EXPLORING THE POTENTIAL OF BLOCKCHAIN AND CRYPTOECONOMICS FOR THE CONSTRUCTION INDUSTRY

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Abstract

The construction industry needs to become more efficient and productive in order to cope with increasing housing and infrastructure demand, as well as problems associated with climate change. Digitalization is often seen as the solution for this transformative change, but so far its anticipated impact did not materialize. The construction industry is complex and current project delivery fails to achieve the needed trusted collaboration, while also emphasizing extreme fragmentation. The resulting omnipresent trust issues also continue with digital coordination.

Blockchain became increasingly popular in the last fourteen years. The technology shifts trust from middlemen and transacting parties towards the technical system. Moreover, smart contracts allow to code interaction logic with blockchain transactions for decentralized workflows. It is not surprising that a technology hyped as "trust machine" attracted attention from scholars as a way to improve trust in the troubled construction industry.

This thesis aims to better understand the potential of blockchain for the construction industry. The focus lies on the under-researched aspect of *cryptoeconomics*, using smart contracts to encode institutional coordination.

The first part of the thesis builds theoretical foundations to understand the promise of blockchain and cryptoeconomics for the construction industry. The thesis assesses the need for blockchain by matching technical capabilities with proposed use cases. Moreover, it outlines how cryptoeconomic mechanisms align with the industry structure, and finally conceptualizes how they can be applied to collaborative project deliveries trough a lens of Common Pool Resource theory.

The second part of the thesis contains two proof of concepts that demonstrate the potential and feasibility of cryptoeconomics in the construction industry. The prototypes show new possibilities for blockchain-based cross-phase and cross-trade incentive mechanisms with performance based smart contracts, but also cryptoeconomic mechanisms for novel forms of coordination between humans and machines with no1s1 - a self-owning house.

In summary, blockchain is interesting for applications in the construction industry that rely on cryptoeconomic mechanisms. They offer new possibilities to create incentives in interplay with the ongoing digitalization towards rethinking economic coordination in the construction industry. Common Pool Resource theory is a powerful lens to conceptualize such new forms of decentralized coordination. Furthermore, cyberphysical integration with blockchain enables economic machine participation. Finally, the research demonstrates that early prototyping of cryptoeconomic applications for the construction industry is already possible.

Overall, this thesis investigates a novel research area at the interdisciplinary intersection of the construction industry, blockchain, and common pool resource theory. It extends the state of the art research in construction management both with novel theoretical work and proof of concepts as a solid foundation for more research on blockchain and cryptoeconomics in the construction industry.

Zusammenfassung

Die Bauindustrie muss effizienter und gleichzeitig produktiver werden, um den steigenden Wohn- und Infrastrukturbedarf, sowie die Herausforderungen des Klimawandel bewältigen zu können. Die Digitalisierung wird oft als Lösung für diesen Wandel angesehen, aber bis jetzt blieben die erwarteten Auswirkungen aus. Die Baubranche ist komplex, und die derzeitige Projektabwicklung ermöglicht nicht die erforderliche vertrauensvolle Zusammenarbeit, sondern fördert eine extreme Fragmentierung der Branche. Die daraus resultierenden, allgegenwärtigen Vertrauensprobleme setzen sich auch in der digitalen Kollaboration fort.

In den letzten vierzehn Jahren wuchs die Bekanntheit von Blockchain stetig. Blockchain verlagert das Vertrauen von Mittelsmännern und Transaktionspartnern zum technischen System. Smart Contracts ermöglichen es, Interaktionslogik mit Blockchaintransaktionen zu kodieren, um dezentrale Prozesse zu schaffen. Es ist nicht verwunderlich, dass eine Technologie, die als "Vertrauensmaschine" beworben wird, die Aufmerksamkeit der Wissenschaft auf sich zog um das Vertrauen in der Baubranche zu verbessern.

Diese Arbeit zielt nun darauf ab, das Potenzial von Blockchain für die Bauindustrie besser zu verstehen. Der Schwerpunkt liegt auf dem wenig erforschten Aspekt der Kryptoökonomie, um mit Smart Contracts Mechanismen für institutionelle Koordination zu kodieren.

Im ersten Teil der Arbeit werden Grundlagen geschaffen, um das Potential von Blockchain und Kryptoökonomie für die Bauwirtschaft zu verstehen. Es werden technische Möglichkeiten der Blockchain mit vorgeschlagenen Anwendungsfällen in der Bauindustrie abgeglichen. Darüber hinaus wird in der Arbeit dargelegt, wie Kryptoökonomie mit der Struktur der Baubranche übereinstimmt und wie Mechanismen auf kollaborative Projektabwicklung durch Abgleich mit Ansätzen der Common-Pool-Resource Theorie angewendet werden können.

Der zweite Teil dieser Arbeit enthält zwei Implementierungen, um das Potenzial und die Machbarkeit zu demonstrieren. Die Prototypen zeigen neue Möglichkeiten für phasen- und handelsübergreifende Anreizmechanismen auf mit leistungsbasierten Smart Contracts, aber auch kryptoökonomische Mechanismen für neuartige Formen der Koordination zwischen Mensch und Maschine mit einem sich selbst gehörenden Haus namens no1s1.

Blockchain ist interessant für Anwendungen in der Baubranche, die auf kryptoökonomischen Mechanismen beruhen. Diese können Anreize für Projektkoordination im Zusammenspiel mit der fortschreitenden Digitalisierung schaffen, sowie neue Organisationsformen für Bauprojekte ermöglichen. Die Common-Pool-Resource Theorie ist hilfreich für die Konzeptualisierung solcher dezentraler Koordination. Zudem ermöglicht Blockchain die wirtschaftliche Beteiligung von Maschinen. Schließlich hat diese Forschung gezeigt, dass erste Prototypen von kryptoökonomischen Anwendungen für die Bauindustrie bereits möglich sind.

Insgesamt untersucht diese Arbeit ein neuartiges Forschungsgebiet an der interdisziplinären Schnittstelle von Bauwirtschaft, Blockchain und Common-Pool-Resource Theorie. Sie erweitert den Stand der Forschung im Bereich Baumanagement sowohl durch neuartige Theorie als auch durch Implementierung als Grundlage für weitere Forschung zu Blockchain in der Bauindustrie.

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Jens Juri Hunhevicz / Zurich, February 2022

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Nomenclature

E	Energy Consumption
EP	Energy Performance
P	Water Vapor Pressure
PMV	Predictive Mean Vote
RH	Relative Humidity
T	Temperature
TC	Thermal Comfort
3d	Three-Dimensional
AI	Artificial Intelligence
API	Application Programming Interface
BIM	Building Information Modelling
BTC	bitcoin
CED	Cryptoeconomic Design
CPR	Common Pool Resource
DAO	Decentralized Autonomous Organization
dApp	Decentralized Application
DAS	Decentralized Autonomous Space
DeFi	Decentralized Finance
DHT	Distributed Hash Table
DLT	Distributed Ledger Technology
ETH	ether
FOSS	Free and Open Source Software
IC	Industrialized Construction
IoT	Internet of Things
IPD	Integrated Project Delivery
KYC	Know Your Customer
MPPT	Maximum Power Point Tracker
NFT	Non Fungible Token
no1s1	no-one's-one
OP	Ostrom's Design Principle
OS	Operating System
P2P	Peer-to-Peer
PBSC	Performance Based Smart Contract
PDM	Project Delivery Model
POS	Proof-of-Stake
POW	Proof-of-Work
TTP	Trusted Third Party

Prologue

1. Introduction

1.1. Motivation and Objective

The construction industry is more and more in the spotlight. Population growth and increasing standards of living drive global housing and infrastructure demand that is increasingly hard to meet (World Economic Forum, 2017). Meanwhile, the built environment is responsible for a lion share of global material consumption, green house gas emissions, and waste production (United Nations Environment Programme, 2020). As a consequence, the construction industry must become more efficient to reduce emissions and resource consumption, while at the same time more productive to cope with the increasing demand.

In other words, the industry cannot continue to build the way it currently does. Major transformation and innovation is needed (World Economic Forum, 2017). This need is in stark contrast with the development of the construction sector. Buildings and infrastructure are designed, built and managed in practice largely unchanged since decades. This is because the industry is slow in adopting new innovations (Winch, 1998; Taylor and Levitt, 2007) and ranks among the least digitized (Gandhi et al., 2016). And while other industries experienced major productivity improvements in the last decades, productivity in construction remained mostly flat (Teichholz et al., 2001; Barbosa et al., 2017). In the face of complexity (Bertelsen, 2003), inflexible project delivery models fail to achieve trusted collaboration and emphasize extreme fragmentation, hindering more innovation and leading to recurrent cost and time overruns (Tavistock Institute of Human Relations, 1966; Latham, 1994; Zolin et al., 2004).

Digitalization has the potential to increase productivity and integrate information for more efficient collaboration (Howard et al., 1989; Agarwal et al., 2016; Whyte and Hartmann, 2017). Building Information Modelling (BIM) is the leading concept in the digital transformation of the construction industry. BIM uses digital three-dimensional modelling tools to create informed processes between construction stakeholders (Azhar, 2011). However, project teams still tend to struggle with trust and liability concerns related to BIM practices (Miettinen and Paavola, 2014; Hall and Scott, 2019; Ghaffarianhoseini et al., 2017). Digitalization will likely only yield more trusted collaboration by simultaneously addressing issues related to the industry structure (Whyte and Hartmann, 2017). Early attempts to create such better suited approaches include more flexible, collaborative project delivery models, e.g. Integrated Project Delivery (IPD) (El Asmar et al., 2013; Cheng et al., 2016; Fischer et al., 2017), or more firm-driven integration like digitally-enabled manufacturing (Hall et al., 2020). But to further accelerate the needed change, new ways to combine innovative approaches of management and digitalization should be explored (Barbosa et al., 2017).

With the omnipresent trust issues in the construction industry, it is not surprising that a new digital technology titled the “trust machine” (The Economist, 2015) sounded auspicious to create more trusted processes. Early articles and reports then also promoted blockchain as a new way to increase trust in the troubled construction industry (Kinnaird and Geipel, 2017; Heiskanen, 2017; Mathews et al., 2017; Belle, 2017; Wang et al., 2017; Turk and Klinc, 2017). Starting in 2018, the goal of this thesis was to extend and confirm this assumption with more research exploring the potential and feasibility of blockchain in the construction industry.

The genesis block of the first blockchain Bitcoin (Nakamoto, 2008) was mined in January 2009. Over the past fourteen years, blockchain technology and its applications evolved into a global revolution of financial concepts, the next generation internet of value and ownership, and unprecedented ways to collectively organize around shared goods. Bitcoin is widely accepted by many financial institutions (The New York Times, 2021) and even as legal tender by countries (World Economic Forum, 2021). A full suite of decentralized finance products built on blockchain is accessible at all times to everyone in the world (The Economist, 2021). Blockchain allows people to own digital assets such as land virtually in the "Metaverse" (Financial Times, 2022). Non-fungible tokens (NFTs) representing ownership of art pieces are selling for millions of dollars (The Verge, 2021), and novel forms of global organization around collective goods emerge, e.g. the CityDAO mobilized an anonymous group to buy land in Wyoming with pooled cryptocurrency-funds (Financial Times, 2021).

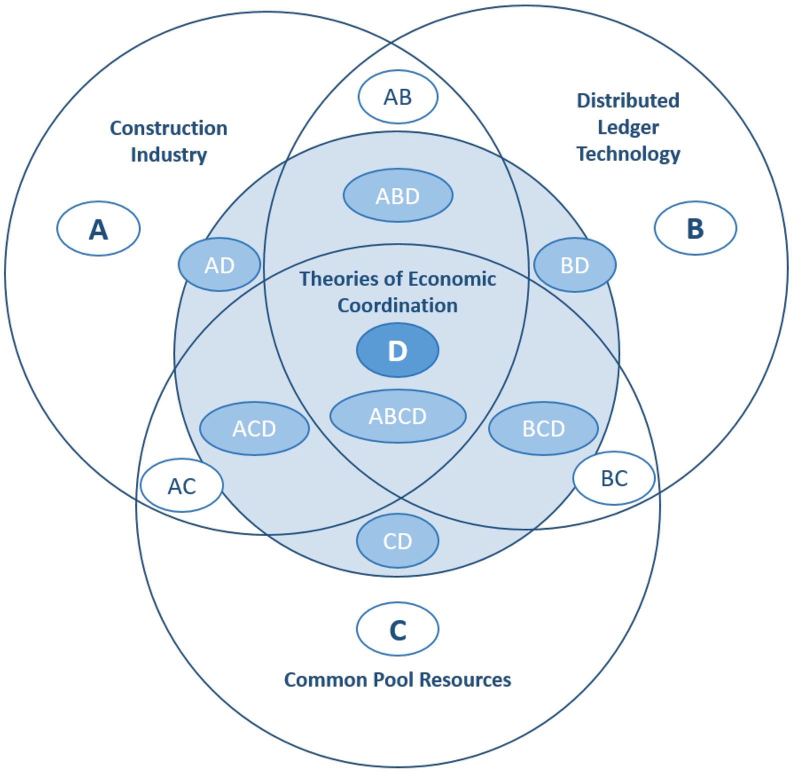
Since the first publications in 2017, new scholarship that assessed blockchain for the construction industry increased at an average rate of 184% each year (Scott et al., 2021). But even though the above examples demonstrate that blockchain is slowly penetrating many facets of our daily lives by disrupting established economic systems, most of the construction literature still tends to assess blockchain as a tool to improve existing processes, e.g. for payments, supply chain tracking, or contract management (Li and Kassem, 2021; Scott et al., 2021). In contrast, this thesis focuses on the under-researched potential to create novel incentives and organization with cryptoeconomic mechanisms. Cryptoeconomics ensures security of decentralized blockchain networks using incentives and/or penalties to regulate the distribution of efforts, goods and services (Brekke and Alsindi, 2021). Utilizing cryptoeconomic mechanisms for novel institutional coordination of digital economies is one of the most exciting aspects of blockchain with the potential to disrupt and substitute existing economic coordination (Davidson et al., 2018; Miscione et al., 2019).

Therefore, this thesis explores cryptoceconomic mechanisms to facilitate a trusted institutional infrastructure in the construction industry. Trusted blockchain-based mechanisms could integrate the increasingly available digital information with new forms of economic coordination (i.e., processes, contracts, and finance) towards a more productive and efficient construction industry. Therefore, the main objective of this thesis is to further investigate the potential of cryptoeconomics for economic coordination in the construction sector:

Research objective: Investigate the potential and feasibility of blockchain in the construction industry with a focus on cryptoeconomics.

1.2. Research Scope

The research objective is assessed within the scope of three intersecting pillars: the construction industry (Figure 1.1, A), distributed ledger technology (Figure 1.1, B), and common pool resource scenarios (Figure 1.1, C). The individual contributions then explore the intersections between these three pillars through a theoretical lens of economic coordination (Figure 1.1, D). Because this thesis



A	**Construction Industry**	AD	Project Based Organization
B	**Distributed Ledger Technology**	BD	Cryptoeconomics
AB	Transaction Optimization and Security in the Construction Industry	CD	Ostrom's Design Principles
C	**Common Pool Resources (CPRs)**	ABD	Cryptoeconomic Incentives for the Construction Industry
AC	Project Resources as CPRs	ACD	Collaborative Project Management Practices
BC	The Ledger and Open Source Code as CPRs	BCD	Crypto Commons
D	**Theories of Economic Coordination**	ABCD	Governance of Project Delivery on the Crypto Commons

Figure 1.1.: Scope of the thesis: The three main pillars A, B, and C overlaid with the theoretical lens D of economic coordination. All the research contained in this thesis lies in the intersection of A and B.

is interdisciplinary, the research scope intends to help the reader understand the topics that are covered in this thesis and how they connect. It gives also a brief overview on the scientific advances in areas relevant for this thesis.

1.2.1. Main Pillars of the Thesis

Pillar A - The Construction Industry

The construction industry is the first pillar of this thesis (Figure 1.1, **A**). As already outlined in the motivation, construction is a troubled industry suffering now for decades from low productivity (Teichholz et al., 2001; Barbosa et al., 2017) and lack of innovation (Winch, 1998; Taylor and Levitt, 2007).

Economic Coordination

Applying a lens of economic coordination (Figure 1.1, **D**) can help to understand the various root causes of low productivity and slow innovation diffusion. The predominant form of economic coordination in the construction industry is project-based organization (Figure 1.1, **AD**). Firms in the industry are usually involved in different projects, where they contribute resources of various kinds, resulting in overall coordination resembling decentralized and loosely-coupled networks (Dubois and Gadde, 2002b; Lehtovaara et al., 2022).

The Complexity Aspect

Construction projects have many complex systems characteristics (Bertelsen, 2003; Gidado, 1996; Winch, 1998). They involve many multidisciplinary individuals and firms equally valuable in the system's operation (Nam and Tatum, 1992; Thórisson, 2003). The construction workflow has high reciprocal interdependence between stakeholders and construction stages (Gidado, 1996; Thompson, 2017; Tsvetkova et al., 2019) and needs to handle many internal and external uncertainties (Gidado, 1996). And construction projects are mostly unique projects with each time a new set of stakeholders. Therefore, the successful completion of such complex projects requires the development of trust and mutual confidence (Pishdad-Bozorgi and Beliveau, 2016). Nevertheless, the predominant forms of organization in the construction industry fail to deliver this trusted coordination (Tavistock Institute of Human Relations, 1966; Zolin et al., 2004).

The classical formal project governance uses "command-and-control" with layers of contractual and organizational hierarchies (Levitt, 2011). In addition, the often used competitive lump-sum tendering process will most likely never provide the promised contractual protection (Tavistock Institute of Human Relations, 1966; Henisz et al., 2012). It assumes that all uncertainties, delayed decisions, and incomplete details can be determined at the time of signing the contract. But since construction is a complex system, changes always occur. And when changes raise costs and trigger delays (Davies et al., 2019), the involved parties attempt to avoid responsibilities for caused discrepancies. Trust and collaboration decreases and the stakeholders blame previous construction activities or pass on risks to stakeholders involved later in the project (Henisz et al., 2012). The project heads into a downwards spiral.

Fragmented Organization Hindering Innovation

Large construction projects go on for many years where they run through multiple stages (i.e., the design, construction, and operation phase) each with a different set of stakeholders. This was described as vertical fragmentation (Fergusson and Teicholz, 1996; Sheffer, 2011) (see Figure 3.3). Each phase involves cross-functional (e.g. the architect, the general contractor, and the specific trades) and geographically distributed teams (Zolin et al., 2004). This was described as horizontal fragmentation (Fergusson and Teicholz, 1996; Sheffer, 2011) (see Figure 3.3). And at the end of projects, teams disband and select the next project by competitive bidding. This was described as longitudinal fragmentation (Taylor and Levitt, 2004; Sheffer, 2011) (see Figure 3.3). Consequently, they need to rebuild collaborative work practices in every new project (Dubois and Gadde, 2002b). The high level of fragmentation across all three dimensions leads to learning and incremental innovations mostly at the individual firm level, and hinder systemic innovation across the industry as a whole (Sheffer, 2011; Taylor and Levitt, 2004; Winch, 1998; Tavistock Institute of Human Relations, 1966). The industry is trapped in its prevailing project delivery system and industry structure that resists attempts to innovate at the system level (Hall et al., 2020; Taylor and Levitt, 2004; Taylor and Levitt, 2007; Levitt, 2011).

Emerging Integration Practices

Only more recently, the construction industry has increased consideration of supply chain integration practices to create more trusted coordination and foster innovation with three main drivers of integration: digitalization (mainly BIM), collaborative project deliveries, and digitally enabled manufacturing (Wamelink and Heintz, 2015).

"The most desirable form of organization would permit a much wider coordination of control to be achieved, so as to reduce the uncertainties which result from the present artificial division between design and construction planning cutting across the information feedback link which is so vital to the effective functioning of the building process."

Tavistock Institute of Human Relations (1966)

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1) Digitalization for Supply Chain Integration

New technologies and digitalization are often advocated as the main untapped potential to save construction productivity and efficiency (World Economic Forum, 2017; Barbosa et al., 2017). Digitalization has the potential to achieve more information integration in the construction industry (Howard et al., 1989; Agarwal et al., 2016; Whyte and Hartmann, 2017). Especially BIM-based coordination can have strong effects on inter- and intraorganizational relations in the construction supply chain and help supply chain integration (Papadonikolaki and Wamelink, 2017). Fueled by the more mainstream uptake of BIM both in construction literature and practice, many scientific articles also emphasize the transformative impact of new technologies (e.g. robotics, 3d printing, IoT, augmented and mixed reality) to improve the productivity of construction project delivery (Volk et al., 2014; Yalcinkaya and Singh, 2015).

Nevertheless, the fragmented industry structure makes BIM as a systemic innovation very slow to adopt (Miettinen and Paavola, 2014; Papadonikolaki, 2018; Dossick and Neff, 2010). It took around four decades with sometimes top-down enforcement from the government to reach the current level of adoption. At the same time, the prevalent trust issues seem to continue in the digital space and project teams still struggle with trust and liability concerns (Miettinen and Paavola, 2014; Hall and Scott, 2019; Ghaffarianhoseini et al., 2017). Therefore, digitalization alone, without addressing economic coordination in the construction industry, will hardly yield its full potential (Whyte and Hartmann, 2017).

2) Collaborative Project Deliveries for Supply Chain Integration

One organizational approach to integration are collaborative project delivery models that attempt to create project-based companies that are virtually integrated among key firms in the project supply chain (Hall and Scott, 2019; Lahdenperä, 2012; Thomsen et al., 2009). Most relevant for this thesis, in the IPD approach the project teams create an interorganizational governance structure to collaboratively manage complex projects across firm boundaries (Hall and Scott, 2019). IPD is built around specific formal and informal mechanisms (Bygballe et al., 2015). Examples of formal mechanisms include multi-party contracts, joint project control and liability waivers; informal mechanisms include social colocation, collaborative decision making, and early involvement of key participants (Ashcraft, 2011; Thomsen et al., 2009; Ghassemi and Becerik-Gerber, 2011; Hall et al., 2018). IPDs are better suited to deal with the inherent uncertainties and interdependence of the construction process (El Asmar et al., 2013; Cheng et al., 2016) and can increase the adoption of systemic innovation within the delivery of complex projects (Hall et al., 2018). However, adopting IPD practices requires effort and commitment from the involved parties to overcome established ways of collaboration (Cohen, 2010; Rodrigues and Lindhard, 2021). Even though collaborative project delivery models are becoming more familiar, their adoption in the industry is still in its infancy.

3) Digitally-Enabled Manufacturing for Supply Chain Integration

Another organizational integration attempt, that is in contrast to the project based approach more firm-driven, is digitally-enabled manufacturing (Hall et al., 2020). Especially industrialized construction (IC) has attracted major investments lately (Pullen et al., 2019). A more stable, sequential production process in a vertically integrated supply chain allows adoption of technological innovations coming from manufacturing. Standardization of the output allows for repetitive prefabrication processes. Modularization allows transport of the parts to the construction site and a sequential assembly. And learning and innovation across one project is possible by pushing information from construction back into the design. Vertically integrated approaches are well suited for economies of scale (Alstyne, 1997), which has resource efficiency and cost advantages for large scale housing projects (Kedir et al., 2020; Kedir and Hall, 2021). Indeed many of the current IC firms target the affordable housing market (Pullen et al., 2019). A downside to this approach is its capital-intensity (Hall et al., 2020).

The Need for Ongoing Exploration of Supply Chain Integration Practices

Overall, the construction industry still struggles towards mainstream utilization of technologies and digitalization despite their potential to increase productivity and efficiency. Collaborative project delivery models and digitally-enabled manufacturing are two attempts to change economic coordination in the industry towards more supply chain integration and trusted collaboration. Nevertheless, these approaches are only at the beginning of industry adoption. There is need for more research that explores innovative ways to combine new organizational approaches and digitalization (Barbosa et al., 2017).

Pillar B - Distributed Ledger Technology

The second main pillar of the thesis is Distributed Ledger Technology (DLT) (Figure 1.1, **B**). DLT is an overarching term that captures many design options (Hileman and Rauchs, 2017; El Ioini and Pahl, 2018). The most prominent type of DLT is blockchain, but many other types of DLT design options exist. At the risk of slightly oversimplifying, the thesis refers in most parts to the term blockchain. Where not specified in more detail, it refers to public permissionless blockchains (see also 2.3.1). Only were it is particularly important to distinguish between the different types of DLT design options, this work refers to DLT or specifically to another type of DLT design option.

The First Blockchain

The first blockchain was Bitcoin that was created by an anonymous individual or group under the name of Satoshi Nakamoto (2008). Nevertheless, the underlying technical components such as distributed ledgers, public-key encryption, merkle tree hashing, and consensus protocols existed already before then (Tasca and Tessone, 2019). The innovation was to recombine these elements in a way that the network prevents double-spending of transactions without any coordination of a trusted third party (Nakamoto, 2008). The main element to achieve this is called a consensus algorithm, in the case of Bitcoin proof-of-work (PoW). In order to add transaction with a new block to the blockchain, these stakeholders (called miners) need to spend a substantial amount of work (involving high hardware and energy costs) to win a "lottery". Because of this effort, they are incentivized to make sure only valid transactions are included in the block they produce, since otherwise the network will reject the block. A rejected block means miners will not earn the cryptocurrency BTC (bitcoin) from the block subsidy and transaction fees.

"To solve [the problem of double spending], we proposed a peer-to-peer network using proof-of-work to record a public history of transactions that quickly becomes computationally impractical for an attacker to change if honest nodes control a majority of CPU power.

[...]

Nodes can leave and rejoin the network at will, accepting the proof-of-work chain as proof of what happened while they were gone. They vote with their CPU power, expressing their acceptance of valid blocks by working on extending them and rejecting invalid blocks by refusing to work on them."

Nakamoto (2008)

With PoW, Sathoshi Nakamoto created a decentralized system (meaning not controlled by any single entity) that ensures with very high probability that executed P2P transactions can be trusted. It coordinates anonymous network participants through incentives by rewarding BTC when contributing to the working of the system. As long as the majority of stakeholders controlling the computing power is incentivized to behave honestly, the chain is protected. Since the first block was mined in 2009, the Bitcoin network grew considerably in size and settled transactions through creating blocks with POW for fourteen years without interruptions or successful attacks.

The Expanding Blockchain Universe

Since Bitcoin, thousands of other DLT networks emerged, either forking the open-source code of Bitcoin and slightly changing various parameters, or experimenting with other possible combinations of the DLT technology stack. At a high level, blockchains like Bitcoin are open for everyone to join and participate in writing transactions (permissionless), and at the same time transactions are transparent to everyone (public). Other DLTs offer restricted access (permissioned) and private transaction (private). Countless variations in the technology stack are possible, leading to different combinations of the above described private/public and permissioned/permissionless set up. For public permissionless systems, a lot of experimentation happened regarding the consensus mechanisms. Next to PoW, proof-of-stake (PoS) is by now one of the most applied consensus mechanisms (King and Nadal, 2012). Both consensus algorithms come with different advantages and downsides (Bentov et al., 2014; Mackenzie, 2013). Various taxonomies help structure the many possible design decisions (Tasca and Tessone, 2019; Ballandies et al., 2021b; Xu et al., 2017).

The Emergence of Expressive Smart Contracts

One of the most important advances in the space was the launch of the Ethereum network (Buterin, 2014) popularizing the use of *smart contracts* on the blockchain.

The idea of smart contracts to translate contractual clauses into code was established by Szabo (1997) in a series of articles. Ethereum introduced with Solidity an expressive and easy-to-use Turing-complete language to encode logic interacting with the transactions on a blockchain. Often these are conditional statements to create digital workflows. Since code executes on the blockchain, the smart contract can only be altered transparently and as specified, and once transactions are submitted they will execute as defined. Expressive smart contracts became the main tool to build new applications and use cases in the blockchain space.

Next to workflow logic, another prominent use of smart contracts is to create custom containers of value called *tokens* that can be transferred among users or smart contracts to move value across a blockchain network. Tokens represent value containers such as currencies, securities, utilities, or others (Mougayar, 2017; Ballandies et al., 2021b; Alsindi, 2019). The most notable token-standards on Ethereum are: ERC-20 defining fungible tokens (each token is interchangeable, e.g. money) responsible for the ICO boom in 2017; or ERC-721 defining non-fungible tokens (each token is unique, e.g. representing a piece of art) responsible for the ongoing NFT boom.

Economic Coordination

Altogether, blockchain as a technology offers a set of fundamental properties (see Table 2.3) or affordances (see Section 3.2.2) that make it interesting for a wide set of economic applications. Therefore, it makes sense to assess blockchain through an economic coordination lens (Figure 1.1, **D**). This helps to understand the promise of the technology for different application areas and how the thinking around blockchain evolved over time from a mere disintermediation of existing systems towards new cryptoeconomic systems (Figure 1.1, **BD**).

The evolution of the economic narrative around blockchain can be observed with the proposed categories of Swan (2015) to organize blockchain activities. Back in 2015, Swan defined “Blockchain 1.0” as currency, “Blockchain 2.0” as contracts for financial products through smart contracts (e.g. bonds or loans), and “Blockchain 3.0” as applications beyond finance.

Blockchain for Currency and Finance

Currency as the base narrative of “Blockchain 1.0” is because Bitcoin’s purpose was a “peer-to-peer electronic cash system” (Nakamoto, 2008). But in the prominent article “visions of Bitcoin”, Carter (2018) showed how different narratives around Bitcoin evolved over time. It shifted at one point away from Bitcoin as a currency towards “digital gold”, ”reserve currency for crypto”, or “uncorrelated financial asset”. With the recent increase in adoption of the lightning network as a scaling solution (Poon and Dryja, 2016), the currency narrative is slowly reviving. This ongoing narrative finding is typical for the whole blockchain space.

Nevertheless, the narrative of “Blockchain 2.0” came true with the emerging DeFi ecosystem as as one of the most used application of blockchain products to date. DeFi makes extensive use of smart contracts to encode financial product logic and tokens to replicate the financial system on the blockchain without the need of intermediaries such as banks or insurances (Schär, 2020).

Blockchain Beyond Finance

Especially for blockchain applications beyond finance the narrative finding is still evolving. The fact that Swan (2015) proposed “Blockchain 3.0” as a category shows that seven years ago blockchain only began to be considered for use cases beyond finance. Since then, many different business sectors assessed various blockchain use cases (Shen and Pena-Mora, 2018; Frizzo-Barker et al., 2020).

For a long time, the main perceived values were transparency, transaction cost reduction, and accelerated global transaction settlement (Tapscott and Tapscott, 2016; Nowiński and Kozma, 2017; Viriyasitavat et al., 2018; Catalini and Gans, 2020). Supply chain management is an often mentioned application where transparency and immutability of transactions limits uncertainty, opportunism, and lowers transaction costs (Schmidt and Wagner, 2019). There exist already several companies such as Everledger (2022) providing tracking on the blockchain as a service. Furthermore, blockchain allows for the creation of new ecosystems, where the benefits from network effects and shared digital infrastructure do not come at the cost of increased market power and data access by platform operators (Catalini and Gans, 2020). Going back to the example of finance, DeFi applications mainly replicate products of the existing finance system, but without institutions as middleman (Schär, 2020). Along these lines, countless decentralized applications emerged that promised to build a decentralized versions of [name here a centralized service]. All of these perspectives have in common that they start from existing processes and investigate how blockchain might impact them.

New Forms of Economic Coordination

While the above applications can already be very meaningful for existing economic systems, the main disruptive element of blockchain is that trust shifts away from the transaction counter party towards the technological system and cryptography. The innovation of blockchain is the consensus protocols using cryptoeconomic mechanisms to reward honest parties to reach consensus about a shared truth (the ledger) without requiring centralized trust (Davidson et al., 2018). This is how blockchains can disintermediate a transaction resulting in new forms of organization and governance, and as a consequence lower transaction costs (Davidson et al., 2018). Therefore, scholars argue the true potential of blockchain is to use these coordination mechanisms for the development of new types of institutional organization with the potential to disrupt and substitute existing economic coordination (Davidson et al., 2018; Jacobo-Romero and Freitas, 2021; Miscione et al., 2019).

Decentralized Autonomous Organizations

One of the most interesting new organizational designs proposed to leverage cryptoeconomic coordination on the blockchain is called a decentralized autonomous organization (DAO). A DAO is a blockchain-powered organization that can run without any central authority (Wang and Krishnamachari, 2019). The decentralized governance of a DAO is facilitated by a set of self-executing rules deployed with smart contracts on a blockchain to enable self-coordination and governance of people (Hassan and De Filippi, 2021). The first DAO was "the DAO" set up as a decentralized investment fund (Financial Times, 2016). The experiment failed when hackers exploited a code vulnerability and stole large parts of the funds, even resulting in a fork of the Ethereum blockchain to role back the hack (The Wall Street Journal, 2016). Since then various frameworks emerged that provide reviewed smart contract building blocks that can be assembled to a DAO (Faqir-Rhazoui et al., 2021). This significantly reduced exploits and sparked the creation of many new DAOs experimenting with this new form of organization (DeepDAO, 2022).

Cryptoeconomics

Recently, the concept of *cryptoeconomics* is gaining traction to explore more systematically and scientifically how blockchain can enable the creation of new economic systems. The term cryptoeconomics was casually coined in the developer community, often attributed to Vitalik Buterin, but with an earliest recording in a talk of Zamfir (2015). Brekke and Alsindi (2021) give a definition of cryptoeconomics:

Cryptoeconomics describes an interdisciplinary, emergent and experimental field that draws on ideas and concepts from economics, game theory and related disciplines in the design of peer-to-peer cryptographic systems.

Cryptoeconomic systems try to guarantee certain kinds of information security properties using incentives and/or penalties to regulate the distribution of efforts, goods and services in new digital economies.

Brekke and Alsindi (2021)

While initially the term was inspired by the use of economic incentives in the design of the base blockchain protocols (i.e. Layer 1, such as Bitcoin or Ethereum), the use of smart contracts and tokens also allows to design new cryptoeconomic systems that live on top of blockchain networks (i.e. Layer 2, such as the application level of DAOs mentioned above) (Alsindi, 2019).

In this thesis, the term cryptoeconomics is used more in the sense of the second utilization to build new forms of economic systems into applications that live on an existing blockchain network. While cryptoeconomics can be used to build systems that resemble existing economic system, the real potential for cryptoeconomics is to facilitate the building of a radically alternative politics and economics (Virtanen, 2018). But the field of cryptoeconomics is only in its infancy and currently going trough a lot of experimentation mainly led by "hacker-engineers" (Brekke, 2021) that understand to write code for these new decentralised digital network economies.

Cryptoeconomics will likely be one of the main focus areas in the ongoing exploration for the purpose and applications of blockchain. More interdisciplinary efforts are needed to assess cryptoeconomcis in a bigger picture of production, distribution, and consumption of goods beyond the sole focus of coding individual incentives and transactions (Virtanen, 2018). Along these lines, Voshmgir and Zargham (2019) propose foundations of cryptoeconomic systems grounded in complex socio-economic systems and multidisciplinary research focusing on the required micro, meso, and macro level perspective.

Pillar C - Common Pool Resources

The third pillar is common pool resources (CPR) (Figure 1.1, **C**). A CPR is freely shared among many users, because it is costly to exclude beneficiaries from obtaining profits from its use (Ostrom, 1990; Gardner et al., 1990). Initially CPR theory studied mainly natural resources such as fishing grounds, pastures, or forests, but expanded towards assessing man-made resource systems, e.g. parking lots, irrigation systems or wiki libraries. Since in general the resource is subtractable, meaning that the withdrawn units by one party are not fully available to others (Ostrom et al., 1994), the overexploitation of the resources leads to a phenomenon called the *tragedy of the commons* (Hardin, 1968). *Freeriders* do not contribute to the maintenance of the resource's environment but only take out the benefits. Users of a CPR end up "overusing", e.g. "overfishing" in the case of fishing grounds, by appropriating resources at a higher than optimal rate in self-interested behavior, resulting in a downward spiral of total resource availability (Hardin, 1968).

"Everyone knows that the basic problem is overfishing; however, those concerned cannot agree how to solve the problem."

Ostrom (2015)

Economic Coordination

Economic coordination of CPR scenarios was mainly conceptualized by Elinor Ostrom's Nobel Price winning work (Figure 1.1, **CD**). For a long time, scholarship have recognized centralized state intervention as the main solution to avoid the tragedy of the commons. More recently, economist Elinor Ostrom (Ostrom et al., 1994; Ostrom, 2010, 2015) and others (Gardner et al., 1990) showed that local actors without a central authority can be also successful in sustaining the commons using a set of eight proposed design principles: Ostrom's design principles (OPs). These design principles explain under what conditions trust and reciprocity can be built and maintained to sustain collective action in CPRs (Cox et al., 2010). The OPs are summarized in Table 4.1.

The Intersection with the Construction Industry and DLT

The CPR pillar connects with both other two main pillars of this thesis: the construction industry and DLT.

Construction Projects as a CPR Scenario

Construction project resources were theorized to share properties with CPRs (Figure 1.1, **AC**). When using a multi-party contract, the project resources are 'pooled' together (Darrington and Lichtig, 2010; Thomsen et al., 2009) and can include the overall budget and time schedule, the contingency, the stakeholders' profit, incentive and at-risk pools, or even the physical space available for construction activities or the required office space for staff co-location (Bonanomi et al., 2019). Hall et al. (2020) find collaborative project deliveries such as IPD to share similarities with CPR systems in the sense that these pooled project resources are subject to overuse and free-riding problems, leading to the "tragedy of the project".

As in the case of the fishing grounds, when the project goes over the budget and schedule, stakeholders know the problem but cannot always agree how to solve it. Moreover, freeriders appropriate resource units from the slack resources or budget contingency in self-interested behaviour without providing to the "maintenance" (e.g. reliable information, improvement of production processes) of the project governance system.

Blockchain as a CPR Scenario

Blockchain was described as a CPR scenario (Figure 1.1, **BC**). This conceptualization is rooted in the concept of commons-based peer production as a new economic model in which people work voluntary and cooperatively on publicly accessible resources (Benkler, 2008). The most significant examples are Free and Open Source Software (FOSS) projects. In the case of Wikipedia, freeriders can benefit from written articles without the need to contribute to the resource.

Blockchains like Bitcoin share many characteristics with FOSS. They are actively constructed by human participants, mainly the creators of the blockchain's software (i.e., developers), and the producers of blocks on the network (i.e., miners) (Red, 2019). Since trust in the code is paramount, open-source assures many eyes on the code reducing the possibility of flaws and malicious attempts. Moreover, it allows anonymous participation to contribute to code or download code to run a network node. The transparent consensus rules ensure that anyone that joins the network can arrive at the same shared understanding of the ledger's current state. As a consequence, blockchains can be described as a CPR scenario, because they are public goods accessible to all, but need to coordinate actors towards collaboration around a single version of a shared ledger to maintain security, network effects, and the perceived value of the blockchain's finite good (i.e. BTC) (Red, 2019). Most users are freeriders just benefiting from making secure P2P transactions and holding BTC without contributing to the system. To avoid the tragedy of the commons, blockchains need to incentivize miners with cryptocurrency to spend money on securing the chain or developers to put work hours into development of the open source code.

1.2.2. Lens D - Linking the Pillars with Theories of Economic Coordination

All the research conducted within this thesis lies in the intersection between the pillars of the construction industry (Figure 1.1, **A**) and DLT (Figure 1.1, **B**). Some of this research intersects also with the pillar of CPR (Figure 1.1, **C**). As a key methodology of this thesis, a theoretical lens of economic coordination is used to connect the main pillars (Figure 1.1, **D**). Within the scope of this thesis, economic coordination refers to organizational practices related to these three main pillars (Figure 1.1, **AD**, **BD**, and **CD**), as outlined in the previous sections.

Linking The Construction Industry with DLT

This section describes the link between the construction industry and DLT towards cryptoeconomic incentives in the construction industry (Figure 1.1 **ABD**).

The Starting Situation: A Focus on Trust and Collaboration

The earliest publications that explored the connection between the construction industry and blockchain date back to the year 2017 (Kinnaird and Geipel, 2017; Heiskanen, 2017; Mathews et al., 2017; Belle, 2017; Wang et al., 2017; Turk and Klinc, 2017). In 2018, the first reviews of blockchain literature for construction were published (Li et al., 2018; Shen and Pena-Mora, 2018). The proposed use cases and application areas varied widely between the publications. A few articles (e.g Ye et al. (2018) and Wang et al. (2017)) proposed blockchain as only to provide data security and transaction automation (Figure 1.1, **AB**). But most articles already position blockchain to increase trust and collaboration, and therefore also at the intersection of economic coordination (Figure 1.1, **ABD**). Use cases spanned from management of contracts, supply chain, information, and payments. For these use cases they praised different affordances of blockchain, including transaction cost reduction, transaction automation, transparency, security, immutability, disintermediation, and incentives.

Therefore, blockchain was positioned at the start of this thesis as very promising for a myriad of different use cases in the construction industry. But there was need to further assess and untangle this connection regarding valuable and feasible applications beyond the hype. Furthermore, all of these early publications only assessed the potential of blockchain theoretically. There were no implementations, and therefore also no deeper consideration of the technology stack. Finally, despite that most literature mentions the relationship between blockchain and its potential economic impact on trust and collaboration, there was no literature that further assessed this intersection, especially related to cryptoeconomics.

Cryptoeconomic Mechanisms for the Construction Industry
Qian and Papadonikolaki (2020) found later that blockchain indeed affects cognition-based (i.e., information sharing, knowledge) and system-based trust (i.e., policy/law, communication system, contracts and agreements) in the construction supply chain. Blockchain can create protection mechanisms to avoid the risks and costs of opportunistic behaviour in collaborations through tracking, contracting, and transferring (Qian and Papadonikolaki, 2020). This in in line with the findings of Schmidt and Wagner (2019) that assess blockchain for supply chain relations. But even though many articles agree that blockchain can establish more trust by reducing uncertainty and opportunism in existing processes, only very few articles mentioned cryptoeconomic incentives to create new forms of economic coordination, potentially to support or create novel supply chain integration mechanisms. Only Mathews et al. (2017) proposed the use of #AEC token to incentivize long term collaboration in the construction sector over the life cycle of a building. And Belle (2017) mentioned blockchain as a tool to create incentives that might speed up digitalization.

Overall, no literature assessed in a structured way cryptoeconomic incentive mechanisms and how they might benefit economic coordination in the construction industry (Figure 1.1, **ABD**). It was necessary to establish theory that outlines why and how such cryptoeconomic incentives can be used in the construction industry in relation to the technological possibilities of DLT. Furthermore, there was a need for prototypes that demonstrate the potential of cryptoeconomic incentives.

Linking the Construction Industry and DLT with CPR Theory

One promising theoretical link is the connection between economic coordination of the construction industry, DLT, and CPR towards governance of project deliveries on the “crypto commons” (Figure 1.1 **ABCD**).

> *“It is however thinkable that firms [...] will [...] explore Decentralized Organizational Systems that facilitate novel forms of collaboration between project members and teams in segments of the value chain that can be expressed with algorithms, particularly where reducing the administrative load on reporting, governance, monitoring responsibilities and transfer of risk could save costs and time.”*
>
> *Belle (2017)*

Along these early claims, new forms of decentralized economic coordination with blockchain-based governance mechanisms towards implementation for the governance of construction activities should be explored. This thesis found the pillar of CPR helpful to identify such mechanisms. Economic theories of CPR scenarios align both with the management of collaborative construction project deliveries such as IPDs, but also with the emerging idea of “crypto commons” built on the blockchain.

Collaborative Project Management Practices
The former connection (Figure 1.1, **ACD**) was conceptualized by Hall et al. (2020). Similar to how construction resources can be seen as CPR resources, design principles of newer collaborative forms of construction project deliveries such as IPDs were found to resemble design guidelines of the OPs. In other words, Ostrom's design principles are already embedded implicitly within many collaborative project delivery practices. A summary of the OP and their definition, as well as some the proposed equivalent management practices in collaborative construction projects can be found in Table 4.1.

The Crypto Commons
As explained before, existing blockchains can be seen as a CPR scenario and proof that decentralized peer production of blockchain networks is possible without any centralized coordination (Red, 2019). Therefore, various articles propose to leverage these cryptoeconomic mechanisms to encode design guidlines of the OPs to scale governance of CPR scenarios (Fritsch et al., 2021; Rozas et al., 2021a,b). These "crypto commons" (Figure 1.1, **BCD**) build digital governance structures for CPR scenarios by leveraging blockchain-based market mechanisms and economic incentives to reward contributions to the common good (Crypto Commons Association, 2021).

Governance of Project Delivery on the Crypto Commons
Combining all previous connections, the alignment with the OPs for both collaborative project deliveries and decentralized governance of blockchains is an opportunity to identify promising blockchain-based governance mechanisms for construction project deliveries on the crypto commons (Figure 1.1, **ABCD**).

1.3. Summary of Research Gaps

Gap 1 Blockchain is a new and hyped technology with many proposed applications for the construction industry. There is a need to understand the technical capabilities of DLT design options, how they translate into properties usable for applications, and whether they match with proposed use cases in the construction industry.

Gap 2 Cryptoeconomics offers interesting opportunities for incentives and new forms of organisation. Research should assess the alignment of blockchain as an institutional innovation with current forms of economic coordination in the construction industry.

Gap 3 CPR theory was used to conceptualize both the governance of collaborative project deliveries, as well as governance of the crypto commons by encoding the OPs with cryptoeconomic mechanisms. This connection can be further explored to potentially identify cryptoeconomic mechanisms useful for the governance of construction project delivery.

Gap 4 More proof of concepts using blockchain and cryptoeconomics in the construction industry are required. They can demonstrate feasibility and challenges, as well as help to assess implications that give insights whether and how to further explore the topic.

1.4. Research Questions

The objective of this thesis is to assess the promise of blockchain for the construction industry, particularly in regards to the potential of cryptoeconomics. Based on the identified gaps, four corresponding research questions (RQ) were identified:

RQ1: How do you choose a blockchain for a use case in the construction industry?

RQ2: Why does cryptoeconomics align with economic coordination in the construction industry?

RQ3: What cryptoeconomic mechanisms can be used for construction project delivery?

RQ4: How can cryptoeconomic applications be realized in the construction industry?

1.5. Research Design

The thesis consists of five stand-alone chapters that explore the research questions within the introduced scope between the construction industry, distributed ledger technology, and common pool resources (see Section 1.2). Since there was little theoretical base to understand the potential of blockchain and cryptoeconomics in the construction industry, as well as no proof-of-concept implementations, the thesis focused on an interplay between building new theory and implementations to demonstrate feasibility and validity of the developed theory. In the following, the structure of the thesis (see Section 1.5.1), the focus of the individual chapters regarding the introduced scope (see Section 1.5.2), and the individual methods and objectives of the chapters (see Section 1.5.3) are further explained.

1.5.1. Structure of the Thesis

The thesis is structured as pictured below in Figure 1.2.

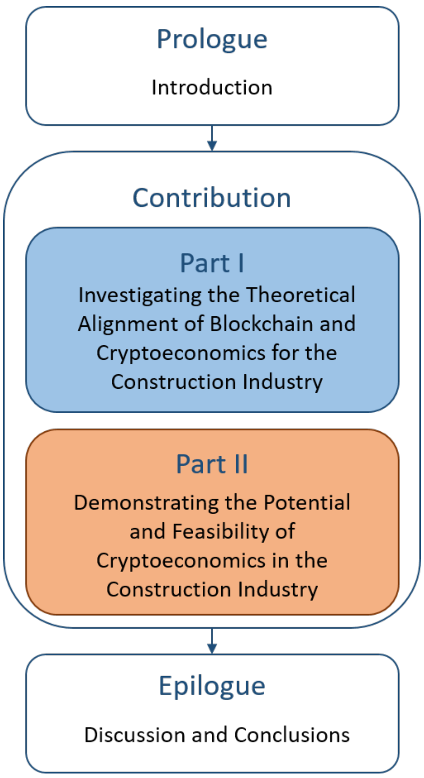

Figure 1.2.: Structure of the thesis.

