischer, M., 2021b. Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. Autom. ConStruct. 132, 103926 https://doi.org/10.1016/j.autcon.2021.103926.
Hamledari, H., Fischer, M., 2021c. Role of blockchain-enabled smart contracts in automating construction progress payments. J. Leg. Aff. Dispute Resolut. Eng. Constr. 13, 04520038 https://doi.org/10.1061/(ASCE)LA.1943-4170.0000442.
Han, J., Rapoport, A., Fong, P.S., 2019. Incentive structures in multi-partner project teams. Eng. Construct. Architect. Manag. 27, 49–65. https://doi.org/10.1108/ECAM-09-2018-0410.
Hanson, R., 2013. Shall we vote on values, but bet on beliefs? J. Polit. Philos. 21, 151–178. https://doi.org/10.1111/jopp.12008.
Hardin, G., 1968. The tragedy of the commons. Science 162, 1243–1248. https://doi.org/10.1126/science.162.3859.1243.
Hassan, S., De Filippi, P., 2021. Decentralized autonomous organization. Internet Policy Review 10. https://doi.org/10.14763/2021.2.1556.
Helbing, D., Lämmer, S., 2008. Managing complexity: an introduction. Understanding Complex Systems 2008, 1–16. https://doi.org/10.1007/978-3-540-75261-5_1.
Henisz, W.J., Levitt, R.E., Scott, W.R., 2012. Toward a unified theory of project governance: economic, sociological and psychological supports for relational contracting. Eng. Proj. Organ. J. 2, 37–55. https://doi.org/10.1080/21573727.2011.637552.
Hewavitharana, T., Nanayakkara, S., Perera, S., 2019. Blockchain as a Project Management Platform, pp. 137–146doi. https://doi.org/10.31705/WCS.2019.14.
Hunhevicz, J., Dounas, T., Hall, D.M., 2022a. The promise of blockchain for the construction industry: a governance lens. In: Blockchain in Construction. Springer. https://doi.org/10.1007/978-981-19-3759-0.
Hunhevicz, J.J., Bucher, D.F., Soman, R.K., Honic, M., Hall, D.M., De Wolf, C., 2023. Web3-based role and token data access: the case of building material passports. In: 2023 European Conference on Computing in Construction and the 40th International CIB W78 Conference. https://doi.org/10.35490/EC3.2023.217.
Hunhevicz, J.J., Hall, D.M., 2020. Do you need a blockchain in construction? Use case categories and decision framework for DLT design options. Adv. Eng. Inf. 45, 101094 https://doi.org/10.1016/j.aei.2020.101094.
Hunhevicz, J.J., Motie, M., Hall, D.M., 2022b. Digital building twins and blockchain for performance-based (smart) contracts. Autom. ConStruct. 133, 103981 https://doi.org/10.1016/j.autcon.2021.103981.
Hunhevicz, J.J., Schraner, T., Hall, D.M., 2020. Incentivizing high-quality data sets in construction using blockchain: a feasibility study in the Swiss industry. In: Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC), pp. 1291–1298. https://doi.org/10.22260/ISARC2020/0177. Japan (Online).
Hunhevicz, J.J., Wang, H., Hess, L., Hall, D.M., 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.
Ibrahim, M.W., Hanna, A., Kievet, D., 2020. Quantitative comparison of project performance between project delivery systems. J. Manag. Eng. 36, 04020082 https://doi.org/10.1061/(ASCE)ME.1943-5479.0000837.
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, NY, USA, pp. 282–290. https://doi.org/10.1145/3412841.3441911.
Jung, W., Ballard, G., Kim, Y.W., Han, S.H., 2012. Understanding of target value design for integrated project delivery with the context of game theory. In: Construction Research Congress 2012. American Society of Civil Engineers, Reston, VA, pp. 556–563. https://doi.org/10.1061/9780784412329.056.
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. Construct. 25, 500–521. https://doi.org/10.36680/J.ITCON.2020.029.
Kim, E.W., Park, M.S., Kim, K., Kim, K.J., 2022. Blockchain-based automatic tracking and extracting construction document for claim and dispute support. KSCE J. Civ. Eng. 26, 3707–3724. https://doi.org/10.1007/s12205-022-2181-z.
Kim, K., Lee, G., Kim, S., 2020. A study on the application of blockchain technology in the construction industry. KSCE J. Civ. Eng. 24, 2561–2571. https://doi.org/10.1007/s12205-020-0188-x.
Kovács, G., Spens, K.M., 2005. Abductive reasoning in logistics research. Int. J. Phys. Distrib. Logist. Manag. 35, 132–144. https://doi.org/10.1108/09600030510590318.
Lahdenperä, P., 2012. Making sense of the multi-party contractual arrangements of project partnering, project alliancing and integrated project delivery. Construct. Manag. Econ. 30, 57–79. https://doi.org/10.1080/01446193.2011.648947.
Lampel, J., Shamsie, J., 2003. Capabilities in motion: new organizational forms and the reshaping of the hollywood movie industry. J. Manag. Stud. 40, 2189–2210. https://doi.org/10.1046/j.1467-6486.2003.00417.x.
Laurent, J., Leicht, R.M., 2019. Practices for designing cross-functional teams for integrated project delivery. J. Construct. Eng. Manag. 145, 05019001 https://doi.org/10.1061/(ASCE)CO.1943-7862.0001605.
Lee, D., Lee, S.H., Masoud, N., Krishnan, M., Li, V.C., 2021. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. Autom. ConStruct. 127, 103688 https://doi.org/10.1016/j.autcon.2021.103688.
Levitt, R.E., 2011. Towards project management 2.0. Eng. Proj. Organ. J. 1, 197–210. https://doi.org/10.1080/21573727.2011.609558.
Li, C.Z., Chen, Z., Xue, F., Kong, X.T.R., Xiao, B., Lai, X., Zhao, Y., 2021a. A blockchain- and IoT-based smart product-service system for the sustainability of prefabricated housing construction. J. Clean. Prod. 286, 125391 https://doi.org/10.1016/j.jclepro.2020.125391.
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. ConStruct. 102, 288–307. https://doi.org/10.1016/J.AUTCON.2019.02.005.
Li, J., Kassem, M., 2021. Applications of distributed ledger technology (DLT) and Blockchain-enabled smart contracts in construction. Autom. ConStruct. 132, 103955 https://doi.org/10.1016/j.autcon.2021.103955.
Li, J., Kifokeris, D., Barati, M., Calis, G., Hall, D., Hunhevicz, J., Kassem, M., Msawil, M., Arnal, I.P., Srećković, M., 2023. Human-Data Interaction (HDI) and blockchain: an exploration of the open research challenges for the construction community. In: 2023 European Conference on Computing in Construction and the 40th International CIB W78 Conference. https://doi.org/10.35490/EC3.2023.263.
Li, X., Wu, L., Zhao, R., Lu, W., Xue, F., 2021b. Two-layer Adaptive Blockchain-based Supervision model for off-site modular housing production. Comput. Ind. 128, 103437 https://doi.org/10.1016/j.compind.2021.103437.
Linåker, J., Runeson, P., 2022. Sustaining Open Data as a Digital Common – Design Principles for Common Pool Resources Applied to Open Data Ecosystems. https://doi.org/10.48550/arXiv.2208.01694 arXiv:2208.01694.
Lombardi, D., Dounas, T., 2022. Decentralised autonomous organisations for the AEC and design industries. In: Dounas, T., Lombardi, D. (Eds.), Blockchain for Construction. Springer Nature. Blockchain Technologies, Singapore, pp. 35–45. https://doi.org/10.1007/978-981-19-3759-0_3.
Lombardi, D., Dounas, T., Cheung, L.H., Jabi, W., 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.
Machart, F., Samadi, J., 2020. The State of Blockchain Governance. Technical Report July. Greenfield One.