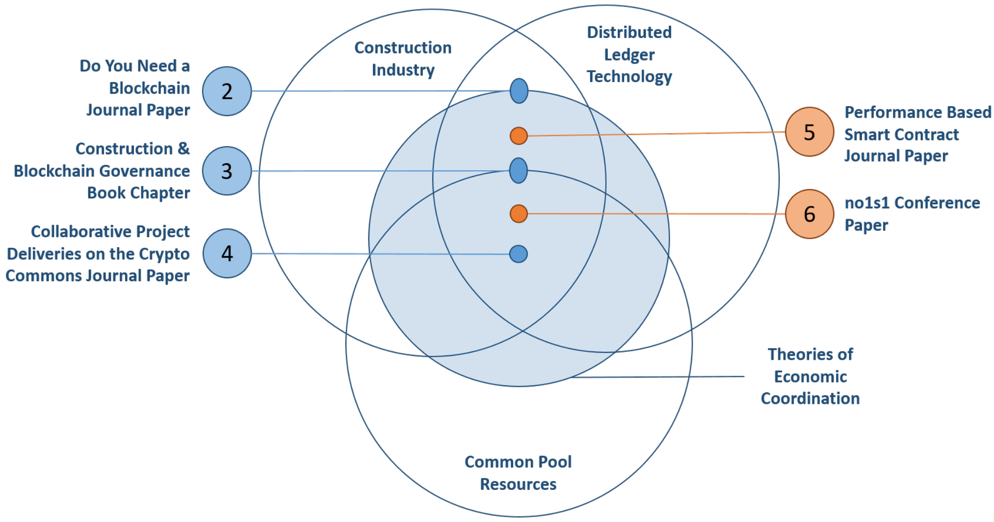

Figure 1.3.: Positioning the five chapters in the thesis scope. The chapters investigate the intersection of the construction industry and DLT by subsequently exploring the various connections between theories of economic coordination of the three pillars.

The Prologue introduces the work including the motivation and objective, the research scope, the research gaps, the research questions, and the research methods (**Chapter 1**).

Part I of the contribution builds the needed theoretical base to better understand the alignment of cryptoeconomics for the construction industry with three chapters (**Chapter 2 - 4**). The theory building chapters are visualized throughout the thesis in blue.

Part II demonstrates the potential and feasibility of cryptoeconomics in the construction industry with two proof of concepts (**Chapter 5** and **6**). The implementation chapters are visualized throughout the thesis in orange.

The Epilogue synthesizes and discusses the results regarding contribution to the research questions and overall objective, gives an overview on the scientific and practical implications, and outlines the limitations and the outlook with future research recommendations (**Chapter 7**).

1.5.2. Going Down the Rabbit Hole - The Scope of the Chapters

Figure 1.3 positions the individual chapters within the introduced scope between the construction industry, DLT, and CPRs. The chapters subsequently explore the intersections between the construction industry (pillar A) and DLT (pillar B) towards their intersection with CPRs (pillar C) and the overlap with theories of economic coordination used in the respective pillars (lens D). The approach is an interplay between building theory and investigating implementations to see whether the established concepts are applicable. The chapters connect in the sense that the findings of each contribution motivate the following chapter.

Chapter 2 starts at the intersection of the construction industry and DLT (sector AB) (see Figure 1.1) to investigate in which cases it makes sense to use a DLT for use cases in the construction industry (Figure 1.2, Do You Need a Blockchain Journal Paper). One of the main take away was that promising use cases are inherently linked to economic coordination. Therefore, the chapter shows why a lens of economic coordination is well-suited to bridge the main pillars of the construction industry and DLT (sector ABD) (see Figure 1.1). Use cases that relied most on DLT were related to cryptoeconomics, e.g. for incentives through financial or non-financial exchange of tokens, or new forms of organization. Overall, chapter 2 lies at the intersection of the sectors AB and ABD (see Figure 1.3).

Chapter 5 implements a specific example of cryptoeconomics in the construction industry to demonstrate the feasibility and promise of the concept and identify the potential and challenges related to implementation and application (Figure 1.2, Performance Based Smart Contract Journal Paper). The selected case is a smart contract to incentivize energy performance across life cycle phases within existing forms of economic coordination in the construction industry. It is therefore positioned in the sector ABD (see Figure 1.1 and 1.3).

Chapter 3 dives then in more depth into various aspects of cryptoeconomics by theoretically assessing the overlap between economic coordination in the construction industry and DLT (sector ABD). The focus lies on the possibility for new incentives and new forms of organization and governance, also related to economic coordination for the management of CPRs (pillar C). It highlights resulting possibilities for new forms of institutional coordination and cyberphysical integration in the construction industry (Figure 1.2, Construction & Blockchain Governance Book Chapter). Therefore, chapter 3 establishes new theory at the intersection of sector ABD and ABCD (see Figure 1.1).

Chapter 6 investigates subsequently an implementation of cryptoeconomics for novel forms of organization with the no1s1 prototype, a self-owning house Figure 1.2, no1s1 Conference Paper). The prototype demonstrates the possibility of machine participation in the future economy, and introduces the early thinking of how a community can collectively decide in the interest of no1s1 through a DAO. In a sense, no1s1 resembles a CPR scenario, where actors need to coordinate around the space and its funds. Hence, it is positioned in the sector ABCD of the thesis scope (see Figure 1.1 and 1.3).

Chapter 4 creates at last the needed theory to guide thinking around possible mechanisms for new forms of economic coordination in the construction industry (Figure 1.2, Collaborative Project Delivery on the Crypto Commons Journal Paper). It exploits the connection between parallel governance procedures of collaborative project deliveries and common pool resource theory to identify blockchain mechanisms applicable to the construction industry. With that it pioneers the theoretical foundation for new forms of blockchain-based economic coordination for collaboration resembling CPR scenarios (such as IPDs or the case of no1s1) and positions itself at the sector ABCD of the thesis scope (see Figure 1.1 and 1.3).

1.5.3. The Objectives and Methodology of the Chapters

After outlining the scope of the individual chapters and the logic of the interplay between building theory and implementations, the objectives to answer the research questions and the methodology of the chapters are introduced. Figure 1.4 provides an overview of the research design.

Part I - Investigating the Theoretical Alignment of Blockchain and Cryptoeconomics for the Construction Industry

The three chapters building theory aim to investigate the first three research questions (see Figure 1.4).

Chapter 2 First, a more in depth understanding of the capabilities of DLT is needed to assess RQ1: How do you choose a blockchain for the construction industry? For that, the journal paper uses a combination of state-of-the-art reviews

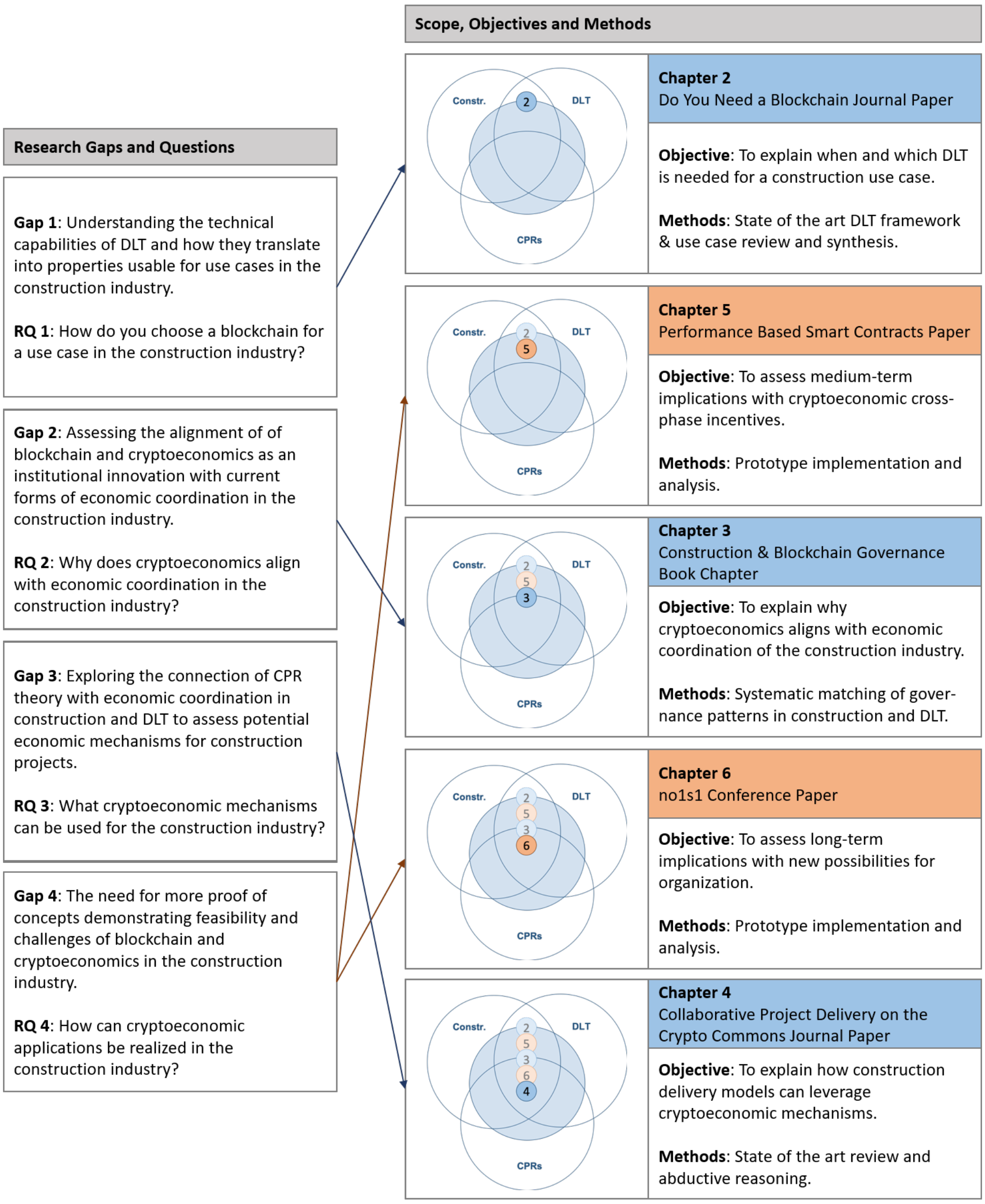

Figure 1.4.: Summary of the cumulative research approach with five chapters contributing to the four research questions of this thesis. The thesis explored its overall objective with an interplay between building new theory (blue) and implementations (orange).

both on DLT decision frameworks and proposed use cases for the construction industry to identify the relevant technological aspects and most mentioned use cases. The subsequent systematic synthesis into a combined DLT decision making framework and use case categories in the construction industry allowed then to assess for each use case category whether a DLT is necessary. The results show that for most use case categories it is not so clear whether a DLT is needed. Most promising are use cases that use cryptoeconomic mechanisms of DLT to facilitate economic coordination characterized by unknown actors or misaligned incentives. While unknown actors are almost never an issue to date in the construction industry, there are a lot of existing processes suffering from misaligned incentives and trust issues that could justify the use of DLT. Nevertheless, almost none of the reviewed scholarship and reports focused primarily on the novel potential of crypteconomics. Therefore, there was need to investigate particularly the potential of cryptoeconomics and how it aligns with economic coordination in the construction industry.

Chapter 3 The third chapter investigates RQ2: Why does cryptoeconomics align with economic coordination in the construction industry? Therefore, the third chapter zooms out to explore how cryptoeconomics aligns with characteristics of the construction industry. Since there was no construction related literature to build these arguments, the chapter first reviews and summarizes the current understanding of cryptoeconomics and possible resulting new forms of governance for CPR scenarios and DAOs. It then identifies and describes three governance lenses of the construction industry that are potentially aligned with the advantages of blockchain-based governance: fragmentation, complexity, and loosely-coupled systems. Afterwards, it matches the governance approaches of DLT and the construction industry to propose a future vision and road map for the promise of cryptoeconomics in the construction industry. But even though the book chapter identifies emerging scholarship that supports the established concepts, it does not yet validate them. Having said that, the subsequent research contained in this thesis supports the established concepts. The presented work in the book chapter helps to understand the bigger picture of blockchain and cryptoeconomics in the construction industry and is an important theoretical anchoring point for this thesis.

Chapter 4 Finally, the fourth chapter assess RQ3: What cryptoeconomic mechanisms can be used for the construction industry? The journal paper reviews state-of-the-art literature that propose cryptoeconomic mechanisms to govern CPR scenarios and synthesizes them into a framework that matches the Ostrom principles with blockchain-based governance mechanisms. The paper then uses abductive reasoning to propose blockchain-based mechanisms for the governance of collaborative project deliveries based on existing conceptualizations between the Ostrom priniciples and collaborative project deliveries. Therefore, the fourth chapter explores how the OPs and CPR theory can inspire applications of blockchain-based mechanisms for the economic coordination of construction projects. The resulting theoretical framework provides a unique starting point to systematically investigate possible ways to apply blockchain-based organization in the construction industry.

Part II - Demonstrating the Potential and Feasibility of Cryptoeconomics in the Construction Industry

In interplay with the theory building and conceptualizations on blockchain and cryptoeconomics in the construction industry, there is need to assess the feasibility and impact of such applications. For that reason, two chapters assess RQ4 (see Figure 1.4): How can crytpoeconomic applications be realized in the construction industry? Both papers use an experiment, in this case a single proof-of concept implementation that "provides justification in practice of the potential transportability of knowledge" (Kendig, 2016), to check whether data supports the established concepts (Shadish et al., 2002).

Chapter 5 The fifth chapter investigates how blockchain can be used to enable new business models and coordination across building life cycle phases with performance based smart contracts (PBSC). The main idea is to build upon the increasingly available real time data of digital building twins and connect them to smart contracts that evaluate defined performance baselines. The PBSC ensures automatic monetary payouts without the need to know all stakeholders by the time of setting up the contract. Since there was no existing prototypes linking digital building twins with public permissionless blockchains, the main approach was to focus on the most straightforward implementation connecting the Ethereum blockchain with the Siemens building twin platform. The resulting proof-of-concept was tested on a real building to collect operational data to later document and analyse the current state of technology and how it can be leveraged to build a cryptoeconomic application in the construction industry. The analysis spanned technological, but also business related and socio-technical aspects in the construction industry needed to realize such a cryptoeconomic application. With that this study provides a first reference point what to consider for future research in this field.

Chapter 6 The sixth chapter shows feasibility of the needed cyber-physical technical infrastructure to create self-owning entities on the blockchain. No1s1 holds funds and encodes operational logic within its smart contract and implements an IoT system to manifest physical reactions in the prototype. Similar to chapter 5, the work focused on available technical solutions using the Ethereum blockchain and a Raspberry Pi to control the IoT system. The operational prototype implementation was used to test the technical implementation and identify areas the need more research, technology-wise but also related to its potential socio-technial impact on the built environment.

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Part I.

Investigating the Theoretical Alignment of Blockchain and Cryptoeconomics for the Construction Industry

2. Do You Need a Blockchain in Construction? Use Case Categories and Decision Framework for DLT Design Options

This chapter corresponds to the published article:[1]

Hunhevicz, Jens J. and Daniel M. Hall (Aug. 2020b). "Do you need a blockchain in construction? Use case categories and decision framework for DLT design options". In: *Advanced Engineering Informatics* 45.February, p. 101094. ISSN: 14740346. DOI: `10.1016/j.aei.2020.101094`.

Abstract: Blockchain and other forms of Distributed Ledger Technology (DLT) provide an opportunity to integrate digital information, management, and contracts to increase trust and collaboration within the construction industry. DLT enables direct peer-to-peer transactions of value across a distributed network by providing an immutable and transparent record of these transactions. Furthermore, there is potential for business process optimization and automation on the transaction level through the use of smart contracts, which are code protocols deployed on supported DLT systems. However, DLT research in the construction industry remains at a theoretical level; there have been few implementation case studies to date. One potential reason for this is a knowledge gap between use-case ideas and the DLT technical system implementation. This paper aims to reduce this gap by (1) reviewing and categorizing proposed DLT use cases in construction literature, (2) providing an overview of DLT and its design options, (3) proposing an integrated framework to match DLT design options with desired characteristics of a use case, and (4) analysing the use cases using the new framework. Together, the use case categories and proposed decision framework can guide future implementers toward more connected and structured thinking between the technological properties of DLT and use cases in construction.

[1]Please note, this is the author's version of the manuscript published in the *Journal of Advanced Engineering in Informatics*. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. The final publication is available at `https://www.journals.elsevier.com/advanced-engineering-informatics`. When citing this chapter, please refer to the original article found in the reference above.

2.1. Introduction

2.1.1. Distributed Ledger Technology

The concept of Distributed Ledger Technology (DLT) provides a distributed peer-to-peer system for value transactions without any intermediation from a central authority. The most prominent type of DLT is blockchain, which has its origin in the peer-to-peer cryptocurrency Bitcoin (Nakamoto, 2008). Bitcoin solved for the first time the double-spending problem through its proof-of-work consensus algorithm (Nakamoto, 2008). The overarching idea was to timestamp transactions and proof-of-work hashing them into a sequential record (also called chain) that cannot be changed without redoing the proof-of-work. As long as the nodes controlling the network and performing the proof-of-work do not collaborate to attack the network, these inherent system properties enable participants to trust that the history of transactions are correct. These properties are called "fundamental properties" of a DLT (Xu et al., 2017).

Overall, high fundamental properties lead to a more secure and trustworthy system. Of course, this security comes at a cost. There is a tradeoff between performance (in terms of transaction speed and overhead of the system) and the fundamental properties. Therefore, one type of DLT (e.g. Bitcoin) is unlikely to meet the prerequisites for all usage scenarios (Xu et al., 2017). Other implementations of DLT have emerged to meet the different implementation requirements. In this paper, DLT design options refers to the potential selection of various DLT implementations. Therefore, DLT is an overarching term that captures various potential design options (Hileman and Rauchs, 2017; El Ioini and Pahl, 2018).

Furthermore, there are other constraints regarding the functionality of certain DLT implementations. Most important, newer DLT implementations enable the use of smart contracts. Smart contracts have been popularized by the DLT Ethereum (Buterin, 2014), which allows the execution of code protocols on the DLT. Smart contracts enables the automation of business logic for assets and data managed on the DLT. They also enable the creation of new types of "tokenized" digital assets.

To summarize, the fundamental properties of DLT enable the building of trust between transacting parties and devices, as well as the potential to increase the settlement time of transactions and reduction of costs associated with intermediaries (Viriyasitavat et al., 2018). In combination with the functionality of smart contracts, the potential applications of DLT in society and industry are manifold. Industries such as financial services, insurance, and supply chain envision it to be a future game changer on how these sectors interact and transact. Future peer-to-peer interactions and process automation using DLT can be more trustworthy and transparent compared to traditional applications.

Most literature agrees that DLT should not be neglected when looking at future business development (e.g. Tapscott and Tapscott (2016) and Nowiński and Kozma (2017)). This is a proposition that should also be considered in the construction industry.

2.1.2. DLT for the Construction Industry

While various industries have already developed different DLT prototypes and applications, the construction sector is only at the beginning of DLT implementation as a tool. However, the application of DLT in construction might be especially promising (Penzes, 2018; Li et al., 2019a). In contrast to many other industries, the construction industry structure can be characterized as a decentralized, loosely-coupled network. This leads to various unique challenges regarding its structure (Dubois and Gadde, 2002b). Construction is delivered by project teams that work in cross-functional, geographically distributed teams (Zolin et al., 2004) composed of complex and fragmented supply chains (Hall et al., 2018). The successful completion of complex projects requires the development of trust and mutual confidence between the interacting parties for each individual project (Pishdad-Bozorgi and Beliveau, 2016). This has been found to be a major challenge for large, complex, and long-term projects that rely on the interdependent actions of numerous stakeholders (Tavistock Institute of Human Relations, 1966; Zolin et al., 2004). Mistrust leads to guarded behaviors and conflicts within project teams. It often results in individuals pursuing and protecting their own interests instead of the benefit of the overall projects (Pishdad-Bozorgi and Beliveau, 2016). Furthermore, without a strong foundation of trust, it is difficult to reach consensus and information exchange in a meaningful manner (Hall et al., 2014).

To summarize, the decentralized and project-based structure of the construction industry requires many stakeholders with various incentives to interact over long time horizons. This leads to coordination challenges such as a lack of trust, poor information exchange, and supply chain fragmentation. In theory, the potential benefits of DLT to provide a trusted means for transactions aligns with these coordination challenges. DLT can help by making construction more efficient, transparent, and accountable between all involved participants (Penzes, 2018). However, despite theoretical alignment of DLT value propositions and coordination challenges in construction, there are few implementations of DLT in a construction context.

Most literature to date instead provides an overview of the potential use cases for DLT in construction. For example, early literature sees the vision for DLT as a complementary technology to building information modelling (BIM) and internet of things (IoT) (Kinnaird and Geipel, 2017; Mathews et al., 2017; Penzes, 2018; Ye et al., 2018). BIM allows designers and builders to design, visualize, and coordinate construction systems with greater efficiency through the use of three-dimensional modelling tools and processes. While helpful for individual firms, BIM provides significantly more value when it can integrate information across multiple firms and organizations in the supply chain (Papadonikolaki and Wamelink, 2017). Despite its potential, the adoption of BIM has lagged as project teams struggle with trust and liability concerns associated with sharing information on the project (Miettinen and Paavola, 2014; Ghaffarianhoseini et al., 2017; Hall and Scott, 2019). It seems that new technologies such as BIM that promise to increase collaboration in the construction industry are again hindered by issues of trust and liability found throughout the industry (Miettinen and Paavola, 2014; Papadonikolaki, 2018). IoT describes an environment where physical objects connect with the digital world using sensors and connected devices (Fleisch, 2010). Ye et al. (2018) see DLT as a way to hold the data produced by IoT in a transparent, secure and convenient environment and BIM as the baseline tool to digitize the construction project data. De La Pena and Papadonikolaki (2019) suggest that the combination of DLT and IoT can increase inter-firm trust in construction. Eventually, this could lead to a future industry state characterized by the “circular economy of BIM things” (Kinnaird and Geipel, 2017; Penzes, 2018). The produced data from projects and IoT can be integrated into a common data environment – first developed and visualized through BIM during design and construction – enabling a digital twin consistently maintained over the whole life cycle of a building. DLT acts as an immutable track-record for higher transparency and potential automation through smart contracts.

2.1.3. Goal and Scope of the Study

The mentioned vision for DLT use cases is ahead of the current state of research, since very few documented implementations of DLT for the construction industry exist. There is now need for prototypes and use-case implementations to assess and validate these value propositions for DLT in construction. More specific use cases on how DLT can be used in construction have been proposed by various authors. Some of them can align with the above vision and rely on combination with BIM and IoT, but some can also stand on their own. Little research has attempted to structure these use cases into categories according to the different value propositions of DLT. A categorization for use cases might help to more easily align the prerequisites of specific use cases with the needed DLT design options, since use cases in construction have been mostly understood at the theoretical level and often lack a detailed understanding of the technical system implementation (Ye et al., 2018). Most importantly, the DLT design option with its fundamental properties should match the trust requirements of the proposed use case. On top of that, other constraints regarding technical capabilities of the needed DLT should be considered. Finally, the fast-moving and vast landscape of DLT is challenging for potential implementation of the diverse DLT use cases in construction. There is need of a framework so that researchers looking to implement DLT for a use case can start by choosing an appropriate system. Without a good understanding of both use case function and DLT design options, it can be difficult for implementers to begin development of a proof-of-concept for a use case.

This paper aims to close the gap between DLT use cases and DLT technical system implementation in construction. To do so, the paper first reviews and categorizes DLT use cases proposed in existing literature into higher level categories aligned with the specific value propositions of DLT. Second, the paper describes the technical features of DLT and from this summarizes four different DLT design options next to traditional database solutions. Third, the paper proposes a decision framework to answer the question "do you need a blockchain in construction?" and if so, which type of DLT design option should be selected. Fourth, the paper uses the framework to evaluate each proposed use case and reports the potential DLT design options that could be used. Finally, interesting findings are discussed and limitations stated.

2.2. Categorization of DLT Use Cases in Construction

A number of papers and consultancy reports started in 2017 to identify potential use case scenarios to deploy DLT in the construction sector. A review of fifteen sources (see Table 2.1) identifies the potential use cases proposed for DLT in construction. Because literature on DLT in construction is still limited, both scholarship and consulting reports are considered. The review scope is limited to literature focusing on the construction industry and excludes literature about the energy sector, smart cities and homes, and very general work about the built environment.

This review of the DLT use case literature identifies twenty-four potential use cases. These cases can be further clustered into higher-level use case categories (see Table 2.2). Table 2.2 provides a summary of the categorized use-cases by source. This is an extension and update of the use case categorization orig-

#	Author	Title	Type
I	Belle (2017)	The architecture, engineering and construction industry and blockchain technology	S
II	Heiskanen (2017)	The technology of trust: How the Internet of Things and blockchain could usher in a new era of construction productivity	S
III	Kifokeris and Koch (2019)	Blockchain in construction logistics: state-of-art, constructability, and the advent of a new digital business model in Sweden	S
IV	Kinnaird and Geipel (2017)	Blockchain Technology: How the Inventions Behind Bitcoin are Enabling a Network of Trust for the Built Environment	C
V	Li et al. (2019a)	Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases	S
VI	Li et al. (2019b)	A Proposed Approach Integrating DLT, BIM, IoT and Smart Contracts: demonstration Using a Simulated Installation Task	S
VII	Luo et al. (2019)	Construction Payment Automation through Smart Contract-based Blockchain Framework	S
VIII	Mason (2017)	Intelligent Contracts and the Construction Industry	S
IX	Mathews et al. (2017)	BIM+Blockchain: A Solution to the Trust Problem in Collaboration?	S
X	Nawari and Ravindran (2019b)	Blockchain and the built environment: Potentials and limitations	S
XI	O'Reilly and Mathews (2019)	Incentivising Multidisciplinary Teams with New Methods of Procurement using BIM + Blockchain	S
XII	Penzes (2018)	Blockchain technology: could it revolutionise construction?	C
XIII	Turk and Klinc (2017)	Potentials of Blockchain Technology for Construction Management	S
XIV	Wang et al. (2017)	The outlook of blockchain technology for construction engineering management	S
XV	Ye et al. (2018)	Cup-of-Water theory : A review on the interaction of BIM, IoT and blockchain during the whole building lifecycle	S

Table 2.1.: Literature for use-case analysis (S: scholarly papers, C: consulting reports)

inally performed by Hunhevicz and Hall (2019) with addition of six relevant recently-published papers. Furthermore, a specific refinement of Hunhevicz and Hall (2019) is made by splitting the use case category of "record of transactions, changes, ownership" into two separate categories related to "immutable records of transactions" and "immutable records of assets/ownership" (Table 2.2, Categories 3 & 4).

On a high level, the categories shown in Table 2.2 are in line with the main value propositions of DLT:

1. Higher transparency and trust in the project and supply chain due to the fundamental properties of DLT (Table 2.2, category 3, 4).

2. Higher efficiency and accuracy in business process optimization and automation through the use of smart contracts (Table 2.2, category 1, 2, 6, 7), as well as creating tokens for financial, incentive, or other purposes (Table 2.2, category 5).

	Use Case Category	Literature I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	XIV	XV
1	Internal Use for Administrative Processes															
1.1	Notarization and Synchronization of Documents														×	
2	Transaction Automation with Smart Contracts															
2.1	Triggering Payments			×	×	×	×	×	×				×		×	×
2.2	Triggering Contract Deliverable			×					×		×		×			
2.3	Self-executing Contract Administration							×					×		×	
2.4	Automated Data/Information Sharing				×								×			×
2.5	Automated Code Compliance Checking										×					
3	Immutable Record of Transactions															
3.1	Timestamping of "Value" Transactions		×			×				×	×	×				
3.2	Record of Changes in Digital Models (BIM)			×	×	×			×		×	×	×	×		×
3.3	Tracking of Supply Chain Logistics		×	×	×								×		×	×
3.4	Tracking of Project Progress and Worked Hours												×			
3.5	Record of Maintenance and Operations Data												×			
3.6	Tracking of Health & Safety Incidents												×			
3.7	Verification of Installation Tasks						×									
3.8	Record/Notarization for Regulation and Compliance					×									×	
4	Immutable Record of Assets/Ownership															
4.1	Record of Ownership in BIM (IP-Rights)	×			×	×			×		×		×	×		×
4.2	Record of Ownership for Physical Assets (e.g. Property)				×				×				×			×
4.3	Managing Identities for Reputation (People, Contractors)	×			×								×			
4.4	Material & Product Passports (Provenance and Properties)				×								×			
5	Coins/Tokens as Payment or Incentive Scheme															
5.1	Payment in Cryptocurrencies														×	×
5.2	Shared Account & Insurances					×			×							
5.3	Incentives Over the Whole Building-Lifecycle									×		×				
6	Decentralized Applications (dApps)															
6.1	Decentralized Marketplaces for Products and Services				×										×	
6.2	Decentralized Common Data Environments (CDE)				×						×					×
7	Decentralized Autonomous Organizations (DAOs)															
7.1	Automated Building Maintenance Systems	×											×			×

Table 2.2.: Use-Case clustering into seven categories, based on the literature listed in Table 2.1 (adapted from Hunhevicz and Hall (2019)).

2.2.1. 1 - Internal Use for Administrative Purposes

DLT can be used for **notarization and synchronization of documents** (Table 2.2, 1.1). This includes the storage and perfect notarization of each creation, deletion, and updating of files across an inter-organizational system (Wang et al., 2017). This can simplify and automate administrative processes. Wang et al. (2017) mentions the recording of quality data or resource consumption data as examples.

2.2.2. 2 - Transaction Automation with Smart Contract

Using smart contracts, DLT can automate transactions between different stakeholders. The most mentioned use case is automatic **triggering payments** (Table 2.2, 2.1). This is helpful because delays for monetary transactions are mentioned repeatedly as a factor causing conflicts and disputes (Eastman, 2011). In addition, automatic **triggering contract deliverables** are mentioned multiple times, where an updated state in the ledger causes a predefined contractual action (Table 2.2, 2.2). Once a smart contract is written, its behavior is unambiguous and predictable. This can be used for **self-executing contract administration** (Table 2.2, 2.3), such as monitoring and updating of the contract status (Wang et al., 2017). Smart contracts are also mentioned as a way to enable **automated information and data sharing** in projects (Table 2.2, 2.4), ensuring consistent reporting for (sub)contractors and owners. Finally, Nawari and Ravindran (2019a) introduce a framework for **automated code compliance checking** (Table 2.2, 2.4) in the BIM design review process. All use cases are independent of the construction project phase and can be applied for procurement and supply chain activities for higher accuracy and efficiency.

2.2.3. 3 - Immutable Record of Transactions

DLT can provide immutability and transparency for transactions. On a high level, DLT can provide **timestamping of value transactions** (Table 2.2, 3.1). The most mentioned use case is the **record of changes in digital models**, especially in combination with BIM (Table 2.2, 3.2). One other often mentioned use case is the **tracking of supply chain logistics**, including procurement, transportation, and storage of goods (Table 2.2, 3.3). Penzes (2018) expands on the tracking of processes towards **tracking of project progress and worked hours** (Table 2.2, 3.4), **maintenance and operations data** of buildings and machines (Table 2.2, 3.5), and **health & safety incidents** (Table 2.2, 3.6). Li et al. (2019a) describes **verification of installation tasks** as a use case for DLT, in particular correct installation of insulation panels (Table 2.2, 3.7). Finally, two papers (Wang et al., 2017; Li et al., 2019a) describe the **record/notarization for regulation and compliance** as potentially advantageous in construction (Table 2.2, 3.8).

2.2.4. 4 - Immutable Record of Assets/Identities

As in the use case category 3, the focus lies on the immutability and transparency provided by DLT. In addition to recording transactions, DLT can also record information of physical or digital assets. One potential use case mentioned is the **record of ownership in BIM** for IP-protection (Table 2.2, 4.1). If not a digital asset, a unique digital counterpart of the respective physical asset can be created. For example, a **record of ownership for physical assets** such as property (Table 2.2, 4.2). Furthermore, **managing identities for reputation** of people or organizations on DLT (Table 2.2, 4.3) for clear and trustworthy identification is possible. Similarly, **material and product passports** with product and provenance-related information (Table 2.2, 4.4) can be maintained throughout the supply chain. This can be used for quality assurance in global construction projects (Wang et al., 2017) or to enable the reuse of materials at a later stage of a building towards a circular economy (Kinnaird and Geipel, 2017). Also, certification of products and buildings could profit from the availability of this trusted data.

2.2.5. 5 - Coins/Tokens as Payment or Incentive Scheme

DLT enables new financial and incentive related use cases by creating coins or tokens. A well-documented use case is **payment in cryptocurrencies** (Table 2.2, 5.1). This allows participants to send money across borders instantly and with small transaction fees. This can be extended even further with shared risk and reward structures for **shared accounts and insurances** among multiple, independent stakeholders (Table 2.2, 5.2). Finally, Mathews et al. (2017) propose the use of an #AECoin as a token to provide **incentives over the whole building life-cycle** to reward project contributors for the contributed value even after project handover to the client (Table 2.2, 5.3). This can create superior value for the project owner, as participants can be incentivized to make long-term life-cycle decisions in order to increase their own rewards. Similarly, O'Reilly and Mathews (2019) describe a DLT based incentive approach in BIM in order to create more energy efficient buildings and save energy in the use phase.

2.2.6. 6 - Decentralized Applications (DApps)

DApps are applications that are based on a DLT that is not run by any intermediary. This means that no censorship of users beyond rules encoded in the smart contracts is possible. DApps enable direct user interaction with DLT, typically through web user interfaces. Even though it is possible to create web applications for the use cases in the previous categories for very project-specific cases, this category refers to DApps for long-term and global users across project boundaries. Users of such applications might be unknown and involved in various projects simultaneously. Different use cases for DApps are mentioned in the literature. **Decentralized marketplaces for products and services** (Table 2.2, 6.1) can be set up based on digital identities (Table 2.2, 4.3). This can enable access to objective data (e.g. the most-qualified person or company in tendering) without the need to disclose sensitive data to third parties (Belle, 2017). Also, **decentralized common data environments for digital models** as a combination of cloud storage and DLT are proposed to store digital models without the need to trust a third party server provider or run private servers vulnerable to attacks (Ye et al., 2018).

2.2.7. 7 - Decentralized Autonomous Organizations (DAOs)

DAOs represent a fully autonomous organization based on smart contracts that run on DLT. Governance rules are coded in smart contracts and incentive mechanisms are implied through crypto-economic design (CED). Often, DAOs make use of IoT to interact with the real world and a digital model to provide location context. Even though fully automated construction companies seem futuristic, three sources (Belle, 2017; Penzes, 2018; Ye et al., 2018) mentioned **automated building maintenance systems** as one possibility for a DAO (Table 2.2, 5.1). The idea is that building performance can be monitored through sensors (IoT) in combination with BIM. This enables an automatized reaction to certain conditions

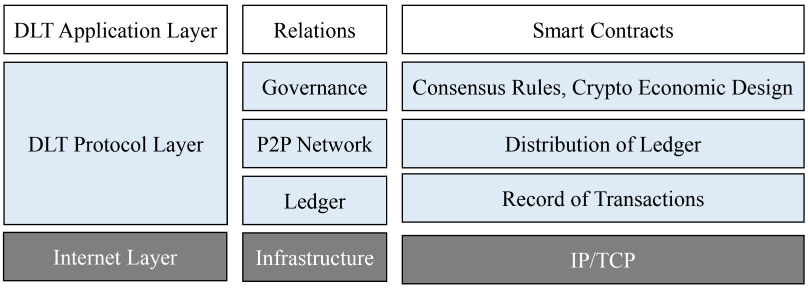

Figure 2.1.: Technology stack of DLT (adapted from Voshmgir (2017))

based on predefined rules. Specific examples include the automatic ordering of spare parts or regulating technical installations based on predefined performance indicators.

2.3. Overview of DLT and Design Options

After having categorized use cases in construction into higher level categories aligned with different value propositions of DLT, technical aspects of DLT and how they relate to the fundamental properties need to be introduced in order to design a connecting framework. This helps to understand the relationship of technical DLT-features with the different expectations of use cases regarding their capabilities.

2.3.1. DLT Technology Stack

While a full explanation of the underlying base technologies of DLT is beyond the scope of this paper, this section provides an overview of the most important factors that influence DLT design options. This section sources from more detailed explanations of DLT (e.g.Wattenhofer (2017)) and scholarship that introduces taxonomies for DLT while providing in-depth explanations on different components (Tasca and Tessone, 2017; Xu et al., 2017; Ballandies et al., 2018). Information is structured based on an adapted version of the technology stack used in Voshmgir (2017), pictured in Figure 2.1. The internet layer acts as the base technology for information sharing. A DLT, sometimes also referred to as protocol layer (Hileman and Rauchs, 2017), is built on top of the internet layer with three main components impacting its characteristics: Ledger, Peer to Peer (P2P) Network, and Governance. If code can be executed on the protocol layer, an application layer is possible with smart contracts.

Ledger

The ledger represents the data structure of DLT. The most-well known ledger type as in the case of Bitcoin is a *blockchain* with sequential entries and total order (Ballandies et al., 2018). Blockchain links the latest block containing the most recent transaction information with the previous blocks to create a “chain”. Integrity of the ledger is reached through the process of hashing, applying mathematical one-way functions repeatedly to the transaction data. These hashes are included in a block together with the block-hash of the previous block, making it possible to notice if past data has been tampered. With every new block, the chances of attacking a previous block decrease exponentially (Nakamoto, 2008). Besides blockchain, other types of ledgers are possible. For example, the *directed acyclic graph* (DAG) is a ledger with a stream of individual transactions entangled together that can be confirmed in parallel (e.g. IOTA (Popov, 2018)).

Typically, there is only one ledger per DLT. However, new research focuses on how to process transactions in more than one ledger (*sidechains* as e.g. in Back et al. (2014)) or among multiple smaller groups of nodes (*sharding* as e.g. in Zamani et al. (2018)) in a network to make it more scalable.

Various elements of a ledger can be defined such as the storage capabilities or data encryption. Next to the defined size of a block or transaction, the ledger can store the default transaction information and/or additional data. Transactions on the ledger are usually encrypted through hashing, but might be still *linkable* and therefore reveal further information about the sender and receiver. Some systems allow *obfuscatable* transactions by using advanced cryptography (for an overview and comparison of existing systems see e.g. Yocom-Piatt (2019)). Encrypted transactions and data become important for privacy considerations in public DLT systems (see section 2.3.1).

Finally, if the ledger supports turing complete language on the protocol layer, an application layer for coded relations is possible (see Figure 2.1). This enables the use of *smart contracts*, described the first time by Szabo (1996). Smart contracts represent code protocols that execute certain logic based on the state of the ledger. The name "smart contracts" can be misleading. They do not represent a contract per se, but could be coded in such a way. Since they run on a DLT, the code is also unchangeable unless programmed to be updateable. These smart contracts can be used to create autonomous work flows or containers of value (e.g. representing currencies, securities, utilities, or other), so-called *tokens* (Token Alliance, 2018). Many smart contracts can be combined to build so-called decentralized applications (DApps) or decentralized autonomous organizations (DAOs) (see Section 2.2.6 and 2.2.7).

P2P Network

The ledgers are distributed on different nodes in the network. Setting up these nodes can be either permissionless or permissioned. *Permissionless* nodes allow anyone to set up a node and write transactions to the ledger by participating in the consensus mechanism (see section 2.3.1). *Permissioned* nodes cannot be set up by anyone and/or limit write-access to the ledger. The second distinction is between public and private ledgers in the network. *Public* ledgers allow anyone to read the ledger. *Private* ledgers allow only defined members to access transactions on the ledger. The distribution and ownership of nodes impacts the decentralization of the system. Public permissionless DLT naturally lead to higher network decentralization. Because anyone can set up a node, this leads to more nodes and a higher variability in the interests of the participating users. Typically, data is replicated on all participating nodes. However, there exists DLT design options that do not replicate data on all nodes but only on nodes that are allowed to access the data (e.g. in Corda (Brown et al., 2016) or Holochain (Harris-Braun et al., 2018)).

Governance

The governance of the DLT defines the set of rules for users interacting with the system. The most important component is the consensus mechanism. The consensus mechanism is responsible for defining how to write, validate, and agree on entries to the ledger. Proof-of-work was the first blockchain *consensus mechanism* and the greatest innovation behind Bitcoin (see Nakamoto (2008)), protecting the network effectively from double-spending and attacks to ensure immutability and non-repudiation of data (Gervais et al., 2016). In the case of proof-of-work, the

Fundamental Property	Explanation
Immutability	The ledger cannot be tampered after transactions were added.
Non-repudiation	Each transaction is added only once to the ledger.
Integrity	Data can be verified to be as initially written to the ledger.
Transparency	Transactions and data are visible to everyone.
Equal Rights	Everyone has the possibility to read and write transactions.

Table 2.3.: Fundamental Properties of DLT.

honest nodes need to control the majority of computing power to protect the network. The more network decentralization, the less likely it becomes that nodes can collaborate to attack the network. Since proof-of-work is very resource intensive, other types of consensus mechanisms have been introduced such as proof-of-stake, where nodes validating and adding transactions need to put money at stake that they can lose if they behave dishonestly (see e.g. Tasca and Tessone (2017)). All types of consensus mechanisms in public DLT are enabled by a crypto-economic design (CED) (Voshmgir and Zargham (2019)). A native coin of the DLT incentivizes participants to behave in the interest of the system (e.g. *bitcoin* in Bitcoin or *ether* in Ethereum). This is important to prevent attacks, but also to compensate nodes that validate and add transaction (sometimes called *miners*) for their expenditures. A successful CED incentivizes honest behaviour in a DLT network. Multiple properties of a CED can be defined, influencing the DLT's governance (see also Ballandies et al. (2018)). A private DLT might not necessarily need a CED, as consensus is often based on permissions (e.g. practical byzantine fault tolerance by Castro and Liskov (1999)). This can have an impact on the cost structure for users when interacting with different systems. Often, users pay for transactions on a public DLT with transaction fees in its native token. In contrast, users do not have to pay for transactions on a private DLT. Costs are predominantly accrued in the acquisition and maintenance of the infrastructure, while making transactions involves usually no fee.

2.3.2. Fundamental Properties

The reason why a DLT is used is given by its fundamental properties. Fundamental properties of DLT are immutability, non-repudiation, integrity, transparency, and equal rights (Xu et al., 2017). If the network is decentralized and protected through a working consensus-mechanism, the ledger is immutable. Each transaction is added only once to the ledger, which leads to non-repudiation of the stored data. The cryptographic tools used on the ledger support data integrity, allowing to verify that all the data is complete and as initially written into the ledger. Public access of ledgers for everyone ensures transparency, and equal rights allow every user the same ability to read and write to the ledger. Table 2.3 gives a summary of the five fundamental properties.

Trust in the DLT is achieved because the participants rely on the fundamental properties of a DLT itself rather than on trusted third-parties. Different DLT design options exist with varying fundamental properties. Table 2.4 (inspired by Xu et al. (2017)) summarizes this for central databases and four typical design options of DLT: private permissioned, private permissionless, public permissioned, and public permissionless. The more permissions, the less trust in the technical system can be accomplished with lower overall fundamental properties. This missing trust in the system needs to be compensated by more trust in the participating users or a third party. In some use cases, this high trust in the technical system might not be needed. A more centralized system offers a better perfor-

Design Option	Comment	Examples	Fundamental Properties: Immutability	Non-Repudiation	Integrity	Transparency	Equal Rights
Centralized	Central databases with a single or alternative providers	-	n	n	n	n	n
Private Permissioned DLT	DLT with permissions on both read & write-access	Hyperledger Fabric[1], Corda[1]	(y)	(y)	y	n	n
Private Permissionless DLT	DLT with permissioned read-access & permissonless write-access	Holochain[2]	y	y	y	n	y
Public Permissioned DLT	DLT with permissionless read-access & permissions for write-access	EOS[1]	y	y	y	y	n
Public Permissionless DLT	DLT with permissionless read access & permissionless write-access	Bitcoin[1], Ethereum[1]	y	y	y	y	y

Table 2.4.: The inversely related impact of the fundamental properties and performance in different design option (n: no; y: yes). [1]Examples classified by Ballandies et al. (2018): Ethereum (www.ethereum.org), EOS (www.eos.io), Hyperledger Fabric (www.hyperledger.org/projects/fabric), and Corda (www.r3.com). [2]Example classified by Daniels (2018): Holochain (www.holochain.org).

mance, as fewer nodes and less resource intensive consensus algorithms are used. In addition, privacy can be of concern with public DLT. For example, on-chain data encryption can have insufficient protection, encryption might not be appropriate for a use case, or parties might want to have the possibility to control more aspects of the DLT on the protocol layer (e.g. for easier implementation of system changes).

The relationship of the five different design options can be related to the five fundamental properties (see Table 2.4). The only fundamental property unaffected by permissions is integrity of the data because it is ensured through the cryptographic hash-functions used in all DLT design options. Centralized databases do not meet any of the fundamental properties. All aspects of a centralized database are controlled by a third party. In contrast, public permissionless DLT is able to achieve the highest level of trust by maintaining all five fundamental properties. Public permissioned DLT restrict write access or even the set-up of nodes and hence do not maintain equal rights for all users. In addition, private permissioned DLT further limit read access of the ledger and are therefore not transparent to users outside the network and inside the network without read-permissions. Furthermore, these permissions might have an impact on the immutability and non-repudiation of data, since depending on the set up of the DLT governance, outsiders have no assurance when shown the ledger that it has never been modified by the majority of network users (this is why a conditional “yes” (y) was used in Table 2.4). However, this might be irrelevant to network participants that trust their DLT governance and/or the participating users. Finally, there is the emerging case of private permissionless DLT design option not considered by Xu et al. (2017), where private records can be pegged to permissionless ledgers for proof-of existence (Miscione et al., 2019). For example, Holochain (Harris-Braun et al., 2018) uses private ledgers connected through distributed hash tables (DHT) (Maymounkov and Mazières, 2002) to validate data. With this, nodes can be set up in a permissionless way and start interacting with other nodes by only sharing defined information of the private ledger. The DHT ensures non-repudiation and immutability of the shared data (but not the private data). Furthermore, equal rights are guaranteed since the network is permissionless. But since read access is limited to shared data, transparency to anyone is not ensured.

#	Author	Type	Inputs	Outputs
[a]	Peck (2017)	Sequential Framework	Seven questions related to: Participants, Likelihood of Attack, **Trust**, Possibility of Third Party, Privacy, Updateability of Data.	Three options: No DLT, permissioned DLT, public DLT.
[b]	Turk and Klinc (2017), based on Suichies (2015)	Sequential Framework	Eight questions related to: Possibility for Traditional Database, **Trust**, Alignment of Interests, Possibility of Third Party, Control of Functionality & Privacy, Type of Consensus.	Four options: No DLT, public DLT, hybrid DLT, private DLT.
[c]	Xu et al. (2017)	Sequential Framework	**Trusted** authority, Ability to Decentralize Authority, Various Technical Configurations, Other Design Decisions	Two options: DLT, Traditional Database
[d]	Rangaswami et al. (2018)	Sequential Framework	11 questions related to: Possibility of Traditional Database, Technical Limitations, Relationship of Participants, **Trust**, Control of Functionality.	Five options: No DLT, not ready for DLT applications, further research needed, private DLT, public DLT.
[e]	Wessling et al. (2018)	Four Steps	Step 1: Identify participants.Step 2: **Trust** relations. Step 3: Interactions.	Step 4: Derive system architecture by overlaying trust and interactions.
[f]	Wust and Gervais (2018)	Sequential Framework	Six questions related to: Database Type, Participants Known & **Trusted**, Alignment of Interests, Need for Public Verifiability.	Four options: No DLT, private permissioned DLT, public permissioned DLT, permissionless DLT.
[g]	Hunhevicz and Hall (2019)	Mapping Based on Proxy	Three questions to determine the proxy "level of **trust**" in a use case. Table with fundamental properties of the DLT design options.	Four options: Fully centralized, private DLT, public permissioned DLT, public permissionless DLT.
[h]	Li et al. (2019a)	Sequential Framework	14 questions: a combination of Peck (2017) and Rangaswami et al. (2018).	Five options as in Rangaswami et al. (2018).

Table 2.5.: DLT decision frameworks and their different approaches to determine the right DLT design option.

2.4. A Decision Framework for DLT Design Options in Construction

2.4.1. Review of Existing Frameworks

Decision frameworks for DLT aim to guide users to the best-suited DLT design option for their use case in a structured way. Overall, many factors can be considered with a large solution space. This is aggravated by the fact that the technical landscape of DLT is fast moving and changing. However, some contributions already dealt with this question. Seven sources were identified (Table 2.5) and analyzed regarding their approach.

2.4.2. Proposed Stages for Construction Decision Framework

An integrated framework was created pictured in Figure 2.2, combining the analyzed approaches (Table 2.5). The most frequent connection between the analyzed framework was the consideration of trust as a criteria to decide on a DLT. Therefore, the authors base the main idea of the framework on the approach of Hunhevicz and Hall (2019). An assessment of the trust relations in a use cases is made according to the fundamental properties needed by the DLT design option. This leads to an optimization of the chosen solution regarding the performance of the system, while ensuring that the chosen DLT option actually provides the needed properties. Wessling et al. (2018) also follow this procedure; participants and interactions are determined first and then the network architecture is designed. For the more detailed structure of the framework the approach of Wust and Gervais (2018) is used for two reasons. First, the framework is aligned with the chosen approach to assess first the fundamental properties needed for a use case (Stage 1 – Do you need a DLT?). Second, it is the most extensive in terms of outputs of DLT design options (Stage 2 – which DLT design option?). Each question or evaluation step of the other frameworks were cross-compared and the framework of Wust and Gervais (2018) was modified where chosen appropriate. Modifications include the addition of question 4, renaming question 7 & 8, and adding a third stage to consider other important, mostly technical constraints (see Figure 2.2). To be complete with the introduced DLT design options (see Table 2.4), the private permissionless DLT option was added by the authors including question 7 and 9 (see Figure 2.2). This was not considered by any other framework reviewed (Table 2.5). The detailed reasoning and sources are given in the explanations below.