Malafosse, M., Pascal, A., Amabile, S., 2022. Commoning with blockchain. The Ğ1 libre currency/Duniter case. Syst. Inf. Manag. 27, 7–34. https://doi.org/10.3917/sim.222.0007.
Maples, M.J., 2018. Crypto Commons.
Marnewick, C., Marnewick, A.L., 2022. Digitalization of project management: opportunities in research and practice. Project Leadership and Society 3, 100061. https://doi.org/10.1016/j.plas.2022.100061.
Mason, J., 2017. Intelligent contracts and the construction industry. J. Leg. Aff. Dispute Resolut. Eng. Constr. 9, 04517012 https://doi.org/10.1061/(ASCE)LA.1943-4170.0000233.
Mathews, M., Robles, D., Bowe, B., 2017. BIM+Blockchain: a solution to the trust problem in collaboration? CITA BIM Gathering. November 23rd-24th November 2017.
McNamara, A.J., Sepasgozar, S.M., 2021. Intelligent contract adoption in the construction industry: concept development. Autom. ConStruct. 122, 103452 https://doi.org/10.1016/j.autcon.2020.103452.
Mesa, H.A., Molenaar, K.R., Alarcón, L.F., 2016. Exploring performance of the integrated project delivery process on complex building projects. Int. J. Proj. Manag. 34, 1089–1101. https://doi.org/10.1016/j.ijproman.2016.05.007.
Miscione, G., Goerke, T., Klein, S., Schwabe, G., Ziolkowski, R., 2019. Hanseatic governance: understanding blockchain as organizational technology. In: Fortieth International Conference on Information Systems. https://doi.org/10.5167/uzh-177370. Munich.
Monostori, L., Valckenaers, P., Dolgui, A., Panetto, H., Brdys, M., Csáji, B.C., 2014. Cooperative control in production and logistics. IFAC Proc. Vol. 47, 4246–4265. https://doi.org/10.3182/20140824-6-ZA-1003.01026.
Msawil, M., Greenwood, D., Kassem, M., 2022. A Systematic evaluation of blockchain-enabled contract administration in construction projects. Autom. ConStruct. 143, 104553 https://doi.org/10.1016/j.autcon.2022.104553.
Nabben, K., 2021. Imagining Human-Machine Futures: Blockchain-Based 'Decentralized Autonomous Organizations. https://doi.org/10.2139/ssrn.3953623.
Naderi, H., Shojaei, A., Ly, R., 2023. Autonomous construction safety incentive mechanism using blockchain-enabled tokens and vision-based techniques. Autom. ConStruct. 153, 104959 https://doi.org/10.1016/j.autcon.2023.104959.
Nakamoto, S., 2008. Bitcoin: a peer-to-peer electronic cash system. www.bitcoin.org.
Nanayakkara, S., Perera, S., Senaratne, S., Weerasuriya, G.T., Bandara, H.M.N.D., 2021. Blockchain and smart contracts: a solution for payment issues in construction supply chains. Informatics 8, 36. https://doi.org/10.3390/informatics8020036.
Niavis, H., Laskari, M., Fergadiotou, I., 2022. Trusted dbl: a blockchain-based digital twin for sustainable and interoperable building performance evaluation. In: 2022 7th International Conference on Smart and Sustainable Technologies (SpliTech), pp. 1–6. https://doi.org/10.23919/SpliTech55088.2022.9854287.
O'Reilly, A., Mathews, M., 2019. Incentivising multidisciplinary teams with new methods of procurement using BIM + blockchain. In: CITA BIM Gathering 2019.
Ostrom, E., 1990. Governing the Commons: the Evolution of Institutions for Collective Action. Cambridge university press.
Ostrom, E., 2010. Beyond markets and states: polycentric governance of complex economic systems. Am. Econ. Rev. 100, 641–672. https://doi.org/10.1257/aer.100.3.641.

Ostrom, E., 2015. Governing the Commons. Cambridge University Press, Cambridge. https://doi.org/10.1017/CBO9781316423936.
Ostrom, E., Burger, J., Field, C.B., Norgaard, R.B., Policansky, D., 1999. Revisiting the commons: local lessons. global challenges. https://doi.org/10.1126/science.284.5412.278.
Ostrom, E., Gardner, R., Walker, J., Walker, J.M., Walker, J., 1994. Rules, Games, and Common-Pool Resources. University of Michigan Press.
Papadimitropoulos, V., 2022. Blockchain and the Commons, 1 ed. Routledge, London. https://doi.org/10.4324/9781003039723.
Pazaitis, A., De Filippi, P., Kostakis, V., 2017. Blockchain and value systems in the sharing economy: the illustrative case of Backfeed. Technol. Forecast. Soc. Change 125, 105–115. https://doi.org/10.1016/j.techfore.2017.05.025.
Peirce, C.S., 1974. Collected Papers of Charles Sanders Peirce. Harvard University Press.
Perera, S., Nanayakkara, S., Rodrigo, M.N., Senaratne, S., Weinand, R., 2020. Blockchain technology: is it hype or real in the construction industry? Journal of Industrial Information Integration 17, 100125. https://doi.org/10.1016/j.jii.2020.100125.
Petersen, D., 2022. Automating governance: blockchain delivered governance for business networks. Ind. Market. Manag. 102, 177–189. https://doi.org/10.1016/j.indmarman.2022.01.017.
Peterson, J., Krug, J., Zoltu, M., Williams, A.K., Alexander, S., 2022. Augur: A Decentralized Oracle and Prediction Market Platform (v2.0).
Poux, P., de Filippi, P., Ramos, S., 2021. Blockchains for the governance of common goods. In: Proceedings of the 1st International Workshop on Distributed Infrastructure for Common Good. Association for Computing Machinery, New York, NY, USA, pp. 7–12. https://doi.org/10.1145/3428662.3428793.
Qian, X.A., Papadonikolaki, E., 2020. Shifting trust in construction supply chains through blockchain technology. Eng. Construct. Architect. Manag. 28, 584–602. https://doi.org/10.1108/ECAM-12-2019-0676.
Rankohi, S., Bourgault, M., Iordanova, I., 2022. The latest operational, contractual and organizational trends in IPD literature: review and future directions. Eng. Construct. Architect. Manag. 30, 4339–4357. https://doi.org/10.1108/ECAM-02-2022-0170.
Red, R., 2019. Peer Production on the Crypto Commons. Technical Report.
Rodrigo, M.N.N., Perera, S., Senaratne, S., Jin, X., 2020. Potential application of blockchain technology for embodied carbon estimating in construction supply chains. Buildings 10, 140. https://doi.org/10.3390/buildings10080140.
Rodrigues, M.R., Lindhard, S.M., 2021. Benefits and challenges to applying IPD: experiences from a Norwegian mega-project. Construct. Innovat. 23, 287–305. https://doi.org/10.1108/CI-03-2021-0042.
Rozas, D., Tenorio-Fornés, A., Díaz-Molina, S., Hassan, S., 2021a. When Ostrom meets blockchain: exploring the potentials of blockchain for commons governance. Sage Open 11, 215824402110025. https://doi.org/10.1177/21582440211002526.
Rozas, D., Tenorio-Fornés, A., Hassan, S., 2021b. Analysis of the potentials of blockchain for the governance of global digital commons. Frontiers in Blockchain 4, 15. https://doi.org/10.3389/fbloc.2021.577680.
Santana, C., Albareda, L., 2022. Blockchain and the emergence of Decentralized Autonomous Organizations (DAOs): an integrative model and research agenda. Technol. Forecast. Soc. Change 182, 121806. https://doi.org/10.1016/j.techfore.2022.121806.