Stage 1: Do You Need DLT?

The first stage intends to evaluate whether DLT is needed or no/another database is better suited. It is based on the framework from Wust and Gervais (2018) with slight modifications, using its three more fine-grained questions instead of just one general question whether another database can be used (as proposed by the frameworks in Table 2.5, [d], [h]). In addition, question 4 was added from the frameworks of Rangaswami et al. (2018) and Li et al. (2019a), and is in line with the question from Xu et al. (2017) whether a trusted authority can be decentralized.

1. "Do you need to store state?" If storing state is not a requirement, a database is not needed (Sources: Table 2.5 [b], [f]).

2. "Are there multiple writers?" Without multiple writers requiring shared write access, a regular database provides better performance (Sources: Table 2.5 [d], [f], [h]).

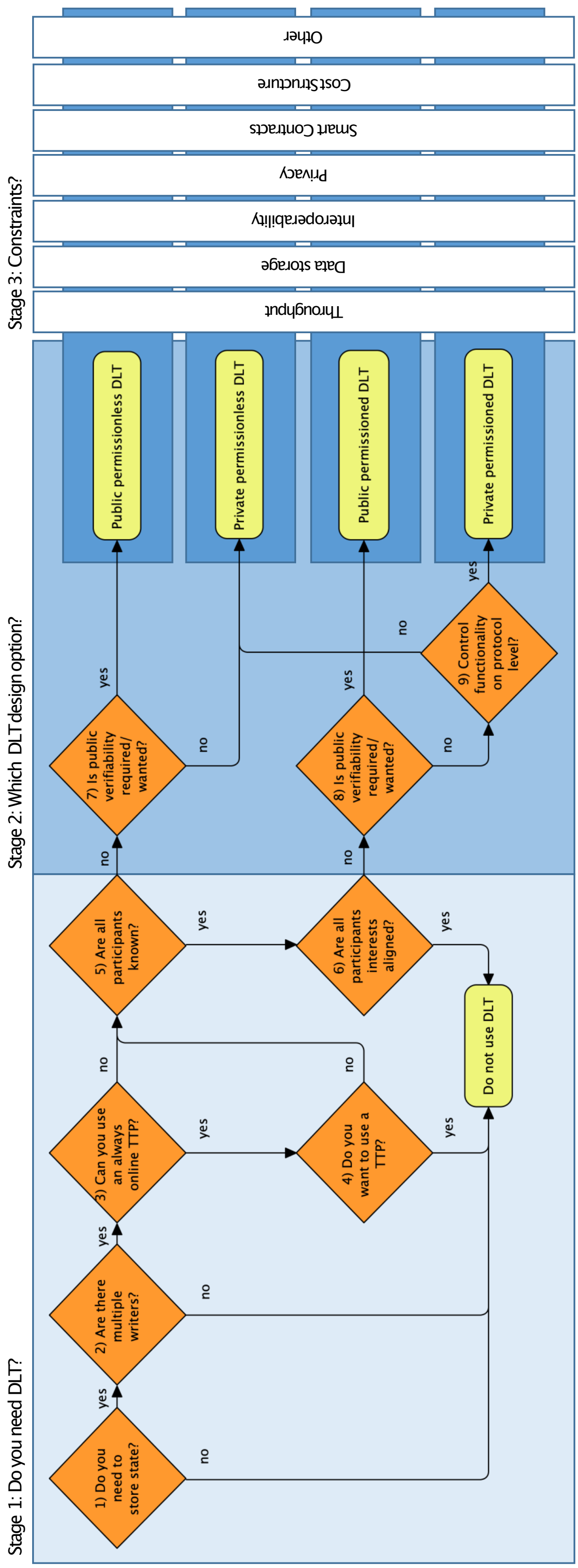

Figure 2.2.: Framework to decide for a DTL design option based on their fundamental properties in three stages (TTP = trusted third party).

3. "Are all participants interests aligned?" If the participants are known, but interests are not aligned, a permissioned system offers better performance (Source: Table 2.5 [f]).

4. "Do you want to use a TTP?" Other reasons such as avoiding intermediaries might be more important than better performance. (Sources: Table 2.5 [c], [d], [h]).

After question 4), the relationship of the involved participants and their trust setup needs to be assessed with question 5) and 6), asking whether participants are known and whether their interests are aligned. If these two question can be answered with "yes", DLT is not needed. Some questions that appeared in the analyzed frameworks were not considered, since it is already covered by one of the above questions or it is not a finite criteria to use DLT. These are: "Use case deals with digital assets?" (Table 2.5 [d], [h]), "Permanent record wanted?" (Table 2.5 [d], [h]), "Manages contractual or value exchange?" (Table 2.5 [d], [h]).

Stage 2: What DLT Design?

Stage 2 of the framework evaluates the best suited DLT design option for a use case. Notably, all analyzed sources (Table 2.5) mention the trust setup of the participants to decide for a certain DLT design option. As discussed previously (chapter 3.2), DLT can be seen as a mean to manage missing trust relations in a use case through the implied fundamental properties (Table 2.4). The reviewed frameworks vary in their approach to trust. Peck (2017) and Wust and Gervais (2018) (Table 2.5 [a], [f]) only ask whether the parties are trusted and leave to the reader what trust means. Rangaswami et al. (2018), Hunhevicz and Hall (2019) and Li et al. (2019a) (Table 2.5 [d], [g], [h]) split it into two questions asking whether contributors are known (which is a separate question also in Wust and Gervais (2018)), and if there interests are aligned. Wust and Gervais (2018) further links the two questions to different DLT design options by relating them to write and read operations on the DLT. Finally, the approach of Wust and Gervais (2018) was used with slightly reformulated questions taken from the other frameworks. First, it is investigated whether a permissioned or a permissionless system is better suited:

5. "Are all participants known?" If not, a permissionless DLT is suited, since the system allows everyone to join the network and write transactions. (Sources: Table 2.5 [f]).

6. "Are all participants interest aligned?" If the participants are known, but interests are not aligned, a permissioned system offers better performance. (Sources: Table 2.5 [f])

Next, whether a public or private DLT is better suited:

7./8. "Is public verifiability required/wanted?" Public DLT allow everyone to see transactions in the ledger, private DLT have permissions on the visibility and accessibility of data. (Sources: Table 2.5 [f]).

Since data can be kept private in both private permissioned and private permissionless DLT, the main difference is the added control on the protocol level in the first. Private permissioned DLT need to be run as an own network with all necessary infrastructure. If this is not needed, using a private permissionless DLT could be considered, since the network already exists and can be joined setting up a node. Therefore, a question whether participants need to control functionality on the protocol level was included as proposed by some of the frameworks:

9. "Control functionality on protocol level?" Private permissionless could be an alternative to private permissioned networks if control on protocol level is not needed. (Sources: Table 2.5 [b], [d], [h]).

Stage 3: Constraints?

The framework in stage 1 and 2 is based on the assumption that a DLT design option should be chosen based on the needed fundamental properties in a use case, which are in general inversely related to the performance of a DLT (see Table 2.4). This approach assumes that performance should be optimized. It

Throughput	Throughput is an important constraint for DLT applications and is known to be a limitation for certain DLT design options. Throughput is generally contradicting decentralization of DLT. More centralized systems offer better performance. Next to variations on the protocol layer (such as the data structure, ledger type, and consensus protocols), possible solutions are sharding or side-chains (see Section 2.3.1). If off-chain transaction are anchored to an existing DLT, they are referred to as 2nd layer solutions. Examples are the plasma side-chain for Ethereum (Poon and Buterin, 2017), or the Lightning state channels for Bitcoin (Poon and Dryja, 2016).
Data Storage	Large data storage on-chain can be costly and bloat up the chain. Non-transactional data storage could be saved off-chain and linked to the DLT. This decision were to store data should be considered before selecting a DLT design option (Xu et al., 2017). Some options for decentralized off-chain data storage already exist (e.g. IPFS (Benet, 2014), or bigchainDB (BigchainDB GmbH, 2018)).
Interoperability	Connection of the DLT with other parts of the technology stack (Web3 Hub, 2019) is very important for successful use cases. DLT either have no interoperability, explicit implemented tools to allow for interoperability or an implicit interoperability by connecting via smart contract to any API tool or interface (Tasca and Tessone, 2017). This interoperability also involves connectivity to "oracles". Entries on the DLT do not verify the correctness of the data itself, it just promises that data cannot be altered. To securely bring data onto the ledger, so-called "oracles" are needed (Xu et al., 2016). This can be human manual data input or data from sensors or third-party services.
Privacy	Privacy is an important constraint. Businesses might not want to share data on public ledgers, or GDPR protections do not allow to make certain data publicly available. On-chain encryption can be an option (see Section 2.3.1), but is sometimes also not a solution, since smart contracts cannot read and act upon encrypted information. Private permissionless systems might allow for more flexibility in this regard.
Smart Contracts	If a use case relies on the use of smart contracts for automation or tokenization, the chosen DLT design should support computation on its application layer. In the future their might be also the possibility to add smart contracts retrospectively to a DLT that does currently not support smart contracts (e.g. as proposed in Wüst et al. (2019)).
Cost Structure	An existing DLT usually involves fees to pay for transactions. In contrast, a private network involves the initial investment costs of servers and the overhead costs in running the network, but often involves no transaction fees. Dependent on the chosen DLT design option, cost and capital structure might differ and affect the decision for a certain DLT design option.

Table 2.6.: Proposed constraint dimensions for stage 3 in the framework.

means that a better performing DLT will be chosen, if the higher fundamental properties of DLT are not required. This decision is in the end directly related to the security of the system. More decentralized, public systems protected by strong consensus mechanisms allow for high security of data without the need to trust an intermediary (see section 2.3.2). Choosing more permissioned systems might bring other benefits (e.g. higher throughput), but compromise the fundamental properties of the system (less security).

Having said that, the decision might shift to another DLT design option, if more importance on other factors is placed. Therefore, stage 3 is introduced in the framework to assess other constraints. For example, the frameworks of Rangaswami et al. (2018) and Li et al. (2019a) (Sources: Table 2.5 [d], [h]) have limited throughput and storage of large amounts of non-transactional data as a question at the beginning, excluding use cases from using DLT if this holds true. In contrast, the proposed framework (Figure 2.2) analyses first if DLT is suited for the use case and investigates then in stage 3 whether there are constraints that are problematic for a use case. This is proposed because of the following reasons:

- Constraints, especially technological ones, are subjective to fast progress and change. A framework including them early in the evaluation is likely to be outdated soon.
- The proposed constraints in stage 3 can be adapted based on the use case, leading to a flexible framework.
- There is an emerging ecosystem around DLT, where DLT is seen as only part of the bigger technology stack. This will increase the possible solution space, where some limitations of DLT can be solved through alternative technologies interacting with it.

In Table 2.6, six constraint dimensions that could be considered for a final DLT solution are proposed. They are partially based on the technical considerations in the framework of Xu et al. (2017) and other reviewed literature and do not claim to be complete. Hence, a dimension "Other" to account for any constraint relevant to a use case not captured by the six dimensions is included. Often, to have all benefits in one system is not possible and compromises need to be made based on the use case requirements.

2.5. Analysis of Use Cases

Having identified the categories based on use-case clustering (Table 2.2), they are analyzed regarding suited DLT design options based on the framework introduced in Figure 2.2. The analysis was performed by the authors, following the rational of the framework by simulating and assuming possible use case constellations. Since the use cases are often described on a high level, sometimes multiple design options could be appropriate, dependent on the final constellation and relationships of the participants. In Figure 2.3, the nine combinations leading to a certain DLT design option after applying the framework to the analyzed use cases are pictured. Table 2.7 shows then the results for each use case after stage 1 and 2 of the framework. In the following sections, the analysis is discussed in more detail, going through the three stages of the introduced framework.

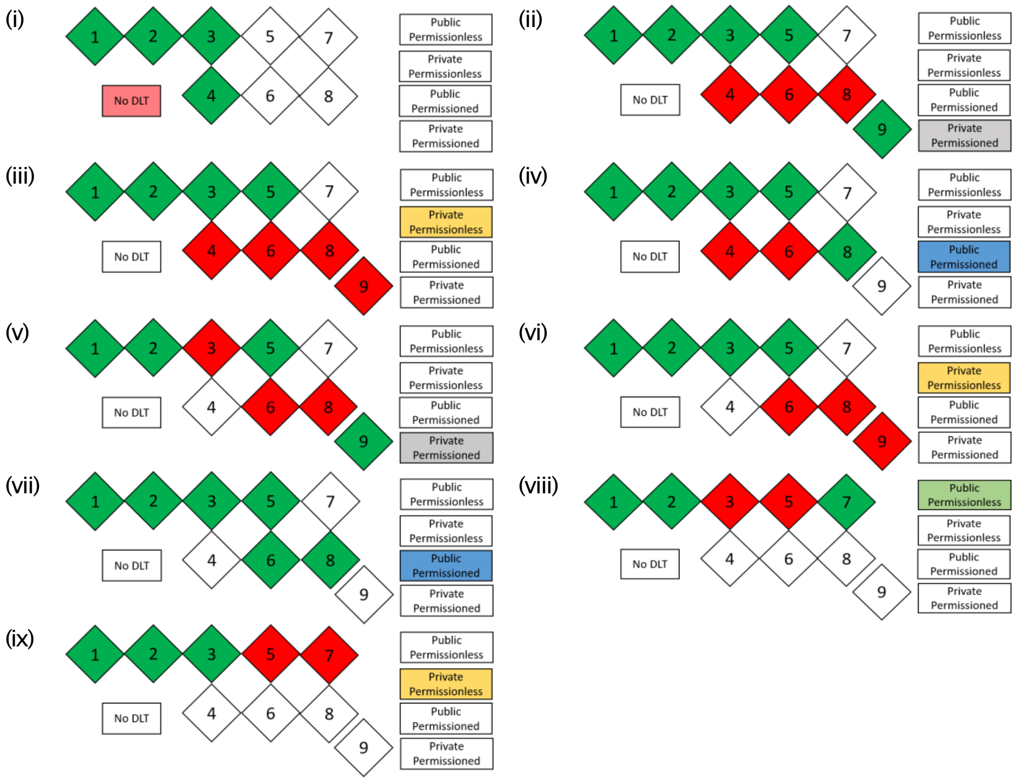

Figure 2.3.: Possible combinations for the analyzed use cases after stage 1 & 2 in the framework (Figure 2.2). Each rectangle stands for the respective question (1-9, see Figure 2.2), red for "no", and green for "yes".

2.5.1. Stage 1 - Do You Need DLT?

All analyzed use cases need to store state and involve multiple writers (Figure 2.2, Question 1 & 2). Question 3 then asks whether an always online TTP can be used. This is definitely possible for many of the described use cases, especially for category 1 (internal use for administrative purposes), category 3 (immutable record of transaction), and category 4 (immutable record of assets/ownership). Also use case 5.2 (shared account & insurances) could make use of a third party operating this service. As soon as a TTP is possible, using DLT is not needed. However, there might be good reasons to still use DLT, such as reduced costs without a TPP or avoiding control by a TTP as an intermediary. Furthermore, the size and complexity of a solution might favor a decentralized network structure using DLT, e.g. in the case of supply chain tracking (Table 2.7, use case 3.3). Hence, if DLT seems desirable despite the possibility of having a TTP, question 4 (Figure 2.2, "Do you want to use a TTP?") can be answered with "no".

The framework then leads to the questions assessing the relationship of the involved participants, in particular whether they are known (Figure 2.2, Question 5) and whether their interests are aligned (Figure 2.2, Question 6). In the analyzed construction use cases, participants are generally known if a TTP is possible, so question 5 can always be answered with "yes". If also question 6 (interests not aligned) can be affirmed, the framework suggests to not use DLT. This acts as a fallback mechanism, even though not using a TTP was wanted (Figure 2.2, Question 4), since the drawbacks of using a DLT (in terms of performance, cost, or other) is most likely not justified. Since the exact relationship of participants in the analyzed use cases was in general not described and at least a non-alignment of interests was possible, this combination was not considered in Figure 2.3 and Table 2.7.

For some use cases a TTP is not possible, directly leading to the evaluation of relationships between the participants (Figure 2.2, Question 5 & 6). This applied to use cases that rely on some functionality of a DLT, such as the payment in cryptocurrencies (Table 2.7, use case 5.1 & 5.3) or the decentralized characteristics of the solution (Table 2.7, categories 6 & 7). These are also use cases that do not already exist in construction, but would be new solutions enabled through DLT.

2.5.2. Stage 2 – Which DLT Design Option?

If a DLT is a suited solution after stage 1, the final DLT design option depends on whether the starting point for the assessment is that participants are unknown (Figure 2.2, Question 5) or interests are not aligned (Figure 2.2, Question 6). If participants are known but interests not aligned (mostly the case if a TTP is possible), three options ii), iii), and iv) in Figure 2.3 need to be considered. If participants are unknown (mostly the case if a TTP is not possible), both question 5 & 6 appear as starting points, depending on the specific relationship of participants. Often, the use cases were not described in enough detail, so both options had to be considered, leading to five possible combinations v) to ix) in Figure 2.3.

As a next step, question 7 & 8 (Figure 2.2) filter use cases where public verifiability is required or wanted. E.g. for use case 2.4 (Automated Data/Information Sharing), most likely no public verifiability is wanted, since the documents can contain sensitive information. A similar situation is use case 1.1 (Notarization and Synchronization of Documents), where documents are only shared internally. In contrast, use case category 4 (Immutable Record of Assets/Ownership) most likely requires public verifiability to ensure trust and transparency to outside parties. For use case 4.1 (Record of Ownership in BIM (IP-Rights)), it could be both depending on the needs of the involved parties, since ownerships in a BIM model could also be managed internally. Similarly, for all the other use cases were a TTP is possible, public verifiability could be either wanted or not depending on the details of the use case. Looking at use cases were it was assessed that a TTP is not possible, it is clear that use case 5.1 (Payment in Cryptocurrencies) and 6.1 (Decentralized Market Places for Products and Services) both need public verifiability to be trustworthy. For all other use cases, it cannot be finally assessed based on the provided information whether public verifiability is needed or not.

The last question in stage 2 assesses if control of functionality on the protocol level is required (Figure 2.2, Question 9) in case of a private DLT option. This highly depends on the parties involved in a use case and their preferences in how to set up a private DLT. Therefore, always both combinations (Figure 2.3, ii/iii & v/vi) were marked as possible options (Table 2.7).

2.5.3. Stage 3 – Constraints?

In stage 3 additional constraints relevant to the final DLT design options should be discussed (see Figure 2.2). Since this is an assessment based on the final relationship of involved parties in the specific use case and the proposed DLT design option resulting from stage 2, it was not possible to facilitate specific discussions without further specification of the use cases. An exemplary discussion around some possible constraints is provided to clarify the procedure for use case category 2. A detailed assessment of constraints would need to be conducted for each

		No DLT	DLT (TTP possible)			DLT (TTP not possible)				
	Use Case Category	**i**	**ii**	**iii**	**iv**	**v**	**vi**	**vii**	**viii**	**ix**
1	Internal Use for Administrative Processes									
1.1	Notarization and Synchronization of Documents	×	×	×						
2	Transaction Automation with Smart Contracts									
2.1	Triggering Payments	×	×	×	×					
2.2	Triggering Contract Deliverable	×	×	×	×					
2.3	Self-executing Contract Administration	×	×	×	×					
2.4	Automated Data/Information Sharing	×	×	×						
2.5	Automated Code Compliance Checking	×	×	×	×					
3	Immutable Record of Transactions									
3.1	Timestamping of ”Value” Transactions	×	×	×	×					
3.2	Record of Changes in Digital Models (BIM)	×	×	×	×					
3.3	Tracking of Supply Chain Logistics	×	×	×	×					
3.4	Tracking of Project Progress and Worked Hours	×	×	×	×					
3.5	Record of Maintenance and Operations Data	×	×	×	×					
3.6	Tracking of Health & Safety Incidents	×	×	×	×					
3.7	Verification of Installation Tasks	×	×	×	×					
3.8	Record/Notarization for Regulation and Compliance	×	×	×	×					
4	Immutable Record of Assets/Ownership									
4.1	Record of Ownership in BIM (IP-Rights)	×	×	×	×					
4.2	Record of Ownership for Physical Assets (e.g. Property)	×			×					
4.3	Managing Identities for Reputation (People, Contractors)	×			×					
4.4	Material & Product Passports (Provenance and Properties)	×			×					
5	Coins/Tokens as Payment or Incentive Scheme									
5.1	Payment in Cryptocurrencies								×	
5.2	Shared Account & Insurances	×	×	×	×					
5.3	Incentives Over the Whole Building-Lifecycle					×	×	×	×	×
6	Decentralized Applications (dApps)									
6.1	Decentralized Marketplaces for Products and Services							×	×	
6.2	Decentralized Common Data Environments (CDE)					×	×	×	×	×
7	Decentralized Autonomous Organizations (DAOs)									
7.1	Automated Building Maintenance Systems					×	×	×	×	×

Table 2.7.: Results of applying stage 1 and 2 of the framework (Figure 2.2) to the identified use cases (Table 2.2), leading to possible combinations pictured in Figure 2.3

final use case. If the proposed DLT design option after stage 2 cannot be realized, or other constraints are more important, another DLT option or no DLT might be chosen.

Example: Category 2 (Table 2.7, Transaction Automation between Stakeholders with Smart Contracts) needs to consider constraints related to smart contracts. First, the chosen DLT needs to support smart contracts on the application layer. If the purpose of a smart contract is to act on external state information in the ledger, a publicly verifiable system that replicates data on all nodes is needed (interoperability). Throughput might be an issue if many smart contract interactions are needed. Private DLT generally provide better performance. Alternatives would be to use 2nd layer solutions for public DLT. Regarding privacy, on-chain encryption in public systems would in most cases not allow a smart contract to execute logic based on that data. Private DLT would still allow for privacy, but mostly come with less security. And since all DLT design options are possible, preferences regarding the different cost structures should be considered.

2.6. Summary and Discussion

This section was structured according to the three main contributions of this paper: 1) the categorization of use cases in construction, 2) the introduced framework to choose a DLT design option for a specific use case, and 3) the analysis of the reviewed use cases with the proposed framework.

2.6.1. Use Case Categorization

Contribution

DLT use cases in construction were summarized from state-of-the art literature, extending the work of Hunhevicz and Hall (2019). A more detailed assessment with the new framework allowed the identification of an additional use case category and some relocations of use cases to another category. The reviewed use cases show the broad potential application field of DLT use cases in construction, of which many promise improvements regarding transparency and process optimizations through automation and disintermediation. While not identifying many new use cases compared to reviews in past literature (e.g. in Li et al. (2019a)), the categorization according to specific value propositions of DLT can lead to a more structured thinking and better overview of the commonalities and differences between construction DLT use cases. This can be particularly helpful in the decision process when trying to implement the use case with the best-suited DLT design option.

Limitations

For the purpose of this paper, even though trying to include all relevant literature, no systematic literature review was conducted. Therefore, there is no claim in being complete with the identified use cases. Moreover, because of the early state of research, it is expected that the use case categorization is subject to change while the use cases and technology evolve. If needed, the use cases and categories should be revised or extended.

Future Research

Considering the early stage of DLT research in construction and its manifold applications, there is potential to identify additional and innovative use cases of DLT in construction. The authors expect that more use cases will be introduced as a refinement or combination of different use cases. Especially the categories

6 (Table 2.2, Dapp) and 7 (Table 2.2, DAO) will likely grow in importance as a combination and extension of use cases. E.g. Li et al. (2019a) mention single shared access BIM models as a combination of use case 3.2 (Table 2.2, record of changes in BIM), 4.1 (Table 2.2, record of ownership in BIM), and 6.3 (Table 2.2, Decentralized data storage). Having said that, there seems to be a tendency to apply DLT to existing processes in construction, which raises the question about the actual benefits in comparison. There is need to move beyond the theorization of use cases towards prototypes and case studies to further advance the research in this field. Either to quantitatively compare the existing processes with and without an implementation of DLT, or to showcase and assess the benefit and change to construction processes through innovative and new use cases enabled by DLT.

2.6.2. Decision Framework for DLT Design Options

Contribution

A framework was introduced to link the use cases to DLT design options. Eight existing frameworks were reviewed and cross-compared (see Table 2.5). This allowed to supplement the various frameworks with aspects not considered previously, while prioritizing points that were considered more often. The final logic of the framework is based on what fundamental properties of a DLT design option are required for a given use case, optimizing the performance of the chosen DLT design option (stage 1 & 2). Since the different DLT design options always compromise one or the other aspect, it is important to consider constraints in stage 3. This allows to readjust the technical solution to factors that might be limiting or of higher importance for certain use cases. In contrast to the reviewed frameworks that also consider some technical constraints (e.g. Rangaswami et al. (2018) and Li et al. (2019a)), the proposed framework determines first whether DLT would be suited based on the fundamental properties and only then assesses various constraints. The authors expect that this will lead to longer validity of the framework, since the fundamental properties of DLT are not expected to change as fast as technical constraints. Finally, in addition to the underlying framework of Wust and Gervais (2018), the authors included also the emerging design option of private permissionless DLT to be complete in the currently available DLT design options.

Limitations

The proposed framework is based on the reviewed frameworks in Table 2.5, highlighting the theoretical connection between the trust relationships of participants in a use case and the varying fundamental properties of DLT design options. This theoretical connection should be verified with future practical implementation. Furthermore, while stage 1 and 2 guide the reader through the different aspects without much knowledge about DLT, a potential limitation is that stage 3 requires in-depth technical knowledge of the user to assess the different constraints.

Future Research

Future research should examine how to create more extensive frameworks to decide for a certain DLT design option. One potential starting point could be a structured decision tree for stage 3 (similar to stage 1 and 2). Furthermore, as more combined DLT use cases emerge (e.g. within one construction project), the question arises how to deal with the potentially different technical prerequisites between them. For that, emerging hybrid solutions combining different DLT design options could be considered in the framework. Having said that, some hybrid solutions might be categorized in the private permissionless DLT design option and might therefore already be implicitly considered. Moreover, the emerging complementary technology stack (see e.g. Web3 Hub (2019)) together with existing software solutions used in construction could be included when searching for the best possible technical solutions for a use case. Finally, once a DLT design option was chosen with the framework, a product in the market needs to be selected for implementation. Future research should list and look at these products and map them to the different DLT design options, highlighting also specific constraints.

2.6.3. Use Case Analysis

Contribution

The introduced framework was used to classify DLT design options of proposed use cases in construction. The main contribution here is that the assessment can hint whether or not DLT would be a good solution for use cases in construction based on the need for a trusted solution, and if true, which specific DLT design option should be chosen.

Regarding whether DLT would be a good solution, the analysis of the use cases with the framework indicate at least that the fundamental properties provided by DLT could be beneficial for the described use cases. Having said that, for many of the described use case a trusted third party (TTP) would be possible to achieve the same result. This means a DLT would not necessarily be needed. In general, this was found to be true if DLT should be applied to existing processes. This does not mean there are no benefits by using DLT in these cases. It is then up to the more detailed assessment whether the savings from not having a TTP justify the cost of having a DLT (i.e. does the DLT really add additional benefits to a use case?). Only few of the proposed use cases actually require the use of DLT. Often, they are described even more high level than the use of DLT in existing solutions. Overall, despite a theoretical alignment of DLT fundamental properties and use case requirements, it is currently not possible to assess if and to what extent DLT use cases benefit construction. It seems that an answer to “Do you need a blockchain (or another type of DLT) in construction?” can only be given once prototypes have been built and the benefits have been validated through case studies.

Regarding the best-suited DLT design options, the framework results in more than one possible option for most of the considered use cases. This is likely due to the fact that use cases are not described in enough detail. In a specific implementation of DLT for construction, the best-suited DLT design option will be dependent on the final constellation of participants. Having said that, there is some consistency of possible DLT design options recognizable within the categories.

Limitations

Even though the performed use case analysis can help to understand potential DLT design options for individual use cases, the picture is somewhat diluted and needs further refinement. This is mostly due to the fact that the participants’ trust relationship was mostly hard to assess with the provided use case descriptions. Hunhevicz and Hall (2019) expected that the different use case categories will have an increasing need towards higher fundamental properties with decreasing level of trust. Looking at the performed classification (Table 2.7), this relationship could not be clearly recognized. Multiple DLT design options are possible for most use cases without better specifications between the participant's relationships. Finally, the analysis was performed by the authors with the best of knowledge about the use case constellations and should be verified by construction industry experts and DLT domain experts.

Future Research

As mentioned in the limitations, most use cases do not describe the exact relationship of participants, which would be important to assess the best-suited DLT design option. Therefore, more in-depth analysis of use cases and the relationships of the participants is needed in future research for a more insightful analysis and classification of suited DLT design options. Moreover, there might be barriers for future use case implementation related to other socio-technical challenges that should be also carefully studied. A starting point for this could be the framework of implementation challenges by Li et al. (2019a) in four dimensions (technical, process, social, policy). Finally, the use case analysis is based on current processes in construction. Having a DLT solution in place could potentially change processes and the relationship of participating parties, which would lead to a different assessment using the framework (e.g. allowing unknown parties to participate in a construction process). Future research could try to incorporate and analyze these relationships.

2.7. Conclusion

This paper structured and assessed use cases in construction for blockchain and other types of distributed ledger technology (DLT) regarding their actual need for such a technical solution. For this, an overarching decision framework based on previous work was introduced to link use cases to four DLT design options according to the needed fundamental properties of a use case.

Indeed, many of the analyzed construction use cases could potentially profit from using DLT. However, most of the use cases applied DLT to existing processes, where a DLT is not necessarily required. In these cases, further investigation is needed whether the added value of having a DLT justifies its application. Only few proposals used DLT as a tool to enable innovative use cases that cannot be realized without DLT. For a better perspective on whether DLT can be overall beneficial for the construction industry, more in-depth analysis of the use cases is needed regarding their added value and socio-economic impacts, best trough prototypes and case studies. For that the different possible DLT design options should be considered, since the proposed use cases in construction seem to vary considerably in the constellation of trust relationship among participants. However, this was found to be challenging, since most use cases do not describe the exact relationship of participants, which would be important to assess the best-suited DLT design option. More in-depth analysis of use cases and the relationships of the participants is needed for a final assessment.

Nevertheless, the at least partial alignment of construction use cases with fundamental properties of DLT should encourage researchers and practitioners to further explore the topic. For that the use case clustering together with the introduced framework is expected to act as a valuable tool to think more interconnected between use cases in construction and DLT design options to advance the research in this field.

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

This chapter corresponds to the accepted book chapter:[1]

Hunhevicz, Jens, Theodoros Dounas, and Daniel M Hall (2022a). "The Promise of Blockchain for the Construction Industry: A Governance Lens". In: *Blockchain in Construction.* Springer. ISBN: 978-981-19-3758-3. DOI: 10.1007/978-981-19-3759-0_2. URL: https://link.springer.com/book/9789811937583.

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

[1]Please note, this is the author's version of the manuscript accepted in *Springer Nature*. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. The final publication will be available at https://www.springernature.com. When citing this chapter, please refer to the original article.

3.1. Introduction

One of the most exciting aspects of blockchain is that it is an institutional innovation with the potential to disrupt and substitute existing economic coordination (Davidson et al., 2018; Miscione et al., 2019). However, many ongoing research projects develop blockchain solutions to increase trust in existing processes. While these are valid and beneficial in the short term, they can miss the opportunity to redesign processes and systems to the full potential of this new technology.

Blockchain allows for the creation of new ecosystems, where the benefits from network effects and shared digital infrastructure do not come at the cost of increased market power and data access by platform operators (Catalini and Gans, 2020). This is achieved through blockchain governance, where cryptoeconomics incentivizes participants through the exchange and distribution of tokens to secure the network. Cryptoeconomics enables new forms of economic activity beyond existing forms of monetary incentives by taking into account both endogenic and exogenic system variables (Tan, 2020). This is a feature that might be particularly useful for more efficient means of coordination in the construction industry. Such new cryptoeconomic systems can be created by individuals for any economic system, independent of the traditional makers of economies (Brekke, 2021). Despite of this new opportunity to individually tailor coordination mechanisms for the construction industry, less thinking has been done to imagine implications on a longer time horizon.

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

3.2. Governance of Blockchains

First, it is important to understand that governance mechanisms are an inherent feature of blockchains. Therefore, this section outlines how governance of public permissionless blockchains such as Bitcoin (Nakamoto, 2008) enable the typical affordances associated with the technology for novel forms of economic coordination. However, we only explain these concepts on a high level. For the curious reader, there are many excellent publications available that give more technical details (Tasca and Tessone, 2019; Ballandies et al., 2021b).

3.2.1. The Three Technical Layers of a Blockchain Protocol

A blockchain consists of three main parts: a ledger to record transactions, the distribution of this ledger forming a network, and a governance layer that defines how participants interact with the ledger (Hunhevicz and Hall, 2020b). Together they form what is called the protocol layer of a blockchain (Figure 3.1).

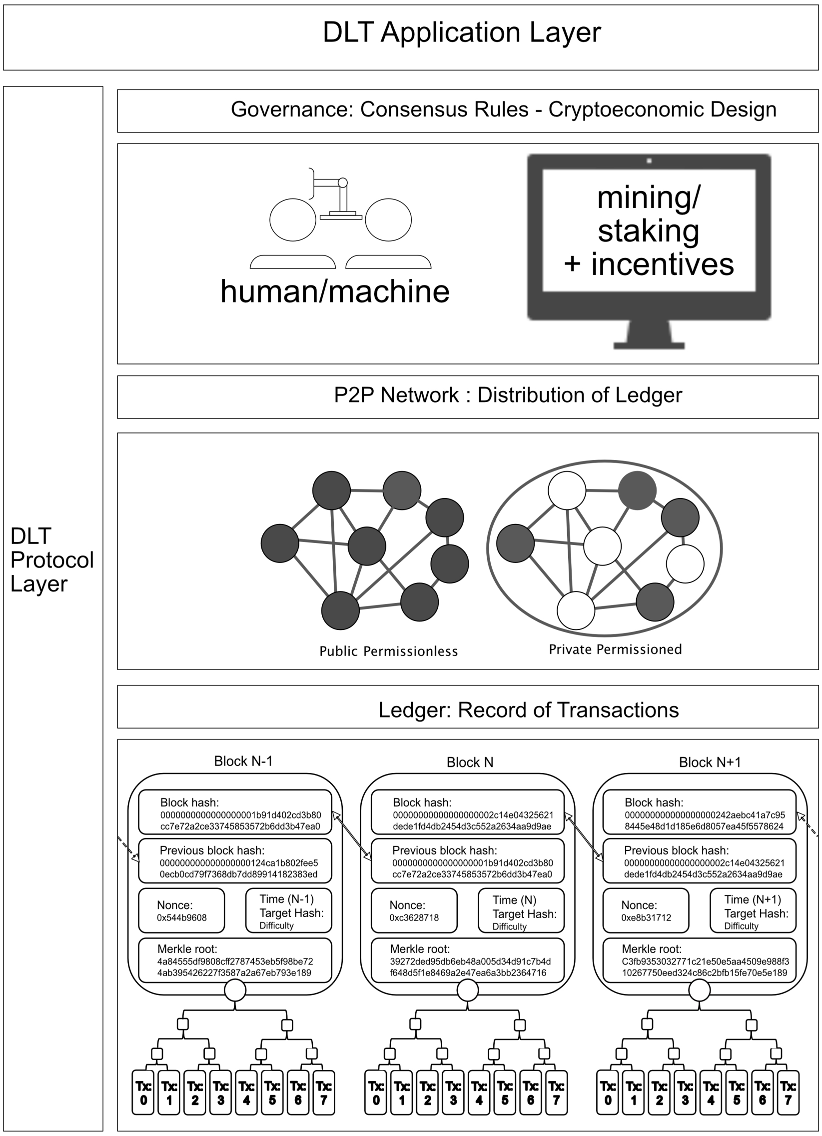

Figure 3.1.: The three technical layers of blockchain forming the protocol layer (P2P network figures adapted from Allessie et al. (2019)).

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

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

Finally, the real challenge is coordinating how nodes in the network validate, agree, and write transactions to the ledger without relying on centralized coordinators. This was solved for the first time with Bitcoin using a cryptoeconomic governance mechanism - the real innovation behind blockchain. On the protocol level of a blockchain, this governance process is called the consensus mechanism. In the specific case of Bitcoin, a mechanism called proof-of-work protects the network effectively from attacks (Gervais et al., 2016). A native coin, e.g. bitcoin in Bitcoin or ether in Ethereum, incentivizes participants to behave in the interest of the blockchain network through compensating nodes that correctly validate and add transactions. As long as the majority of these so-called miners are more profitable to behave honestly, the chain is protected.

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

3.2.2. Blockchain Affordances

When blockchains have a transparent ledger, run in a distributed network, and have working cryptoeconomic governance mechanisms, they build confidence (De Filippi et al., 2020) in the affordances typically associated with the technology:

Immutable P2P Transactions (Figure 3.2, [A1]) Transactions happen directly between users of the network. Services of third parties that previously enabled these functions are not needed anymore. This effect is sometimes referred to as “disintermediation”. The network inherently ensures trust between the users through the implemented consensus mechanisms. They check transaction compliance and ensure immutability. Transactions are very hard to alter once agreed and written to the ledger.

Transparency (Figure 3.2, [A2]) Transactions and data are visible to all participants in the network and can be verified for their integrity, meaning if they are still in the condition as initially written to the blockchain. Furthermore, the entire transaction history can be checked. Also, the underlying code is open source and can be verified by anyone.

Scalability (Figure 3.2, [A3]) Blockchain networks can be scaled to large decentralized networks that connect many users. This contributes to the robustness of the network and its trustworthiness since many independent participants (especially running nodes) reduce the possibility for a single point of failure and keep each other in check.

Logic (Smart Contracts) (Figure 3.2, [A4], [B2]) Smart contracts are composed of the logic of a prearranged agreement that can be encoded to interact with transactions on a blockchain network. Once deployed on the network, smart contracts execute automatically (anonymous and trustless) as soon as the defined conditions are met. The presence of smart contracts on a blockchain transforms it into a Turing complete state machine (Buterin, 2014). Smart contracts can be used to create autonomous workflows for any process that can be formalized into programmable rules. In essence, smart contracts encode custom rules on the blockchain. Often these are conditional statements that will execute when predefined network state conditions are met. Since the code runs on a blockchain, it will perform exactly as specified, with no intermediary stopping the process.

Incentives (Tokens) (Figure 3.2, [B1]) Smart contracts can also be used to create so–called tokens. Tokens represent value containers such as currencies, securities, utilities, or others (Mougayar, 2017; Ballandies, Dapp and Pournaras, 2021). Tokens can then be transferred among users or smart contracts to move value across the network. Thus, through tokens, it becomes possible to create incentive systems that influence network participants in their behavior.

3.2.3. A Short Excursion to Private Premissioned Blockchains

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

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

Sometimes institutions are enticed by some blockchain characteristics, but the envisioned applications conflict with other affordances of public permissionless blockchains. This is often because they want to apply blockchain to existing use cases or industry particularities that require restricted infrastructure control or data visibility for only a known group. Setting up a blockchain so that only this group can join the network and verify transactions results in what is called a *permissioned* blockchain. If the network only allows this group to see the transactions, it is referred to as a *private* blockchain. If the use case indeed needs one of these properties, private permissioned blockchains could be a suitable solution (Hunhevicz and Hall, 2020b).

Nevertheless, private permissioned blockchains replicate in some sense existing systems with their limitations and curtail possible new forms of economic coordination. This is because the rules and operation of the network are ensured and coordinated by known actors. Therefore, no cryptoeconomic governance is needed. This makes these networks typically faster than public permissionless blockchains[2]. It is also possible to launch smart contracts and tokens on private permissioned blockchains. However, such applications will always need to trust the operators of the network. Users must be confident that the operators will not shut down the system or that the system could be manipulated by a few actors (De Filippi et al., 2020). Of course, dependent on the number and diversity of stakeholders running the network, private blockchains can still be more trustworthy than traditional centralized platforms. In the end, the chosen system should reflect the requirements of a given use case by assessing whether and which blockchain is needed (Hunhevicz and Hall, 2020b).

3.3. Blockchain-Based Governance for New Economic Systems

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

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

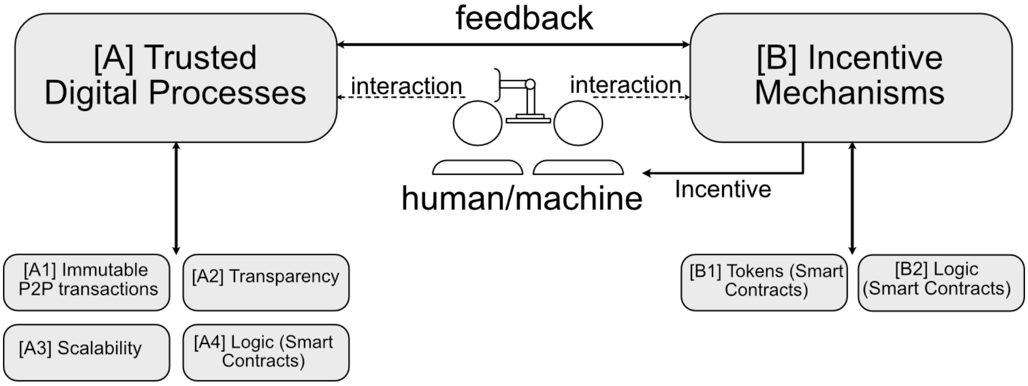

Figure 3.2.: Blockchain affordances allow to establish trusted digital processes [A] and incentive mechanisms [B] for decentralized governance mechanisms (adapted from Hunhevicz et al. (2020a)).

3.3.1. Trusted Digital Processes

The introduced affordances make the application of blockchain interesting for a wide selection of use cases. On the one hand, immutable P2P transactions (Figure 3.2, [A1]), transparency (Figure 3.2 [A2]), and scalability (Figure 3.2, [A3]) allow creating trusted digital processes to coordinate the global economic activity of actors in a decentralized way. Transactions can be conducted directly between parties and not subject to control by other actors (Figure 3.2, [A]). The simplest use case is transferring protocol native coins (e.g., bitcoin or ether) between users. However, other use cases can profit from reaching consensus about individual transactions at the system level. To implement more advanced logic on-chain, smart contracts (Figure 2.2, [A4]) can encode processes on the application layer for various purposes. Since blockchains identify network actors only through addresses, both humans and machines can trade with each other without the need to disclose their identity. The blockchain ensures confidence between pseudonymous (only address is known) actors to trade value peer-to-peer - facilitating decentralized market structures not controlled by anyone. For now, such decentralized applications (termed dApp's) are predominantly decentralized financial applications (termed DeFi) that replicate existing financial services without the need for intermediaries (Schär, 2020).

3.3.2. Incentive Mechanisms

Such trusted digital processes can be complemented with incentive mechanisms (Figure 3.2, [B]) that define new economic systems through the use of tokens (Figure 3.2, [B1]) and their associated system logic encoded with smart contracts (Figure 3.2, [B2]). With that it is possible to create economic activity on the application level, similar to how the underlying blockchain protocols use cryptoeconomics to incentivize the operation of their networks. Applications can create their own networks with comparable blockchain characteristics, without the need to run their own network infrastructure.

3.3.3. New Forms of Economic Activity

Overall, cryptoeconomic systems can provide an institutional infrastructure that facilitates a wide range of socio-economic interactions (Voshmgir and Zargham, 2019). Cryptoeconomic systems have the potential to disrupt and substitute existing economic coordination (Davidson et al., 2018; Miscione et al., 2019). They leverage the innovation of blockchain for trust-minimized social coordination to create new forms of economic activity beyond the processes we can facilitate nowadays. There is an ongoing exploration of what forms of economic activity can be supported or replaced through cryptoeconomic systems. Within this chapter, it is impossible to cover all aspects of this new and rapidly evolving research field. Instead, we focus on two often mentioned concepts that we find aligned with the challenges of the construction industry: crypto commons and DAOs.

Crypto Commons

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

CPRs are natural (e.g., forests, pastures, or fishing grounds) or man-made (e.g., irrigation systems or wiki libraries) resources, which are freely shared among many users (Ostrom, 1990). The tragedy of the commons occurs when users of a CPR "overuse", e.g. "overfish" in the case of fishing grounds, by appropriating resources at a higher than optimal rate in self-interested behavior, resulting in a downward spiral of total resource availability (Hardin, 1968). Historically, the common belief was that only centralized and top-down control can coordinate optimal resource appropriation, e.g. government interventions. More recent work pioneered by economist Elinor Ostrom (Ostrom et al., 1994; Ostrom, 2010, 2015) and others (Gardner et al., 1990) showed that local actors without a central authority could be more successful in sustaining the commons. This self-coordination of resource appropriation can be guided by governance design principles – referred to as the eight Ostrom principles. The Ostrom principles have been successfully used in many commons-based communities to craft effective governance rules without any top-down control (Cox et al., 2010). However, bottom-up coordination incurs a high cost of information exchange. It is tough to scale community governance based on the Ostrom principles to large and global systems (Ostrom et al., 1999).

Various scholars demonstrate how the governance of blockchain networks is very much aligned with the lens of CPR theory and the Ostrom principles (Shackelford and Myers, 2016; Werbach, 2020). Blockchains have been described as commons-based peer production of free and open-source software (Red, 2019). Consequently, blockchains can be seen as early evidence of successful scaling of real-world commons (software) on a global scale through new forms of bottom-up economic coordination.

Therefore, it is not surprising that emerging literature suggests blockchain as a tool to build applications that can scale real-world examples of commons (Fritsch et al., 2021). The potential lies in overcoming collective action problems by using blockchain's transparency and incentive systems to build bottom-up coordination. Because of their cryptoeconomic governance mechanisms, blockchains decrease the cost of information exchange through minimizing opportunism and uncertainty by combining transparency with cryptographic enforcement (Schmidt and Wagner, 2019; Machart and Samadi, 2020). The adoption of blockchain-based transparent decision-making procedures and decentralized incentive systems for community governance in commons could help avoid the tragedy of the commons (Bollier, 2015). The Ostrom principles could guide such applications by encoding respective governance rules (Rozas et al., 2021a). With that blockchain could create networked governance to scale real-world commons, similar to how the stock market enabled corporations to scale (Maples, 2018). Such crypto commons could allow new types of value creation with crypto assets rather than shares of stock, contributors rather than employees, and decentralized collaboration rather than centralized ownership (Maples, 2018). Overall, collective action use cases might be more efficiently governed by crypto commons rather than existing forms of centralized and top-down forms of coordination.

Decentralized Autonomous Organization (DAO)

One of the most interesting new organizational designs proposed to leverage cryptoeconomic coordination on the blockchain is called a decentralized autonomous organization (DAO). A DAO is a blockchain-powered organization that can run without any central authority (Wang and Krishnamachari, 2019). The decentralized governance of a DAO is facilitated by a set of self-executing rules deployed with smart contracts on a blockchain to enable self-coordination and governance of people (Hassan and De Filippi, 2021). By defining governance mechanisms in smart contracts, the DAO can self-operate, self-govern, and self-evolve (Wang and Krishnamachari, 2019). It is essential to note the difference between a DAO and operations that use artificial intelligence (AI) (Vitalik Buterin, 2014). An AI system is often designed to make internal autonomous decisions. By contrast, a DAO defines its own coordination rules and governance system. In this way, it can make decisions based on the external input of participating actors. These actors only need to own a recognized address, so the actors can be machines, another DAO, or a distributed group of human decision-makers.

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

Protocol-level DAOs are permissionless blockchains governed by code to coordinate stakeholders. Early versions of blockchain such as Bitcoin and Ethereum encode coordination mechanisms to create and protect the blockchain through cryptoeconomics. However, these blockchains only implement off-chain governance mechanisms for decision-making (Machart and Samadi, 2020). Newer blockchains like Decred, Polkadot, or Tezos attempt to also implement on-chain governance mechanisms for decision making (Machart and Samadi, 2020). These decisions can include how to evolve the protocol or on what to spend the network-owned treasury. With that protocol-level DAOs increase their independence from external funding sources and decision-makers.

Application-level DAOs live on a blockchain encoding their governance rules with smart contracts. The first-ever application DAO was likely “the DAO” on Ethereum, which resulted in a catastrophic failure after a successful attack had stolen funds worth millions of US dollars (Mehar et al., 2019). Learning from this failure, new application-level DAOs are often based on frameworks like Aragon or The DAO stack (Faqir-Rhazoui et al., 2021). They provide reviewed code building blocks that can be assembled to reduce risk of similar fates as in “the DAO”.

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

Finally, DAOs are not decoupled from the previous idea of scaling common pool resource scenarios. A DAO can be used to set up coordination mechanisms so that a community can co-create the respective organizational system in line with ideas

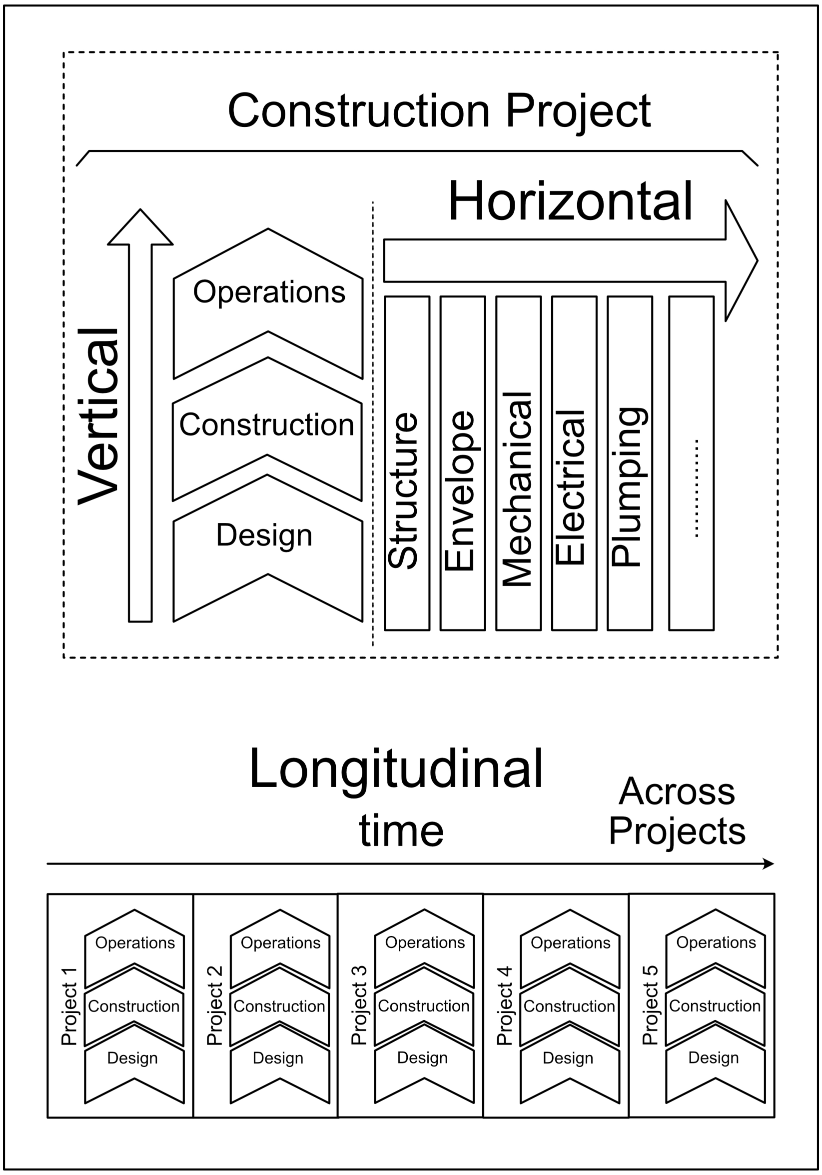

Figure 3.3.: Three degrees of fragmentation in the construction industry (adapted from Sheffer (2011)).

of the sharing economy or CPR theory. Once the experimentation with DAOs moves past replicating existing corporate structures, the ideas of crypto commons and DAOs eventually blend. In the long run, DAOs might shift power structures away from centralized corporations towards user communities that decide on their own system's purpose and governance rules, fundamentally changing the structure and dynamics of organizations (Jacobo-Romero and Freitas, 2021).

3.4. Cryptoeconomic Governance for the Construction Industry

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

3.4.1. Lens 1 - Cryptoeconomic Incentives to Embrace Fragmentation

The construction industry has been described with three dimensions of fragmentation: horizontal, vertical, and longitudinal fragmentation (Sheffer, 2011), as depicted in Figure 3.3. Vertical fragmentation occurs between project phases (Howard et al., 1989). Each phase has a different set of stakeholders, decision-makers, and values. This creates a 'broken agency' - where involved parties will engage in self-interested behavior and pass costs off to others in the supply chain in a subsequent phase (Henisz et al., 2012). Horizontal fragmentation occurs in the trade-by-trade competitive bidding environment of traditional project deliveries. Because it is difficult to cross-subsidize changes across trades, globally-optimal innovations cannot compete with traditional solutions that are more cost-effective from the perspective of a particular building element or phase (Hall et al., 2018). Longitudinal fragmentation occurs when project teams disband at the end of projects and select future projects by competitive bidding. They are thus unlikely to work with the same set of partner firms on future projects. Consequently, team members lose tacit knowledge about how to work together effectively (Dubois and Gadde, 2002b), and organizations cannot build long term trusting relationships across firm boundaries.

The prevailing fragmented structure is one of the reasons why the uptake of many systemic innovations such as BIM is challenging in the construction industry (Miettinen and Paavola, 2014; Papadonikolaki, 2018). Without addressing the structural issues related to the construction industry, the immense potential of digitalization will not yield better collaborations (Whyte and Hartmann, 2017). New digital technologies must be integrated with adaptations in management, contracts and collaboration forms (Barbosa et al., 2017). Blockchain can build new incentive systems to influence human behavior based on trusted digital processes (see Figure 3.2). Cryptoeconomic incentives are promising to align stakeholders across phases, trades, and projects to reduce the impact of fragmentation.

The idea to incentivize better collaboration in a construction project is not new. For example, integrated project delivery (IPD) is a project delivery model that creates inter-organizational governance structures to jointly manage complex projects across firm boundaries (Hall, Algiers and Levitt, 2018). While some project delivery models use only informal mechanisms of collaboration (Larson, 1995; Bygballe et al., 2015; Hall et al., 2018), the current trend has been the development of formalized incentive structures through the use of multi-party relational contracts. Project clients, contractors, and planners collaborate on equal standing with their own decision-making power and autonomy (Levitt, 2011), yet are incentivized to make decisions for the collective good. Target Value Design and Shared Risk Rewards are examples of such performance-oriented bottom-up incentive structures (Lee et al., 2010; Zimina et al., 2012). Cryptoeconomic governance could improve and extend such incentive structures with tokenization and smart legal contracts. In the longer term, embracing cryptoeconomic incentives could slowly reduce the negative impacts of fragmentation without the need to integrate the value chain through centralized approaches.

3.4.2. Lens 2 - Guided Self-Organization to Manage a Complex Construction Industry

Complex systems are characterized by many interacting subsystems, where dependencies and interactions among these influence the functioning of the overall system (Bar-Yam, 1997; Miller and Page, 2007). System-level characteristics cannot be understood as a simple sum of sub-system behaviors. Instead, properties such as emergence, adaptation, spontaneous order, feedback-loops, and non-linear behavior of the overall system need to be expected (Bar-Yam, 1997). The internal interactions of the networked subsystems are often stronger than external control attempts (Miller and Page, 2007). This is why complex systems behave strangely in the eyes of humans that are used to think in linear ways with a proportional outcome to a given input, and therefore governance of such systems is often perceived as very difficult (Helbing and Lämmer, 2008).

Construction projects have many complex systems characteristics. They involve many multidisciplinary individuals and firms equally valuable in the system's operation (Nam and Tatum, 1992; Thórisson, 2003). The construction workflow has high interdependence between stakeholders and many overlaps of construction stages and elements (Gidado, 1996). Design and coordination tasks often require reciprocal interdependence between the involved parties (Thompson, 2017; Tsvetkova et al., 2019). Project outcomes and performance indicators must be already defined at the initial stage of a project, so they are likely to change throughout the project (Bertelsen, 2003). Finally, there are many uncertainties from external parties (e.g., from authorities, governments, or law), resources (labor, equipment, material), or the environment (e.g., weather, traffic) (Gidado, 1996).

Construction projects are typically governed and managed using a project delivery model. Over the past several decades, the classical project delivery is managed using "command-and-control" project management with layers of contractual and organizational hierarchies (Levitt, 2011). A typical construction project hierarchy will spread across multiple vertical tiers and can include hundreds of subcontracted specialty firms across the supply chain. Even though cooperation would be crucial to deal with the mentioned challenges, insufficient and untimely communication is more the norm than the exception (Tavistock Institute of Human Relations, 1966). Contentious behavior and lack of cooperation reduce the system's efficiency compared to the sum of individual efforts (Hall et al., 2018). Over time, this can result in sub-optimization and self-interest to the detriment of the overall project (Bertelsen, 2003). We can find indications for the failure of hierarchical management structures in many construction projects that ended up in court to resolve disputes over "unforeseen problems leading to cost and time overruns" (Davies et al., 2019).

According to Helbing and Lämmer (2008), we must accept that a complex system does not always do what is desired. The internal non-linear interactions often dominate the external control attempts. Sometimes small but right changes cause the system to change, while large efforts might remain useless. Classical, hierarchical control attempts are likely to fail. Instead, one should use self-organization as part of the management strategy. Self-organized networks need room to establish with increased flexibility of participants. Detailed regulations hardly ever create an effect. They rather reduce flexibility and make the required processes inefficient, complicated, and expensive. Harmonic overall dynamics is more important than individual performance at their limit, and faster end up to be often slower in complex systems.

In natural self-organizing systems, the agents act and interact with other agents based on some simple rules at the individual level, behaving towards an optimal overall system state. A well-known example in nature is bee hives, where simple rules govern the behavior of individual bees (Thuijsman et al., 1995), but at the population level, maximize the payoff of foraging (Pradelski and Young, 2012).

Even though self-organization works very well in nature, it will likely not meet the targeted outcome in many artificial systems. In most cases, it is not possible to find such simple rules at the individual level that optimize the overall system state. Therefore, complex engineered systems need to be directed minimally invasive to create desired outcomes with "guided self-organization" by changing the interactions in complex systems (Helbing, 2014) through approaches of mechanism design or complexity science to guide individuals towards optimizing the overall system state. Guided self-organization can successfully optimize production systems (Helbing et al., 2006), logistics (Mayer and Furmans, 2010; Gue et al., 2014), traffic flow with bottom-up traffic light control (Kesting et al., 2008), or the overall system output of wind farms (Marden et al., 2013). Furthermore, changing human interactions can turn the so-called "madness of the crowd" into a "wisdom of the crowd" (Helbing and Klauser, 2018; Helbing, 2021; Hänggli et al., 2021).

Consequently, guided self-organization is, in theory, an optimal management approach for a complex system like the construction industry. This is also in line with scholars (Bertelsen and Koskela, 2004) suggesting to use bottom-up control in construction projects to deal with its complex nature, instead of formalizing top-down control to plan for a linear and sequential process. The question arises how such guided self-organization could be achieved in the construction industry?

Even though this question will need more investigation, governance of systems through cryptoeconomics can be an enabler for bottom-up coordination (Jacobo-Romero and Freitas, 2021) towards self-organization. In decentralized systems, decreasing the cost of coordination is extremely important through real-time and transparent information feedback distributed to all relevant parties. This allows informed and coordinated bottom-up reactions to unexpected events. Currently, these information flows are passed through the hierarchical systems, leading to slow responses. New technological advances enable these needed fast feedback loops by providing an extensive real-time data baseline (Helbing, 2014). Blockchain-based governance processes are promising to support data-driven bottom-up and collective decision-making by creating cryptoeconomic incentives to guide individual actors towards behavior that optimizes the overall project.

3.4.3. Lens 3 - Decentralized Governance for a Decentralized Industry

Since the construction industry is mainly organized around projects, Dubois and Gadde (2002b) described the construction industry as a "loosely coupled system". Firms in the industry are usually involved in different projects, where they contribute resources of various kinds (Figure 3.4, a). While they maintain loose couplings in the permanent network embedded in the community of practice, they need to keep tight couplings in the individual projects to perform and coordinate their activities with the many actors regarding resources, space and time. The resulting networks are very similar to a decentralized network structure (Baran, 1964) (Figure 3.4, b).

Recent mapping of construction firm networks seems to confirm the decentralized nature of construction collaboration. Graser et al. (2019) map the information network of a construction project showing this very typical form of collaboration with many coordinating smaller internal and external actors (Figure 3.4, c). Also, the network analysis of Bouck (2014) shows that construction firms communicate extensively with outside players in their ecosystem, resembling again a decentralized network structure.

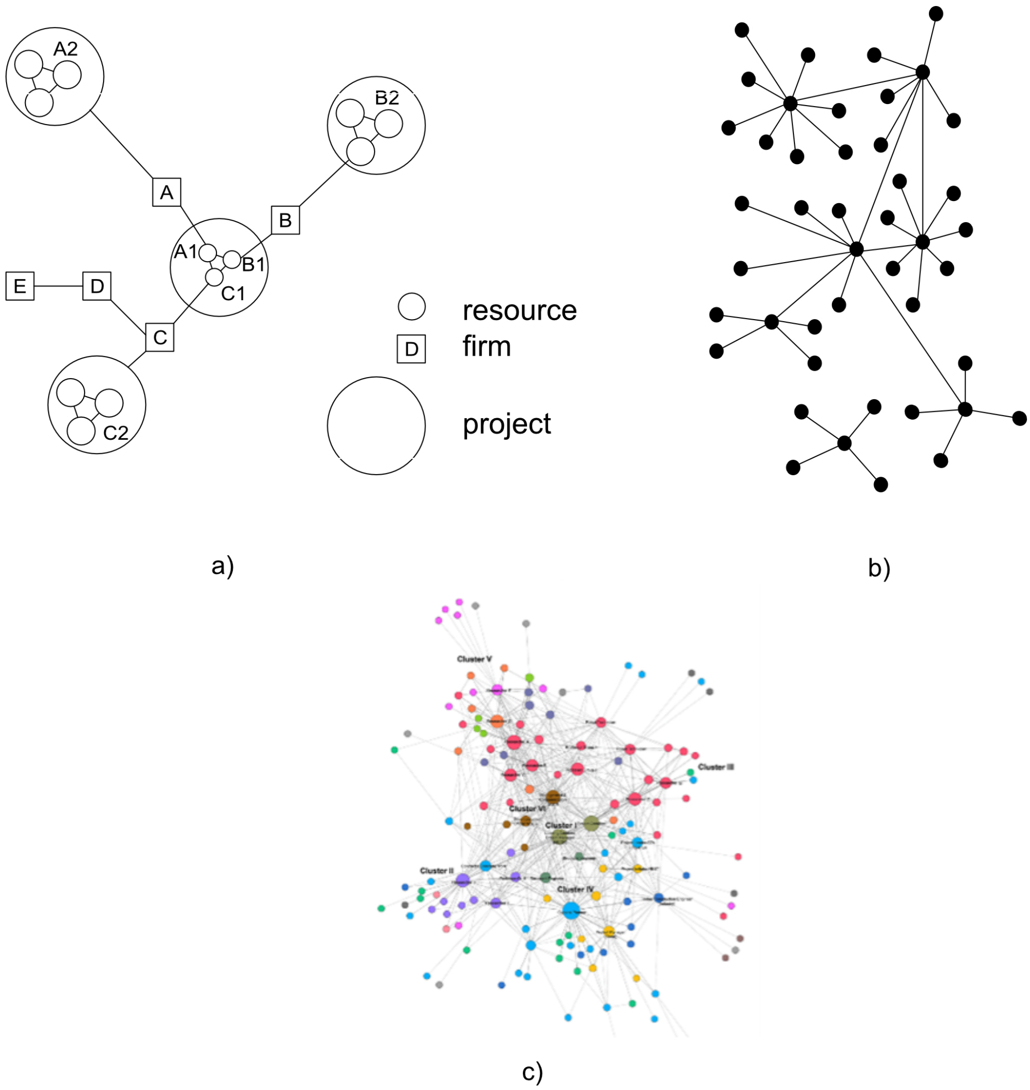

Figure 3.4.: The construction industry as decentralized collaboration network (Sources: a) Dubois and Gadde (2002b) b) Baran (1964) c) Graser et al. (2019)).

Overall, decentralized network structures seem typical to the construction industry. Other industries have mostly bigger players that integrate and coordinate large parts of the value chain (Bouck, 2014). Since industries with more integrated and centralized structures have often higher productivity than construction, efforts under the term of industrialized construction trying to adopt these approaches have attracted major investments lately (Pullen et al., 2019). Industrialized construction tightens couplings of firms across construction projects, an approach that is successful in manufacturing. While this can also be successful strategies in the built environment, it involves restructuring a whole industry towards more vertical integration of the supply chain. Could decentralized collaboration mechanisms enabled by cryptoeconomic governance approaches provide an alternative pathway to make the prevalent decentralized and loosely coupled industry structure more efficient by decreasing cost of coordination?

3.4.4. Aligning Governance with the Industry Structure

The three different lenses indicate the potential for cryptoeconomic governance for the construction industry. The construction industry is characterized by complexity and can be described as a loosely coupled network managed with

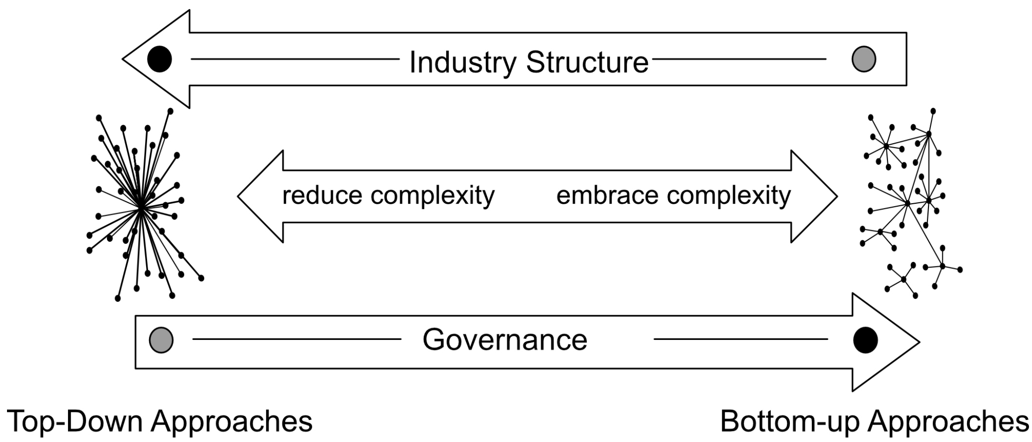

Figure 3.5.: Approaches to deal with complexity in construction. Light grey dots: the predominant situation today – a misalignment between top-down management and decentralized project organization (loosely coupled networks). The organization can either be adapted towards vertical integration (reducing complexity), or the governance can shift towards bottom-up approaches (embracing complexity).

top-down approaches (Figure 3.5, light grey dots). However, an efficient overall system should be either targeted towards hierarchies or networks (Alstyne, 1997). Hypothetically, one option is to move the industry structure towards vertical integration, removing complexity through more streamlined supply chains (Figure 3.5, industry structure arrow). This would lead to less fragmentation with the same actors across phases and trades and standardization across projects. The other option would be to move governance approaches towards bottom-up management and embrace complexity aspects of the industry (Figure 3.5, governance arrow). Both approaches are feasible if assuming that it is indeed possible to reduce complexity. However, it is somewhat hard to believe that all the complexity aspects of the industry can be eliminated. Additionally, industrialization and digitalization will only increase in our world, directing global systems towards new socio-technical paradigms with inevitable cascading effects on interconnected and complex ecosystems (Helbing, 2013). As our world's complexity and interaction strengths increase, centralized and controlled systems can become unstable, and highly-skilled, well-informed and well-intentioned system managers can still lose control (Helbing, 2013). With this in mind, the decentralized nature of the construction industry could also be perceived as a strength that makes the industry more resilient towards such risks. With the increased adoption of technology in the construction industry, cryptoeconomic governance provides an opportunity to build bottom-up coordination mechanisms towards "peer-production" of the built environment to better handle complexity aspects of construction aligned with its decentralized and fragmented nature.

3.5. Blockchain Adoption Framework

Even though cryptoeconomic mechanisms are an opportunity to govern a complex construction industry, the industry is unlikely to move all at once towards blockchain-based governance. We imagine a stepwise exploration of blockchain applications, starting from applying the technology to existing processes, potentially adopting more affordances towards new economic systems governed by blockchain-based mechanisms. To lay out a potential pathway for research and industry alike, we introduce an adoption framework through the lens of blockchain-based governance and try to support it with emerging examples (Figure 3.6).

3.5.1. Step 1 - Blockchain for Existing Processes

In a first step, blockchain is used as an assurance layer for existing processes in the built environment (Figure 3.6). Such use cases rely on blockchain-based governance to ensure confidence in the needed blockchain affordances. Blockchain affordances like immutability and transparency secure transactions, while smart contracts allow for interaction logic if needed (see Figure 3.2, trusted digital processes). This can shift trust from relational to system-based and cognition-based, providing stakeholders in the construction supply chain with protection mechanisms to avoid the risk and costs of opportunistic behavior in collaboration (Qian and Papadonikolaki, 2020).

Most current research and implementations fall under this adoption step (Hunhevicz and Hall, 2020b). Examining more recently published literature (Li and Kassem, 2021; Scott et al., 2021) confirms this. Below we list literature that we categorize into this first adoption level.

One of the most prominent affordances of blockchain is tracking and securing data. In its purest form, this means hashing and timestamping data. Research suggests blockchain records for construction-related data for liability control of design data (Erri Pradeep et al., 2021), assurance of construction quality information (Sheng et al., 2020; Zhong et al., 2020; Wu et al., 2021), versioning and authenticity of construction documents (Das et al., 2021), and tracing data from digital twins for accountable project-related (Lee et al., 2021) and life-cycle related (Götz et al., 2020) information. Tracking of construction data can then be combined with automatic execution of construction contract clauses through smart contracts (Shojaei et al., 2020; McNamara and Sepasgozar, 2021).

Many papers also explore the tracing of information in a more specific construction supply chain context to assure reliable information of built assets (Watson et al., 2019), construction materials, and products (Lanko et al., 2018; Copeland and Bilec, 2020; Shojaei et al., 2021), information in the precast supply chain (Wang et al., 2020), the facility management procurement process (Gunasekara et al., 2021), construction logistics in Sweden (Kifokeris and Koch, 2020), production of off-site modular housing (Li et al., 2021), or for more transparency in construction waste management (Pellegrini et al., 2020).

Finally, one of the most often mentioned use case in current literature is blockchain and smart contract enabled payments to make existing financial processes more transparent, secure and efficient (Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020; Das et al., 2020; Di Giuda et al., 2020; Elghaish et al., 2020; Hamledari and Fischer, 2021b; Nanayakkara et al., 2021; Ye and König, 2021).

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

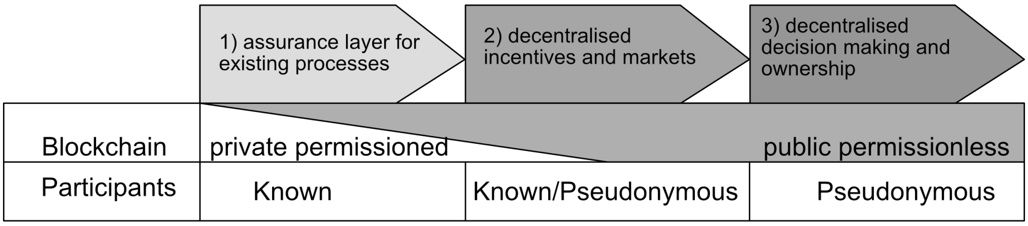

Figure 3.6.: Three steps of blockchain adoption through a blockchain-based governance lens.

blockchains as a trusted settlement layer in this first category.

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

3.5.2. Step 2 - Blockchain-Based Governance for New Incentives and Markets

In a second step, use cases will explore cryptoeconomic incentives to realign the economic interests of existing processes towards better collaboration and new business models (Figure 3.6). Tokens and smart contracts (Figure 3.2, incentive systems) can be used to move financial rewards, reputation, or ownership across space and time between industry participants to create new economic systems. Such performance and target-oriented incentives can increase cross-phase, cross-trade, and cross-project collaboration towards reducing the impact of fragmentation.

For this second blockchain adoption step, we see considerably less literature related to the construction industry. Some research goes in this direction by exploring how crypto assets can integrate the physical and financial supply chains (Hamledari and Fischer, 2021c) or enable novel financial mechanisms such as project bank accounts, reverse auction-based tendering for bidding, and asset tokenization for project financing (Tezel et al., 2021). Also, Tian et al. (2020) explored new possibilities to finance infrastructure through tokenization, and Dounas et al. (2021) how to use non-fungible tokens (NFTs) to represent physical building components in the digital world.

Related to cryptoeconomic incentives, O'Reilly and Mathews (2019) propose blockchain incentivizing multidisciplinary design teams to design for the best possible building performance. Along these lines, Hunhevicz et al. (2022c) explored performance-based smart contracts to incentivize the design and building for the best possible performance across phases. Producers and owners might provide their built assets with publicly available service contracts on the blockchain, while other service providers and users can evaluate available offers and directly sign these contracts on the blockchain, getting paid or paying for services anonymously and peer-to-peer. Blockchain-based incentive mechanisms are further proposed for complete data sets in construction projects to prevent data loss, incentivize data quality across phases and trades (Hunhevicz et al., 2020b), and create new economically profitable use cases to manage and reuse construction waste (McMeel and Sims, 2021).

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

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

3.5.3. Step 3 - Decentralized Coordination through Blockchain-Based Governance

In a third step, the industry could start to coordinate activities decentralized through blockchain-based governance mechanisms with commons like community governance, potentially in the form of a DAO (Figure 3.6). Decentralized coordination can be more scalable and efficient in dealing with complexity aspects of the construction industry compared to current centralized approaches. It can integrate with other emerging technologies such as digital twins to create fast feedback loops for decision making, potentially similar to concepts of guided self-organization. Public permissionless blockchains allow pseudonymous actors and machines to participate. Ownership and coordination will shift towards flexible and pseudonymous communities, or potentially even towards the built assets themselves.

Even though this sounds futuristic, early research proposes the evolution of AEC organization towards DAOs conceptually (Sreckovic and Windsperger, 2020) and also investigates potential applications for the design, construction, and operation of built assets. These early examples give a glimpse into the possibilities of a future construction industry embracing blockchain-based governance for decentralized coordination.

Lombardi et al. (2020) and Dounas et al. (2020) envision new collaboration organized through a DAO for the design process. The envisioned scenario simulates designers proposing multiple solutions for a given task and adopting shape grammars and environmental analysis and regulations as design drivers. Proposed solutions are uploaded, stored, presented, and evaluated in a DAO in which the decision process gets validated via the reputation of the participants and its governance system.

Furthermore, blockchain-based governance mechanisms could facilitate future forms of project delivery models (Hunhevicz et al., 2020a). The argument is based on the theoretical fit between new forms of delivery models such as IPD with CPR theory (Hall and Bonanomi, 2021), and the alignment of blockchain-based governance to scale CPR scenarios. The Ostrom principles could be used as a guide to create blockchain-based governance to manage construction projects in a decentralized way on the crypto commons (Hunhevicz et al., 2022b).

Finally, the ongoing research project no1s1 explores the concept of decentralized autonomous space to create self-owing built assets (Hunhevicz et al., 2021). The prototype no1s1[3] demonstrates and explores how self-ownership of physical space would allow a self-sustaining and non-rent seeking built environment that could replace current organizational structures. The idea is that funds are owned by the house itself on its own blockchain address, while decision-making of no1s1 is coordinated through a DAO.

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

3.6. Discussion

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

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

From a technical viewpoint, the adoption of blockchain-based governance highly depends on the overall technology adoption rate of the industry, as well as the maturity of the blockchain ecosystem. Until now the construction industry has embraced digitalization at a slower rate than other industries (Agarwal et al., 2016; Barbosa et al., 2017). However, there is now hope that the construction industry will see a transformative change with the recent increasing maturity of technical advancements (Singh, 2019). The new movement is often termed construction 4.0 - embracing industry 4.0 concepts within the construction industry (García de Soto et al., 2019; Klinc and Turk, 2019; Forcael et al., 2020; Sawhney et al., 2020). The term industry 4.0 describes the overarching concepts to leverage digital and automation technologies to create interconnected, intelligent, autonomous, and self-learning cyber-physical systems (Lasi et al., 2014).

Cryptoeconomic governance mechanisms for new incentives and coordination depend heavily on the adoption of construction 4.0 concepts. In contrast to other industries such as finance that can be shifted to a mostly digital environment, the construction industry will always build physical products. The interconnection and feedback loops from the physical to the digital world and the integration with existing software stacks need to be ensured. To build effective incentive and coordination systems, data need to reflect the physical state of the project and asset to be governed. For that the role of sensors (IoT), virtual reality capturing technologies, and digital twins will play a vital role (Hamledari and Fischer, 2021a; Lee et al., 2021; Hunhevicz et al., 2022c). Having said that, the construction industry is only at the beginning of its journey towards construction 4.0. According to the industry 4.0 maturity model developed by Reuter et al. (2016), the construction industry is only at the initial stage to realize industry wide information generation (digital models and sensors) and saving generated data accessible to all relevant industry stakeholders across phases, trades, and projects (common data environments).

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

From an organizational viewpoint, the emergence of the above mentioned construction 4.0 concepts comes at an interesting time given industry trends. Industry 4.0 creates opportunities to disintermediate physical supply chains, increase servitization, and create 'light' firms with more local and regional assets (Brun, 2019). By contrast, recent momentum in the construction industry trends toward vertically integrated firms (Hall et al., 2020) and increased conceptualization of the building as a product (Fischer et al., 2018). The current vision of construction 4.0 seems very much oriented towards the adoption of successful concepts in the manufacturing industry, promising higher productivity levels for construction. Potential bottom-up coordination targeted towards a more decentralized industry structure organized around smaller firms and projects seems somewhat contrarian to this approach. More research should investigate how current visions of construction 4.0, such as platformization and productization, are connected to this vision. How would the construction industry organize through crypto commons based community structures and DAOs? Is this an alternative vision to current construction 4.0 roadmaps? Or is it a similar approach, just enabled through many smaller actors rather than big vertically integrated players? To motivate more research towards building decentralized and bottom-up coordination, the industry needs to perceive blockchain as valuable towards the overall vision of construction 4.0. It is an opportunity to rethink organizational relationships of the construction industry in the context of the ongoing cyber-physical convergence (Maciel, 2020).

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

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4. Applications of Blockchain for the Governance of Integrated Project Delivery: A Crypto Commons Approach

This chapter corresponds to the submitted article:[1]

Hunhevicz, Jens J., Pierre-Antoine Brasey, Marcella M M Bonanomi, Daniel M Hall, and Martin Fischer (July 2022b). "Applications of Blockchain for the Governance of Integrated Project Delivery: A Crypto Commons Approach". In: *arXiv*. DOI: `10.48550/arXiv.2207.07002`. arXiv: `2207.07002`. URL: `http://arxiv.org/abs/2207.07002`.

Abstract: This paper outlines why and how blockchain can digitally support and evolve the governance of collaborative project deliveries, such as integrated project deliveries (IPDs), to provide the foundation for novel and disruptive forms of organizational collaboration in the construction industry. Previous work has conceptualized IPDs as a common pool resource (CPR) scenario, where shared resources are collectively governed. Through the use of blockchain and smart contracts for trustworthy peer-to-peer transactions and execution logic, Ostrom's design principles can be digitally encoded to scale CPR scenarios. Building on the identified connections, the paper 1) synthesizes fourteen blockchain-based mechanisms to govern CPRs, 2) identifies twenty-two applications of these mechanisms to govern IPDs, and 3) introduces a conceptualization of the above relationships towards a holistic understanding of collaborative project deliveries on the crypto commons for novel collective organization of construction project delivery between both humans and machines.

[1]Please note, this is the author's version of the manuscript published as a preprint in *arXiv*. After later acceptance and publishing in a journal, changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may be subsequently added. When citing this chapter, please refer to the latest preprint or the published article.

4.1. Introduction

Construction project delivery models (PDMs) describe how the multiple parties involved in a project are organized and managed to create and capture value (Davies et al., 2019). Even though the construction industry has been slow in adopting digitalization, new digital technologies and processes slowly make their way into the construction industry (Singh, 2019). Digital information is changing how projects are delivered (Whyte, 2019); it can motivate the development of novel collaborative PDMs with new incentive structures, procurement methods, and approaches to communication.

Meanwhile, digital information technologies in the construction industry are also rapidly changing. One technology that is increasingly researched for the construction industry is blockchain (Li et al., 2019a; Li et al., 2021; Nawari and Ravindran, 2019a; Perera et al., 2020; Wang et al., 2017). Blockchain is a particular design option of distributed ledger technology (DLT) (Ballandies et al., 2021b; Tasca and Tessone, 2019) that enables direct peer-to-peer transactions of value without relying on trusted facilitators.

The first ever blockchain created is Bitcoin (Nakamoto 2008). Since then, many new blockchains iterated on the approach of Bitcoin to enable new features and infrastructure (Spychiger et al., 2021). Most notable, the Ethereum blockchain (Buterin, 2014) made it possible that Turing-complete code pieces termed smart contracts could be executed on a blockchain. Smart contracts allow for the coding of interaction rules with blockchain transactions for digital workflows to coordinate economic activity of actors in a decentralized and borderless way. In addition, smart contracts can encode containers of value, so-called tokens, such as currencies, securities, or utilities (Ballandies et al., 2021b; Mougayar, 2017). Tokens can then be transferred among blockchain users.

Blockchain has been repeatedly theorized as promising to improve construction project management practices (Sonmez et al., 2021), especially to support financial management, automatic contract administration, and tracing and securing data along the supply chain (Hewavitharana et al., 2019; Kim et al., 2020). This also aligns well with the most often explored use cases for the construction sector (Hunhevicz and Hall, 2020b; Li et al., 2019a; Li et al., 2021; Perera et al., 2020; Scott et al., 2021).

However, scholarship also suggests that the impact of blockchain is highly disruptive to the coordination of existing economic systems (Davidson et al., 2018; Miscione et al., 2019). Smart contracts can create new organizational systems, incentivizing individual actors towards intended collective behaviour (Voshmgir and Zargham, 2019). Therefore, blockchain can be an opportunity for new organizational designs governing the upcoming digital reality of PDMs (Sreckovic and Windsperger, 2020; Hunhevicz et al., 2022a). Since construction PDMs are already transforming due to increasing digital information (Whyte, 2019), there is need to investigate further the impact of the potentially disruptive impact of blockchain.

In this paper, we conceptualize why and how blockchain can digitally support and evolve the governance of PDMs. To build this conceptualization, we specifically make use of ideas about governance of common pool resource (CPR) scenarios (i.e., the "commons") (Ostrom, 2015). Scholars argue that blockchain-based mechanisms can scale CPR scenario governance (Fritsch et al., 2021; Rozas et al., 2021a,b). Such "crypto commons" (Maples, 2018) build digital governance structures for commons by leveraging blockchain-based market mechanisms and economic incentives to reward contributions to the common good (Crypto Commons Association, 2021).

This is interesting because there is strong theoretical alignment between Integrated Project Delivery (IPD) and the management of CPR scenarios (Hall and Bonanomi, 2021). IPD is a new collaborative PDM that uses a relational contracting approach to manage large and complex construction projects. One driver for the development of IPD was the need for more flexible and collaborative organizational structures to gain benefit from digital building information modelling (Hall and Scott, 2019). To do this, IPD uses a financial pool to share risk and reward among project participants depending on the outcome of the project. IPD also emphasizes decentralized, agile, and self-organized project governance arranged by the project participants. Collaborative PDMs such as IPD can better deal with the complexity and ever-changing nature of modern construction projects (Levitt, 2011; Luo et al., 2017).

The strong alignment of the collective nature of blockchain and collaborative approach of IPD has not escaped the attention of researchers. Nawari and Ravindran (2019b) theorize blockchain as a "evidence of trust" for IPD. Elghaish et al. (2020) and Rahimian et al. (2021) have developed a blockchain prototype for the IPD financial risk-and-reward system. However, these works mainly apply blockchain to improve existing financial processes. As stated above, blockchain has the potential to lead to new forms of organization and governance (Davidson et al., 2018; Jacobo-Romero and Freitas, 2021; Miscione et al., 2019), but no work yet has explained how this might occur for construction PDMs.

Therefore, this paper now explores how the relationships of blockchain, CPR theory, and IPD can be used as a theoretical foundation to inform which specific blockchain applications can be developed to evolve and redesign PDMs. This is achieved through systematically exploring the connections between blockchain, CPRs, and IPD. The results of this work can help to conceive the opportunity of blockchain for IPDs to evolve, or even enable the formulation of new digitally supported PDMs on the crypto commons.

4.2. Methodology and Structure of the Paper

An overview of the research approach and contribution is presented in Figure 4.1. The methodology contained three main steps: 1) We outlined established connections between CPRs, the Ostrom design principles (OPs), and IPDs to manage construction resources; 2) we conducted a state-of-the art review of all papers and articles that propose to use blockchain to manage CPR and identify the proposed mechanisms for the respective OPs; 3) we identifiedy applications of those mechanisms for collaborative construction projects through using the link between IPDs and the OPs. Each of these steps is now described in more detail.

In the departure section 4.3, we introduce relevant established concepts between CPR theory and IPD that act as basis for our research. First, we introduce Ostrom's design principles (OPs) for the management of CPR scenarios (Section 4.3.1). Second, we explain the high-level concepts of IPD to manage construction project resources (Section 4.3.2). Finally, we outline the recently established connection between the OPs and IPD practices (Section 4.3.3).

To verify the link between blockchain and CPR theory (Section 4.4), we conducted a comprehensive literature review of all papers and articles that proposed blockchain for the management of CPRs. We identify four journal papers (Fritsch et al., 2021; Pazaitis et al., 2017; Rozas et al., 2021b) and five articles (Dao, 2018; Decoodt, 2019; Emmett, 2019; Rouviere, 2018; Schadeck, 2019) proposing to gov-

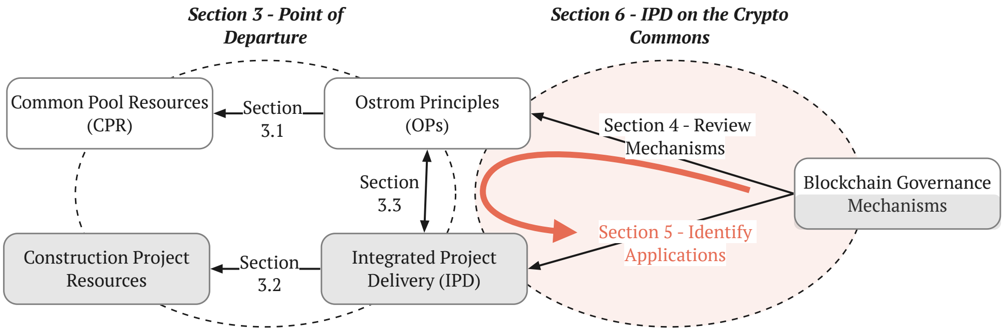

Figure 4.1.: Schematic representation of the research approach and contribution. CPR related boxes are pictured in white, the IPD related boxes in grey. The paper builds on the existing conceptualization between CPR, OPs, and IPD (see "Point of Departure", Section 4.3.1 – 4.3.3). Afterwards, the paper comprehensively reviews literature proposing blockchain for CPRs and the OPs and summarizes the proposed mechanisms (Section 4.4). Finally, the paper identifies applications of blockchain governance mechanisms for IPD (Section 4.5) towards a holistic conceptualization of IPD on the crypto commons (Section 4.6) through abductive reasoning using the connection between the mechanisms, OPs, and IPD practices (see red arrow).

ern real-world commons with blockchain-based mechanisms. Building on these works, we cluster and categorize fourteen blockchain governance mechanisms encoding the OPs for the governance of crypto commons.

We then use abductive analysis (Timmermans and Tavory, 2012) to theorize how blockchain governance mechanisms can be transferred to the governance of IPDs. Abduction is making a probable conclusion from what is known by systematically interpreting, matching, or re-contextualizing phenomena within a contextual framework, from the perspective of a new conceptual framework (Dubois and Gadde, 2002a; Kovács and Spens, 2005). An abductive approach is fruitful if the objective is to develop the understanding of a "new" phenomenon or new insights about existing phenomena by examining these from a new perspective (Dubois and Gadde, 2002a; Kovács and Spens, 2005).

To do this, we first synthesized applications based on observed alignment between the blockchain mechanisms for the OPs and IPD practices in line with the OPs (Hall and Bonanomi, 2021). We then refined and complemented applications based on supporting blockchain research both from within and outside the construction industry. In total, we identified 22 blockchain applications that can be used to build IPD governance on the crypto commons (Section 4.5).

A holistic overview of the proposed conceptualization of IPD on the crypto commons demonstrates the cohesiveness between the relationships of the OPs, the blockchain governance mechanisms, and the specific blockchain applications to build novel governance mechanisms for IPDs (Section 4.6).

The paper ends with a discussion of the opportunities for blockchain to be applied to IPD and other future forms of project delivery, as well as the challenges for governance design and for industry implementations to facilitate next research steps (Section 4.7).

4.3. Point of Departure

4.3.1. Governing CPR Scenarios

CPRs are natural resources, which are freely shared among many users (Ostrom, 1990). Examples include forests, pastures, fishing grounds, parking lots or wiki libraries. In a CPR scenario, users might appropriate resources at a higher than optimal rate, resulting in a downward spiral of total resource availability (Hardin, 1968). This is known as the tragedy of the commons. For decades, scholars argued that centralized control was the only way to coordinate optimal resource appropriation in CPR scenarios.

However, more recent work pioneered by economist Elinor Ostrom (Ostrom, 2010, 2015; Ostrom et al., 1994) and others (Gardner et al., 1990) overturned these beliefs. Ostrom used case studies to demonstrate that local actors are often successful at self-organizing to better sustain CPR scenarios when compared to centralized interventions. Ostrom identified eight design principles – the OPs – that can guide effective governance of CPR scenarios (Table 4.1). The OPs explain necessary conditions that should be achieved, to facilitate trust and reciprocity and to sustain collective action in long-lasting CPR scenarios (Cox et al., 2010).

4.3.2. IPD Governance of Construction Projects

IPD is a project delivery model that formally multiple, independent firms to collectively share financial risk and reward among themselves and with the project sponsor during the design and construction of a facility (Lahdenperä, 2012). IPD governance today can be best described as the combination of multiple formal and informal practices (Bygballe et al., 2015; Hall and Scott, 2019). Such practices include early involvement of key stakeholders, risk and reward mechanisms, joint project control, and target value design (Cheng et al., 2016; Hall et al., 2018).

IPD departs from the traditional model of project delivery in three notable ways (Hall and Bonanomi, 2021). First, the multiparty contract of the IPD model creates a shared financial resource pool for the project. The project resources become contractually available for free use by any of the project signatory parties. Second, the participants of IPD projects share decision-making rights over the project governance structures. Decision-making is no longer centralized (Tillmann et al., 2014). Third, the project team shares the financial risks and rewards of the project. Positive outcomes are split among participants. The project teams must self-organize (Bertelsen, 2003) and determine who has access to the shared pools and who is allowed to withdraw from this pool.

4.3.3. Governing IPD using CPR Design Principles

Recent work has proposed a conceptualization bridging the governance of IPD projects and the OPs (Table 4.1) (Hall and Bonanomi, 2021), suggesting that the IPD project environment resembles a CPR scenario (Hall and Bonanomi, 2021). Project resources are "pooled" together through a multi-party contract which shares risk and (Darrington and Lichtig, 2010; Thomsen et al., 2009).

Similar as CPR scenarios must avoid the tragedy of the commons, IPD projects must then avoid the tragedy of the project – where the project budget and schedule can be subject to over-appropriation by the project stakeholders to the long-term detriment of the project resource system (Hall and Bonanomi, 2021). To avoid the tragedy of the project, project managers create effective self-governance structures manifesting in specific management practices for IPDs, which demonstrate many shared characteristics to the OPs. Additional work has validated this connection with examples from IPD project practices (Bonanomi et al., 2019; Bonanomi et al., 2020). Table 4.1 lists such example practices for IPDs aligned with the OPs for CPRs.

Ostrom Principle (OP)			Description of OP (Cox et al., 2010; Ostrom, 2015)	Example Practice(s) for IPD (Hall and Bonanomi, 2021)
1	Clearly Defined Boundaries	a) For the users	The boundaries between legitimate and non-users who have right to withdraw resource units from the CPR must be clearly defined.	The participating firms collectively determine who is a risk and reward "partner" and who is not in the multiparty contract.
		b) For the resources	Resource boundaries of the system must be clearly defined and separated from the larger socio-economic system.	The project sponsor and project team collectively define which specific aspects of project scope and budget are open to all and which are not.
2	Ensure congruence	a) With local conditions	CPR scenarios should ensure congruence with local conditions of appropriation rules restricting time, place, technology, and/or quantity of resource units.	Trade contractors are engaged early in the project, because they have knowledge of local conditions, such as availability of labor, material, work routines, and other resources.
		b) Between appropriation & provision rules	The benefits obtained by users from a CPR, as determined by appropriation rules, should be proportional to the amount of inputs required in the form of labor, material, or money, as determined by provision rules.	The level of participation in the risk/reward pool is weighted according to a firm's individual cost structure or accounting practices, its period of involvement, and/or influence on the outcomes.
3	Collective-choice arrangements		Most individuals affected by the operational rules can participate in modifying the operational rules.	Firms that have signed the multiparty contract are entitled to participate in management group functions and to vote on decisions that directly concern their work and area of expertise.
4	Monitoring of the users and the resources	a) Presence	Monitors are present to actively audit CPR conditions and appropriator behavior of the users to ensure that all parties are adhering to agreed-upon tasks.	Participants share information on resources, costs, profit, and performance openly and transparently. Teams also create cost targets and then track the weekly withdrawals of resource units, monitoring for deviations (Target Value Design).
		b) Accountability	Monitors are accountable to or are the appropriators.	Participants make commitments about the work to be completed. The Planned Percent Completed (PPC) metric tracks the percentage of items promised last week that were completed and is publicly reported to all team members.
5	Graduated sanctions		Appropriators who violate operational rules are assessed graduated sanctions (depending on the seriousness and context of the offense) by other appropriators, officials accountable to these appropriators, or both.	Sanctions can increase due to continuous non-conformance or underperformance of PPC, leading to the removal of individual participants and/or firms if necessary.
6	Conflict-resolution mechanisms		Appropriators and officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials.	Project participants craft conflict resolution mechanisms that include clear dispute resolution strategies intended to avoid costly litigation proceedings.
7	Minimal recognition of rights to organize		The rights of appropriators to devise their own institutions are not challenged by external governmental authorities.	Conflict resolution mechanisms allow participants to make collective decisions, including procedures for the team to override the wishes of the project sponsor.
8	Nested enterprises		Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.	Governance activities of IPD projects are organized into multiple layers of hierarchy using a nested enterprise design.

Table 4.1.: The eight Ostrom principles and their connection with IPD practices (Source: Hall and Bonanomi (2021)).

4.4. Blockchain and the Crypto Commons: a Review

4.4.1. Blockchain as an Institutional Innovation

The dominant narrative for economic coordination through the blockchain argues that blockchain enables increased productivity of existing processes by lowering transaction costs through costless verification and without the need for costly intermediation (Catalini and Gans, 2020). However, some scholars argue the true potential of blockchain is the development of new types of institutional organization with the potential to disrupt and substitute existing economic coordination (Davidson et al., 2018; Jacobo-Romero and Freitas, 2021; Miscione et al., 2019). Blockchain is a new way to reach consensus about a shared truth without requiring centralized trust (Davidson et al., 2018). The innovation of blockchain is the consensus protocols using cryptoeconomic mechanisms to reward honest parties to reach consensus on network transactions, e.g. in Bitcoin with proof-of-work(Gervais et al., 2016; Nakamoto, 2008). Blockchain disintermediates transactions with a new form of organizational design, and as a consequence can lower transaction costs (Davidson et al., 2018).

As a consequence, applications can leverage the innovation of cryptoeconomic mechanisms of blockchains for trust-minimized social coordination to build new forms of economic activity on top of blockchains. Such applications can leverage the innovation of cryptoeconomic mechanisms of blockchains for trust-minimized social coordination to build new forms of economic activity on top of blockchains. Such cryptoeconomic systems can provide an institutional infrastructure that facilitates a wide range of socio-economic interactions to influence participants in their behavior (Voshmgir and Zargham, 2019).

There is ongoing exploration of what forms of organization and governance can be supported or replaced through blockchain. Within this paper, we focus on blockchain as a possibility to scale CPR scenarios on the crypto commons.