Saygili, M., Mert, I.E., Tokdemir, O.B., 2021. A decentralized structure to reduce and resolve construction disputes in a hybrid blockchain network. Autom. ConStruct. 104056doi https://doi.org/10.1016/j.autcon.2021.104056.
Schär, F., 2020. Decentralized finance: on blockchain- and smart contract-based financial markets. SSRN Electron. J. https://doi.org/10.2139/ssrn.3571335.
Schmidt, C.G., Wagner, S.M., 2019. Blockchain and supply chain relations: a transaction cost theory perspective. J. Purch. Supply Manag. 25, 100552 https://doi.org/10.1016/j.pursup.2019.100552.
Schneider, N., 2021. Cryptoeconomics as a limitation on governance. Regulation and Governance 33.
Scott, D.J., Broyd, T., Ma, L., 2021. Exploratory literature review of blockchain in the construction industry. Autom. ConStruct. 132, 103914 https://doi.org/10.1016/j.autcon.2021.103914.
Scott, D.J., Broyd, T., Ma, L., 2022. Conceptual model utilizing blockchain to automate project b ank account (PBA) payments in the construction industry. In: Dounas, T., Lombardi, D. (Eds.), Blockchain for Construction. Springer Nature. Blockchain Technologies, Singapore, pp. 141–165. https://doi.org/10.1007/978-981-19-3759-0_8.
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.
Sheng, D., Ding, L., Zhong, B., Love, P.E., Luo, H., Chen, J., 2020. Construction quality information management with blockchains. Autom. ConStruct. 120, 103373 https://doi.org/10.1016/j.autcon.2020.103373.
Shojaei, A., Flood, I., Moud, H.I., Hatami, M., Zhang, X., 2020. An implementation of smart contracts by integrating BIM and blockchain. In: Advances in Intelligent Systems and Computing. Springer, pp. 519–527. https://doi.org/10.1007/978-3-030-32523-7_36.
Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H., Wang, J., 2021. Enabling a circular economy in the built environment sector through blockchain technology. J. Clean. Prod. 294, 126352 https://doi.org/10.1016/j.jclepro.2021.126352.
Singh, A.K., Kumar, V.G.R.P., Hu, J., Irfan, M., 2023. Investigation of barriers and mitigation strategies to blockchain technology implementation in construction industry: an interpretive structural modeling approach. Environ. Sci. Pollut. Control Ser. 30, 89889–89909. https://doi.org/10.1007/s11356-023-28749-6.
Sive, T., Hays, M., 2009. Integrated project delivery : reality and promise A strategist's guide to understanding and marketing IPD. Marketing Research 1–34.
Son, J., Rojas, E.M., 2011. Evolution of collaboration in temporary project teams: an agent-based modeling and simulation approach. J. Construct. Eng. Manag. 137, 619–628. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000331.
Son, P.V.H., Lien, P.N., 2022. Blockchain crowdsourced arbitration in construction project delay resolution. J. Sci. Technol. Civ. Eng. (JSTCE)-HUCE 16 (4), 100–115.
Sonmez, R., Sönmez, F.Ö., Ahmadisheykhsarmast, S., 2021. Blockchain in project management: a systematic review of use cases and a design decision framework. J. Ambient Intell. Hum. Comput. 1, 3. https://doi.org/10.1007/s12652-021-03610-1.
Spychiger, F., Lustenberger, M., Martignoni, J., Schädler, L., Lehner, P., 2023. Organizing projects with blockchain through a decentralized autonomous organization (DAO). Project Leadership and Society 4, 100102. https://doi.org/10.1016/j.plas.2023.100102.
Spychiger, F., Tasca, P., Tessone, C.J., 2021. Unveiling the importance and evolution of design components through the "tree of blockchain.". Frontiers in Blockchain 3, 613476. https://doi.org/10.3389/fbloc.2020.613476.
Sreckovic, M., Windsperger, J., 2020. Decentralized autonomous organizations and network design in AEC: a conceptual framework. SSRN Electron. J. https://doi.org/10.2139/ssrn.3576474.