4.4.2. The Connection of Blockchain and CPR Governance

The OPs describe how commons-based communities can create effective bottom-up governance rules (Cox et al., 2010). However, a major limitation is scaling community governance to large and global systems (Ostrom et al., 1999).

Recent scholars point out that blockchains can be assessed through the lens of CPR theory and the OPs. This can enable the creation of effective bottom-up governance rules for decentralized peer production of the network without any centralized coordination (Red, 2019; Shackelford and Myers, 2016; Werbach, 2020). There is growing recognition that the underlying system governance mechanisms are the key to long-term success of blockchain networks (Beck et al., 2018; Machart and Samadi, 2020; Red, 2019; Werbach, 2020). CPR theory and the OPs are a repeatedly mentioned concept to guide the development of blockchain governance (Shackelford and Myers, 2016; Werbach, 2020).

Fritsch et al. (2021) find now that blockchain and other DLTs can enable scaling of a new generation of commons-oriented economies, both for digital and physical commons. On the one hand, cryptoeconomic mechanisms decrease the cost of information exchange through minimizing opportunism and uncertainty trough transparency and cryptographic enforcement (Machart and Samadi, 2020; Schmidt and Wagner, 2019). On the other hand, blockchain provides reliable organizational means to equitably produce and distribute resources in accordance with the shared values of productive communities (Fritsch et al., 2021). The transparent decision-making procedures and decentralized cryptoeconomic incentive systems help avoid the tragedy of the commons (Bollier, 2015). The idea is to craft blockchain-based governance mechanisms by encoding the OPs (Rozas et al., 2021a,b). Blockchain could create networked governance to scale real-world commons, similar to how the stock market enabled corporations to scale (Maples, 2018). Such crypto commons could allow new types of value creation with crypto assets rather than shares of stock, contributors rather than employees, and decentralized collaboration rather than centralized ownership (Maples, 2018).

4.4.3. Blockchain Governance Mechanisms for the Commons

As a basis to later investigate potential applications of blockchain mechanisms for IPD, we reviewed blockchain governance mechanisms proposed for CPRs (see also Section 4.2). Most notably, Rozas et al. (2021a) assesses the relationship between blockchain affordances and the eight OPs to support peer production of real-world commons. Rozas et al. (2021b) explore then how those can be applied to scale-up CPR governance of global software commons to address limitations identified by Stern (2011). Even though IPD can be characterized as a real world common, it hardly falls into the same category of global real world commons. Therefore, we clustered proposed mechanisms from all identified articles into 14 high level mechanisms for the eight OPs (Table 4.2), instead of just relying on the categorization of Rozas et al. (2021a).

Blockchain Governance Mechanism	**OP**	**Sources**
M1: Identity, ownership, and access rights based on addresses and tokens	1a	(Dao, 2018; Rozas et al., 2021a,b; Schadeck, 2019)
M2: Tokenization of the resources	1b	(Decoodt, 2019; Emmett, 2019; Fritsch et al., 2021; Rouviere, 2018)
M3: Decentralized markets to match supply and demand of local needs and conditions	2a	(Schadeck, 2019)
M4: Formalizing appropriation and provision rules with smart contracts	2b	(Dao, 2018; Rozas et al., 2021a,b)
M5: Decentralized proposal and voting platforms	3	(Dao, 2018; Emmett, 2019; Rozas et al., 2021a,b; Schadeck, 2019)
M6: Decentralized prediction markets	3	(Dao, 2018)
M7: Transparent record and automation of transactions	4a	(Emmett, 2019; Rozas et al., 2021a,b; Schadeck, 2019)
M8: Digital signatures for tamper-proof commitments	4b	(Dao, 2018; Rozas et al., 2021a,b)
M9: Decentralized peer-review mechanisms	4b	(Pazaitis et al., 2017; Rozas et al., 2021a,b)
M10: Reputation tokens	4b	(Pazaitis et al., 2017; Schadeck, 2019)
M11: Transparent and self-enforcing sanctions	5	(Dao, 2018; Emmett, 2019; Rozas et al., 2021a,b; Schadeck, 2019)
M12: Decentralized jurisdiction systems	6	(Dao, 2018; Emmett, 2019; Rozas et al., 2021a,b; Schadeck, 2019)
M13: Ensure decisions are made by affected parties	7	(Rozas et al., 2021a,b)
M14: Bottom-up interaction among multiple hierarchical levels	8	(Dao, 2018; Emmett, 2019; Rozas et al., 2021a,b; Schadeck, 2019)

Table 4.2.: Clustered blockchain governance mechanisms based on reviewed literature.

OP1 – Clearly Defined Boundaries

a) For the Users

According to OP 1a, the boundaries between legitimate and non-users who have right to withdraw resource units from the CPR must be clearly defined (Cox et al., 2010; Ostrom, 2015). The main identified blockchain mechanism for OP 1a is to govern CPR boundaries through **blockchain addresses and tokens to control identity, ownership, and access rights** (Table 4.2, M1). Blockchain identifies users with a blockchain address, so there is no need to know the human or machine controlling the address. Access rights and ownership can be assigned to addresses either through smart contract logic that defines roles with specific permissions, or through membership or utility tokens that can be transferred between users (Dao, 2018; Rozas et al., 2021b,a). While the second allows to trade these rights with other addresses by transferring the token, the address based roles stays with that address until revoked. In both cases, blockchain controlled ownership and access rights can be more easily and granularly defined, propagated, and revoked (Rozas et al., 2021b).

b) For the Resources

OP 1b states that resource boundaries of the system must be clearly defined and separated from the larger socio-economic system (Cox et al., 2010; Ostrom, 2015). Within the context of CPRs, **tokenization of the resources** (Table 4.2, M2) can help to achieve clearly defined resource boundaries on the crypto commons. Once resources are tokenized, cryptoeconomic mechanisms through smart contracts can facilitate a wide range of interaction patterns. Tokenization can be in the form of asset-backed currencies or commodity tokens representing the resource, good, or service in the commons (Fritsch et al., 2021). New mechanisms such as bonding curves (Balasanov, 2018; Titcomb, 2019) can incentivize early protectors of CPR scenarios (Decoodt, 2019; Emmett, 2019; Rouviere, 2018). Bonding curves allow investors to buy a resource token by locking up their investment. Investors can later sell back these tokens according to the new price determined by the bonding curve. The bonding curve increases price with issued supply, and therefore rewards early investors. Bonding curves have been proposed for "continuous organizations", where the underlying tokens represent rights to future revenues (Favre, 2019). Augmented bonding curves introduce additional functionalities to create a more robust system that is less subjective to speculation and manipulation (Titcomb, 2019). They act simultaneously as means of funding, liquidity provider and market maker, while the issued tokens represent access or voting rights to the resource (Zargham et al., 2020). Therefore, augmented bonding curves combine access rights through tokens (M1) with the idea of tokenizing the resource. The interplay between the interests of token holders to sell when token price rises and buy as price drops to claim additional governance power over a growing treasury, creates a negative feedback loop that leverages speculative behavior into a continuous source of income for the commons (Fritsch et al., 2021). The Commons Stack implemented such an augmented bonding curve based on research of Zargham et al. (2020).

OP2 – Ensure Congruence

a) With Local Conditions

OP 2a states that CPR scenarios should ensure congruence with local conditions of appropriation rules restricting time, place, technology, and/or quantity of resource units (Cox et al., 2010; Ostrom, 2015). **Decentralized markets to match supply and demand of local needs and conditions** (Table 4.2, M3) are proposed as a blockchain mechanism (Schadeck, 2019). Smart contracts encode the rules to trade with other actors not controlled by any intermediary, so the community using the decentralized marketplace can benefit from unrestricted mutual trading. At the same time, the market place can be tailored to comply with the formalized appropriation rules.

b) Between Appropriation & Provision Rules

According to OP 2b, the benefits obtained by users from a CPR, as determined by appropriation rules, should be proportional to the amount of inputs required in the form of labor, material, or money, as determined by provision rules (Cox et al., 2010; Ostrom, 2015). **Formalizing appropriation and provision rules** (Table 4.2, M4) with smart contracts can make sure these agreements get obeyed (Dao, 2018; Rozas et al., 2021a,b). The transparency of rules also promotes an active discussion of the notion of value in the community (Rozas et al., 2021a). The community can then collectively decide which contributions to recognize, as well as suited local appropriation rules (Rozas et al., 2021b).

OP3 – Collective Choice Arrangements

OP 3 states that individuals affected by the operational rules can participate in modifying the operational rules (Cox et al., 2010; Ostrom, 2015). Decentralized decision making and voting are often discussed topics to govern blockchain networks and decentralized applications. It is therefore not surprising that smart contract based **decentralized proposal and voting platforms** (Table 4.2, M5) are suggested to govern real world commons (Dao, 2018; Emmett, 2019). Tokens could grant rights for decision making, either to ensure equal power distribution by design (Rozas et al., 2021a,b), or based on the contribution and reputation of parties (Emmett, 2019; Schadeck, 2019).

Furthermore, **decentralized prediction markets** (Table 4.2, M6) are proposed as a way to establish a trusted knowledge base (Dao, 2018). Prediction markets were introduced by Hanson (2013) to establish a more representative picture of a future outcome by using a betting platform. The underlying idea is that predictions made by people willing to risk a loss are more likely to be well-informed.

OP4 – Monitoring

a) Presence

OP 4a states that monitors should be present to actively audit CPR conditions and appropriator behavior of the users to ensure that all parties are adhering to agreed-upon tasks (Cox et al., 2010; Ostrom, 2015). Blockchain allows a **transparent record and automation of transactions** (Table 4.2, M7) through smart contracts of user behavior and participation in the commons observable by all community members (Emmett, 2019; Rozas et al., 2021a,b; Schadeck, 2019).

b) Accountability

OP 4b states monitors are accountable to or are the appropriators of a CPR (Cox et al., 2010; Ostrom, 2015). Multiple blockchain mechanisms are proposed to help ensure accountability within CPR scenarios. Every blockchain transaction is signed by a valid private key creating **digital signatures for tamperproof commitments** (Table 4.2, M8). The immutability and censorship resistance of blockchain ensures that decisions and transactions are accountable since all transactions are transparent and verifiable on the blockchain (Dao, 2018; Rozas et al., 2021b,a).

In cases were no automatic checking of work and contributions to the commons is possible, **decentralized peer-review mechanisms** (Table 4.2, M9) facilitated by smart contracts allow to review the status of work or the perceived value of contributions (Pazaitis et al., 2017; Rozas et al., 2021b).

Pazaitis et al. (2017) proposed then **reputation tokens** (Table 4.2, M10) to represent the perceived value of contributions in the blockchain system. They can be earned by users through complying with the CPR rules and are hence a measure of accountability (Schadeck, 2019).

OP5 – Graduated Sanctions

According to OP 5, appropriators who violate operational rules are assessed graduated sanctions depending on the seriousness and context of the offense (Cox et al., 2010; Ostrom, 2015). Blockchain allows for **transparent and self-enforcing sanctions** (Table 4.2, M11). Sanctions can be made transparent to the whole community (Schadeck, 2019), while smart contracts can self-enforce token-based sanctions (Dao, 2018; Emmett, 2019; Rozas et al., 2021a,b; Schadeck, 2019) through the loss of either financial or reputation tokens (Dao, 2018; Emmett, 2019; Schadeck, 2019), or a value-decrease of tokens (Schadeck, 2019).

OP6 – Conflict Resolution Mechanisms

OP 6 states that appropriators and their officials should have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials (Cox et al., 2010; Ostrom, 2015). Blockchain offers the possibility for faster conflict resolutions with **decentralized jurisdiction systems** (Table 4.2, M12) (Dao, 2018; Emmett, 2019; Rozas et al., 2021a,b). Tokens ensure skin in the game in disputes, as well as incentivize game theoretic proofs (Schadeck, 2019). Such protocols must integrate with existing legal and regulatory systems (Schadeck, 2019; Emmett, 2019).

OP7 – Minimal Recognition of Rights to Organize

OP 7 states that the rights of appropriators to devise their own institutions should not be challenged by external governmental authorities (Cox et al., 2010; Ostrom, 2015). Within crypto commons, smart contract mechanisms were proposed to **ensure decisions are made by affected parties** (Table 4.2, M13) (Rozas et al., 2021a,b), e.g. local community rules can only be enforced locally.

OP8 – Multiple Layers of Nested Enterprises

OP 8 states that the rules for appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities should be organized in multiple layers of nested enterprises (Cox et al., 2010; Ostrom, 2015). Smart contracts can facilitate **coordination across nested enterprises** (Table 4.2, M14) between various hierarchical levels of participants to realize shared objectives in the best interest of the commons (Dao, 2018; Emmett, 2019; Rozas et al., 2021a,b; Schadeck, 2019).

4.5. Applications of Blockchain Governance Mechanisms for IPD

Based on the 14 blockchain mechanisms for CPR scenarios (Table 4.3), we identified 22 potential applications of blockchain mechanisms for IPDs (Table 4.3) to govern IPDs as a CPR scenario (Hall and Bonanomi 2021a). The methodological approach is explained in Section 4.2.

We discuss here for each of the 22 identified applications the potential to improve or extend the IPD practices, either based on already existing practices or for potentially new mechanisms not yet applied within IPD. Moreover, we collate the applications with existing blockchain research in the construction industry to indicate their novelty, or if already realized, their alignment.

4.5.1. M1 – Identity, Ownership, and Access Rights Based on Addresses and Tokens (for OP1a)

IPD projects need clearly defined rights for each actor based on their role in the project (Cheng et al., 2016).

Blockchain allows **scalable management of user identities and rights** (Table 4.3, M1-1) through address-based identity and/or transferable tokens. Control of access and rights is the foundation for most blockchain applications proposed for the construction industry, as well as all of the other blockchain-based governance mechanisms, such as access to resources (M2-1), access to decentralized markets (M3-1), access to resources (M4-1) as well as shared risk and rewards (M4-2), access to proposal or voting platforms (M5-2), tracking of user and resource actions (M7-1), participation in smart legal contracts (M8-1), peer-review mechanisms (M10-1), jurisdiction systems (M13-1), or coordination among organizational tiers (M14-1). Smart contract logic ensures that only allowed participants can perform certain actions based on their addresses or token-ownership, providing a scalable approach to define user boundaries in IPD multi-party contracts. Research should investigate whether addresses in IPD projects should be controlled at an individual level or by organizational entities. This depends on many aspects, e.g. how profit, liability and risk should be distributed, or whether an incentive system targets individual actors or firms.

Moreover, blockchain only identifies actors through their addresses, therefore allowing for **machine participation** (Table 4.3, M1-2), e.g. to tender (M3-1) and sign (M8-1) work packages, as well as giving them access to resources (M3-1) and compensating them for their work (M4-2). We see already example of this in research of Lee et al. (2021) where robots get incremental payments for performed work, as well as in the case of no1s1, a self-owning house that can receive funds for provided services, as well as spend funds for maintenance and operations (Hunhevicz et al., 2021). For now, we assume that decision making for IPD will be still human-based, so collective choice mechanisms (M5-1), peer-review mechanisms (M10-1), conflict resolution mechanisms (M12-1), and coordination among organizational tiers (M14-1) does not involve machine participation.

4.5.2. M2 – Tokenization of the Resources (for OP1b)

IPD projects require clearly-defined boundaries for the resources, i.e. which specific aspects of project scope and budget are open to all, and which are not (Hall and Bonanomi, 2021).

With tokenized project resources, e.g. the project budget, **representation and ownership of project resources** (Table 4.3, M2-1) can be clearly defined, also allowing monitoring of resources (M7-1). We are so far not aware of any research that proposes tokenization of physical resources in a construction industry context. Some research goes in this direction by exploring how crypto assets can integrate the physical and financial supply chains (Hamledari and Fischer, 2021c), or suggesting non-fungible tokens (NFTs) to represent building components (Dounas et al., 2021). Inspiration how and which physical resources to tokenize could also come from the asset-backed tokenization of “Holochain’s Commons Engine” or the commodity tokens of the “Economic Space Agency” (Fritsch et al., 2021). Tokenization of the resource would allow to manage digitally one or multiple resource pools with distinct appropriation and payoff functions. Related

IPD Application of Blockchain Mechanism	Mechanism	Ostrom Principle	Related Blockchain Research in the Construction Industry
M1-1: Scalable management of user identities and rights	M1	1a	Current research uses address-based rights as a prerequisite for blockchain applications. None investigate token-based rights.
M1-2: Machine participation	M1	1a	Robot participation (Lee et al., 2021); Self-owning house (Hunhevicz et al., 2021).
M2-1: Representation and ownership of project resources	M2	1b	Project bank accounts (Li et al., 2019a; Tezel et al., 2021).
M2-2: Decentralized funding and investment mechanisms	M2	1b	Project bank accounts (Li et al., 2019a; Tezel et al., 2021).
M3-1: Non-rent seeking and unrestricted matching of project needs with local conditions	M3	2a	Reverse auction-based tendering (Tezel et al., 2021); Decentralized design competition (Dounas et al., 2020; Lombardi et al., 2020).
M4-1: Transparent logic for the appropriation and access to resources	M4	2b	Financial mechanisms for IPD projects (Elghaish et al., 2020; Rahimian et al., 2021).
M4-2: Scalable and self-enforcing shared risk and rewards	M4	2b	-
M4-3: New incentive structures	M4	2b	Token-based incentives for data records (Hunhevicz et al., 2020b; Mathews et al., 2017); performance-based life cycle incentives (Hunhevicz et al., 2022c; O'Reilly and Mathews, 2019).
M5-1: Scaling of collective choices	M5	3	-
M5-2: Definition of voting rights for intended power distributions	M5	3	-
M6-1: Gamified and scalable sourcing of local actors' knowledge	M6	3	-
M7-1: More trust because of transparent user actions and resource flows, as well as predictive automation with smart contracts	M7	4a	Blockchain increases trust in supply chains through data tracking, contracting, and transferring resources (Qian and Papadonikolaki, 2020). Many papers focus on these aspects.
M7-2: Transaction history enables reaction to events and learning from past decisions	M7	4a	Many papers focus on triggering financial transactions based on events, e.g. as in Elghaish et al. (2020) and Hamledari and Fischer (2021c). None focus on learning aspect based on transaction history.
M8-1: Smart legal contracts	M8	4b	Theoretical investigation of intelligent contracts (Mason, 2017; McNamara and Sepasgozar, 2020, 2021). Performance based smart contracts (Hunhevicz et al., 2022c).
M9-1: Reputation tokens for special rights or for credentials	M9	4b	-
M10-1: Peer-review for project progress, quality, and cost	M10	4b	-
M11-1: Token-based sanctioning	M11	5	-
M11-2: Social sanctioning through transparent action	M11	5	-
M12-1: Smart contract based "mini courts" for fast and transparent conflict resolution	M12	6	Blockchain-based dispute resolution platform (Saygili et al., 2021).
M12-2: Token-based dispute participation to ensure "skin in the game"	M12	6	-
M13-1: Smart contracts ensure that powerful parties cannot solely enforce collective choices and conflict resolution	M13	7	-
M14-1: Smart contracts coordinate decision making among organizational tiers	M14	8	-

Table 4.3.: The 22 identified IPD applications based on the blockchain governance mechanisms. Some were already explored in existing construction blockchain literature.

to the project budget, this relates to the suggestion of blockchain-based project bank accounts for construction projects (Li et al., 2019a; Tezel et al., 2021).

In addition, **decentralized funding and investment mechanisms** (Table 4.3, M2-2) leveraging cryptoeconomics can be explored to extend incentive structures (M4-3). Augmented bonding curves could be one such mechanism to extend current risk/reward structures (M7-1) in IPD by yielding additional profit for invested stakeholders. Having said that, even though tokenized investment mechanisms for construction projects were already proposed (Tezel et al., 2021; Tian et al., 2020), normally a client pays for the project and there is no need to raise funds. Moreover, the power distribution to manage the resources is usually determined by the respective project roles, and not dependent on their point in time when they invest and support the project. Nevertheless, future PDMs might benefit from such new funding and investment mechanisms.

4.5.3. M3 – Decentralized Markets to Match Resources to Local Needs and Conditions (for OP2a)

Within IPD, key stakeholders often have experience with local conditions, such as availability of labor, material, work routines and other resources. Their early involvement provides the rest of the project team with a holistic understanding of the project conditions (Hall and Bonanomi, 2021).

Decentralized markets could improve and extend this with **non-rent seeking and unrestricted matching of project needs with local conditions** (Table 4.3, M3-1). Projects can find local resources and knowledge important for the success of the project without middleman profiting from facilitating these marketplaces, improving profitability of both the project and contributors. Decentralized marketplaces also allow users of the marketplace, e.g. the IPD stakeholders, project suppliers, and local residents, to collectively define rules. Furthermore, blockchain-based marketplaces can introduce new decentralized market mechanisms, only requiring a blockchain address and/or holding credentials such as reputation tokens. This could lead to more inclusive markets, potentially not only restricted to humans but also machines. We are not aware of any implemented decentralized marketplaces in the construction industry. Along these lines, Tezel et al. (2021) investigated a reverse auction-based tendering mechanism facilitated by smart contracts, and Dounas et al. (2020) and Lombardi et al. (2020) analyze a decentralized design competition.

4.5.4. M4 – Formalizing Appropriation and Provision Rules with Smart Contracts (for OP2b)

In IPD, the risk/reward pool is the main instrument to balance a firm's required participation with the potential reward according to their individual cost structure or accounting practices, their period of involvement in the project and/or their influence on the project's outcome (Cheng et al., 2016).

Smart contracts encode selection criteria and market mechanics visible to everyone and allow to forecast expected behavior according to the formalized rules. **Transparent logic for the appropriation and access to resources** (Table 4.3, M4-1) can be collectively ensured, especially if the resources are represented in the system through tokens (M2-1). This has been acknowledged for mechanisms of monetary resources in IPD projects (Elghaish et al., 2020; Rahimian et al., 2021). Moreover, smart contracts can ensure **scalable, self-enforcing, and stakeholder specific rules for shared risk and rewards** (Table 4.3, M4-2), hereby clearly defining provision rules of the system that confirm with the defined appropriation rules. However, this replicates existing IPD allocation rules at the firm level. **New incentive structures** (Table 4.3, M4-3) for IPDs only possible with blockchain mechanisms can be created. For example, blockchain could be used to issue non-monetary reputation tokens or access-tokens for decentralized markets (M3-1), decision making processes (M5-2), and to ensure “skin in the game” in legal disputes (M12-2). It is also possible to create new ways of token-based rewards (M4-2) and sanctioning (M11-1) at the individual or at the firm level.

Token-based incentives are to date rarely proposed in construction industry literature. Mathews et al. (2017) propose a token to reward parties for maintaining and improving BIM databases. Similarly, Hunhevicz et al. (2020b) explore smart contracts and tokens to ensure high-quality data sets in a construction project. Although not token-based, O’Reilly and Mathews (2019) and Hunhevicz et al. (2022c) explored performance-based incentives across life-cycle phases to design and build for the best possible energy performance across phases. Inspiration could come also from outside of the construction industry, e.g. from the Finance 4.0 initiative that explored token-based incentives to address sustainability (Ballandies et al., 2021a; Dapp, 2019).

4.5.5. M5 – Decentralized Proposal and Voting Platforms (for OP3)

In an IPD context, firms that have signed the multi-party contract are entitled to participate in management group functions and to vote on decisions that concern their work and area of expertise (Ashcraft, 2011; Perlberg, 2009).

Scaling of collective choices (Table 4.3, M5-1) in IPD could be achieved via decentralized proposal and voting platforms. First, stakeholders can gather opinions and proposals on project spending and execution. Afterwards, they allow for trusted voting on proposals to reach fast decisions even among organizational tiers (M14-1). Finally, they could collectively decide, e.g. through peer-review mechanisms (M10-1), on the appropriation and provision rules of the resources (M4-1) or how to incentivize project stakeholders (M4-3). If the project uses a tokenized resource pool or rewards, approved funds or resources could be automatically released upon approval (M2-1).

Although there are not yet examples in the construction industry, we can find multiple examples of implemented blockchain based decision making mechanisms. Token Curated Registries (TCR) (Asgaonkar and Krishnamachari, 2018; Wang and Krishnamachari, 2019) can be used to manage the validity and functionality of tokens (Rouviere, 2018). With a TCR users can collectively decide and entries to lists, e.g. to decide on new tokens or changes to existing tokens. Within IPD, a TCR could allow trustworthy and fast collective change processes after the initial project definition to existing tokens or propose new tokens as the IPD participants see fit. Another example for a decentralized governance platform is Politeia for the Decred blockchain, where stakeholders owning the cryptocurrency can upload proposals for network changes and treasury spending and then vote on it. Also, the Aragon project implemented a token based voting platform called Aragon Voice . IPDs could use similar decentralized applications to manage decision making.

Address or token-based access control allows fine-grained **definition of voting rights for intended power distributions** (Table 4.3, M5-2) among organizational tiers (M14-1), while maintaining scalability of the system. Suited voting forms and decision-making mechanisms would need to be explored in an IPD context. In the blockchain space, various voting mechanisms are proposed that could inspire new ways of voting within IPD. In Decred for example, holders have 1 vote per token (although pooled into larger amounts and locked for an uncertain time period). This approach is anonymous, whereas in 1 vote per person as often used in existing democratic systems, voters need to be identifiable. Another proposed voting mechanism for CPR governance (Dao, 2018; Emmett, 2019) includes 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 more prominently value the vote of minority opinions (Fritsch et al., 2021). Finally, in conviction voting stakeholders continuously allocate votes in form of tokens to different options that slowly decay if not renewed (Emmett, 2019). This allows to sense user preferences over long time periods and prevent last minute vote swings by large token holders (Fritsch et al., 2021).

4.5.6. M6 – Decentralized Prediction Markets (for OP3)

To make well informed decisions, decentralized prediction markets could be used for **gamified and scalable sourcing of local actors' knowledge** (Table 4.3, M6-1), maybe in combination with decentralized markets for local actors (M3-1) and to extend present incentive structures towards external actors (M4-3). Augur is likely the most common implementation of a blockchain based prediction market. To our knowledge there are so far no similar mechanisms within IPD. Nevertheless, research can explore if decentralized prediction markets can be useful in cases where actors are unknown or should remain anonymous, e.g. a betting platform to gauge expected costs of the project.

4.5.7. M7 – Transparent Record and Automation of Transactions (for OP4a)

IPD projects make use of monitoring practices such as "open-book finances" to track financial resources or "Big Room" to collocate stakeholders to commit publicly to work packages and continuously report their progress to the rest of the team (Hall and Bonanomi, 2021).

Blockchain creates **more trust because of transparent user actions and resource flows, as well as predictive automation with smart contracts** (Table 4.3, M7-1). IPD stakeholders can be identified through address-based access control and their transactions tracked visibly to all stakeholders, creating an inherent incentive to behave trustworthy since the other stakeholders can recognize malicious behavior (M11-2). Because of transparent financial transactions, open-book finances is inherently ensured. Furthermore, with resource tokenization implemented, resource flows and appropriation are observable. For example, a blockchain could help monitor the weekly withdrawals of resource units and alert participants to deviations from the cost targets initially estimated with the target value design process. In addition, smart contract automation gives more certainty in the expected transaction logic. Overall, transparency and smart contract automation creates trust in defined explicit incentive structures (M4-3), in collective choices (M5-1), in conflict resolution mechanisms (M12-1), and for coordination among organizational tiers (M14-1). The available **transaction history enables reaction to events and learning from past decisions** (Table 4.3, M7-2) for the management of user identities and rights (M1-1), ownership of resources (M2-1), decentralized market logic (M3-1), logic for the appropriation and access to resources (M4-1), refining incentive structures (M4-3), the definition of voting rights (M5-2), and the execution of smart legal contracts (M8-1), peer-review mechanisms (M10-1), and decentralized jurisdiction systems

(M12-1).

Blockchain increases trust in supply chains through data tracking, contracting, and transferring resources (Qian and Papadonikolaki, 2020). Many papers in a construction context focus on transparent and traceable records, e.g. of design data (Erri Pradeep et al., 2021) or construction related quality data (Sheng et al., 2020; Wu et al., 2021). Literature also investigates how to ensure traceability of built asset product information along the construction value chain in various contexts (Kifokeris and Koch, 2020; Li et al., 2021; Wang et al., 2020; Watson et al., 2019). Automated and traceable financial transactions are often suggested to enhance financial processes within construction projects (Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020; Das et al., 2020; Elghaish et al., 2020; Di Giuda et al., 2020; Hamledari and Fischer, 2021c; Nanayakkara et al., 2021; Ye and König, 2021).

4.5.8. M8 – Digital Signatures for Tamper-Proof Commitments (for OP4b)

To improve accountability within IPD, stakeholders can commit to work packages by signing a blockchain transaction. This enables **smart legal contracts** (Table 4.3, M8-1) when linked to terms encoded in smart contracts for trackable and automatic execution. Construction literature theoretically suggested smart legal contracts (Maciel, 2020; Shojaei et al., 2020), also termed intelligent contracts (Mason, 2017; McNamara and Sepasgozar, 2020, 2021). Based on agreed terms about committed work or performance data (Hunhevicz et al., 2022c), progress and completion can be tracked and confirmed (M7) to ensure accountability. Because machines can hold access rights, they also could commit to work packages and participate in smart legal contracts.

4.5.9. M9 – Reputation Tokens (for OP4b)

The concept of **reputation tokens for special rights or for credentials** (Table 4.3, M9-1) presents an interesting approach to reward or punish IPD participants (M4-3). Instead of monetary incentives, reputation tokens based on stakeholder accountability could give access to extended governance functions (M5-2) or could be used for credentials in decentralized markets for later projects (M3-1).

4.5.10. M10 – Decentralized Peer-Review Mechanisms (for OP4b)

Decentralized **peer-review for project progress, quality, and cost** (Table 4.3, M10-1) can be implemented with blockchain. For example, the Covee protocol realized a smart contract based peer review mechanism to determine fair profit distribution for decentralized collaborative teams (Dietsch et al., 2018). Anonymous work contributors get rewarded with cryptocurreny according to their peer-review score. A combination of blockchain-signed work packages, reputation tokens, and decentralized peer-review mechanisms could create a digital "big room platform" to ensure presence and accountability within IPD, and to evaluate appropriate rewards (M4-3) and sanctions (M11-1).

4.5.11. M11 – Transparent and Self-Enforcing Sanctions (for OP5)

Graduated sanctions are often not explicitly implemented in IPDs (Hall and Bonanomi, 2021). At most, the weekly public reporting of "Planned Percent Complete" (PPC) (Thomsen et al., 2009) acts as an early stage of social sanctioning (Kenig et al., 2010). In the case of continuous non-conformance or underperformance, the removal of individual participants and/or firms can be necessary (Cheng et al., 2016).

Blockchain can be an opportunity to reimagine and improve upon graduated sanctioning for IPD projects through decentralized and self-enforcing **token-based sanctioning** (Table 4.3, M11-1), e.g. loss of access tokens, loss of reputation tokens, or decrease in value of monetary tokens. Underperformance is also visible to everyone leading to **social sanctioning through transparent action** (Table 4.3, M11-2). In many cases this might be enough to ensure accountability but could be gradually combined with loss of tokens e.g. for access to the financial project rewards or even the project itself.

4.5.12. M12 – Decentralized Jurisdiction Systems (for OP6)

IPD projects craft conflict resolution mechanisms such as project decision protocols (Ashcraft, 2011) or liability waivers (Sive and Hays, 2009) that include clear dispute resolution strategies intended to avoid costly litigation proceedings.

Blockchain enables **smart contract based "mini-courts" for fast and transparent conflict resolution** (Table 4.3, M12-1) in IPDs. An exemplary decentralized jurisdiction system is already implemented in the Aragon Court to resolve subjective disputes that cannot be resolved by smart contracts alone. A global network of guardians helps intervene and arbitrate disputes. Saygili et al. (2021) already propose a decentralized blockchain-based online dispute resolution platform to resolve construction disputes. To incentivize compliance and accountability in a decentralized jurisdiction, **token-based dispute participation to ensure "skin in the game"** (Table 4.3, M12-2) is suggested. In case of non-compliance with the rules or the verdict, tokens at stake can be sanctioned.

4.5.13. M13 – Decisions are Ensured by Affected Parties (for OP7)

In IPD projects, project sponsors trade decision-making autonomy for consensus mechanisms among project team members (Hall and Bonanomi, 2021). In other words, authority is given by the project owner to the project participants to self-organize and self-govern the project. Blockchain transparency and censorship resistance enables **smart contracts to ensure that powerful parties cannot solely enforce collective choice and conflict resolution** (Table 4.3, M13-1) in IPDs (M5-2, M12-1, and M14-1). Ideally, decisions should be only possible to be made and challenged by actors that are also affected.

4.5.14. M14 – Coordination Rules Across Nested Enterprises (for OP8)

Large IPD projects have multiple nested management levels, including senior management team for executive leadership, a cross-functional project management team to coordinate project management activities, and functional teams that handle the direct work execution and organization (Ashcraft, 2011; Laurent and Leicht, 2019). Therefore, it will be important that **smart contracts coordinate decision making among organizational tiers** (Table 4.3, M14-1). This is either according to existing nested management levels of IPD or for new forms of organization better suited for fast information propagation and reactions to local events enabled by blockchain-based project governance.

4.6. IPD on the Crypto Commons: An Overview of the Conceptualization

Figure 4.2 summarizes the overall conceptualization, visualizing the OPs (Table 4.1), the 14 identified blockchain governance mechanisms (Table 4.2), and the 22 proposed applications for IPDs (Table 4.3).

The interaction arrows indicate then graphically the described connections in

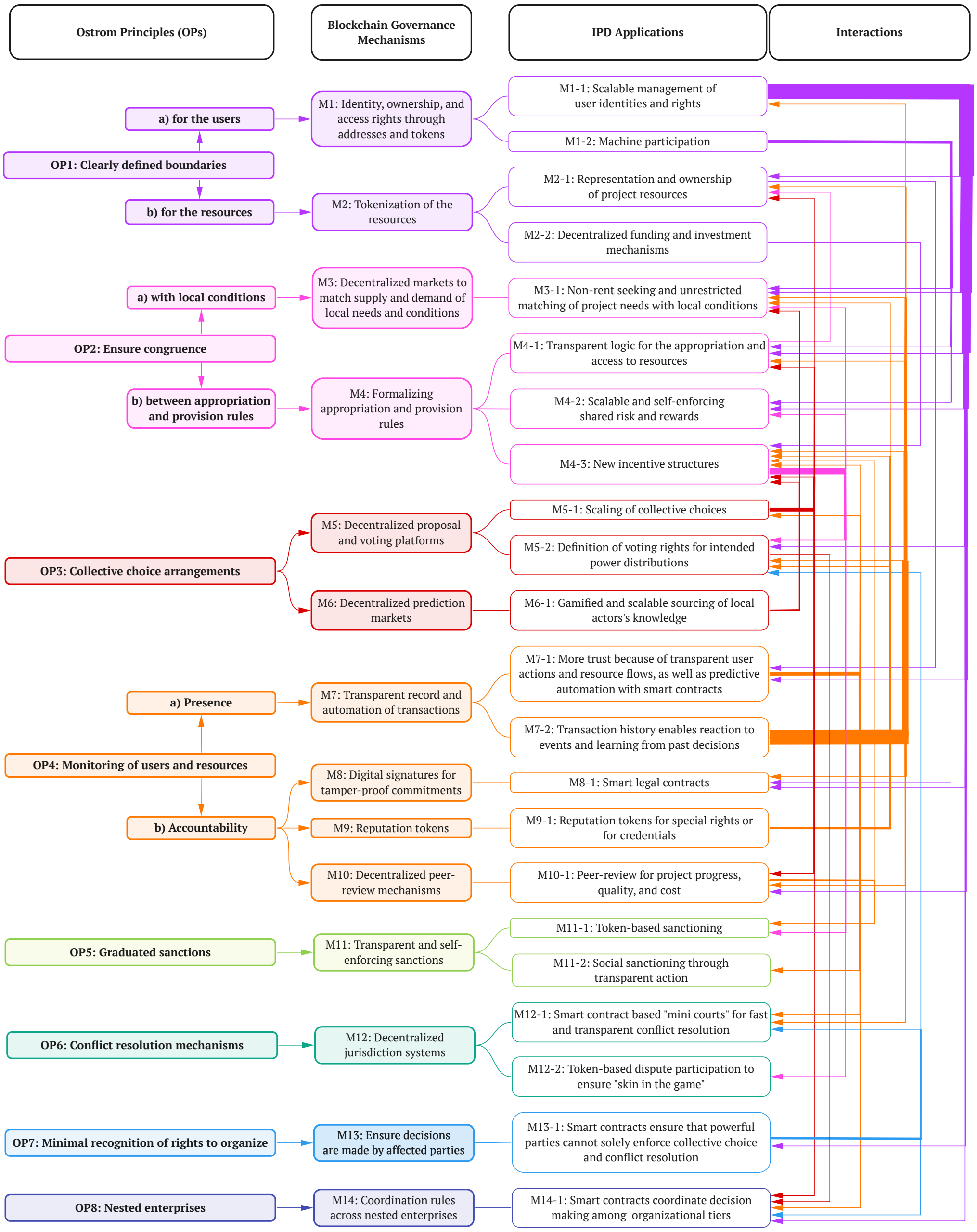

Figure 4.2.: Overview of the conceptualization of IPD on the crypto commons: the 12 blockchain governance mechanisms for the eight OPs as identified in Section 4.4, and the 22 identified applications for IPD and their interactions outlined in Section 4.5

Section 4.5 between the different IPD blockchain applications. The arrows are either outgoing, meaning they are a prerequisite or support other applications, or incoming, meaning they are supported or enabled by other applications. The width of the arrows and/or number of incoming connections can give an approximate indication of the importance of applications (outgoing) or prerequisites to build applications (incoming) within the overall conceptualization.

Applications that stand out regarding important prerequisite for IPD on the crypto commons are: M1-1 defining boundaries for the users through addresses and tokens, and M7-2 monitoring the presence of users and resources for fast system reaction and learning based on transparent record of automation and transactions. Applications that depend on many interactions of other applications in the system are in decreasing order of incoming connections: M4-3 for new incentive structures to influence the system participants towards collective action, M3-1 decentralized market structures to match project needs with local conditions, M5-2 for definition of voting rights to create intended power distributions, and M14-1 coordination among organizational tiers.

It is likely that not all connections have been identified and the interactions need to be updated when more research investigates individual applications and/or the interaction between them.

4.7. Discussion

4.7.1. Impact

The novel proposition of this paper is to create blockchain-based governance structures for IPD construction projects using the OPs as design guidelines. Trusted digital processes together with cryptoeconomic incentive mechanisms can align stakeholders, both human and machine, to better collaborate towards the overall project success. We see two main scenarios for the application of blockchain-based governance mechanisms as introduced in this paper.

First, blockchain based governance could address tradeoffs of current relational contracting approaches to improve IPDs. Relational contracting is well-suited to deal with contractual hazards of "displaced agency" (Henisz et al., 2012) found in the fragmented (Fergusson and Teicholz, 1996; Howard et al., 1989; Levitt, 2011) and loosely coupled (Dubois and Gadde, 2002b) construction project structures. However, relational contracts also comes at various costs (Henisz et al., 2012) that could be improved through blockchain-based governance mechanisms, e.g. reduced competition with scalable decentralized market structures, or lengthier processes for decision-making with decentralized decision-making platforms.

Second, the introduced blockchain mechanisms could be used to build new forms of project delivery coordinated on the crypto commons. Construction projects can be characterized by complexity (Bertelsen, 2003; Dubois and Gadde, 2002b; Gidado, 1996). Research suggests that bottom-up management and self-organization are better suited than hierarchical approaches to manage complexity (Bertelsen and Koskela, 2004; Helbing and Lämmer, 2008). The OPs introduce guidelines to achieve this for CPR scenarios. Since IPD can be described as a CPR scenario, blockchain governance mechanisms could improve IPD-like project deliveries by creating better bottom-up and self-organizing project structures, while still allowing for scalable coordination mechanisms.

This is aligned with the emerging organizational form of a decentralized autonomous organization (DAO), which is a blockchain-based system that enables people to coordinate and govern themselves mediated by a set of self-executing

Design Challenges	Type	Description
Transparency vs. Privacy	Tracking	Crypto Commons must be monitored, but transparent tracking could lead to privacy concerns.
Economic vs. Social Values Quantified vs. Qualified Values	Coding	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	Coding	Crypto Commons must encode incentives without causing unjustified manipulation and exclusion of stakeholders.
Private vs. Collective Interests	Coding	Encoding rules for Crypto Commons must weigh individual gains of stakeholders against the greater good of the community.
Human vs. Algorithmic Governance	Negotiation	Crypto commons must preserve human reasoning and debate in a system of formalized and algorithmic logic.

Table 4.4.: Design challenges for crypto commons (Based on the identified blockchain governance challenges by Cila et al. (2020)).

rules deployed on a public blockchain, and whose governance is decentralized (Hassan and De Filippi, 2021).

Sreckovic and Windsperger (2020) already proposed the evolution of the construction industry organization towards DAOs. Lombardi et al. (2020) and Dounas et al. (2020) even prototyped a DAO for decentralized coordination of the design finding process through smart contracts. Their research suggests that construction project governance as a DAO is at least in a prototyping context technically feasible. Other ongoing research explores how decision making of a self-owning house can be coordinated through a DAO (Hunhevicz et al., 2021).

Emerging examples of DAO frameworks (Faqir-Rhazoui et al., 2021) resemble many of the identified governance mechanisms. The proposed applications of blockchain mechanisms for IPDs based on Ostrom's design principles might help to design governance building blocks towards project delivery coordinated through DAOs.

4.7.2. Design Challenges

Designing new blockchain based governance systems is challenging. Cila et al. (2020) identified six design challenges (Table 4.4) that are further discussed below in the context of IPDs on the crypto commons.

Tracking

While transparent monitoring is essential to manage commons, it could lead to privacy concerns regarding the community-based data (Cila et al., 2020). Especially in public blockchain systems, traditional data privacy solutions are hard or even impossible to implement. It needs to be carefully evaluated what data needs to be transparently stored to enable IPD governance, how construction stakeholders perceive implications of sharing this data, and potential measures to maintain a suited level of privacy without hindering the monitoring.

Coding

A major challenge is decide, represent, and encode values in artificial commons (Cila et al., 2020). It tends to be easier to focus on economic and quantifiable values in a blockchain system (e.g. monetary values through market pricing mechanisms) than social and qualified values (e.g. reputation mechanisms). However, in commons non-monetary values often play an important role (Fritsch et al., 2021). Also, in IPDs, both quantitative and informal systems are used. Future research should investigate value flows in IPD, as well as how to encode them into incentive systems without suppressing creativity and teamwork with too rigid and inflexible smart contract structures.

Furthermore, incentives give people a sense of agency, yet at the same time they can have downsides of forced conformity with collectively set rules (Cila et al., 2020). At some point earning rewards might become a duty to not be excluded from the system and rewards cause efforts to shift towards the actions that will be rewarded, causing potentially unforeseen negative secondary effects (Cila et al., 2020). This needs to be subject of further study when designing project delivery mechanisms.

Artificial commons needs to find a balance between so trading individual gains for the greater good of the community (Cila et al., 2020). IPDs have differences to natural commons that need to be considered. For example, resources in IPDs are consumed intentionally over time, whereas in natural commons they are renewable. Natural commons also have an infinite lifetime (if the community is able to sustain them), while IPDs only last for the duration of a project (although this could be several years). And the product is owned by the project sponsor, whereas natural commons are not owned by any of the involved parties.

Overall, there is a need for more research to thoroughly understand current and new IPD mechanisms, how they contribute to the success of IPDs, and how they need to be set up in different project settings. Methods used to design and test such mechanisms should be able to reflect the complex nature of construction projects (Bertelsen, 2003; Dubois and Gadde, 2002b; Gidado, 1996). Previous research used game theory for the evaluation of profit distribution (Teng et al., 2019) and target value design (Jung et al., 2012), agent based simulations to assess the evolution of collaboration (Son and Rojas, 2011), or mechanism design to investigate new incentive structures (Han et al., 2019).

Negotiation

The last dilemma concerns how to preserve human reasoning and debate in a system of formalized and algorithmic logic (Cila et al., 2020). Also for IPD, there are major risks involved in ex-ante designs of smart contract, where system engineers need to account from the beginning for all expected cases. Therefore, the governance system should be able to adjust over time to exceptions and design errors through community input. But even with such governance processes embedded, the process will likely only start after the first failure already happened. A stepwise and careful adaption with extensive testing of these systems will be desirable.

4.7.3. Challenges Related to the Construction Industry Context

While technical and system design challenges towards a blockchain governed project delivery can be proactively addressed, there are many inherent construction industry barriers. Other scholars have already investigated barriers and socio-technical challenges for blockchain in the construction industry (Li et al., 2019a). The provided frameworks likely apply also for the proposed system. Below we highlight some of the key challenges.

The level of digitalization in the construction industry is still low (Agarwal et al., 2016; Barbosa et al., 2017). Blockchain-governed PDM require an extensive digital base-line of project related data. As long as this data is not available, the proposed mechanisms cannot make use of it to govern construction projects.

Moreover, the fragmented construction industry structure poses major challenges in the adoption of systemic innovations (Hall et al., 2018), e.g. as in the case of BIM (Papadonikolaki, 2018). Blockchain based governance for construction PDMs likely falls into the same category of systemic innovations, since value of the solution only comes at scale. At the same time, cryptoeconomic governance promises to reduce implications of fragmentation through incentives across phases and trades (Hunhevicz et al., 2022a). Nevertheless, it will be challenging to organically grow adoption.

Finally, there are major legal implications with such new solutions. Research needs to investigate how smart contract code can conform with law and regulations (De Filippi and Hassan, 2016).

4.7.4. Limitations

For blockchain based governance processes, the underlying blockchain infrastructure is a key component to success. For simplicity, this paper only refers to blockchain, but there are many kinds of DLTs suitable for different types of use cases. The choice of the right type is not part of this work, but should be considered once a use case will be implemented (Hunhevicz and Hall, 2020b). Many parameters such as security, throughput, privacy, approaches to smart contracts, and others need to be assessed. The still early technological state and the many different available solutions (Ballandies et al., 2021b; Spychiger et al., 2021) make this challenging. The paper assesses blockchain for CPR and IPD based on the assumption of public permissionless blockchains, since they align with the promise to govern decentralized economic coordination. When using other DLT options, the affected properties need to be adjusted. Future research should assess suited technical infrastructure to realize the proposed blockchain governance mechanisms in an IPD context.

Furthermore, the paper acts only as a starting point to conceptualize the connections between blockchain, CPR theory, and IPD. As a next step, further research is needed to validate the conceptualization. This includes validation of both the individual mechanisms and applications as well as their interaction. The contribution of this paper is limited as a proposed conceptualization, meant to underpin future research efforts that can validate and extend the conceptualization.

4.8. Conclusion

The paper extends the thinking around blockchain as an institutional innovation for the delivery of construction projects. It exploits the theoretical connection between both blockchain and IPDs as a CPR scenario to offer a systematic starting point how blockchain can support and evolve PDMs by creating novel governance mechanisms.

For that the paper introduces a conceptualization of blockchain-based governance applications for IPDs on the crypto commons. Twenty-two applications for IPD were identified based on fourteen mechanisms of blockchain for the governance of CPR scenarios proposed to encode the eight OPs. The conceptualization is useful to think more structured and modular about blockchain building blocks to govern construction projects collectively on the "crypto commons". Furthermore, the conceptualization can support the thinking around how blockchain could improve current IPD concepts, potentially lead to the next generation of PDMs, or ultimately end in novel project coordination through DAOs. On the one hand, blockchain-based governance mechanisms promise to facilitate trusted, scalable and efficient bottom-up coordination mechanisms that cope with complexity and displaced agency in construction projects. On the other hand, blockchain-based project delivery offers exciting new opportunities for machine participation.

Even though the paper introduced a coherent conceptualization for blockchain-based governance of PDMs, it requires further validation through proof of concepts investigating the feasibility of individual and combined mechanisms. For that the paper discusses challenges related to the early state of blockchain technology, the difficulties in designing blockchain-based governance systems, and the industry-related challenges to overcome.

The paper primarily targets the construction industry, but the identified blockchain governance mechanisms and applications could eventually be transferred to other cases of real-world commons.

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Part II.

Demonstrating the Potential and Feasibility of Cryptoeconomics in the Construction Industry

5. Digital Building Twins and Blockchain for Performance-Based (Smart) Contracts

This chapter corresponds to the published article:[1]

Hunhevicz, Jens J., Mahshid Motie, and Daniel M. Hall (Jan. 2022c). "Digital building twins and blockchain for performance-based (smart) contracts". In: *Automation in Construction* 133, p. 103981. ISSN: 09265805. DOI: `10.1016/j.autcon.2021.103981`.

Abstract: Servitization business models can use performance-based contracts to consider overall life-cycle costs rather than just production costs. However, practical implementation of performance contracts has been limited due to challenges with performance evaluation, accountability, and financial concepts. As a solution, this paper proposes the connection of the digital building twin with blockchain-based smart contracts to execute performance-based digital payments. First, we conceptualize a technical architecture to connect blockchain to digital building twins. The digital building twin stores and evaluates performance data in real-time. The blockchain ensures transparency and trusted execution of automatic performance evaluation and rewards through smart contracts. Next, we demonstrate the feasibility of both the concept and technical architecture by integrating the Ethereum blockchain with digital building models and sensors via the Siemens building twin platform. The resulting prototype is the first full-stack implementation of a performance-based smart contract in the built environment.

[1]Please note, this is the author's version of the manuscript published in the *Journal of Automation in Construction*. Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. The final publication is available at `https://www.journals.elsevier.com/automation-in-construction`. When citing this chapter, please refer to the original article found in the reference above.

5.1. Introduction

The global building and construction sector is a major contributor to global energy consumption (IEA, 2019). Despite governmental efforts to lower energy use and emissions, the trend is still rising (IEA, 2020). One untapped possiblity for emission reduction is the construction of more sustainable buildings with better lifecycle performance (IEA, 2020). However, these buildings suffer from the so-called building-energy performance gap, where the actual building life-cycle energy performance does not match predictions (De Wilde, 2014; Liang et al., 2019). Despite the push for more innovative and energy-efficient designs (Attia et al., 2017), the actual energy usage can be up to 250% higher than the predicted energy usage (Menezes et al., 2012).

Although some root causes for the building-energy performance gap can occur at the design stage (e.g., miscommunication among stakeholders, poor technology performance, or incorrect simulation models (De Wilde, 2014)), the construction and operations stages are also at fault. Energy performance can suffer from poor quality of initial construction and or poor operation of the building (De Wilde, 2014) resulting from organizational and behavioral factors (Liang et al., 2019). The final construction quality of the building might not be in accordance with the specification (e.g., poor attention to insulation and airtightness) (Newsham et al., 2009). Ad-hoc construction solutions can deviate from specified designs and result in unintended consequences that lower performance (Newsham et al., 2009). Further problems occur during the actual operation of the building. For example, occupant behavior and thermal comfort levels can deviate from assumptions and control settings can be manually changed by the facility management (FM) (De Wilde, 2014). Overall operational performance can suffer from a lack of continuity in monitoring, analysis, and control throughout the building lifecycle (De Wilde, 2014).

Such explanations for the building-energy performance energy gap illustrate the role of localized decisions and self-interested actions commonly found in the highly-fragmented architecture, engineering, and construction (AEC) sector. AEC suffers from a misalignment of incentives across the different stakeholders and life-cycle phases, which hinders holistic and systemic innovations (Sheffer, 2011). The different set of stakeholders, decision-makers, and values in each phase creates displaced agency – also called “broken agency” – where involved parties will engage in self-interested behavior and pass costs and risk off to others in the supply chain in subsequent life cycle phases (Henisz et al., 2012). Furthermore, the prevalent low-bid culture in construction also favors low-cost solutions at the tendering stage over solutions that minimize costs over the whole building life cycle (Scheepbouwer et al., 2017).

To address this, performance-based building has been recognized as a promising solution (Meacham et al., 2005). Performance-based building contracts are legal instruments intended to financially incentivize parties to deliver a building that meets targeted performance levels. These contracts bind the profit of parties to longer-term commitments based on mutually determined baseline performance levels during operations (Yik and Lee, 2004). Performance-based contracts in the built environment can be understood as a new and compelling business case (Bakens et al., 2005) called servitization. Servitization – also known as “Product-as-a-Service” – is a business model embraced by the manufacturing industry where products are leased out to the customer on performance contracts, while still being operated, maintained, and recycled by the producer (Baines et al., 2007). Servitization offers competitive advantages to the producers, lets customers profit from higher quality products and services, and benefits the environment through more reuse, recycling, and dematerialization (Vandermerwe and Rada, 1988; Mont, 2002; Baines et al., 2007; Crozet and Milet, 2017). Implemented in the built environment through performance-based contracts, servitization can align incentives over the life cycle of a building and address the energy performance gap (Liang et al., 2019).

However, servitization using performance-based contracts has not been widely adopted in the built environment (Bakens et al., 2005). Scholars note issues with accountability (Meacham et al., 2005), the lack of standardized performance evaluation (Pätäri and Sinkkonen, 2014), new and unfamiliar financial concepts (Pätäri and Sinkkonen, 2014), and the burdens of additional upfront communication efforts between parties (Gruneberg et al., 2007). Trial projects (e.g., the private finance initiative (Dixon et al., 2005) in the United Kingdom) promote the idea of the "built environment as a service" but have not generated much traction. The standard practice remains that building owners pay designers and builders a capital sum for initial construction while bearing themselves the long-term risk that comes from operating and maintaining the assets, even when they do not meet promised performance requirements.

The ongoing digitalization of the industry and new technologies like digital twins and blockchain present a new opportunity to better implement performance-based building (Saxon, 2020). The rise of digital building twins creates a bi-directional link between physical reality and the digital replica of a built asset (Brilakis et al., 2020). The digital twin concept is widely used in manufacturing to accurately reflect the real-world state in a virtual model. At the same time, the digital twin can adjust the real-time behavior of the physical product according to the performance assessments of the virtual model (Tao et al., 2019). Digital twins can enable performance-based contracting by setting performance expectations through simulation, measuring and updating the actual state of performance, and providing recommendations for operations and maintenance through analytics. Overall, digital twins can help to predict and measure performance accurately and equitably, thus overcoming a noted barrier to performance-based energy contracting in the built environment (Yik and Lee, 2004).

Furthermore, blockchain can ensure an unchangeable and transparent digital record of transactions. Some blockchains also support the execution of scripts called smart contracts to define tamperproof transaction logic. A fundamental challenge for performance based building is accountability (Meacham et al., 2005), an issue that blockchain can address by ensuring protection mechanisms that help to avoid the risks and costs of opportunistic behavior in construction supply chain collaboration (Qian and Papadonikolaki, 2020). However, to date, few attempts have been made to study or to implement performance-based smart contracts.

This paper investigates how blockchain based (smart) contracts in combination with digital building twins could support a transition to a more performance-driven built environment.

5.2. Departure

5.2.1. Towards a Performance-Based Built Environment

Product-as-a-service business models have been successful in the manufacturing industry (Baines et al., 2007). Adapting this model, Figure 5.1 conceptualizes the difference between a traditional and a servitized business model in the built

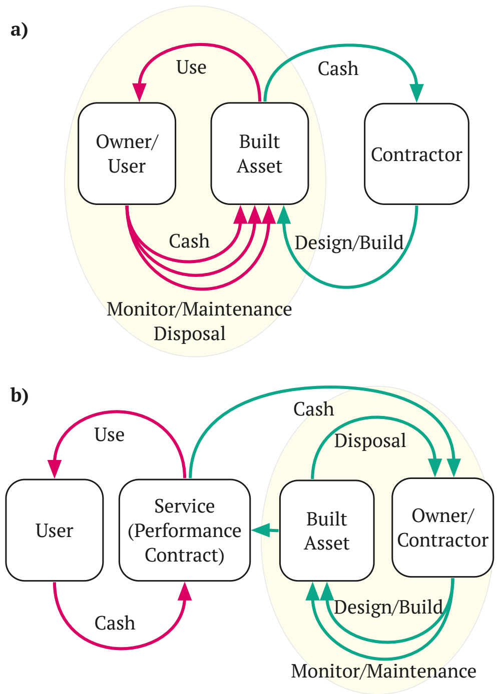

Figure 5.1.: (a) Traditional payment of a capital sum for the building at the end of construction. The user is responsible for operations, maintenance, and disposal. (b) In a built environment as a service, the user purchases the agreed services provided by the built asset. The owner/contractor takes care of production, operations, maintenance, and disposal. (Adapted from Baines et al. (2007))

environment.

In traditional construction, the owner usually pays a capital sum for the delivery of a built asset such as a building. This price includes the construction and initial commissioning of the project. Over the lifecycle of the asset, the owner is responsible for financing the operation, maintenance, and disposal of the asset (Figure 5.1, a)). This gives little incentive to contractors to design and build for the best possible life cycle performance, as they are not involved in later phases and their reward does not depend on life cycle performance.

In a performance-based building, the user would only pay for the provided services. Ownership and responsibility for operations, maintenance, and disposal stay with the producer (Figure 5.1, b)). This aligns the interest in designing and building for the best possible performance with the interest in minimizing operational, maintenance, and disposal costs (e.g. through recycling and reuse) in order to maximize profits.

Figure 5.1 is a simplification and does neglect many differences between the built environment and manufacturing. A built asset consists of numerous subproducts that provide different services. Also, more stakeholders might be involved, e.g. the owner could still be an investor rather than the producer. Nevertheless, the core message remains unchanged: servitization aligns interests across the asset life-cycle to maximize performance (Vandermerwe and Rada, 1988; Mont, 2002; Baines et al., 2007; Crozet and Milet, 2017). This is true regardless of which servitized asset or which stakeholders participate in the performance contract. Furthermore, it would be possible to only servitize certain technical sub-systems instead of whole buildings (e.g. heating or lighting) (Saxon, 2020).

This paper focuses on the potential role of digital building twins and blockchain-based smart contracts to enable digital, trusted, and automated performance contracts as the central element towards a servitized built environment (Figure 5.1, b)).

5.2.2. Current Practice of Performance-Based Contracts

Performance-based contracts link the building contractor or supplier to a longer-term commitment beyond the initial construction and handover of a facility (Gruneberg et al., 2007). To form the contract, parties mutually agree on a baseline performance level as the reference for determining the returning profits (Yik and Lee, 2004). Performance contracts can unite a building owner with a building contractor/operator for a shared profit goal (Deng et al., 2014). As a specific example, an energy performance contract establishes a link between building equipment and energy performance gains. The payments provide builders and operators with a long-term incentive to maintain and improve equipment performance (Sorrell, 2007; Papachristos, 2020). This contrasts with contractors in a conventional project, who are not involved in operations or maintenance and have no incentive to improve equipment performance after installation (Papachristos, 2020).

It is increasingly necessary to link construction project management to building performance and in particular to environmental sustainability performance (Papachristos et al., 2020). For example, Papachristos et al. (2020) use a system dynamics model combining project management and building energy performance to demonstrate that intra- and inter-stage partner alignment can increase building performance quality by 6.3%.

However, overall progress in the adoption of such performance contracts remains slow (Pätäri and Sinkkonen, 2014). Pätäri and Sinkkonen (2014) identify several risks and barriers to implementing performance-based contracts that are relevant to our study. Financial challenges include a lack of appropriate forms of finance due to conservative lending practices, limited experience in understanding performance-based project financing, a lack of confidence in servitization contracting, and a lack of standardized measurement and verification procedures for performance savings. Additional challenges come from the increased duration and complexity of the communication between the contractor, the client, and the tenants and building users (Gruneberg et al., 2007), as well as from issues of accountability in the case of performance failures (Meacham et al., 2005). Performance-based contracts might require contractors to re-examine business models, exploring vertical integration or direct employment to provide continuity of care over their completed buildings (Gruneberg et al., 2007; Pätäri and Sinkkonen, 2014). Scholars have called for exploration of how the new business models and new financing models of performance contracts can be combined with emerging automation technologies such as digital twins and the internet of things (IoT) (Mourtzis et al., 2018), but little research to date has explored this in detail.

5.2.3. Digital Building Twins

The digital twin is a virtual replica of a physical asset (Lu et al., 2020b). The concept of digital twins requires three parts: the physical product, the virtual replica, and the linkage between them (Kritzinger et al., 2018). The linkage is achieved using the IoT, which describes the concept of devices (things) with embedded electronics and software that collect and exchange data through the internet (Fleisch, 2010). In the digital twin concept, such smart devices collect data and transmit it to the virtual representation in the cloud, but also vice versa to optimize the physical product state based on analytics conducted on the virtual model (Tao et al., 2019). Digital twins are understood as one of the key enablers of digital transformation in the manufacturing industry (Rosen et al., 2015; Uhlemann et al., 2017; Kritzinger et al., 2018; Tao et al., 2019). While already adopted in many cases, research in manufacturing still investigates how the real-time integration of IoT and simulations can be improved (Ruppert and Abonyi, 2020; Glatt et al., 2021; Jiang et al., 2021).

As in manufacturing, digital building twins are envisioned as the next big step towards a digital construction and built environment, allowing for real-time performance optimization of built assets (Gerber et al., 2019; Brilakis et al., 2020; Sacks et al., 2020). The adoption of building information modeling (BIM), which is the continuous use of digital building models throughout the lifecycle of the built facility (Borrmann et al., 2018), is seen as the basis for this transformation. In contrast to digital twins, most digital building models still do not include any form of automated data exchange between the physical object and the digital object. Connecting BIM with IoT allows the digital model to be updated according to changes in the physical state of the building (Li et al., 2018; Tang et al., 2019; Zhai et al., 2019). Studies have only recently begun to research the potential of digital twins for performance optimization through real-time assessment of what-if scenarios in the virtual space in construction processes (Boje et al., 2020; Pan and Zhang, 2021), sustainability-based life cycle management of railway (Kaewunruen and Lian, 2019), operations management of HVAC systems (Lu et al., 2020a), and maintenance of bridges (Shim et al., 2019).

Despite the early research state, digital building twins are commonly seen as the inevitable evolution of BIM concepts towards more integrated and automated life cycle approaches (Boje et al., 2020) that focus on closing the information loop between digital and physical built assets (Sacks et al., 2020). They provide a platform to build data-driven and real-time performance-based contracts.

5.2.4. Blockchain

Blockchain is the most common type of Distributed Ledger Technology (DLT) (Tasca and Tessone, 2019; Ballandies et al., 2021b; Spychiger et al., 2020). It consists of a distributed record of transactions (called a ledger) in a peer-to-peer (P2P) network, where encoded governance rules incentivize participants to cooperate in adding transactions and securing the network. As a result, a blockchain can ensure an unchangeable and transparent digital record of transactions, which allows anonymous transacting parties to trust each other without intermediaries. For now, cryptocurrencies (e.g. Bitcoin (Nakamoto, 2008)) are the most prominent use case of blockchain. Newer networks innovate on the application layer built on top to enable new use cases through so-called smart contracts. Smart contracts encode interaction logic with transactions and run unchangeably on the blockchain. Ethereum (Buterin, 2014) was the first blockchain to enable such Turing-complete smart contracts. One of the most prominent smart contract use cases to date is decentralized finance (DeFi), which replicates financial services on the blockchain without the need of financial institutions (Schär, 2020).

Recently published literature reviews reveal a strong increase in publications that investigate blockchain across many sectors and in combination with other technologies (Casino et al., 2019; Frizzo-Barker et al., 2020; Gorkhali et al., 2020). Likewise, recent reports (Kinnaird and Geipel, 2017; Penzes, 2018; Nguyen et al., 2019) and articles (Turk and Klinc, 2017; Li et al., 2019a; Nawari and Ravindran, 2019b; Hunhevicz and Hall, 2020b; Perera et al., 2020; Scott et al., 2021) discuss blockchain use cases also for construction and the built environment. Hunhevicz and Hall (2020b) cluster use cases into seven categories and assess with their framework whether a DLT (blockchain) is needed. In brief, blockchain is needed when no third party can or should be involved, as well as when not all participants are known or interests are not aligned. Many of the proposed use cases apply blockchain to existing processes where stakeholders are known, so blockchain might not be necessarily required or at least needs further investigation (Hunhevicz and Hall, 2020b). However, use cases that involve coins and tokens for new payment or incentive schemes were found to be highly likely to rely on the use of blockchain (Hunhevicz and Hall, 2020b). Several publications support this observation by investigating blockchain-based payments along the construction supply chain (Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020; Das et al., 2020; Di Giuda et al., 2020; Elghaish et al., 2020; Hamledari and Fischer, 2021b; Sigalov et al., 2021; Tezel et al., 2021; Ye and König, 2021). In sum, the use of blockchain in construction promises to increase trust in existing processes through transparent and immutable transactions (Qian and Papadonikolaki, 2020).

The building of new incentive systems with trusted processes and unknown participants has led to new research streams referred to as token engineering or cryptoeconomic design (Voshmgir and Zargham, 2019). In the construction industry, the concept of cryptoeconomic incentives has been proposed as means to add a layer of monetary/non-monetary incentives to processes to increase trust and collaboration across life cycle phases and stakeholders (Hunhevicz and Hall, 2020a), e.g. to incentivize high-quality data sets (Hunhevicz et al., 2020b). Performance-based smart contracts seem well aligned with this concept and are therefore likely to benefit from a blockchain.

5.2.5. State of the Art

This section reviews the state-of-the-art research in construction and the built environment at the intersection of BIM, IoT, blockchain, and performance-based contracts.

Huang et al. (2020) found blockchain in combination with digital twins promising as a means to improve data management. Timestamping transactions helps to keep track of changes, as well as to manage data access, data sharing, and data authenticity among a network of actors. Lee et al. (2021) propose that the above can also be promising in construction for accountable information sharing. Their prototype records and timestamps data from a robot sent to its digital twin in near real-time on the blockchain, therefore implementing a full-stack prototype that connects a digital twin with blockchain. They highlight the future potential of automatic payments, but do not discuss or implement any link to performance-based smart contracts. Similarly, Hamledari and Fischer (2021a) present a full-stack prototype that transmits data from reality capture technologies on-site to a blockchain smart contract, in order to automate payments and the transfer of lien-rights through tokens. Also, Chong and Diamantopoulos (2020) present a full-stack protoype that sends data from smart sensors to the BIM model and smart contracts in order to execute secure payment in a façade panel supply chain. Neither of these last studies assesses performance based contracts.

O'Reilly and Mathews (2019) propose blockchain and a digital twin to enable financial incentives to design for better building performance during operations. They modeled an imaginary room with four heat sensors and connected it to a dynamo code that fetches the virtual sensor data and stores it in a simulated blockchain environment. However, their prototype simulates both the blockchain and IoT part and does not yet implement the described incentives through a smart contract. Li et al. (2019b) demonstrate how sensors can gather data on the performance of a simulated installation task, store this data in the blockchain, and use a smart contract to issue automatic payments if the predefined performance conditions are met. However, this prototype does not fully connect IoT, a digital model, and an operational blockchain. While some literature discusses the potential of legal contracts on the blockchain on a conceptual level (Mason, 2017; McNamara and Sepasgozar, 2020), Gurcan et al. (2019) developed the first prototype of an energy performance smart contract using the Ethereum blockchain. They successfully tested their smart contract on a private network instance with five-day weather and building performance data set. However, there was no actual connection to sensors and a digital twin, nor was the purpose of the performance contract to incentivize performance across life cycle phases.

5.2.6. Research Gap and Scope of the Study

Although performance-based building has the potential to address the observed energy performance gap, performance-based contracts have not yet been widely implemented. Digital building twins analyze real-time performance data of buildings and can provide a data baseline for performance-based contracts. Nevertheless, the fragmented construction industry faces trust problems across life-cycle phases and trades, and digital building twins alone are unlikely to address this substantially. Blockchain, however, could facilitate trusted cross-phase processes and contracts, building upon the performance data provided by digital twins.

Despite the potential, no research has yet investigated cross-phase performance contracts leveraging blockchain smart contracts and digital building twins to incentivize stakeholders along the built asset life-cycle. Therefore, we illustrate how blockchain smart contracts and digital building twins can interact to enable digital, performance-based contracts. To move beyond theory, we prototype a full-stack architecture using the Ethereum blockchain and the Siemens building twin platform to implement an exemplary cross-phase thermal performance smart contract. The smart contract was successfully tested over two days with sensor data obtained from the digital building twin of a real-world building. Based on the findings, the paper discusses the challenges and opportunities of performance-based smart contracts in combination with digital building twins to move towards the potential new paradigm of a built environment as a service.

5.3. Proposed Performance-Based Smart Contract Architecture

We introduce the necessary components to facilitate performance-based smart contracts for a built asset as visualized in Figure 5.2. A cyber-physical system is characterized by two layers: the physical world and the cyber world. In the physical world, the actual built asset is equipped with sensors that can measure various performance metrics. Furthermore, human stakeholders interact with the built asset, the digital twin of the built asset, or the performance-based contract.

The following section describes in more detail the core components of the cyber world: the building twin platform, the performance-based smart contracts, and the data bridges required for the blockchain we call "front-end oracle" and "back-end oracle".

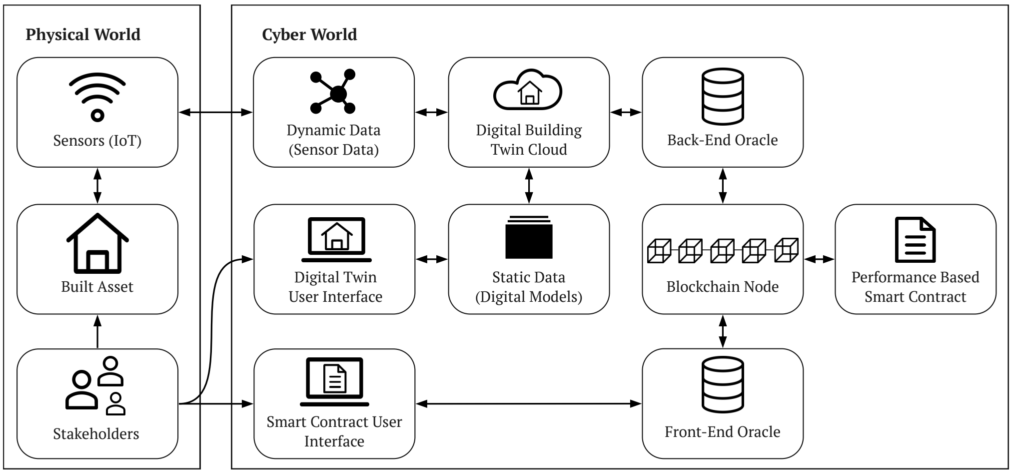

Figure 5.2.: Interaction of needed cyber-physical components for performance-based smart contracts of built assets.

5.3.1. Building Twin Platform

The digital building twin is hosted on one or multiple cloud servers, where data is processed and stored and performance simulations are facilitated. We refer to two types of data: dynamic and static data. Dynamic data refers here to the constant live-data stream captured by the sensors. Static data refers to all other data created by human stakeholders, most importantly the digital BIM models (i.e. IFC files). The stakeholders interact through a graphical user interface with both the static and dynamic data. In most digital building twins, the dynamic data is mapped to a spatial location in the digital model, accessible in the digital twin user interface.

5.3.2. Performance-Based Smart Contracts

The smart contracts created on the blockchain encode the rules of the performance-based contract. Their core functionality can be describe as continuously receiving performance data, checking the data against the encoded contract logic, and executing the subsequent workflow steps (e.g. payments). Figure 5.3 displays the interaction of needed components that together form a performance based smart contract.

First, a performance based smart contract must manage the different contracting parties. A smart contract manager is needed settting up the smart contract. Other roles could be the building owner and/or contractors who need to deliver the service, and one or multiple users who receive and pay for the service. So-called roles can then be assigned to blockchain addresses that are allowed to modify and execute the respective transaction. For example, the owner of a smart contract can register for an address “contract_owner”, or the owner of the built asset can register for an address “asset_owner”. These two roles can have different rights assigned to them for interaction with smart contract functions. It is important to note that one address can also be assigned to multiple roles.

Second, the smart contract encodes the contract logic through smart contract functions. Permissions are assigned to the defined roles and addresses registered in the smart contract. Before executing workflow logic, the smart contract must check whether the address initiating a transaction is allowed to do so. The performance terms then encode the agreed levels of service that are continuously checked against the received actual performance data. If the performance lev-

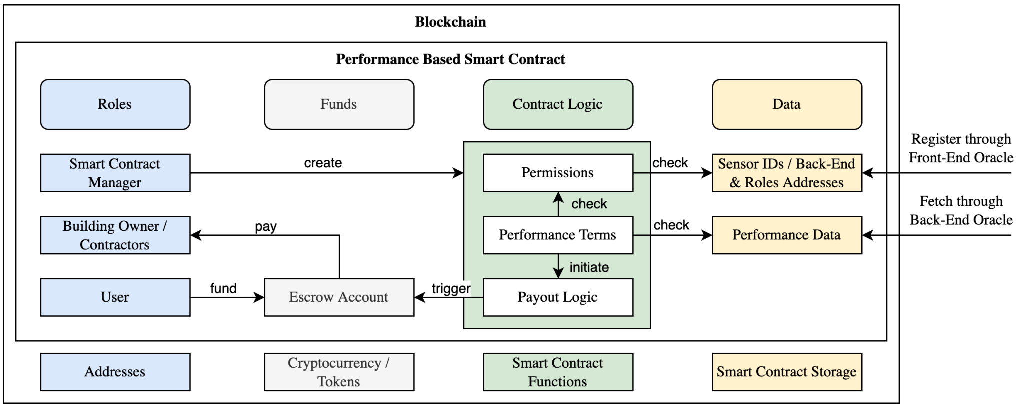

Figure 5.3.: The interaction of roles, funds, contract logic, and data in a performance based smart contract.

els are met, the payout logic manages the according payments to the service providers. Third, funds managed by the smart contract ensure that payments can be timely executed through the use of cryptocurrency or tokens. For that the service users need to pay an upfront payment to the smart contract escrow account.

Lastly, relevant data needed to execute the contract logic is stored within the smart contract. This includes addresses of the users and back-end allowed to interact with the smart contract functions, as well as IDs of the sensors and digital twin. Furthermore, external performance data about the observed real-world events is stored within the smart contract. Since blockchain cannot directly obtain external data, a middleware called an "oracle" is required to create a secure connection between the smart contract and an off-chain data resource. The use of such oracles also introduces the "oracle problem" (Caldarelli, 2020). In essence, blockchain can verify data integrity on its own ledger and network but it cannot know whether data input by humans or sensors are correct in the first place. This leaves open the possibility that malicious actors try to cheat the system by inputting incorrect data. Every implementation of smart contracts relying on oracles should strive to minimize this possibility.

In the case of a performance-based contract for a built asset, two oracles are needed: the "front-end oracle" (see 5.3.3) as a middleware to connect the web front-end with the blockchain to allow direct stakeholder input, and the "back-end oracle" (see 5.3.4) to connect the digital building twin platform with the blockchain to fetch performance data.

5.3.3. Front-End Oracle

A performance-based smart contract benefits from a connection to a graphical user interface so stakeholders can interact directly with the contract in a convenient way. Stakeholder interaction is required to set up the contract and define the contract logic, register the addresses and roles of the users, register the addresses and IDs of the sensors and digital building twin, interact with the smart contract functions, and check the status of the smart contract (so-called states).

Therefore, the front-end provides a web user interface for the input of static information as well as an oracle middleware to transfer this data to the blockchain and smart contract. These tasks could also be achieved without a graphical user interface, but this complicates the setup, deployment, and interaction with the smart contract considerably. Without a graphical interface, all contract addresses, functions, and parameters would need to be known by all stakeholders interacting with the contract.

5.3.4. Back-End Oracle

Once the smart contract is set up, it needs to fetch the performance data of the built asset to assess performance logic. Data from the sensors need to be automatically transmitted to the smart contract. Therefore, a back-end oracle ensures the connection between the digital building twin and the blockchain to transmit the sensor data that has already been processed and stored in the digital twin database. The back-end oracle calls the Application Programming Interfaces (APIs) of the digital building twin database, fetches relevant performance data, translates the data received into the right format, and initiates the transaction.

5.4. Proof of Concept

5.4.1. Use Case

To demonstrate the proposed concept and validate the technical architecture, an exemplary performance-based smart contract was developed and tested on a real-world building in combination with its digital twin.

The prototype was tested on the real-world building "Technology Center 2" (Tz2) located in Seestadt, Vienna (see Figure 5.4). It is part of the Aspern Smart City Research center. The commercial building has a floor area of 5600 m2 and can be rented by innovative companies and start-ups. The building is equipped with photovoltaic panels, a heat pump, various energy storage facilities, thermally activated building systems (TABS), smart meters, and sensors. The building condition is monitored and controlled via its digital twin using the Siemens building twin platform.

To limit the scope, we focused on the specific use case scenario of a cross-phase thermal performance contract (see 5.4.3). The full technology stack was implemented, including a front-end oracle with UI to allow participants to set up and input contract information, and a back-end oracle to connect the smart contract to the digital building twin and sensor data. The high-level workflow is depicted in Figure 5.5.

Incentive Design

Since it is a cross-phase performance-based contract, the workflow starts in the design phase (see Figure 5.5). The scope, logic, and performance basis of the thermal performance contract is defined before the building is constructed. In the implemented use case scenario, the performance contract is established between the building owner, the contractor who designs and constructs the building, and the facility manager that will operate the building. The owner sets the performance target in agreement with the other stakeholders. If the contractor and facility manager meet the performance target, they are paid for the service provided. The smart contract is coded and deployed, and the initial users (owner and contractor) are registered. Instead of paying the contractor a capital sum, the owner funds the smart contract with an escrow to assure that the payments are allocated in the operational phase. Once the building is built and the digital building twin is set up, the building with its sensors and the facility manager role is registered. The smart contract then operates and executes the performance logic and subsequent payments as defined. When not needed anymore, the smart contract is deactivated.

Figure 5.4.: The IFC model of Tz2 used as a static data source for the digital building twin (Copyright: ATP architekten ingenieure).

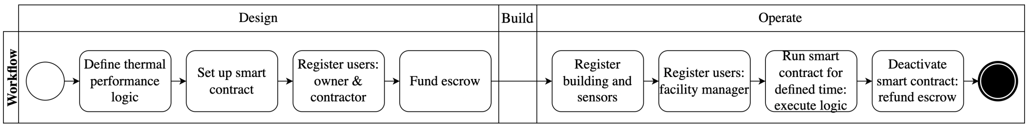

Figure 5.5.: Work flow for the tested cross-phase thermal performance scenario.

Performance Contract

The performance contract incentivizes the construction and operations for a mutually established thermal performance level during the use phase by leasing out thermal performance as a service. The smart contract directly executes payment from the escrow to the contractor and facility manager for delivering the agreed-upon performance levels. It is not the focus of this work to propose a finished performance contract, but rather to demonstrate an exemplary cross-phase incentive case that can be tested with the actual sensor data of the Tz2 building. Nevertheless, the contract is based on common thermal performance evaluation metrics.

The energy consumption of the building and the level of comfort of the building occupants are two of the most important thermal performance factors. While it is clear that high energy consumption causes increased costs, dissatisfaction of occupants regarding comfort levels also increases costs. For example, users might set up their own local heaters and coolers (Jazizadeh et al., 2014) or their work performance might decrease, leading to a rise in personnel costs (Wagner et al., 2007). Therefore, the implemented thermal performance logic measures and evaluates 1) overall energy consumption, and 2) thermal comfort levels of the building.

The logic regarding overall energy performance (EP, Eq. 5.1) compares the actual average energy consumption for a given time interval ($E_{\Delta t}$) with the expected energy consumption (E_0).

$$EP_{\Delta t} = \frac{E_{\Delta t}}{E_0} \tag{5.1}$$

Thermal comfort assessement is based on a simplified predicted mean vote

	Temperature	Relative Humidity	CO2 Concentration
Defined range (facility manager)	$0.9 \leqslant TC_{T,\Delta t} \leqslant 1.1$	$0.75 \leqslant TC_{RH,\Delta t} \leqslant 1.5$	$TC_{CO2,\Delta t} \leqslant 1.5$
Reduced reward (facility manager)	$0.8 \leqslant TC_{T,\Delta t} < 0.9$ $1.1 < TC_{T,\Delta t} \leqslant 1.2$	$0.4 \leqslant TC_{RH,\Delta t} < 0.75$ $1.5 < TC_{RH,\Delta t} \leqslant 1.8$	$1 < TC_{CO2,\Delta t} \leqslant 1.1$
Failure (facility manager)	$TC_{T,\Delta t} < 1.2$ $1.2 < TC_{T,\Delta t}$	$TC_{RH,\Delta t} < 1.8$ $1.8 < TC_{RH,\Delta t}$	$1.1 < TC_{CO2,\Delta t}$

Table 5.1.: Performance reward logic for the facility manager.

	Energy Consumption	Facility Manager's Performance ($TC_{T,\Delta t}$)		
Defined range (contractor)	$EP_{\Delta t} \leqslant 1$	$TC_{T,\Delta t}$	$TC_{T,\Delta t}$	
Reduced reward (contractor)	$EP_{\Delta t} \leqslant 1$	$TC_{T,\Delta t} < 0.8$		
	$1 < EP_{\Delta t} \leqslant 1.5$	$TC_{T,\Delta t}$	$TC_{T,\Delta t}$	$TC_{T,\Delta t}$
	$1.5 < EP_{\Delta t}$	$1.2 < TC_{T,\Delta t}$		
Failure (contractor)	$1.5 < EP_{\Delta t}$	$TC_{T,\Delta t}$	$TC_{T,\Delta t}$	

Table 5.2.: Performance reward logic for the contractor, given the facility manager's performance.

model (PMV, Eq. 5.2) developed by Buratti et al. (2013) based on Rohles (1971), and it only relies on air temperature and relative humidity, since the original PMV model developed by Fanger (1970) also takes into account air speed and mean radiant temperature, neither of which is measured in Tz2. Buratti et al. (2013) provide an extensive data baseline distilled into diagrams for acceptable levels of PMV for a specific comfort scenario (determined by the parameters a, b, c), given the temperature (T) and water vapor pressure (P_v) derived from the relative humidity (RH).

$$PMV(T, P_v) = aT + bP_v - c \tag{5.2}$$

Based on this data, one can select a target comfort scenario and derive the required set point temperature and relative humidity.

First, the thermal comfort for room temperature (TC_T, Eq. 5.3) compares the actual average room temperature for a given time interval ($T_{\Delta t}$) to the targeted set point temperature (T_0).

$$TC_{T,\Delta t} = \frac{T_{\Delta t}}{T_0} \tag{5.3}$$

Second, the thermal comfort for relative humidity (TC_{RH}, Eq. 5.4) compares the actual average relative humidity for a given time interval ($RH_{\Delta t}$) to the targeted relative humidity (RH_0).

$$TC_{RH,\Delta t} = \frac{RH_{\Delta t}}{RH_0} \tag{5.4}$$

Finally, since CO2 measurements are also available in Tz2 as a good indicator of air quality, we compare the CO2 thermal comfort ratio (TC_{CO2}, Eq. 5.5) with the actual average $CO2$ level in a given time interval ($CO2_{\Delta t}$) with a targeted $CO2$ level ($CO2_0$) often assumed to be below 1000ppm (European Commission, 2011).

$$TC_{CO2,\Delta t} = \frac{CO2_{\Delta t}}{CO2_0} \tag{5.5}$$

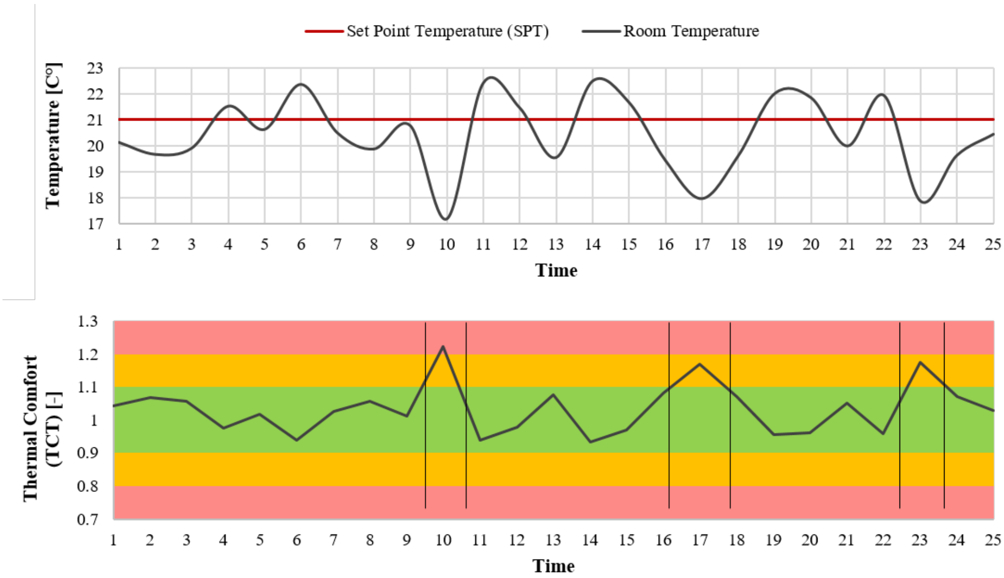

Figure 5.6.: Exemplary visualization of performance assessment for the temperature thermal comfort (TCT). For a given SPT of 21°C and the measured room temperature values (a), the TCT ratio must stay within the defined range (green), causing a reduced reward (orange) or failure (red) for the facility manager when deviating (b).

To summarize, the data fetched from the Tz2 sensors are indoor temperature, relative humidity, $CO2$ concentration, and energy consumption for heating and cooling. To assess the thermal performance, several factors have to be agreed on: an expected energy consumption, a thermal performance scenario determining the expected values for the set point temperature and relative humidity, and a target $CO2$ level.

The performance contract determines whether the contractor and facility manager succeed or fail in delivering the agreed performance levels. For the proof-of-concept, the logic assesses performance deviations in percent defined by the authors based on reasonable assumptions (Table 5.1, Table 5.2, Figure 5.6). The facility managers need to ensure indoor comfort, so the reward depends on reaching the expected levels for temperature, relative humidity, and CO2 concentration (Table 5.1). The full reward requires two out of three targets (green) to be reached. For two out of three failed targets (red), no reward is issued. In between, there is a reduced reward (orange). The contractor's reward depends on the total energy performance ratio, but in relation to the thermal comfort levels for room temperature (Table 5.2). This ensures both that a contractor cannot bribe the facility manager to reduce indoor comfort to meet the energy performance and that extensive heating of the building by the facility manager does not cause a failure for the contractor.

5.4.2. Technical Implementation

This section describes in more detail the technical implementation of the proof of concept. An overview of the implemented components is shown in Figure 5.7. The code is available under an open source licence[2].

[2] `https://github.com/mahshidmotie/PerformanceBasedSmartContracts`

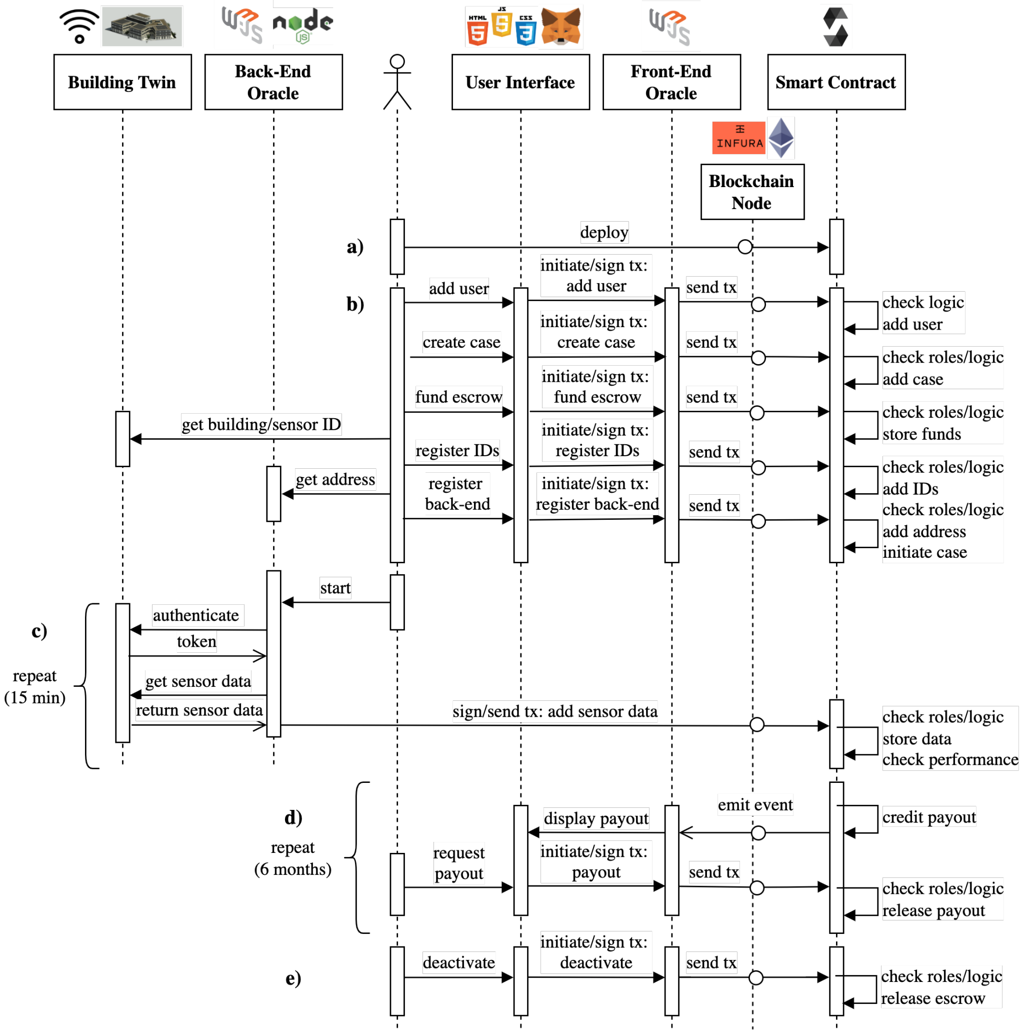

Figure 5.7.: Interaction of the implemented technical architecture for the proof of concept workflow.

Thermal Performance Smart Contract

For the scope of this proof of concept, we selected the Ethereum blockchain to develop and deploy the performance-based smart contract. At the time of conducting this research, Ethereum was the most prominent Turing-complete smart contract platform with extensive documentation available. Nevertheless, other blockchains could be chosen in the future (see 5.5.1).

The smart contract is written in Solidity, the native smart contract language of Ethereum. We developed the smart contract using the Truffle suite, with Ganache as a local blockchain environment (see Figure 5.8). The smart contract logic can be separated into two main parts: roles and access management, and the thermal performance contract logic. Roles management for access control was implemented by inheriting the OpenZepplin "roles" and "ownable" smart contract templates. In addition to the roles of the building owner, the contractor, and the facility manager, the role of the smart contract owner is important. The smart contract owner role is assigned to the person deploying the contract. This role then has the right to assign the other roles, so that they can interact with the smart contract.

The thermal performance logic in the coded smart contract functions follows

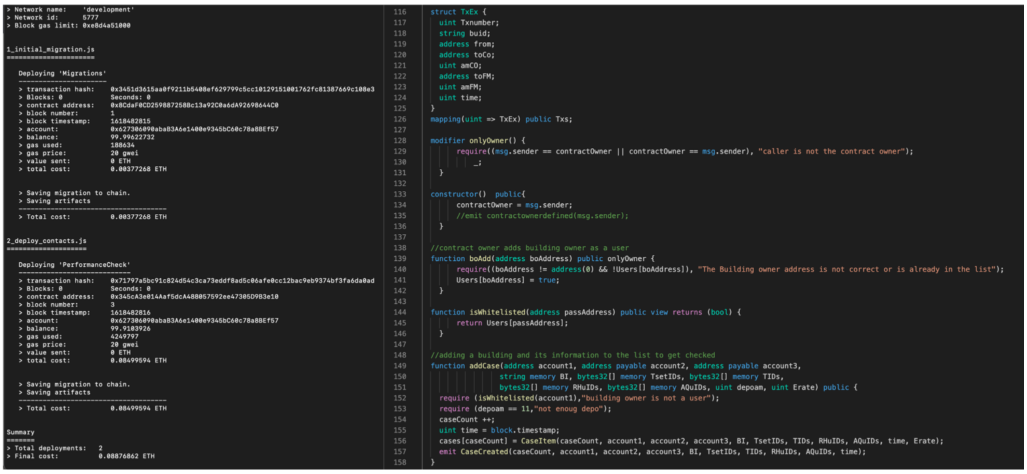

Figure 5.8.: Smart contract deployment to the development network using Truffle.

the logic described in section 4.1.2. When all logic is encoded, the smart contract is deployed (see Figure 5.7, a)).

Afterwards, case-specific information can be added to the contract (see Figure 5.7, b)). First, stakeholder roles are assigned and the specific contract case is created. The stakeholders define the contract details, such as the duration, the building, the relevant sensor data, and the agreed performance baseline. Furthermore, the building owner funds and locks the escrow. This assures the other parties that funds are available and reserved for payment throughout the duration of the contract. Finally, the building and sensor IDs, as well as the address of the back-end, need to be registered in the smart contract before execution can start.

When all information is input and the contract is funded, the contract execution can begin (see Figure 5.7, c)). The back-end oracle is started and the defined performance data (energy and indoor-comfort data) is passed at defined time intervals from the building twin platform to the smart contract by calling the respective smart contract functions. The data is stored, the values are evaluated by the contract logic, the results are saved, and respective actions are triggered. For monetary payments, the smart contract keeps track of the amounts earned by each role.

Finally, the rewards can be redeemed through the front-end at defined intervals of 6 months (see Figure 5.7, d)). This interval was chosen to reduce the number of monetary transactions that need to be triggered by the stakeholders, but also other time intervals can be used. After the contract duration is complete, the building owner can release the remaining escrow amount (see Figure 5.7, e)).

Front-End Oracle

The web application is built with HTML, CSS, and JavaScript. The graphical user interface provides an input mask for the smart contract arguments to set up the smart contract or to interact with the smart contract functions. The front-end triggers transactions using the Web3.js API. To sign transactions, the user needs to use a wallet that handles the correct private keys. This ensures that only authorized roles can perform actions. In this proof of concept, we use Metamask to connect with an Ethereum node. For development purposes, we used a local blockchain instance (Ganache), but to deploy to the test network (Rinkeby), we used the Infura API to connect to remote nodes.

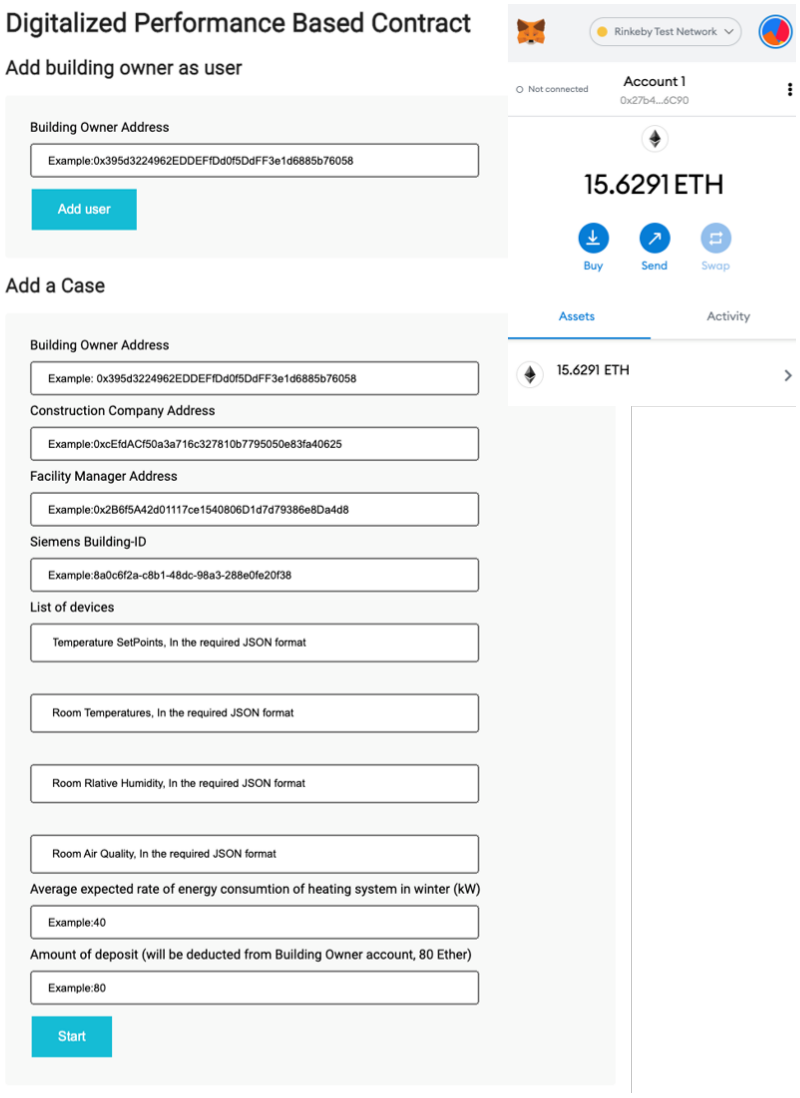

Figure 5.9.: Snippet of the graphical input mask to execute the performance-based smart contract functions, using the Metamask wallet to sign transactions.