Stern, P.C., 2011. Design principles for global commons: natural resources and emerging technologies. Int. J. Commons 5, 213–232. https://doi.org/10.18352/ijc.305.
Tasca, P., Tessone, C.J., 2019. A taxonomy of blockchain technologies: principles of identification and classification. Ledge 4. https://doi.org/10.5195/ledger.2019.140.
Taylor, J.E., Levitt, R., Villarroel, J.A., 2009. Simulating learning dynamics in project networks. J. Construct. Eng. Manag. 135, 1009–1015. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000065.
Taylor, S.S., Fisher, D., Dufresne, R.L., 2002. The aesthetics of management storytelling: a key to organizational learning. Manag. Learn. 33, 313–330. https://doi.org/10.1177/1350507602333002.
Teisserenc, B., Sepasgozar, S.M.E., 2022. Software architecture and non-fungible tokens for digital twin decentralized applications in the built environment. Buildings 12, 1447. https://doi.org/10.3390/buildings12091447.
Teng, Y., Li, X., Wu, P., Wang, X., 2019. Using cooperative game theory to determine profit distribution in IPD projects. International Journal of Construction Management 19, 32–45. https://doi.org/10.1080/15623599.2017.1358075.
Tezel, A., Febrero, P., Papadonikolaki, E., Yitmen, I., 2021. Insights into blockchain implementation in construction: models for supply chain management. J. Manag. Eng. 37 https://doi.org/10.1061/(ASCE)ME.1943-5479.0000939 (ASCE) ME.1943–5479.0000939.
Thomsen, C., Darrington, J.W., Dunne, D., Lichtig, W.A., 2009. Managing Integrated Project Delivery, 105. Construction Management Association of America.
Tian, Y., Lu, Z., Adriaens, P., Minchin, R.E., Caithness, A., Woo, J., 2020. Finance infrastructure through blockchain-based tokenization. Frontiers of Engineering Management 7, 485–499. https://doi.org/10.1007/s42524-020-0140-2.
Tillmann, P., Berghede, K., Ballard, G., Tommelein, I.D., 2014. Developing a Production System on IPD: Considerations for a Pluralistic Environment.
Timmermans, S., Tavory, I., 2012. Theory construction in qualitative research. Socio. Theor. 30, 167–186. https://doi.org/10.1177/0735275112457914.
Titcomb, A., 2019. Deep Dive: Augmented Bonding Curves.
Torkanfar, N., Azar, E.R., McCabe, B., 2023. BidChain: a blockchain-based decentralized application for transparent and secure competitive tendering in public construction projects. J. Construct. Eng. Manag. 149, 04023050 https://doi.org/10.1061/JCEMD4.COENG-12449.
van Vulpen, P., Jansen, S., 2023. Decentralized Autonomous Organization Design for the Commons and the Common Good.
Venugopalan, S., Aydt, H., 2023. Incentivising Building Data Availability and Accessibility Using Tokenized Data Assets. https://doi.org/10.48550/arXiv.2304.07309 arXiv:2304.07309.
Voshmgir, B.S., Zargham, M., 2019. Foundations of Cryptoeconomic Systems. Cryptoeconomics Working Paper Series, Vienna University of Economics, pp. 1–18.
Wahab, A., Wang, J., Shojaei, A., Ma, J., 2022. A model-based smart contracts system via blockchain technology to reduce delays and conflicts in construction management processes. Eng. Construct. Architect. Manag. https://doi.org/10.1108/ECAM-03-2022-0271 ahead-of-print.
Wang, H., Hunhevicz, J., Hall, D., 2022. What if properties are owned by no one or everyone? foundation of blockchain enabled engineered ownership. In: EC3 Conference 2022. University of Turin. https://doi.org/10.35490/EC3.2022.213, 0–0.