The contract stakeholders can use the graphical input mask in combination with Metamask to conveniently interact with the smart contract (see Figure 5.9). They can set up a new case, check on the contract status, and redeem their rewards.

Back-End Oracle

The back-end oracle server acts as a middleware between the Siemens building twin platform and the Ethereum blockchain. It is built using Javascript and NodeJS. The connection to the Siemens building twin platform is established using its APIs. A valid access token needs to be appended to the API calls. The fetched data is then formatted and passed to the smart contract by calling the respective smart contract function using the Web3.js API and Infura API. In contrast to the front-end oracle, the same address owned by the back-end oracle always signs the transaction. Therefore, Metamask is not needed. The back-end address is registered in the smart contract, so no other address can call the function. The transactions are directly signed by the server with the private key using the web3.js wallet functionality. Since the data is saved in the smart contract, the transaction costs increase with the number of submitted data points. Storing large amounts of data in the smart contract can be very costly and not economically viable. Therefore, the transmitted data points should be minimized without affecting the performance contract functionality. At the same time, the possibility for data manipulation (see 5.3.2, oracle problem) should be addressed.

Various scenarios were investigated. First, the number of sensors and therefore monitored spaces can be limited. Obviously, this would also limit data diversity since only some rooms are monitored. Moreover, a scenario with fewer sensors means a higher chance that the selected physical sensors or the sensor data in the building twin central storage could be manipulated. Second, all sensors can be fetched simultaneously, but the time intervals of fetching data can be decreased. However, specifying known and consistent time intervals poses also more attack vectors to manipulate data at exactly these points in time. The third scenario can follow a randomization strategy regarding both space and time. On average, data is fetched every 15 minutes, but with randomized variations. Moreover, at each time a random sensor is chosen out of the registered list of sensors. Finally, the number of measurements should match the number of data points needed for the evaluation logic.

After evaluation, the third scenario was selected for test implementation in this paper. In the implemented case, indoor environment measurements of sensors are selected on average five times a day, while heating energy consumption is measured only once a week.

Siemens Building Twin Platform

The Tz2 building is monitored and controlled with the Siemens building twin platform (Siemens, 2021). The platform is a single source for both static and dynamic data. This data is visualized in a digital 3d model by constantly updating the static building information (based on the BIM IFC files from the design and construction) with the dynamic real-time data from the connected sensors. The platform can also run performance analytics to help optimize the technical systems of the building.

In the proof of concept, we used the Siemens building twin platform of Tz2 as an external data source for the performance-based smart contracts (see Figure 15.10). The sensors are referenced in the static IFC files of the digital model with their BACnet addresses. This allows the sensor data to be mapped to the respective physical devices and spaces in the 3d visualization. Relevant sensors can be identified to register their BACnet addresses in the smart contract. The respective sensor data are then fetched from the digital twin database and transmitted to the smart contract.

5.4.3. Test Results

Test Setup

To test the implemented architecture (see 5.4.2), the performance-based smart contract was deployed to the Rinkeby network[3], a test network of Ethereum. An exemplary case was created with three imaginary stakeholders (building owner, contractor, and facility manager). The smart contract ran for two days starting on May 14th and ending on May 16th, 2020 on the test network.

The performance baseline for the weekly energy consumption was chosen as

[3] https://rinkeby.etherscan.io/address/0x2b8aaf9B539fA288e1dFEa8866B6b51d1cD804B3

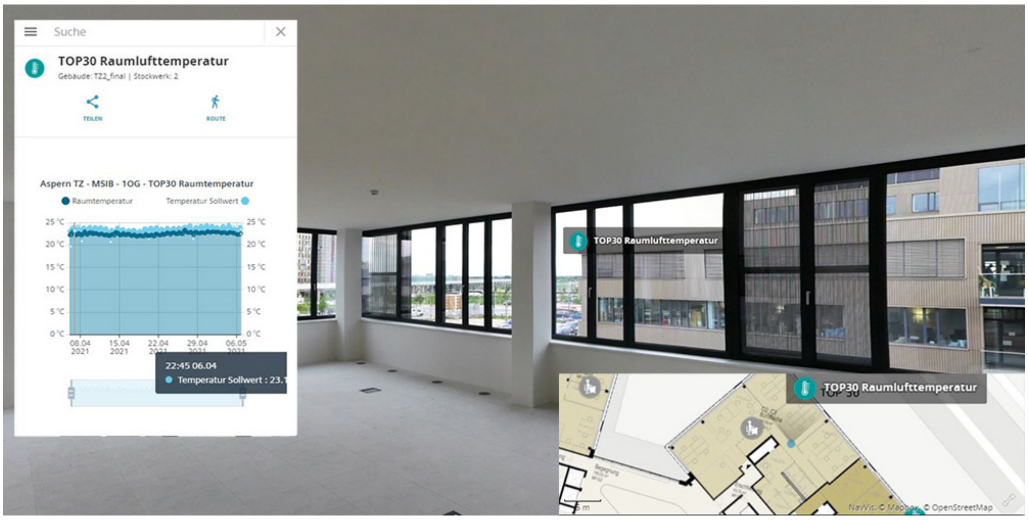

Figure 5.10.: The Siemens building twin platform for Tz2 (Copyright: Siemens AG).

45 kWh. The comfort level baselines were chosen as follows: 21 C set point temperature, 40% relative humidity, and a CO2 level of 1000ppm. To cover an equivalent number of measurements as in a full winter season (6 months) within the two days, the number of thermal performance measurements was increased from 5 to 190 per day. This was needed to generate one payout event after a 6-month time interval as defined in the smart contract logic.

Transaction Data

The implemented prototype functioned as intended, validating the feasibility of the proposed architecture. By the end of the test, 1241 measurements were stored in the smart contract. All transactions were executed following the encoded transaction logic (see). There were several thermal performance failures observed. Further analysis revealed that the terms coded in the smart contract identified the failure correctly, so the smart contract logic worked as expected. However, it is clear that with the assumptions of the performance baseline, as well as the accelerated collection of data points, the observed performance and respective reward logic are not meaningful in terms of the actual performance of the building.

In addition, we observed the transaction costs for the test run to examine financial viability. Every transaction incurs a transaction cost paid to the miners in the blockchain network for adding the transaction to the blockchain. In public blockchains, this fee is paid in the native cryptocurrency of the network. Our prototype uses the Ethereum blockchain, so in this case the cryptocurrency is Ether (ETH). The ETH fee is calculated based on the necessary computing cost (Gas amount) for a transaction, multiplied by the Gas price determined by the current network utilization.

The Gas price in the a test network can be set by the developer and is therefore not meaningful. Because the prototype was deployed to the Rinkeby test network, this applied to the investigated use case. However, the Gas amount for a transaction in the test network is comparable to the Ethereum main network. Therefore, Figure 5.11 pictures the Gas amount for the executed transactions of the implanted contract (see also Figure 5.7). In the beginning, the contract was created, roles were added, a performance case was created, and the escrow was funded. For those transactions, the consumed gas amount depends on the chosen

Figure 5.11.: Transaction costs (Gas) for the executed transactions of the test case.

implementation of the smart contract and the number of transactions needed to pepare the contract for execution, e.g. the number of roles to be registered, or the number of transactions to fund the contract. Over the two days, the sensor data of energy and comfort values were then added acoording to the chosen intervals considered sufficient for the use case (see also 5.4.2 and 5.4.3). A final transaction calculated the rewards and released the respective payouts. The total Gas consumed by the performance contract was 460’217’196. The three most expensive transactions for the executed use case were the contract creation, case registration with all sensor IDs, and final payout calculation. Nevertheless, the cost to add the sensor data accumulated to 97% of the total transaction costs. This demonstrates the importance of reducing data stored on-chain in the smart contract for cost considerations of running performance-based smart contracts.

For an indication of expected costs in case of a real deployment to the Ethereum main net, Figure 5.12 shows the average historic price for the above test case (total Gas amount). The final cost in USD depends on the Gas price and the ETH price at the time of the transaction execution. Figure 5.12 shows the expected total cost for a six-month time period (since the tested use case would run for six months) using average Gas and ETH prices. For example, at the time of deploying the contract in the test run (May 14th, 2020), the average Gas price over the next 6 months was 89.8 Gwei, resulting in approximately 41.33 ETH total cost. With an average market price of 322.5 USD/ETH, this results in 13’327 USD. The graph reflects the impressive uptick in network use (Gas price) followed by the USD market price for ETH in late 2020, resulting in a significant increase in cost compared to the previous years.

It is important to note that the above data is highly dependent on to the presented prototype implementation using the Ethereum network and on the network state at the time of execution, as well as on the specifics of the performance based contract implemented. Costs could vary significantly using another blockchain or a different use case scenario.

Stakeholder Feedback

A short survey collected stakeholder feedback on the concept of performance-based building using digital building twins and blockchain smart contracts after showcasing the prototype. Figure 5.13 shows the benefits and challenges mentioned by nine stakeholders, sorted according to the number of mentions. The

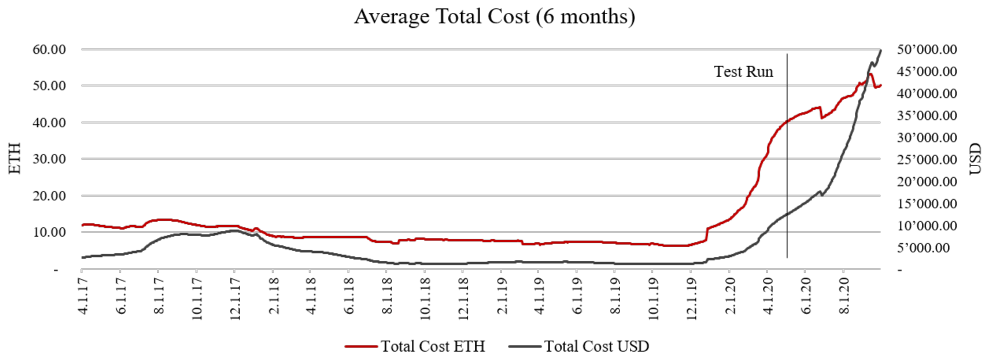

Figure 5.12.: Total costs if deployed to the main net based on a six-month average Gas and ETH price after the time of deployment (Data source: Coindesk (2021) and Etherscan (2021)).

small sample size has no statistical significance, but we found it nevertheless helpful to see the perceived benefits/challenges and to cross-check them with our own assessment.

Overall, the stakeholders demonstrated interest in using a (more mature) solution based on blockchain and digital building twins and had general confidence that it could be successful in introducing new incentives towards better performance and more efficient buildings (Figure 5.13, b). If stakeholders referred to the technical solution, they found the automated and verifiable approach especially appealing.

On the other hand, many challenges and concerns were mentioned (Figure 5.13, c). The concern that was most often mentioned was that performance-based building will change processes so that they are no longer compatible with existing business relations. This is somewhat surprising, since the inherent idea of performance-based building is in fact to change business processes (see 5.2) and provide the respective incentives to make these changes be perceived as a benefit. Moreover, among the other top mentioned challenges were the definition of fair performance evaluation criteria, accurate energy performance simulations to determine the expected performance baseline, and legal limitations. Interestingly, none of these is related to the technical system but rather to general barriers to performance-based building. The most often-mentioned technical challenge was the development and maintenance of digital building twins, followed by the technical security and maturity of both digital building twins and blockchain, and then followed by the shift in trust to the technical system.

5.5. Discussion and Outlook

5.5.1. Proof of Concept

In this paper, we present what is to our knowledge the first full-stack prototype for a performance-based smart contract in the built environment. To do this, we integrate the Ethereum blockchain with digital building models and sensors via the Siemens building twin platform. The successful proof-of-concept shows the feasibility of both the concept and implemented technical architecture. Nevertheless, we found that as emerging technologies, both digital building twins and blockchain need to mature for scalable and secure real-world implementation. The following discussion structured according to the different technical components (see Figure 5.2) identifies the limitations we observed as well as relevant considerations for future research.

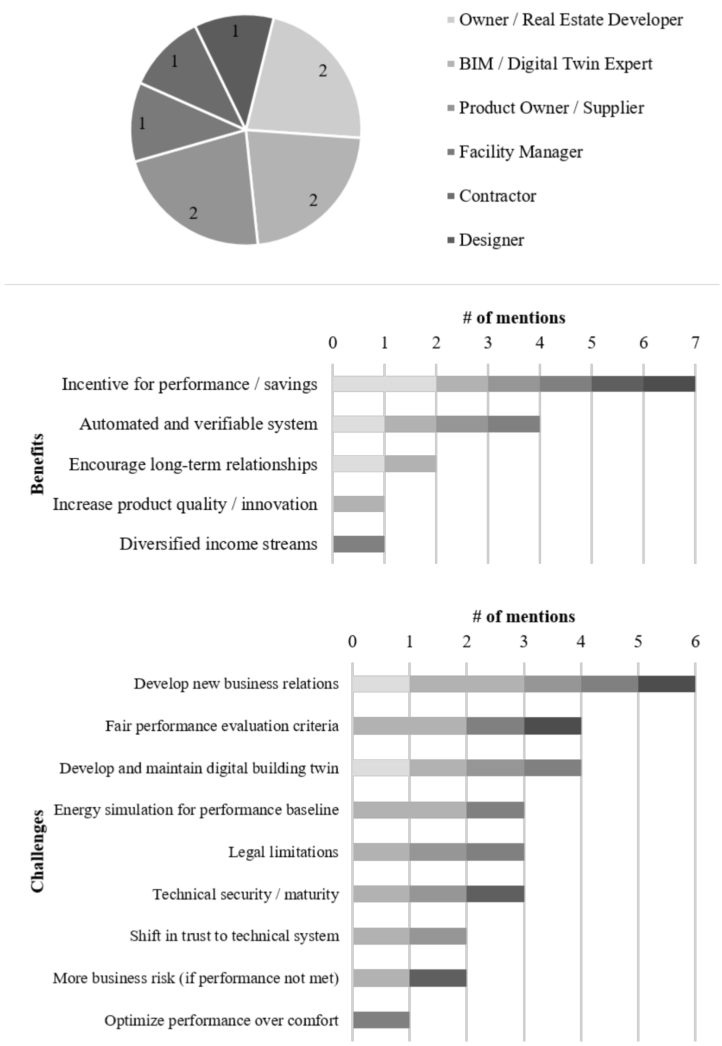

Figure 5.13.: Survey results. Participating stakeholders (a), mentioned benefits (b), and mentioned challenges (c).

Blockchain

The proposed use case falls at the intersection of three proposed use cases for blockchain in construction (Hunhevicz and Hall, 2020b). It is an example of "coins/tokens as payment or incentive scheme across the whole life-cycle" for the performance of a built asset, combined with "transaction automation with smart contracts" for automatic evaluation of performance and contract terms and with "immutable and transparent records of transactions" to the facilitate trust of participating stakeholders in its actual execution.

Even though this proof of concept used the public permissionless blockchain Ethereum, the question of which DLT option best fits the proposed use case can be further assessed and debated. According to the proposed classification in Hunhevicz and Hall (2020b), the above categories could use different DLT options, depending on whether the participating stakeholders are known and whether public verifiability is desired. Currently, all stakeholders are generally known and companies are mostly skeptical towards public verifiability. Therefore, in the short term, private permissioned blockchains can be attractive for more network control and privacy. In the future, new servitized business cases might emerge that promote long-term incentive mechanisms that need to be set up without knowing all potential stakeholders at the time of setting up the service contract. This would shift preferences towards public permissionless DLT systems. Permissionless DLTs are more decentralized and robust networks are likely to exist also in decades to come, whereas the permissioned networks might rise and fall with the central entities controlling the network.

Furthermore, the use of cryptocurrencies is a strong argument for public permissionless blockchains to assure long-term trust (Hunhevicz and Hall, 2020b). While this could be bypassed in the short term by connecting to legacy payment systems, using cryptocurrencies reduces effort when relying on smart contracts for the performance contract. However, as demonstrated in this study, reliance on cryptocurrencies such as Ethereum can suffer from both ETH price volatility and network congestion rates resulting in high Gas prices (see Figure 5.12). While ETH price volatility could be addressed through the use of stable coins or DEFI future contracts, high network use driving Gas costs is a concern for long-term contracts as proposed in this paper. This might be resolved with further advances in technology or alternative DLTs, but it nevertheless shows the importance of writing efficient code that reduces on-chain computation and storing as little data as possible on-chain. Both of these could have been optimized in our implementation. Further assessment is needed to determine if this optimization would suffice to obtain the price levels required for greater industry adoption.

Overall, public permissionless blockchains seem like a good future fit for the use case, even though the shortcomings of current public permissionless DLTs (e.g. throughput, privacy, transaction costs) need to be addressed for large-scale implementation. In the short term, it could make sense to start with more scalable and cheaper private permissioned DLTs to test performance-based smart contracts in a real business setting and move with more technical advancements towards public permissionless DLTs. However, further research with different DLTs should be conducted to provide more nuanced insights.

Performance-Based Smart Contract

The implemented cross-phase thermal performance contract demonstrated an exemplary smart contract implementation in Solidity. The smart contract functionality worked as expected in the two-day test run. Nevertheless, the proof of concept revealed many challenges and limitations that should be addressed in future research.

The implemented thermal performance contract logic is very preliminary. The workflow and participants involved were simplified for demonstration purposes. Moreover, the thermal performance evaluation needs to be refined. Also, the payouts were chosen randomly – no appropriate rewards for the given business case were calculated.

To move the field of performance-based smart contracts further, more research needs to first assess the suitable logic and incentives for cross-phase performance-based contract terms. We encountered many questions when setting up the contract logic. Does only the owner need to pay an escrow or do all stakeholders need to lock funds to demonstrate skin in the game? Should participants only be rewarded or also punished if the target is not met? How is performance measured fairly and how can cheating be avoided? How can external effects (e.g. weather) be excluded? What is a fair price for a service provided? Overall, valid business cases need to be established as servitization use cases, most importantly the fair performance baselines and rewards. This was also mentioned as an important challenge in the stakeholder survey (see Figure 5.13). Finally, from the exemplary prototype in this research, it is not yet clear whether the performance-based smart contracts with the presented technology stack can be applied to all aspects of building performance.

The smart contract can be coded only when the contract logic is defined, and for this simple proof-of-concept, the Solidity language was sufficient to encode the terms. However, it became apparent that Solidity has its limitations when trying to implement advanced mathematical calculations. Furthermore, experts should be consulted to make sure there are no security issues that could lead to the loss of funds. Once the smart contract is deployed, it is very hard or even impossible to patch ex-post when no governance mechanism for such adjustments was implemented beforehand. Therefore, ensuring the flexibility of smart contracts in handling unexpected cases will likely be a major challenge. It is important not to erode the advantages of smart contracts by implementing admin functionalities that again introduce third-party risk (e.g. to halt the contract). Gurcan et al. (2019) proposed establishing agreed-upon processes on how to encode smart contracts. Ultimately, a smart contract could be assembled based on modular pieces that automatically comply with legal terms. But this was not further assessed in this research. Future research needs to investigate the legal and regulatory situation and challenges within different jurisdictions when trying to implement the proposed performace based smart contracts. This was also mentioned repeatedly by the interviewed stakeholders as a challenge (see Figure 5.13).

Furthermore, the storage of data poses major challenges. In the proof-of-concept, fetched sensor data was stored within the smart contract. This causes increased transaction costs and potential issues with the privacy of data in public blockchains, and it strains the network through blockchain bloat.

We identified different approaches to on-chain and off-chain data storage. First, as done in our proof of concept, the number of stored measurements could be decreased through the randomization approach. Nevertheless, data stored on-chain still aggregates over time to sizable amounts. As a possible alternative, performance metrics could be calculated off-chain from externally stored sensor data and only aggregated information stored in the smart contract. This might provide an even better balance between trusted execution of critical functions in the smart contract (final reward decisions) and storing large amounts of data off-chain. Lastly, no performance data could be stored and calculated on-chain. Data sent on-chain would only include whether performance was met (true/false) from the digital building twin to initiate payments. A tradeoff remains between more trust but more expensive on-chain data storage, or off-chain data storage but less trust (see also 5.5.1). Future research should assess further possibilities for harmonization and preprocessing of data before saving in smart contracts together with the implications for overall trust in the solution.

Digital Building Twin as External Data Source

In the proof of concept, the building twin is used as an intermediary platform that connects to the sensors and stores sensor data. The advantage is the ease of data access, the possibility to select sensor data, and the potential for harmonization of data upfront. Overall, the digital building twin reduces the amount of data that must be stored in the smart contract. The disadvantage is that this introduces a dependency on a centralized third-party service with a potential single point of failure (e.g. the building twin provider cease operations). The randomization approach implemented here to fetch data addresses some of the potential attacks that could manipulate data, but it does not eliminate the dependency on the building twin platform. Moreover, cross-phase performance contracts also require that a building twin is available and maintained across all life-cycle phases of the built asset. This is still a challenge (see stakeholder feedback in Figure 5.13) and rarely achieved nowadays, which considerably limits the number of built assets to which the proposed architecture can currently be applied. To reduce dependency on digital building twins, sensor data could be fetched directly from the sensors into the smart contract, so the only prerequisite for the built asset is that it is equipped with the relevant sensors. However, this solution would again complicate efforts to clean and process data and cause problems with data storage on-chain.

Furthermore, connecting the blockchain with the digital building twin and directly to the sensors relies on a back-end oracle. Since this single point of failure is critical to the functioning of the system, the use of a centralized digital building twin platform is, in the view of the authors, acceptable in the near term. Future research could investigate how the single points of failure described here could be addressed, e.g. through implementing decentralized server meshes.

Overall, implementing a secure back-end is challenging and requires further research. The convenience of using digital building twin platforms comes with a tradeoff in security and redundancy that could affect trust in the whole system but might be necessary to reduce on-chain data storage. Besides ensuring a secure technical infrastructure, future studies need to look into additional security layers to combat the potential impact of human factors (e.g. fraud) when interacting with the BIM models, digital building twin platform, or physical sensors (Chong and Diamantopoulos, 2020), as well as with the blockchain (Shemov et al., 2020).

Front-End

The front-end application ensures that stakeholders can set up and interact with the smart contract. Therefore, it is a critical piece of infrastructure to make the solution as simple to use as possible to overcome socio-technical barriers (Li et al., 2019a). More research should investigate easy-to-use front-end applications that provide functionality for setting up and interacting with performance-based smart contracts. As for the back-end side (see 5.5.1), security issues caused by human factors should also be examined for the front-end oracle.

5.5.2. Cryptoeconomic Life-Cycle Incentives for Servitization

It was found that presenting performance-based building as a compelling business case rather than a technical issue can be one of the main enablers to performance-based building (Bakens et al., 2005). This proof-of-concept has provided insight into the potential of using performance-based smart contracts for a future servitized built environment. The use case scenario demonstrates the potential of crypto-economic incentives to align performance targets for new profitable business cases without relying on any trusted third party, and as a side effect benefit the environment by saving energy and reducing CO2 emissions.

Benefits could increase with more advanced servitization business cases. Smart contracts enable scalable collaboration between many parties with low bureaucratic overhead by continuously saving transactions transparently in the blockchain coupled to automated reward logic. Also, the possibility of coding incentive systems through tokens has not been assessed in this paper. Next to crypto currencies (money) for payments, other reward tokens could be issued for reputation or non-monetary performance metrics, e.g. environmental impacts (Dapp, 2019; Ballandies et al., 2021a). Such new crypto-economic life cycle incentives could motivate further business cases. These incentives could move the built environment towards servitization between anonymous stakeholders, enabled by the trust provided by performance based smart contracts. Producers and owners might provide their built assets with publicly available service contracts on the blockchain, while other service providers and users can evaluate available offers and directly sign these contracts on the blockchain, getting paid for their performance or paying anonymously and peer-to-peer for the service used.

5.6. Conclusion

The combination of blockchain-based smart contracts with digital building twins is promising to 1) digitize performance contracts in a trusted way and scale performance-based use cases in the built environment, and 2) enable new business models through crypto-economic incentives linked to the life-cycle performance, which might motivate more stakeholders to explore a built environment as a service. Feasibility of the above was demonstrated with the first full-stack proof-of-concept of an exemplary thermal performance-based smart contract, using the Ethereum blockchain and the Siemens building twin platform connected to the sensors of a real-world building. The early technical infrastructure is available. Nevertheless, many limitations apply. We see the main contributions of this paper as pointing out the challenges that require further research.

Despite the positive feedback of stakeholders regarding the potential of the solution, a major challenge will be to define a fair logic for performance-based contracts and performance baselines. This is also what the authors observed when setting up the thermal performance smart contract: coding the contract logic was relatively straightforward compared to the challenge of defining performance logic and respective payouts. Smart contracts are an emerging tool to realize more scalable and attractive performance contracts, but more research needs to first investigate the underlying performance logic and associated business models.

The early state of blockchain leads to many technical challenges that need to be addressed for scalable and secure implementation of performance-based smart contracts. Currently, the usability of blockchain infrastructure is not at the required level to protect stakeholders from errors when setting up and interacting with the contracts. While in the early years of Ethereum the observed costs were reasonable for the tested performance-based smart contract, the recent price and network use increase have led to unreasonable price levels that need to be addressed for large-scale implementation. A related challenge is how to reduce on-chain data storage without compromising the trust provided by the smart contract. Furthermore, while digital building twins simplify the connection of smart contracts to the real-time performance data of the building, the precise interaction needs more research. A secure interplay between centralized infrastructure and the trusted and decentralized blockchain environment is not straightforward. Finally, the proposed solutions rely heavily on well-developed and maintained digital building twins. As of now, this is not often pursued or achieved in the industry.

The paper demonstrates the potential of the interplay between blockchain and digital building twins for performance-based smart contracts to leverage crypto-economic incentives in moving towards a trusted peer-to-peer economy in a built environment as a service. This combination can align incentives for better performance with a smaller environmental footprint, while still allowing for profitable business cases.

5.7. Author Contributions

JH and MM contributed equally to this work. JH conducted the writing and data analysis for this article. MM implemented the code and wrote the master thesis that acted as a base for this paper under the supervision of JH and DH. DH contributed to the background of performance-based contracts, materials and publications for citation, feedback, and direction for content. All authors helped to finalize the article and approved the submitted version.

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6. no1s1 - A Blockchain-Based DAO Prototype for Autonomous Space

This chapter corresponds to the published article:[1]

Hunhevicz, Jens J, Hongyang Wang, Lukas Hess, and Daniel M Hall (Sept. 2021). "no1s1 - a blockchain-based DAO prototype for autonomous space". In: *Proceedings of the 2021 European Conference on Computing in Construction.* Vol. 2. University College Dublin, pp. 27–33. DOI: 10.35490/ec3.2021.185.

Abstract: We introduce our ongoing research on no1s1 ("no-ones-one"), a meditation pod that aims to be the first autonomous space. To frame our early thinking, we conceptualize what we call Decentralized Autonomous Space (DAS) as a Decentralized Autonomous Organization (DAO) linked to a physical location. DAOs leverage a combination of Decentralized Ledger Technology (DLT) and the Internet of Things (IoT) to create self-governing coordination mechanisms through smart contracts. Therefore, DAS can self-create and self-manage, and ultimately self-own. DAS is presented as a potentially disruptive paradigm of future housing and infrastructure with wide-ranging implications to the built environment.

[1]Please note, this is the author's version of the manuscript published in the *Proceedings of the 2021 European Conference on Computing in Construction.* Changes resulting from the publishing process, namely editing, corrections, final formatting for printed or online publication, and other modifications resulting from quality control procedures may have been subsequently added. The final publication is available at https://ec-3.org/publications/conferences/2021/. When citing this chapter, please refer to the original article found in the reference above.

6.1. Introduction

Since Nakamoto (2008) published the fundamental ideas of blockchain in the Bitcoin white paper, blockchain applications have increased across many domains and industries. Blockchain is the most prominent type of distributed ledger technology (DLT), enabling direct peer-to-peer (P2P) transactions of value across a decentralized network that is not controlled by any single entity, but consensus mechanisms (code) that incentivize the participants towards collaboration. Bitcoin was the first and most popular example of such a network. It created a new decentralized monetary system and asset class. However, Bitcoin is likely only a first step towards a new paradigm of economic coordination using blockchain (Davidson et al., 2016, 2018; Miscione et al., 2019).

The rise of the Ethereum blockchain (Buterin, 2014) led to the use of (turing complete) scripts called "smart contracts" to encode logic for interaction with transactions in the network. Smart contracts enable the creation of new incentive systems and coordination mechanisms that do not rely on human coordination but still provide interfaces for human interaction. There is much ongoing exploration of what new forms of organization can be supported or replaced through such blockchain based governance.

One of the most interesting new organizational designs is called a decentralized autonomous organization (DAO). A DAO is a blockchain-powered organization that can run on its own without any central authority or management hierarchy (Wang and Krishnamachari, 2019). The management and operational rules of a DAO are solely governed by the rules encoded in smart contracts. Through distributed consensus protocols or other crypto-economic incentives, the DAO is able to self-operate, self-govern and self-evolve (Wang and Krishnamachari, 2019). It is important to note the difference between a DAO and operations that use artificial intelligence (AI). An AI system is designed to make internal autonomous decisions. By contrast, a DAO only defines its coordination rules and governance system. In this way it can make decisions based on external input of participating actors (Vitalik Buterin, 2014). These actors only need to own a recognized address, so the actors can be machines, another DAO, or a distributed group of human decision-makers. Therefore, DAOs ultimately allow for coordination mechanisms between both humans and things.

In the past few years, several projects explored the concept of DAOs (e.g. *Decred* (2021) on the protocol level, or *Aragon* (2021) on top of Ethereum on the application level). For the most part, current DAOs exist only in a virtual setting. However, it is also possible that the purpose of a DAO is to sustain a physical thing. A thing in turn can also control an address that holds funds and interact with the DAO. McConaghy (2018) describes this new potential reality as self-ownership of things. Physical objects, in combination with the network of sensors and connected devices often referred to as the internet of things (IoT), can then autonomously transact with humans and other things through a form of a DAO. The DAO can also evolve its functionalities, through either the use of AI or collective governance of human participants.

There are various examples proposed for this new vision, from futuristic ideas of artificial life forms (e.g. the plantoids of Filippi (2020)) to self-ownership of self-driving cars or the self-ownership of public infrastructure (e.g. power grids and roads) (McConaghy, 2018). A key proposed benefit of self-ownership of things is the removal of rent-seeking human intermediaries (i.e. the motivation for most organizations is to derive some form of profit). Because DAO governance mechanisms allow things and systems to be self-sustaining and non-rent seeking, these things can in turn only seek to cover operational expenses. The savings could be passed on to the users, or profit could be fed back into other community-owned systems.

This ties into the potential of blockchain governance to empower and scale communities aligned with principles of the sharing economy (Pazaitis et al., 2017) or common pool resources theory (Maples, 2018; Rozas et al., 2021a). In theory, a DAO can set up coordination mechanisms so that a community can co-create the respective organizational system. In the larger picture, this has the potential to shift current power structures away from centralized corporations towards user communities that decide on their own system's functionalities and governance rules.

Overall, DLT and IoT create new opportunities to rethink ownership and autonomy of things through decentralized coordination mechanisms. Given these possibilities, we see a need to investigate how this will impact the future built environment.

6.2. Motivation and Contribution

The application of DAOs to create self-owning things remains a conceptual idea with little application or operalization. In particular, we find no existing application of DAOs to physical spaces in the built environment. As described above, it seems that the application of DAOs to the built environment is likely to shape how physical space will be built, owned and operated in the future. There is a need to investigate the feasibility, opportunities, and challenges for the application of DAOs to the built environment. Therefore, the paper offers a starting point to conceptualize what we call decentralize autonomous space (DAS) through the current research project no1s1 - a self-owning meditation pod.

First, we present a preliminary conceptualization of DAS. The conceptualization serves as an overview on areas that could be coordinated autonomously and therefore as a road map for future research.

Second, to showcase the feasibility of autonomous space, we introduce the ongoing research project no1s1, a full scale building prototype that implements autonomy regarding chosen management aspects through DLT and IoT.

6.3. Autonomous Space as DAO

We define DAS as the manifestation of a DAO linked to a specific physical location in the built environment. To structure our thinking around potential functionalities of DAS in consideration of the no1s1 prototype, we propose a preliminary conceptualization in Figure 6.1. We identified two main categories for autonomy: “creation autonomous” and “management autonomous”. Furthermore, there will always be “human interaction” because of the human-centered design of DAS.

6.3.1. Creation Autonomous

DAS has the ability to self-create. In the terms used for the built environment, this means that a DAS can commission and coordinate its own design and construction. Design autonomy means that the DAS creates a set of rules to solicit design proposals, and then select a final design. Examples of blockchain-based design management using DAOs show that it is possible to coordinate the architectural design process (Dounas et al., 2020). Construction autonomy means that the DAS can request, approve and monitor construction activities. While no current examples yet exist, blockchain-based governance mechanisms have

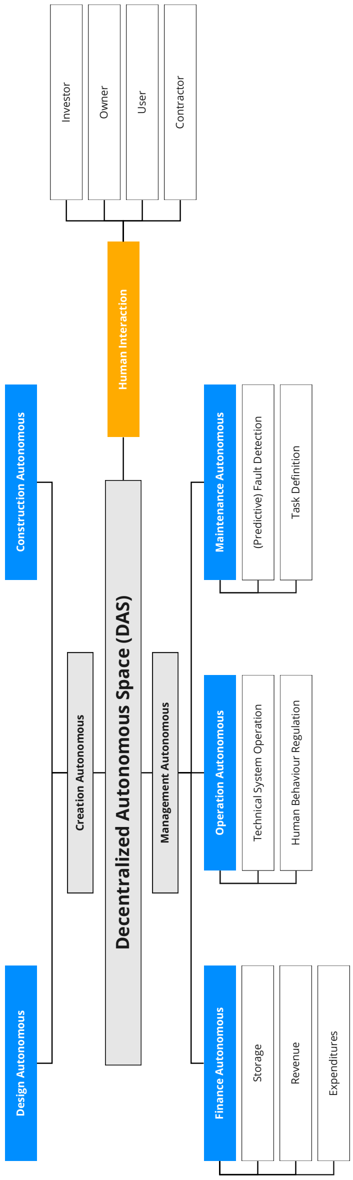

Figure 6.1.: Preliminary conceptualization of decentralized autonomous space (DAS).

been proposed for integrated project deliveries to manage construction projects (Hunhevicz et al., 2020a). Creation autonomy could also leverage exiting synergies with emerging topics like mass-customization and product configurators for modular construction (Cao et al., 2021), or new exploratory approaches of autonomous digital fabrication and robotics (Pereira da Silva and Eloy, 2021), e.g. with drones (Wood et al., 2019) or self-reconfigurable robotics (Seo et al., 2019). In most cases, financial autonomy (described below) must be present at the initiation of the project to commission the self-creation.

6.3.2. Management Autonomous

DAS has the ability to self-manage its own space. Autonomy for space requires self-management of three areas: finance, operation, and maintenance.

Finance Autonomous

Financial autonomy for DAS begins with the self-storage of funds in a treasury. Every blockchain address can hold funds in its native cryptocurrency. Without such a treasury, self-ownership is not possible. Furthermore, DAS requires a form of revenue generation. These funds can then be spent for needed expenditures and investments. For example, revenues can be used to pay for work (by humans or machines) related to operation and maintenance, or for liability insurance usually required for owners of assets in the built environment.

Operation Autonomous

Operational autonomy is related to the technical systems of the DAS. Technical systems include the network of control systems, sensors, and smart devices currently found in most buildings and infrastructure. For operational autonomy, the DAS should control these systems through inputs from sensors and smart devices (i.e. IoT). Technical systems can be reactive or proactive. Reactive technical systems respond to human activities within space. Proactive technical systems influence human behaviour through incentive mechanisms. For example, a DAS can use variable pricing based on the demand of usage to influence users. DAS can also use tokens or currency to influence decisions, such as the use of non-monetary incentives (e.g. reputation-based tokens) (Pazaitis et al., 2017) on the blockchain to incentivize diligent behaviour (e.g. to prevent vandalism).

Maintenance Autonomous

Maintenance autonomy ensures longevity of operations. Therefore, the DAS needs the ability to detect faults. If a failure or error occurs, the DAS must be notified either through its sensing inputs, through human feedback, or proactively through predictive maintenance feedback from live usage data. In case of necessary maintenance, the DAO needs coordination mechanisms to define and commission the required maintenance for the space.

6.3.3. Human Interaction

Finally, DAS must be capable of human interaction. While in theory DAS could be fully independent of human guidance (e.g. governed through the use of advanced AI), it is unlikely that such governance will be feasible or even desirable in the near future. Instead, the DAS will act autonomously for its own creation and management by implementing the rules and guidelines encoded in its smart contracts on the blockchain. The selection and guidance of which rules to use and what these rules do will require human interaction and decision making. Therefore, we find it most likely that humans will be involved in the decision making, functionality reviews, and execution of physical work for a DAS.

This is also related to the so-called "oracle problem" (Caldarelli, 2020). In essence, the problem is that blockchain can verify data integrity on its own ledger and network, but cannot know if inputted data by humans or sensors are correct in the first place. This creates a gap between the physical and digital world that can be intentionally exploited by malicious actors. Therefore, a DAS should implement coordination mechanisms to reduce the possibility of wrong data input. Most likely, this process will also involve human action to check on the correctness of data, e.g. through peer-review mechanisms. Nevertheless, the DAS can stay in control of financial aspects and coordinate work, so is still self-owning.

In addition to their role as users of the space, humans can also interact with DAS in other ways, such as investing in the project, holding tokens that signify

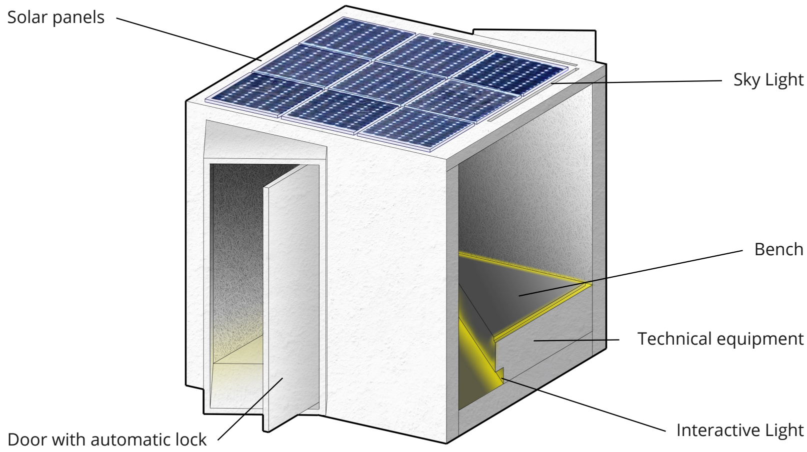

Figure 6.2.: Rendering of the no1s1 prototype.

ownership or decision-making rights, or working for the DAS to provide a service (e.g. holding a maintenance contract to clean the DAS). The challenge of human interaction is to define coordination mechanisms that align human interest with the long term interests of the DAS. Here, insights from the concept of sharing economy or common-pool resource theory can guide creation of such governance mechanisms for human interaction with DAS.

6.4. no1s1 Prototype

We introduce no1s1, an ongoing research project to build the first full-scale DAS prototype. The focus lies on simple functionalities for the smart contracts of the no1s1 DAO and their interaction with the physical space through sensors and smart devices (IoT). It can be understood as a minimum viable prototype (MVP) that will be extended and improved over time. The main research purposes are:

- Demonstration of the concept of autonomous space and its technical feasibility.
- Study and spark discussion on the socio-technical impact of autonomous space.
- Identify technical, legal, and regulatory challenges of autonomous space for future research.

6.4.1. Functionality

The meditation pod is designed as a simple modular constructed cube that will host a quiet internal space for one person to meditate (see Figure 6.2). The pod will be self-owned and self-operated by smart contracts. The proposed revenue for financial autonomy will be generated by offering time slots for quiet meditation in exchange for currency. The electrical energy that supports the system operations will be generated from the top solar panels and stored in a battery.

The functionality of a mediation pod was chosen because of several reasons. (1) The meditation pod can be built as a small module that can also be moved to various exhibitions for demonstration purposes. (2) The meditation pod is relatively simple to use with only one functionality and reduces effort to think about complicated user interaction and user interfaces. (3) The meditation pod requires enough technical equipment to act as an effective proof of concept but does not require extensive cyber-physical coordination. (4) The use case aligns with the emerging concept of the sharing economy, offering a private space that can be used by anyone.

6.4.2. Technical Setup

To connect the physical concept of no1s1 with the digital world, the proposed technical setup of no1s1 is presented in Figure 6.3. We suggest five primary interacting components for any DAS: the physical space and equipment, the front-end, the back-end, the blockchain-based DAO, and human participation. These five components are needed to bridge the gap between the digital and the physical world and transmit data to the no1s1 DAO and back to the user or the physical no1s1.

Actors

For human participation in no1s1, the autonomous meditation space is provided as a service to human users. In turn, the DAS earns rewards to pay for operations and maintenance. Therefore, an important part is the definition of human interaction (see Figure 6.3, Actors). For that, two feedback mechanisms are necessary to transmit information from the actors to the DAO. The first mechanism is for direct user interaction with the smart contracts (e.g. payment) through the web front-end (see Figure 6.3, counter clockwise orange arrows). The second, indirect feedback mechanism captures user behaviour in the physical space through IoT (see Figure 6.3, clockwise orange & red arrows). For now, the DAS only considers users. Further human participation in the DAS should be considered in future work. Humans will need to make decisions about modifications or changes to the DAS. Humans can also act as investors providing input funds to the DAS or as contractors who are paid funds by the DAS in exchange for work performed.

no1s1 (physical)

For the physical space and equipment (see Figure 6.3, no1s1), no1s1 requires several technical systems for operation. First, the energy for the module is self-generated through the solar panels. A battery stores the energy and provide power for technical equipment. If the energy level drops below a level that makes the module insufficient for use, then no1s1 is not operational. When a user wants to use the meditation pod, they will purchase access (see below for front-end set up). In exchange, a user will receive a QR code, which must be scanned by a camera to gain access to the module. An automatic lock then opens to unlock the entrance door. To ensure a comfortable environment, no1s1 includes LED light strips, speakers for meditative music, and a fan for basic ventilation. Motion sensors verify occupancy of the meditation pod. For security reasons, we implement an emergency exit button that users can press at any time if they need to exit the space.

Back-end

For the back-end, no1s1 will require a set up to monitor and control the physical systems (see Figure 6.3, Back-end). For now, we control the physical systems by Python scripts running on Raspbian OS and a Raspberry Pi. Additionally, an Arduino-based maximum power point tracker (MPPT) is used to control the electricity flow between the solar panel, the battery and the Raspberry Pi. The back-end ensures data transmission of captured user behaviour and other relevant data of the technical systems to the DAO smart contracts (see Figure 6.3, red arrows). Moreover, it controls the technical equipment based on the DAO response (see Figure 6.3, purple arrow).

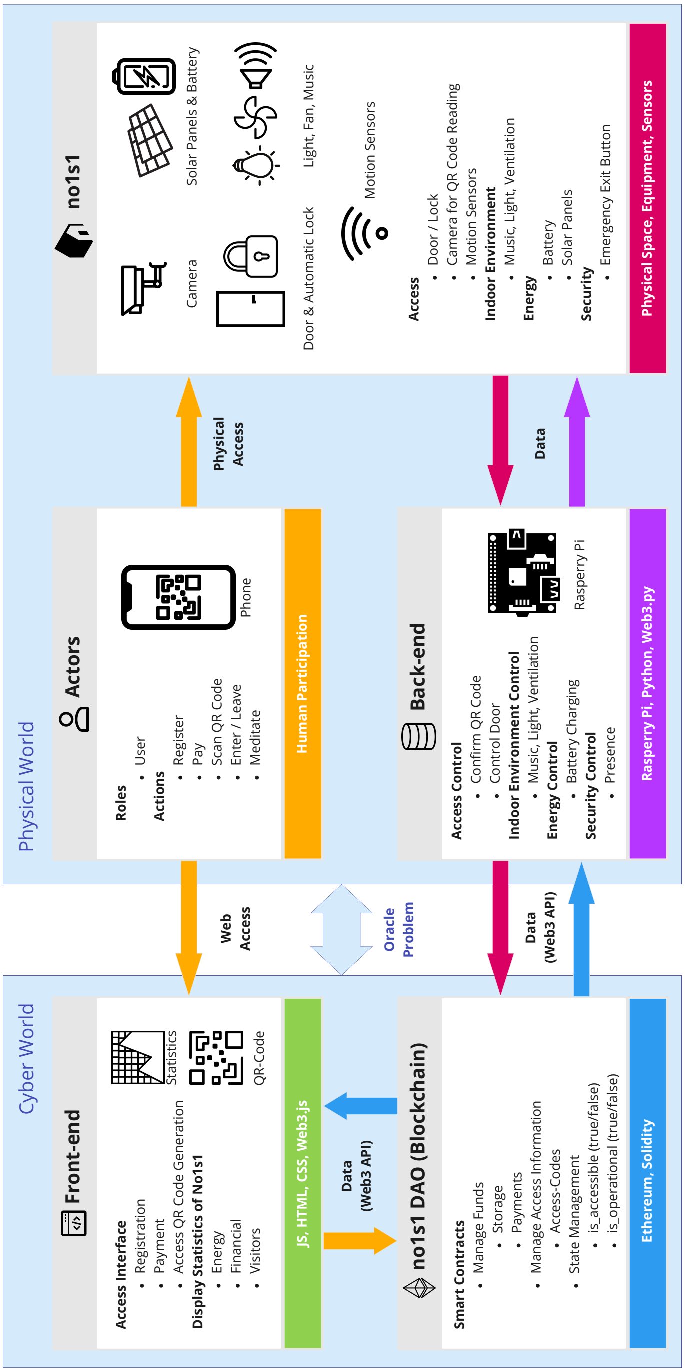

Figure 6.3.: Technical overview of the five proposed components for DAS. The information transition from the actors to the DAO needs to be ensured, both directly through the front-end (orange arrow, counter-clockwise) and indirectly by capturing user behaviour at no1s1 (orange & red arrows, clockwise). The actors also need to understand the DAO response, either visualized in the front-end (blue arrow, clockwise) or through interaction design at no1s1 controlled by the back-end (blue & purple arrow, counter-clockwise).

Front-end

For the front-end (see Figure 6.3, Front-end), no1s1 requires a graphical web user interface that enables human interaction with the no1s1 smart contracts. The users can register and pay to access no1s1. It also stores and displays finance, energy, and visitor-statistics of no1s1 that are retrieved from the smart contracts.

Figure 6.4.: The no1s1 alpha-prototype tests feasibility of the technical system.

no1s1 DAO (Blockchain)

The smart contracts on the blockchain (see Figure 6.3, no1s1 DAO) represent the core elements of no1s1's autonomy. For now, we plan to deploy them on the Ethereum blockchain. The smart contracts control the main "states" of no1s1 anchored in the blockchain. Example states can be the amount of funds owned by no1s1, whether no1s1 is operational at a moment in time and access is possible, or if current service is down. To change a state, a transaction needs to be signed by the involved addresses. The back-end can trigger transactions based on usage data, either on a regular basis (e.g. battery charging levels), or by certain actions (e.g. user verifies QR-code). In addition, human actors can trigger transactions through the front-end. If a state changes, an event is emitted that can be caught by the front-end and back-end (see Figure 6.3, blue arrows), which triggers an update on the front-end or initiates technical control mechanisms in the back-end respectively.

6.5. Discussion

The presented ideas are in a very early state. The research on the final prototype (see Figure 6.2) is still ongoing, but an alpha prototype of no1s1 (see Figure 6.4) was constructed to test the feasibility of the technical architecture. The alpha prototype implements and connects the needed technical components (see Figure 6.3), although with still limited functionality and usability. Nevertheless, the no1s1 alpha prototype demonstrates that DAS is (within limitations) already possible and has interesting application areas.

Overall, we intend to stimulate with this paper more thoughts and research around the topic of DAS. For this purpose, and the challenge to discuss in depth this early research, we present instead an incomplete list of questions that appeared most interesting to us when working on no1s1. The questions will also guide our further research on the topic.

6.5.1. Conceptualization

- Which functionalities are necessary to define space as autonomous?
- Will DAS ultimately replace current ownership structures?
- What are the most promising application areas of DAS?
- Does DAS necessarily involve concepts of the sharing economy, i.e. is DAS in the end really owned by no one, or instead by anyone?
- What are the worst possible outcomes with self-ownership of buildings and infrastructure?

6.5.2. Prototype

Technical Aspects

- Which DLT is best suited for the no1s1 DAO (Hunhevicz and Hall, 2020b)?
- How to ensure security against hacks of no1s1 as in the infamous example of "the DAO" (Mehar et al., 2019)?
- How to achieve adaptability (e.g. replacing the smart contracts) of the no1s1 DAO without risking manipulation?
- What are ways to increase trustworthiness of data input into the no1s1 smart contracts, e.g. how can no1s1 verify with certainty that work tasks were done and determine whether a payout is appropriate?
- How would AI be applied to DAS?

Socio-Technical Aspects

- How can a self-owning building be resilient against exploitation or attacks by humans?
- Who designs and finances the house in the first place when it is not a research project?
- Can the concept of self-owned houses lead to lower living cost because there are no profit seeking intermediaries?
- How to overcome socio-technical barriers for no1s1 (Li et al., 2019a)?
- Would organic growth of DAS be enough for adoption or does it require external policies?

Regulatory and Legal Aspects

- Are new legal frameworks needed to deal with autonomous entities?
- Do autonomous entities need to comply with current legislation? How can this be assured if no1s1 is not programmed to do so?
- What if no1s1 becomes very rich but no one can access the money?
- Is the house liable if it does not provide a promised service or someone gets hurt inside?
- Does no1s1 have rights and could e.g. call the police if rioters occupy it?

6.6. Conclusion

Decentralized autonomous space (DAS) could disrupt the built environment in many ways. Self-ownership of physical space would allow in theory a self-sustaining and non-rent seeking built environment that could replace current organizational structures. We identified similarities to principles of the sharing economy and community driven organizational structures as in common pool resource scenarios. In the end, physical space could just "be", provide its services, and be used, co-created, and governed (within the specified rule-set of the DAO) by a human collective.

Even though DAS seems futuristic, it is already now possible to experiment with this new concept. The introduced ongoing research on the prototype no1s1 should demonstrate feasibility of autonomous space. no1s1 - a mediation pod - is governed by a DAO on the Ethereum blockchain that implements aspects of operational and financial autonomy. However, the MVP still has many limitations and only materializes a very small subset of what may be possible in the future. More insights are expected to follow with further research and the construction of the final no1s1 prototype.

Overall, this paper introduces our early thinking to help frame the research on no1s1, and intends to draw attention to the possibilities and many unknowns on the topic of DAS.

6.7. Acknowledgment

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Epilogue

7. Discussion and Conclusions

7.1. Synthesis

This section summarizes the findings of the five chapters to answer the four research questions (Subsection 7.1.1 to 7.1.4) towards synthesizing conclusion for the overall objective of the thesis (Subsection 7.1.5): "Investigate the potential and feasibility of blockchain in the construction industry with a focus on cryptoeconomics". Figure 7.1 visualizes the research questions, methods, the outcome, and impact of the individual chapters.

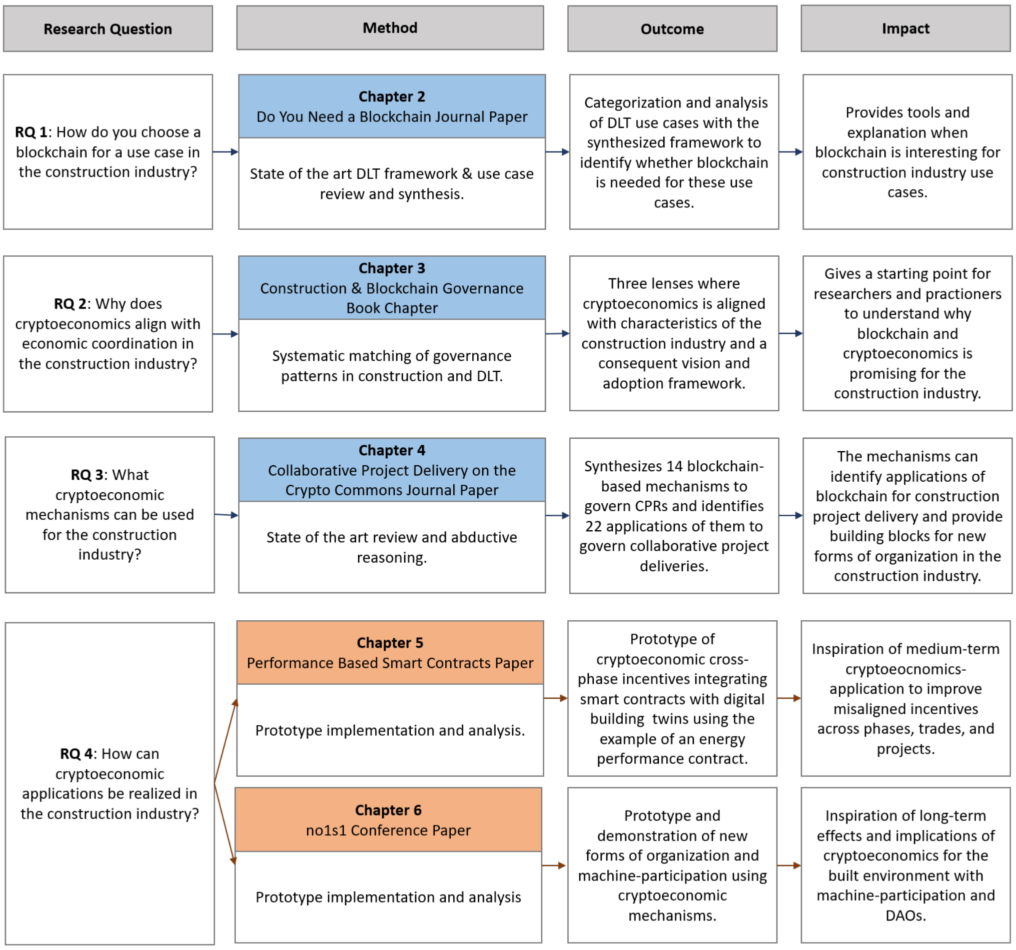

Figure 7.1.: Overview how the different chapters contribute to the individual research questions towards investigating the overall thesis objective: the potential and feasibility of blockchain in the construction industry with a focus on cryptoeconomics.

7.1.1. Research Question 1

RQ1: How do you choose a blockchain for a use case in the construction industry?

This thesis assessed with Chapter 2 (Figure 7.1; Do You Need a Blockchain

Journal Paper) how various proposed construction use cases align with different DLT design options. It compares fundamental properties resulting from technical differences of DLT design options with desirable properties for a use case in the construction industry. The main findings are:

- Not all "blockchain" is equal. There exist profound differences in DLT design options dependent how a network sets up the technology stack. Careful consideration is needed when choosing a DLT for a use case implementation. This decision process should start by assessing the trust relationships between involved actors to narrow down suitable DLT design options that provide the required transaction security. Only then potential technical constraints should be assessed, such as throughput or smart contract capability amongst many others (see Figure 2.2 and Table 2.6).

- It is highly unlikely that a blockchain makes sense when use cases only use blockchain as a tool to automate transactions or to synchronize data for existing processes. Existing processes almost always can use a trusted third party (TTP) providing these same services with more efficient technologies.

- Blockchain becomes interesting when either not all participants are known, and/or when interests of participants are not aligned (see Figure 2.2). The edge case is when some of these characteristics in a use case are given, but there is still an option to use a TTP. In these cases careful consideration of various pros and cons are needed to assess whether it is worth using a DLT. This assessment depends heavily on the used DLT design option. As put correctly by Belle (2017), it needs to be worth replacing intermediaries (a TTP) with the cost of transaction verification imposed by a blockchain. Most proposed use cases in the construction industry fall into this category. They apply blockchain to existing processes, where all parties are known (meaning it is possible to use a TTP), but economic interests are not aligned.

- Assuming a situation where economic interests are not aligned, blockchain becomes a prerequisite when no TTP can be used. This is either true when trying to intentionally decentralize a use case for reasons of censorship resistance, and/or when moving towards new economic processes that involve either unknown human actors or machines. In such cases, cryptoeconomic mechanisms of a blockchain are needed by enabling disintermediated P2P transactions, eventually in combinations with smart contracts to encode process logic and/or tokens. Only public permissionless DLT do not compromise on the fundamental properties (see Table 2.3) typically associated with blockchain.

- Since misaligned incentives are often present in the reviewed construction industry use cases, chapter 2 showed that there is indeed alignment of the affordances of blockchains with some of the proposed use case characteristics in the construction industry. While application of blockchain for existing processes (automation of transactions, tracking of physical and digital assets) requires more research and analysis to investigate when to use blockchain, an interesting and very promising application of blockchain is for novel forms of decentralized incentives and organization through cryptoeconomic mechanisms.

7.1.2. Research Question 2

RQ2: Why does cryptoeconomics align with economic coordination in the construction industry?

Despite identifying in chapter 2 cryptoeconomic mechanisms for new incentives and organization as a use case that relies on blockchain, little literature described potential use cases of cryptoeconomic mechanisms in the construction industry. Therefore, Chapter 3 (Figure 7.1; Construction & Blockchain Governance Book Chapter) explores how cryptoeconomics aligns with general characteristics of the construction industry to narrow down why it could be promising for construction use cases. It connects technological aspects of blockchain enabling cryptoeconomics with economic coordination of the construction industry as a guiding overview for this emerging research field. The book chapter does not yet verify these connections, but acts as a scientifically grounded inspiration for how blockchain can lead to a new vision of construction 4.0. It intends to be one of the most comprehensive, yet short introductory pieces why cryptoeconomics is worth exploring for the construction industry. The main findings are:

- Cryptoeconomic incentives could reinforce existing incentive structures or create new incentive structures to align stakeholders across phases, trades, and projects as a further supply chain integration practice to reduce the impact of fragmentation in the construction industry.
- Cryptoeconomic mechanisms can be used to build decentralized governance processes with smart contracts and tokens. Such governance processes align well with bottom-up coordination suggested to manage complex systems. They can support data-driven and collective decision-making by creating cryptoeconomic incentives to guide individual actors towards behavior that optimizes goals of the overall construction project.
- The decentralized nature of blockchain matches well the decentralized nature of the construction industry. Decentralized governance with cryptoeconomic mechanisms could improve coordination towards more efficiency and productivity, without the need to change the industry structure towards more centralized structures as seen in other industries.
- Overall, cryptoeconomic governance mechanisms provide an opportunity to build bottom-up coordination mechanisms towards “peer-production” of the built environment to embrace its aspects of complexity and decentralization. Blockchain enables an alternative vision of construction 4.0 without the need to vertically integrate its supply chain.
- Even though cryptoeconomic mechanisms are an opportunity to govern a complex construction industry, the industry is unlikely to move all at once towards blockchain-based governance. A stepwise exploration will be more likely, starting with blockchain as an assurance layer for existing processes, subsequently exploring new incentives to realign economic interests in existing processes towards better collaboration and new business models, and finally examining decentralized coordination of activities through blockchain-based governance mechanisms with commons like community governance.

7.1.3. Research Question 3

RQ3: What cryptoeconomic mechanisms can be used for construction project delivery?

Chapter 4 (Figure 7.1; IPD on the Crypto Commons Journal Paper) explores what cryptoeconomic mechanisms can be used for organization in the context of collaborative construction project deliveries, in particular IPDs. This assessment is made based on existing conceptualizations between IPD and CPR theory (Hall et al., 2020) and CPR theory and blockchain (Fritsch et al., 2021; Rozas et al., 2021a,b). The main findings are:

- Scholarship and articles outlined the connection between blockchain and CPR theory. Based on this existing literature, the paper reviewed proposed applications of blockchain affordances and cryptoeconomic mechanisms for the eight OPs. Fourteen blockchain governance mechanisms were then identified as a way to govern CPR scenarios on the crypto commons (Table 4.2). They act as a foundation to conceptualize governance of CPR scenarios on the crypto commons for the construction industry, but likely also for other cases of digital or real world CPR scenarios.

- The paper connects then governance practices of IPDs that resemble practices of the OPs with the identified fourteen blockchain governance mechanisms. Where there was no existing match, the paper proposed novel applications. Overall, twenty-two applications for IPDs were suggested (Table 4.3). Among many others, exemplary novel organization mechanisms include scalable management of users, rights, and ownerhsip with blockchain-addresses and tokens, and new incentive structures through radical transparency and token-based incentives and sanctions. Furthermore, decentralized voting platforms and markets might enable collective organization and participation in the building process without steep hierarchies or powerful parties enforcing collective choice and conflict resolution. Finally, since blockchain only identifies users through addresses, also economic participation of machines becomes feasible.

- The overall conceptualization (Figure 4.2) is so far one of the most comprehensive guidelines how blockchain and cryptoeconomic mechanisms can facilitate organization in the construction industry. It shows how many of the proposed applications of blockchain for the construction industry connect, but also where no research so far assessed applications that theoretically align with decentralized governance of construction projects on the crypto commons.

- The lens of CPR theory and the OPs is well-suited to assess blockchain-based organization of project deliveries in the construction industry and should be subject of further research. The identified applications can be explored to improve current relational contracting approaches or to inspire thinking towards the next generation of project delivery models that better align with bottom-up and guided self-organization approaches promising to deal with complexity in the construction industry.

7.1.4. Research Question 4

RQ4: How can cryptoeconomic applications be realized in the construction industry?

First, Chapter 5 explores an exemplary implementation of a performance based smart contract connected to the real time data coming from the Siemens digital building twin platform to create cryptoeconomic cross-phase incentives to maximize energy performance (Figure 7.1; Performance Based Smart Contracts Journal Paper). The main findings are:

- The prototype successfully demonstrated that a cyber-physical connection between sensors and the Ethereum blockchain is feasible. Performance logic can be encoded in a smart contract that evaluates data and triggers subsequent payout logic. The research took a "as straightforward as possible" approach and used the available APIs of the Siemens digital building twin platform and a server to coordinate API requests and blockchain transaction execution. The chosen technical implementation gave useful insights regarding feasibility and unveiled many open questions how to integrate the pyhsical world with the cyber world. Difficulties mainly relate to the "oracle problem" and costly on-chain data storage.
- The example demonstrates how digital twins and blockchain complement each other and emphasizes how blockchain adds an additional economic layer to transact value based on generated data and/or govern the ongoing digitalization. Digital building twins act as the data base layer that update and visualize performance data in real time. Blockchain smart contracts can encode performance logic and use cryptoeconomic incentives linked to the performance data of the digital building twin to incentivize performance across phases and trades. This can lead to more attractiveness of business models like servitization, also referred to as the built-environment-as-a-service. In the future, owners and service providers could both offer and sign publicly available service contracts that could be signed by pseudonymous humans/firms and machines. Despite the potential, establishing meaningful performance baselines and attractive business models needs more research.

The second prototype, no1s1, explores in Chapter 6 (Figure 7.1; no1s1 Conference Paper) the feasibility and impact of machine-participation based on the example of a self-owning house. No1s1 is ongoing research an the conference paper shows the early thinking processes together with the first prototype. The main findings up to this stage are:

- The paper introduces the idea of DAS (decentralized autonomous space) as a combination of a DAO linked to a physical location. The idea is that space can be self-sustaining in the sense that it owns a blockchain address with funds and encodes operational coordination logic in smart contracts. Other actors, most likely humans, coordinate then according to this logic in the form of a DAO to sustain the physical space. The prototype no1s1 explores these concepts in a self-owning house that has the functionality of a meditation pod.

- Next to the theoretical conceptualization of DAS, the main contribution is the demonstration that self-ownership of things is within limitations already feasible. No1s1[1] has its own smart contracts[2] living currently on the Ethereum Rinkeby Network[3] that hold ETH earned by selling access. The cyber-physical connection with the sensors was successfully achieved with the introduced technology stack (Figure 6.3). Humans can interact with no1s1's smart contracts through the front-end and a blockchain wallet. Feedback from the physical space is achieved by sending sensor and equipment data with a Raspberry Pi computer to the smart contract.
- While the technical implementation has still many limitations, the prototype can initiate further discussions around implications of blockchain-based machine participation and new forms of organization in the construction industry and the built environment. There is potential to redefine ownership in a way that it can belong to both humans and machines, as well as to rethink how collective organization can deliver and govern digital and physical value in the construction industry more efficiently. For the latter the developed framework based on CPR theory (see Figure 4.2) could be helpful.

7.1.5. Overall Thesis Conclusions

Thesis objective: Investigate the potential and feasibility of blockchain in the construction industry with a focus on cryptoeconomics.

Based on the generated insights in the five chapters of this thesis, the following overall conclusions are drawn:

> ***Conclusion 1)*** *Blockchain is especially interesting for applications in the construction industry that rely on cryptoeconomic mechanisms.*

The main innovation of public permissionless blockchains is rooted in cryptoeconomic mechanisms that allow the network to coordinate transactions in a decentralized way between pseudonymous actors. While use cases can also profit from transparency and data integrity characteristics of blockchain networks to execute and automate transactions, there exist likely more efficient technical ways to achieve this without using a blockchain. It is only when no third party can or should be used in a use case, because of anonymity of actors and/or required censorship resistance of transactions, that blockchain can play out its true potential. The possibility to disintermediate transactions while maintaining trust between pseudonymous transaction parties positions the technology at a very interesting intersection of digitalization and economic coordination.

> ***Conclusion 2)*** *Cryptoeconomics offers possibilities to create incentives for supply chain coordination in interplay with the ongoing digitalization to support or establish new supply chain integration practices.*

[1] `https://no1s1.space`, accessed 15.02.2022
[2] `https://github.com/Unawhatitis/no1s1_TI/tree/main/contracts`, accessed 15.02.2022
[3] `https://rinkeby.etherscan.io/address/0x23c9c6aeb8083864d89816da91630f19ef65a09c`, accessed 15.02.2022

Cryptoeconomic mechanisms allow to create incentive systems with smart contracts by encoding coordination rules and tokens that hold value. Such data-driven cryptoeconomic systems can build on the increasing digitalization of the construction industry with BIM and digital twins to create incentives that foster integration across phases, trades, and construction projects. The construction industry is one of the most fragmented industries and consistently suffers from cases of misaligned incentives over the life cycle of built assets. Therefore, construction could be one of the industries that benefits most from the advantages of cryptoeconomic incentives to support or establish new supply chain integration practices.

> ***Conclusion 3)*** *Cyberphysical integration with blockchain enables machine participation in the construction industry that might challenge many existing industry practices.*

Blockchain does only identify network users through addresses. Such an address can belong to a human or machine. Since an address can hold funds, a future blockchain-based construction economy does not need to distinguish between funds that belong to a human or a machine. Machines could e.g. be self-owning holding its own funds (e.g. no1s1), or they could contribute to value creation and get paid (e.g. generative design algorithms participating in design competitions). Blockchain has the potential to act as a key-connecting layer between the digital and the physical world in the ongoing cyber-physical integration often termed as "construction 4.0". This intersection needs more research to understand challenges and opportunities.

> ***Conclusion 4)*** *Common Pool Resource theory is a powerful lens to conceptualize decentralized coordination in the construction industry using cryptoeconomic mechanisms for new forms of organization.*

Blockchain is an institutional innovation with the potential to substitute and disrupt existing economic coordination in the construction industry. CPR theory and Ostrom's design principles are a powerful theoretical lens to conceptualize novel forms of bottom-up coordination on the crypto commons. Since there is a striking overlap between collaborative project deliveries such as IPDs and cryptoeconomic mechanisms used for the crypto commons, the identified connection with CPR theory can guide the design of new forms of collective and decentralized organization using cryptoeconomic mechanisms. Such decentralized bottom up coordination could be a way to scale existing approaches of collaborative project delivery or enable new forms of bottom-up coordination for project delivery that are better suited to deal with complexity aspects of the construction industry.

> ***Conclusion 5)*** *Early prototyping of cryptoeconomic applications for the construction industry is possible, but industry implementation of novel blockchain-based forms of organization will need a more mature technology stack, more interdisciplinary research efforts, and more consideration how to overcome current industry barriers.*

The two prototypes in this thesis demonstrate feasibility of cryptoeconomic applications in the construction industry. But they also revealed the still many limitations. For scalable and frictionless application of blockchain-based incentives and organization in the construction industry, the technology stack needs to mature and become more user friendly. Moreover, Voshmgir and Zargham (2019) show how cryptoeconomic systems lie at the intersection of many research fields. More interdisciplinary research is needed before the design of novel forms of incentives and organization based on cryptoeconomic systems will become applicable in the construction industry. Finally, current industry barriers will make it challenging to grow adoption of blockchain usage. First, cryptoeconomic mechanisms rely heavily on real time data feedback loops that need first more uptake of digitalization in the construction industry. Second, the value of blockchain likely only comes at scale, which makes it a systemic innovation that is hard to implement. It is not without irony that the barrier to overcome is at the same time the promise of the technology. The effectiveness of cryptoeconomic incentive systems to overcome these industry barriers needs more investigation.

7.2. Discussion

This Section discusses the findings related to the starting situation and other blockchain research in the construction industry. With that it emphasizes the contribution of the thesis (see also Section 7.3), but also shows where more research is needed (see also Section 7.5).

7.2.1. Blockchain-Based Trust for the Construction Industry

As shown in the motivation and introduction, early literature saw the promise of blockchain as a "trust machine" to address trust issues in the troubled construction industry (Kinnaird and Geipel, 2017; Heiskanen, 2017; Mathews et al., 2017; Belle, 2017; Wang et al., 2017; Turk and Klinc, 2017). Later work confirmed through the lens of transaction cost theory (Schmidt and Wagner, 2019) and by textual interpretation of semi-structured interviews (Qian and Papadonikolaki, 2020) that blockchains can increase trust in supply chains by reducing risk and costs of opportunistic behaviour. The research of this thesis aligns with these works, but also showed that the technical aspects of blockchain that guarantee this trust are nuanced and should receive more consideration. Blockchain is not "one thing" that automatically assures the desired trusted properties, but different design choices of DLT can heavily influence the established trust level in a use case (Hunhevicz and Hall, 2020b). While Qian and Papadonikolaki (2020) acknowledge the need for public permissionless blockchains to ensure the generally referred fundamental properties (Table 2.3) or affordances (Subsection 3.2.2) of blockchain, a public permissionless system per se does again not automatically lead to decentralization making the protocols resilient. In addition to the in this thesis mentioned aspects related to the choice of DLT design options, more blockchain in construction research should assess aspects and implications related to decentralization, data storage, and privacy.

Decentralization Decentralization ensures that no single entity can control the blockchain network and functionality, so users can trust the technical infrastructure instead of transaction counter parties or intermediaries. The resulting transaction disintermediation is the key difference of blockchain compared to existing technical infrastructure. Nevertheless, decentralization is hard to achieve, mostly because such networks need to slowly grow their user base to avoid concentration of power. In addition, using a truly decentralized infrastructure comes with many challenges to build applications.

First, *decentralization is expensive.* To keep a decentralized network protected against attacks, the protocols implement high standard security mechanisms. Blockchains that are truly decentralized always have a consensus mechanism that involves transaction fees paid in cryptocurrency. This means that every single transaction needs to pay a transaction fee, so using a Web3 application is generally more expensive than traditional applications.

Second, *decentralization is slow.* Reaching consensus on the finality of the transaction in a decentralized network takes time. This means that transactions do not settle instant, but need, depending on the network, up to a couple minutes to execute. This, of course, directly affects Web3 users, as they need to wait for their transactions to settle.

Finally, *decentralization is inflexible.* Decentralization also means that rules are hard to change once implemented. What is key for the functioning of the underlying blockchain protocols comes with significant challenges for applications built with smart contracts on top. Once a smart contract is deployed, it cannot be revoked. Careful design and testing is required in advance to ensure that the logic works once it is deployed.

Overall, many existing applications seem not very decentralized, because operators and developers choose to bypass decentralization for a more friendly user experience or more control over the application. Implications of this should be subject of further research.

Data Storage Truly decentralized blockchains are both expensive and slow to use. This means that they are not suited to store large amounts of data on-chain. Next to cost implications, it bloats the blockchain and threatens decentralization. This is because it increases the hardware requirements to store and process data, so it becomes increasingly infeasible to run a node on standard consumer hardware, leading to fewer nodes. As a result, it is only worth putting data and processes on-chain that need high security and censorship resistance. Therefore, off-chain data storage should be more researched along with the use of blockchains.

The main challenge with off-chain data storage is the "Oracle Problem" (Caldarelli, 2020). Therefore, the design of the middleware to facilitate the connection between on-chain and off-chain deserves great attention. Furthermore, the interaction logic between on-chain logic and off-chain data seems especially difficult when data should remain hidden or private. It seems easier with a transparent data storage solution to prove the existence and correctness of the data. More research should assess how to facilitate better interaction between on-chain and off-chain data storage in construction.

Privacy In a truly decentralized blockchain, all transaction history and data is very transparent and accessible. Since linking transactions can be problematic for user privacy, newer blockchains implement measures to obfuscate transaction origin and destination through mixing or advanced cryptography. At the same time, using such privacy-focused blockchains is not allowed in all jurisdictions.

In addition, existing institutions are interested in the use of smart contracts, but the very transparent nature of blockchain conflicts with the current view that data is valuable and should be protected. Since to date it is very challenging in a decentralized blockchain to keep on-chain data private while ensuring trusted readability through smart contracts, many institutions turn to more centralized solutions such as private blockchains.

When investigating blockchain use cases in the construction industry, aspects of privacy should receive more attention. Ideally, applications using smart contracts in the construction industry target anonymous participants and public data to benefit from the true innovation of blockchain without causing high complexity to keep data private.

7.2.2. The Near-Term Application in the Construction Industry

Most current research focuses on blockchain to make existing processes more trustworthy. After reviewing many of the published scholarship since 2017, the main category that stands out here is tracking and securing data in various construction supply chain contexts, sometimes combined with the use of smart contracts for contracting and transferring value such as payments (for specific examples see Hunhevicz and Hall (2020b) in Chapter 2 and Hunhevicz et al. (2022a) in Chapter 3).

Nevertheless, there seems to be mostly a focus on the use of private permissioned blockchains for consortium or construction project focused blockchains, e.g. as in Elghaish et al. (2020), Chong and Diamantopoulos (2020), Sheng et al. (2020), Zhong et al. (2020), Wu et al. (2021), and Li et al. (2021). To some extend this makes sense since data and privacy control can be maintained with a similar logic as in current processes. But at the same time, they share similarities with existing systems that still depend on the trust of humans running the network. For typical building and infrastructure life cycles of many decades, this can be a significant drawback (Hunhevicz et al., 2022c). In addition, also other technical approaches could be used instead of a private permissioned blockchain that are more efficient, e.g. BigchainDB (BigchainDB GmbH, 2018).

As repeatedly discussed during this thesis, the main innovation of "trustless" transactions comes with decentralized public permissionless blockchains. Since trusted processes in the construction industry based on public permissionless blockchains are the basis for the later opportunity of new incentives and organization (see Chapter 3 and 4), it would be desirable to have more research focus on the potential of public permissionless blockchains already for today's processes. The individual blockchain governance mechanisms in Hunhevicz et al. (2022b) (see Chapter 4) can also be used to identify promising near-term opportunities of such mechanisms using public permissionless DLTs for the construction industry. In the authors opinion, the most promising ones in the short term are timestamping, access control, and payments. More research should focus on these individually, especially also from an implementation standpoint comparing different available Web3 technologies.

Timestamping Blockchain is, at its core, a time stamping machine for transactions. Each transaction gets hashed and included in the merkle root of a block, and each block has a timestamp. This means that one knows for each transaction when it existed and whether it was changed by searching for the transaction hash. By hashing and appending data to a transaction, it is now possible to create proof of existence of data through timestamping. This is not only possible for blockchains that support expressive smart contracts (e.g. Ethererum), but also for UTXO based blockchains such as Bitcoin using the OP_Return script. There are free timestamping services for timestamping data with Bitcoin such as OpenTimestamps[4]. Storing a hash of a file for proof of existence (e.g. PDF file, a contract, a picture, or basically any other data) can be useful to make many existing processes more transparent and trustworthy without putting all data on-chain, e.g. for certification of supply chain related information. More research should investigate timestamping through the use of public permissionless blockchains with a combination of on-chain storage of the hash and off-chain storage of the data, but also which data is relevant to timestamp.

Access Control Blockchain provides a new way to identify and access dig-

[4] https://opentimestamps.org/

ital services. Users, both humans and machines, can hold the private keys to a public address as a unique identifier. Proof of identity and ownership is possible by signing a transaction using the associated private key. While in Web1 one needed an email and password as an identifier stored on each server of the service provider, with Web2 third-party providers make it possible to use only their credential to access many services. However, access credentials are usually stored centrally with one provider, allowing them to see the entire usage history.

Web3 gives complete access control to the user. To access an application, a wallet that controls the own private keys verifies the identity. One address can be used to access all applications that support identification with a selected blockchain network. To make access transferable, tokens can be used as access mechanisms. With the private key, the wallet can be installed or recovered on different machines. The downside to this is that self-custody can lead to the loss of access when the private key is lost. Using blockchain addresses is pseudonymous, meaning it identifies a user but only reveals the address. To associate users by name with an address, the concept of DIDs (Decentralized Digital Identifiers) or KYC (Know Your Customer) is needed. Overall, independent and secure access control with blockchain in the construction industry seems like a well-suited use case given its fragmented nature.

Payments Finally, cryptocurrency can improve payment workflows and delays in the present construction industry (Ahmadisheykhsarmast and Sonmez, 2020; Chong and Diamantopoulos, 2020; Das et al., 2020; Di Giuda et al., 2020; Elghaish et al., 2020; Hamledari and Fischer, 2021b; Nanayakkara et al., 2021; Ye and König, 2021). Nevertheless, there is more research needed to investigate the socio-technical barriers, but also technical risks when using e.g. algorithmic stable coins. Moreover, the industry seems to be still resistant to accept cryptocurrency, likely due to legal and regulatory uncertainties, the generally high price volatility of many crytocurrencies, but certainly also because of lack of knowledge how to handle blockchain wallets.

7.2.3. The Opportunity for New Incentives and Organization

While most current scholarship sees blockchain as a tool to increase trust in existing processes, this thesis mainly focused on the opportunity for new incentives and organization through blockchain between both humans and machines as anticipated by some early articles (Belle, 2017). Since the thesis covered and discussed many aspects related to this in the various chapters and the synthesis (see Section 7.1), only a very brief and high-level discussion is given at this point.

Summarized, the most exiting aspect of cryptoeconomics for new incentives and organization is the possibility to create and re-imagine new processes and economic systems for the construction industry. This shifts the focus away from blockchain to create trust as a reactive approach to improve existing problematic organizational structures in the industry, towards a proactive approach using the possibility of disintermediated transactions and incentives to design new organizational approaches for the the industry. Chapter 3 summarizes the main opportunities to deal with fragmentation through cryptoeconomic incentives across phases, trades, and projects to overcome current barriers to collaboration and innovation; to create bottom-up organizational structures to deal with complexity; and to match the decentralized nature of the industry with more peer-to-peer collaboration mechanisms (see also Chapter 4). Blockchain is not just another technical tool, but offers an alternative organizational approach to the future of construction, often termed Construction 4.0 (Hunhevicz et al., 2022a).

While it is clear that this thesis only offers a starting point to understand this emerging research field, the author hopes that both the theoretical concepts (Chapter 3 and 4), as well as practical implementations (Chapter 5 and 6) will inspire more research towards new decentralized and collective construction approaches inspired by concepts such as CPR theory to help the industry deliver housing and infrastructure more efficiently and productive.

7.2.4. The Interplay Between Theory Building and Prototyping

Finally, some last words regarding the research design and methodology of this thesis are needed. The main challenge was the very early state of the technology and research. There was little scientific base to support the research in this thesis and therefore a very exploratory approach had to be taken to identify potential research directions and applications. Also, empirical approaches proofed difficult at this early state since most of the construction industry has not even started to explore blockchain, so the general understanding of the technology in the industry seemed insufficient to result in meaningful projections on the potential of the technology.

In the end, the chosen approach of interplay and iterations between building new concepts and theory and subsequent implementation and testing worked well. Building new concepts mainly relied on synthesizing the scattered literature across many fields with already proposed and established concepts and theory in the construction industry. The final frameworks and concepts provide now a scientifically grounded vision for the application of blockchain in the construction industry. The implementations helped to understand the capabilities of the technology and establish credibility by demonstrating feasibility of the concepts. Nevertheless, there is now a lot of potential to build on the early work presented in this thesis to further extend and validate both the concepts and the proof-of-concepts. More case study and empirical research will be important to obtain more in-depth results and push blockchain closer to real world implementation. Finally, it would be helpful to have a structured selection of suited methods and approaches at hand to ease research in this new and interdisciplinary field.

7.3. Contributions

7.3.1. Scientific Contributions

Summarized, this work contributed to the field of construction management by extending the research on the potential of blockchain in the construction industry. The thesis established a novel research area at the interdisciplinary intersection of economic coordination in the construction industry, cryptoeconomics, and CPR theory (see Figure 1.1). Understanding the promise of blockchain is not always a straightforward task. In order to gain a deeper understanding of blockchain for the construction industry, novel theoretical work is needed to connect technical capabilities of blockchain with use case requirements, as well as to understand how cryptoeconomic mechanisms can facilitate novel forms of incentives and organization. This thesis provides this early theoretical work together with proof-of-concept implementations as a solid foundation for more research on cryptoeconomic applications for the construction industry.

The findings were disseminated in the scientific community through various contributions. So far, three journal publications [1-3], six conference publications [4-8], one book chapter [9], and eight research presentations [10-16] were developed during this thesis. Five of the contributions [1-3, 8, 9] are contained as individual chapters in this work. Furthermore, the first “blockchain in construction workshop" was organized and hosted at ETH in 2019. There was already a second workshop held in 2021, with plans to continue the series as a platform to exchange cutting-edge blockchain in construction research.

Journal Publications

[1] Hunhevicz, Jens J. and Daniel M. Hall (Aug. 2020b). "Do you need a blockchain in construction? Use case categories and decision framework for DLT design options". In: *Advanced Engineering Informatics* 45.February, p. 101094. ISSN: 14740346. DOI: 10.1016/j.aei.2020.101094.

[2] Hunhevicz, Jens J., Mahshid Motie, and Daniel M. Hall (Jan. 2022c). "Digital building twins and blockchain for performance-based (smart) contracts". In: *Automation in Construction* 133, p. 103981. ISSN: 09265805. DOI: 10.1016/j.autcon.2021.103981.

[3] Hunhevicz, Jens J., Pierre-Antoine Brasey, Marcella M M Bonanomi, Daniel M Hall, and Martin Fischer (July 2022b). "Applications of Blockchain for the Governance of Integrated Project Delivery: A Crypto Commons Approach". In: *arXiv*. DOI: 10.48550/arXiv.2207.07002. arXiv: 2207.07002. URL: http://arxiv.org/abs/2207.07002.

Conference Publications

[4] Hunhevicz, Jens J. and Daniel M. Hall (July 2019). "Managing mistrust in construction using DLT: a review of use-case categories for technical decisions". In: *2019 EC3 Conference, Greece*. Vol. 1, pp. 100–109. ISBN: 978-1-910963-37-1. DOI: 10.35490/EC3.2019.171.

[5] Hunhevicz, Jens J and Daniel M Hall (2020a). "Crypto-Economic Incentives in the Construction Industry". In: *ARCOM Doctoral Workshop: Exploring the mutual role of BIM, Blockchain and IoT in changing the design, construction and operation of built assets*. Newcastle, UK. DOI: 10.3929/ethz-b-000420837.

[6] Hunhevicz, Jens J, Pierre-Antoine Brasey, Marcella M M Bonanomi, and Daniel Hall (2020a). "Blockchain and Smart Contracts for Integrated Project Delivery: Inspiration from the Commons". In: *EPOC 2020 Working Paper Proceedings*. Engineering Project Organization Society (EPOS). DOI: 10.3929/ethz-b-000452056.

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[8] Hunhevicz, Jens J, Hongyang Wang, Lukas Hess, and Daniel M Hall (Sept. 2021). "no1s1 - a blockchain-based DAO prototype for autonomous space". In: *Proceedings of the 2021 European Conference on Computing in Construction*. Vol. 2. University College Dublin, pp. 27–33. DOI: 10.35490/ec3.2021.185.

Book Chapters

[9] Hunhevicz, Jens, Theodoros Dounas, and Daniel M Hall (2022a). "The Promise of Blockchain for the Construction Industry: A Governance Lens". In: *Blockchain in Construction*. Springer. ISBN: 978-981-19-3758-3. DOI: 10.1007/978-981-19-3759-0_2. URL: https://link.springer.com/book/9789811937583.

Research Presentations

[10] Hunhevicz, Jens (2019). Managing mistrust in construction using DLT: a review of use-case categories for technical design decisions. At *Conference: European Conference on Computing in Construction (EC^3)*. Conference Location: Crete, Greece. Conference Date: July 10-12, 2019. Available on *YouTube*.

[11] Hunhevicz, Jens (2020). Blockchain briefer & Do you need a blockchain in construction? At *1st Workshop on Blockchain in Construction*. Conference Location: Zurich, Switzerland. Conference Date: February 20-21, 2020.

[12] Hunhevicz, Jens (2020). Blockchain and Smart Contracts for Integrated Project Delivery: Inspiration from the Commons. At *Engineering Project Organization Conference (EPOC)*. Conference Location: Colorado, US (Virtual). Conference Date: October 20-21, 2020.

[13] Hunhevicz, Jens (2020). Incentivizing High-Quality Data Sets in Construction Using Blockchain: A Feasibility Study in the Swiss Industry. At *37th International Symposium on Automation and Robotics in Construction (ISARC)*. Conference Location: Japan (Virtual). Conference Date: October 27-28, 2020. Available on *YouTube*.

[14] Hunhevicz, Jens (2021). Crypto-Economic Incentives for the Construction Industry. At *2nd Blockchain in Construction Workshop*. Conference Location: Virtual. Conference Date: April 15-16, 2021. Available on *YouTube*.

[15] Hunhevicz, Jens (2021). no1s1 - A Blockchain-Based DAO Prototype for Autonomous Space. At *European Conference on Computing in Construction (EC^3)*. Conference Location: Rhodos, Greece (Virtual). Conference Date: July 26-28, 2021. Available on *YouTube*.

[16] Hunhevicz, Jens (2021). Digital Building Twins and Blockchain for Performance Based (Smart) Contracts. At *Construction Blockchain Consortium (CBC) Conference*. Conference Location: London (Virtual). Conference Date: October 20-22, 2021. Available on *YouTube*.

7.3.2. Industry Contributions

One of the goals of this thesis was to demonstrate also to industry tangible applications of blockchain and cryptoeconomics in the construction industry. The PBSC prototype showcased how the technology can support novel business models that incentivize actors across life-cycle phases, and the no1s1 prototype demonstrates the feasibility of cyber-physical integration in the built environment towards self-sovereignty of things. Both examples can help industry to grasp the potential and implications of blockchain in the built environment. Furthermore, they demonstrate early feasibility of blockchain implementation. In addition to the research publications, three external articles about no1s1 [1-3], and four presentations at industry events [4-7] disseminated the ideas to industry and the public.

Articles

[1] ETH Zurich (2021). *A small house raises big questions.* URL: https://ethz.ch/en/news-and-events/eth-news/news/2021/10/a-small-house-raises-big-questions.html (visited on 02/10/2022).

[2] EY Switzerland (2021). *What happens when buildings own and manage themselves.* URL: https://www.ey.com/en_ch/strategy/what-happens-when-buildings-own-and-manage-themselves (visited on 02/10/2022).

[3] Digitec (2021). *Vom Warenkorb ins Blockchain-Haus: So haben wir no1s1 ausgestattet.* URL: https://www.digitec.ch/de/page/vom-warenkorb-ins-blockchain-haus-so-haben-wir-no1s1-ausgestattet-21619 (visited on 02/10/2022).

Industry Presentations

[4] Hunhevicz, Jens; Hall, Daniel (2019). Blockchain in Construction. At *5th Digital Real Estate Summit.* Conference Location: Brugg-Windisch, Switzerland. Conference Date: March 5, 2019.

[5] Hunhevicz, Jens; Hall, Daniel (2021). Smart Contracts in Construction. At *UZH Blockchain Center Lecture Series, Co-hosted by Trust Square and Dezentrum.* Location: Zurich (Virtual). Conference Date: May 18, 2021. Available on *YouTube*.

[6] Hunhevicz, Jens (2021). Kryptoökonomische Systeme für die Bau und Immobilienbranche. At *Gebäudetechnikkongress 2021.* Conference Location: Dübendorf (Virtual). Conference Date: October 27, 2021. Available on *YouTube*.

[7] Wang, Hongyang; Hunhevicz, Jens (2021). Decentralized Autonomous Space no1s1 Development. At *Engineering ArchiTECHure Podcast.* Date: October 29, 2021. Available on *YouTube*.

7.4. Limitations

This thesis has succeeded in making relevant contributions to the field of construction management assessing the potential and feasibility of blockchain and cryptoeconomics in the construction industry. Nevertheless, there is room for improvement. In addition to limitations pointed out in the individual chapters, the following aspects represent overall limitations of the work.

The Early State of DLT

A limitation lies in the early and fast moving space of DLT. As also discussed in the introduction, the narrative around blockchain is constantly evolving. This makes it hard to describe and pinpoint related concepts. For example, the understanding and definitions of DAO even evolved during the duration of this thesis. In addition, with the ever-shifting narrative around blockchain, also new use cases can emerge that are not captured within this thesis. Finally, the blockchain space is growing fast and attracts consistently more capital and talent to extend the technology stack and its capabilities. Therefore, the theoretical foundations of blockchain and its application need to be reevaluated and confirmed over time.

The Work Needs Extension and Further Validation

While the work in this thesis proposes how and why to apply cryptoeconomics in the construction industry, there is opportunity to extend the thinking around the introduced concepts. There is need to identify more applications for cryptoeconomic incentives in the construction industry, to create more clarity how future project delivery can profit from ideas of blockchain-based organization and governance, and to better understand implications of different design choices regarding ownership and liabilities and rights using blockchain-based mechanisms in different contexts and for various actors, both human and machines.

Furthermore, anticipated benefits such as cryptoeconomic incentives as a promising supply chain integration practice and accelerator for innovation need further validation. The two prototypes are both limited in that they are proof-of-concepts demonstrating feasibility of cryptoeconomics in a research setting. Therefore, they only allow to anticipate the impact of blockchain and cryptoeocnomics to the construction industry. The impact and implications of blockchain and cryptoeconomics in the construction industry needs further investigation and validation.

The Focus on Fragmentation, Decentralization, and Complexity

This thesis mainly discusses the promise of blockchain and cryptoeconomics as a way to strengthen trusted collaboration within the decentralized and project-based construction industry suffering from fragmentation and complexity. Even though cryptoeconomic mechanisms align well with bottom-up governance approaches of collaborative project deliveries, more research should assess whether blockchain could also integrate and connect with approaches of digitally-enabled manufacturing.

Moreover, the research in this thesis was conducted in Switzerland. The research context is therefore influenced by this research setting, with Switzerland mainly experimenting with new collaborative project delivery approaches based on the IPD approach coming from the US. Therefore, much of the literature is based on papers from the US, occasionally supplemented with papers from the UK or other locations. While there are many similar patterns observable around the world when it comes to fragmentation, decentralization, and complexity of the construction industry, more research needs to check applicability of the results within different industry contexts and contractual settings.

Reasons to Avoid Blockchain

Finally, this thesis is limited in that it mainly focuses on benefits when apply blockchain in the construction industry. More research is needed to why blockchain should not be applied. For example, do potential efficiency gains using blockchain outweigh environmental costs of blockchain systems? This alone is not a straightforward question depending on the use case, the used DLT system, and the consumed energy mix.

7.5. Directions for Future Research

Despite the contributions made in this thesis and by the increasing research body on blockchain in construction around the world, research on blockchain and cryptoeconomic applications for construction remains in its infancy. Based on the generated insights in this thesis, some ideas on next research steps are presented.

7.5.1. Keeping Up with the Technology

Using a private permissioned blockchain for a construction use case can solve problems related to transaction costs, throughput and privacy. But as this thesis showed, the potential medium to long-term benefits for the construction industry coming from cryptoeconomic design mainly unfold with public permissionless blockchains. Also in the blockchain space, most innovation happened around public permissionless blockchain systems with ICOs, DeFi, NFTs, or DAOs. Since associated challenges with public permissionless systems around transaction costs, privacy and throughput not only concern use cases in the construction industry, the technology landscape is evolving fast: layer 2 solutions to address scalability, advanced cryptography to address privacy, decentralized data storage in combination with blockchain to save on transaction cost, and many more offer potential solutions. Blockchain in construction research should keep up with the technological evolution to move promising use case applications closer to industry implementation. The thinking should shift away from only using blockchain in isolation towards an ecosystem thinking around the emerging Web3 technology stack (Web3 Hub, 2019). Therefore, it would be desirable to see more research focusing on public permissionless blockchains and the bigger Web3 technology stack already for more short term applications in the construction industry to facilitate a basis for later use of incentives and new forms of organization.

7.5.2. A Multi-Token Built Environment

One of the most interesting cryptoeconomic mechanisms is tokenization. More research should explore how tokens in the construction industry can be used for incentive systems. The value of a token does not need to monetary, but could represent everything that a community values, from tokens representing embodied carbon of buildings, the reputation of contractors, the voting rights of a resident on where to spend money on public infrastructure, or the ownership rights to all steel-columns contained in a building. Multi-tokenization allows to shift incentive systems away from purely monetary driven optimization (Kleineberg and Helbing, 2016). The Finance 4.0 project (Ballandies et al., 2021a) investigated this concept for a new sustainable finance system. A similar system could also be explored to make the construction industry more sustainable. For construction projects, the introduced conceptualization could act as a guideline (Figure 4.2). Along with tokenization, decentralized infrastructure such as market places and governance platforms will be needed and should be also further explored.

7.5.3. The Next Generation of Project Delivery

While the introduced conceptualization (Figure 4.2) structures cryptoeconomic mechanisms and their application for collaborative construction delivery, application towards the next generation of project delivery remains vague. Similar to other DAOs, organization could shift towards a collective that self-organizes towards the creation and construction of built assets. Coordination could be informed by real-time digital representations (i.e., digital twins) of the built assets. The two can be potentially overlaid with blockchain-based governance and ownership to build parallel or subsequently in the “Metaverse” and in the physical world. Already today, land and property ownership in the virtual world becomes increasingly important with various companies embracing business activities in the Metaverse (Goldberg et al., 2021). Overall, there is opportunity using the introduced cryptoeconomic mechanisms to rethink how in the future construction projects can be delivered.

7.5.4. A Human-Machine Future

This thesis showed with no1s1 that things and machines will be able to participate in economic systems. Nevertheless, there are a lot of uncertainties and challenges around this possibility. To facilitate a trusted bridge between the physical and digital world needs more research exploring various technical solutions. Nevertheless, inaccurate data provision is not only a problem related to blockchain. Potential proposed solutions such as incentive systems for correct data provision through stakeholders in construction projects (Hunhevicz et al., 2020b) could be also applied to feed reliable data into smart contracts. Furthermore, possible applications of machine-participation in a construction context beyond no1s1 should be explored (e.g. subcontracting work to machines) together with prerequisites (e.g. machine-readability of data through the semantic web (Berners-Lee and Hendler, 2001)). Finally, there are many conceptual and legal implications of machine ownership with associated liabilities and rights that need more research.

7.5.5. An Interdisciplinary Research Approach

The creation of cryptoeconomic systems such as for tokenization or new forms of governance can be a very challenging endeavor. The design of new economic systems naturally involves many scientific fields (Voshmgir and Zargham, 2019). Because incentive structures that manage projects worth millions of dollars need to be proven to work even in the context of complexity, research investigating cryptoeconomic systems design for construction project deliveries should strive for an interdisciplinary approach beyond construction industry and DLT expertise. This thesis demonstrated that other fields like CPR theory can be very helpful lens to identify applications of cryptoeconomic mechanisms. Nevertheless, a next step will be the design and testing of incentive or organizational systems. For that, research methods suitable for complex system modelling and testing should be explored (Boccara, 2010). Also, advances in the fields of cryptoeoconomics (Voshmgir and Zargham, 2019) or token-engineering (Token Engineering Community, 2022) should be closely followed.

7.5.6. The Industry Factor

More research should investigate how the proposed cryptoeconomic applications could be disseminated in the construction industry. Construction stakeholders or customers need to perceive blockchain affordances or new economic systems as valuable in order to adopt. What will be the main selling points? And who will drive adoption of cryptoeconomic systems? There is both potential to create incentives that motivate bottom-up adoption (as e.g. to incentivize data sets (Hunhevicz et al., 2020b)) as well as new business models (as e.g. in PBSC (Hunhevicz et al., 2022c). Furthermore, the usability of blockchain needs to be ensured and should be subject of further assessment. There is also still a lot of uncertainty around legal and regulatory implications that could either hinder or drive adoption of cryptocurrencies, tokens, and blockchain-based organization. Overall, there are still many unknowns in the socio-technical interactions influencing adoption of cryptoeconomic systems in the construction industry that need to be researched.

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