Wang, Y.L., Krishnamachari, B., 2019. Enhancing engagement in token-curated Registries via an inflationary mechanism. In: ICBC 2019 - IEEE International Conference on Blockchain and Cryptocurrency. Institute of Electrical and Electronics Engineers Inc., pp. 188–191. https://doi.org/10.1109/BLOC.2019.8751443
Wang, Z., Wang, T., Hu, H., Gong, J., Ren, X., Xiao, Q., 2020. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Autom. ConStruct. 111, 103063 https://doi.org/10.1016/j.autcon.2019.103063.
Watson, R., Kassem, M., Li, J., 2019. Traceability for Built Assets: Proposed Framework for a Digital Record.
Weerasuriya, G.T., Perera, S., Calheiros, R.N., 2023. Ensuring trusted and traceable construction certifications with blockchain: a conceptual model. In: 45th AUBEA Conference. Western Sydney University, Australia.
Werbach, K., 2020. The Siren Song: Algorithmic Governance By Blockchain (September 24, 2018). After the Digital Tornado: Networks, Algorithms, Humanity (Kevin Werbach, ed., 2020, Forthcoming). Available at SSRN: https://ssrn.com/abstract=3578610.
Weyl, E.G., Lalley, S.P., 2017. Quadratic voting. Social Science Research Network 1–5.

Whyte, J., 2019. How digital information transforms project delivery models. Proj. Manag. J. 50, 177–194. https://doi.org/10.1177/8756972818823304.

Woo, J., Fatima, R., Kibert, C.J., Newman, R.E., Tian, Y., Srinivasan, R.S., 2021. Applying blockchain technology for building energy performance measurement, reporting, and verification (MRV) and the carbon credit market: a review of the literature. Build. Environ. 205, 108199 https://doi.org/10.1016/j.buildenv.2021.108199.

Wu, H., Li, H., Luo, X., Jiang, S., 2023a. Blockchain-based on-site activity management for smart construction process quality traceability. IEEE Internet Things J. https://doi.org/10.1109/JIOT.2023.3300076, 1-1.

Wu, H., Zhong, B., Li, H., Guo, J., Wang, Y., 2021. On-Site construction quality inspection using blockchain and smart contracts. J. Manag. Eng. 37, 04021065 https://doi.org/10.1061/(ASCE)ME.1943-5479.0000967.

Wu, L., Li, X., Zhao, R., Lu, W., Xu, J., Xue, F., 2022. A blockchain-based model with an incentive mechanism for cross-border logistics supervision and data sharing in modular construction. J. Clean. Prod. 375, 133460 https://doi.org/10.1016/j.jclepro.2022.133460.

Wu, L., Lu, W., Peng, Z., Webster, C., 2023b. A blockchain non-fungible token-enabled 'passport' for construction waste material cross-jurisdictional trading. Autom. ConStruct. 149, 104783 https://doi.org/10.1016/j.autcon.2023.104783.

Xiao, W., 2019. 8 Nobel-Prize Winning Rules for Governance Design.

Xu, X., Weber, I., Staples, M., Zhu, L., Bosch, J., Bass, L., Pautasso, C., Rimba, P., 2017. A taxonomy of blockchain-based systems for architecture design. In: 2017 IEEE International Conference on Software Architecture (ICSA). IEEE, pp. 243–252. https://doi.org/10.1109/ICSA.2017.33.

Ye, X., König, M., 2021. Framework for automated billing in the construction industry using BIM and smart contracts. Lecture Notes in Civil Engineering 98, 824–838. https://doi.org/10.1007/978-3-030-51295-8_57.

Zargham, M., Shorish, J., Paruch, K., 2020. From Curved Bonding to Configuration Spaces, pp. 1–3doi. https://doi.org/10.1109/icbc48266.2020.9169474.

Zavyalova, E., Sokolov, D., Lisovskaya, A., 2020. Agile vs traditional project management approaches: comparing human resource management architectures. Int. J. Organ. Anal. 28, 1095–1112. https://doi.org/10.1108/IJOA-08-2019-1857.