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REVIEW ARTICLE

Xuling YE, Ningshuang ZENG, Markus KÖNIG

Systematic literature review on smart contracts in the construction industry: Potentials, benefits, and challenges

Abstract The development of digital transformation in the construction industry has led to the increasing adoption of smart contracts. As programmable applications to automatically write, verify, and enforce transaction conditions, smart contracts can be used in different areas mainly to improve automation level, information security, and built digital environment enhancement. However, the smart contract is commonly mentioned as a blockchain appendage, while its unique connotation and value in the construction industry have not been recognized. Therefore, this study carries out a systematic review based on 81 research articles published from 2014 to 2021 on smart contract applications in construction to explore and highlight their potentials under domain-specific requirements. Results are analyzed according to research type categorization and domain codification. Eight research domains are identified, where the three most highly explored domains are contract and payment, supply chain and logistics, and information management. The integration of smart contracts with other innovative concepts and advanced technologies is analyzed. The applicability, benefits, and challenges of smart contract applications regarding different research domains are discussed.

Keywords smart contracts, blockchain, construction industry, BIM, systematic review

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Xuling YE, Markus KÖNIG
Department of Civil and Environmental Engineering, Ruhr-Universität Bochum, Universitätsstraße 150, D-44801 Bochum, Germany

Ningshuang ZENG (✉)
Department of Civil and Environmental Engineering, Ruhr-Universität Bochum, Universitätsstraße 150, D-44801 Bochum, Germany; Department of Construction Management and Real Estate, School of Civil Engineering, Southeast University (Jiulonghu Campus), Nanjing 210096, China
E-mail: ningshuang.zeng@rub.de

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1 Introduction

The construction sector plays an essential role in the global economy, accounting for approximately 6% of the world gross domestic product (GDP) in 2018, which is expected to reach approximately 14.7% in 2030 (Craveiro et al., 2019). However, for decades, this sector has been criticized for low productivity, poor performance, and lagging innovations (Arditi and Mochtar, 2000; Sacks, 2016). At present, Information and Communication Technology (ICT) innovations are changing almost every industry with increasing digitalization and the exponential growth of sensible data (Lu et al., 2015). Other industries, such as automotive, aeronautics, and aerospace, have undergone significant improvements due to the adoption of ICTs to improve efficiency and productivity (Li et al., 2019a). However, in this trend of digital innovation, the Architecture, Engineering, and Construction (AEC) industry lags behind (Li et al., 2019a).

Advances in smart contracts are increasingly investigated as a constituent in the construction industry’s digital transformation. Smart contracts have the potential to help solve a series of growing problems in construction, such as contract disputes and payment issues, and can facilitate Building Information Modeling (BIM) adoption (Xue and Lu, 2020; Hamledari and Fischer, 2021d). Contract disputes are common in the construction industry (Wang et al., 2019a). Contradictions, errors, or inaccurate terms in construction contracts can cause difficulties in execution. The current prevalence of paper-based contracts leads to the difficulty of tracking changes and recording execution. Thus, claims and disputes lack basis, encouraging irregular behavior and low contract enforcement of clients or contractors. Using smart contracts, immutability can be ensured while all changes are securely recorded and can be easily traced. Another growing problem occurs in payment. Timely payment and stable cash flow are vital to the success of construction projects. Problems, such as non-, delayed, and incorrect payment, lead to construction delays, additional costs, decreased performance, and disputes (Ramachandra and Rotimi, 2015). Recent developments in smart contracts provide the ability to achieve safe and accurate automated payment (Ahmadisheykhsarmast and Sonmez, 2020). An issue on ICT innovations is the difficulty in BIM adoption. The barriers of adopting and better use of BIM cannot be ignored, and among these, the intellectual property ownership and information security risks are highlighted (Fan, 2014; Chan et al., 2019). In practice, one party using the BIM model of another party might inadvertently infringe upon the latter's intellectual property rights (Fan, 2014). Therefore, the ownership of electronic information in BIM becomes an ongoing problem, which can be improved by using smart contracts in construction projects (Gürkaynak et al., 2018). Meanwhile, information security can also be ensured because all changes in BIM can be traced (Xue and Lu, 2020).

Recent reports and academic literature highlight blockchain in construction, where smart contracts are commonly mentioned or addressed as an appendage of the blockchain. Smart contracts are considered as a bond (Kiu et al., 2020), component (Nawari and Ravindran, 2019a; 2019b), layer (Perera et al., 2020), feature (Wan et al., 2020), or "one of the most important aspects" (Li et al., 2019a) in the blockchain. However, as an engine for relevant automation and a key innovation for digital transformation in construction, the smart contract has unique definition, connotation, and contribution to the construction industry.

In this context, the adoption of smart contracts is still in its infancy. In the early stage, a technology application encounters various problems, such as difficulties in evaluating its effectiveness and technical and managerial obstacles to further development. As such, clarifying the benefits and determining the challenges in the development of smart contracts from its initial stage to the mature application is of high value. Therefore, in this study, we carry out a systematic review to present the potential application of smart contracts in construction and explore its benefits and challenges. Meanwhile, this review aims to reveal the technical compatibility of smart contracts with other ICTs.

The remainder of this paper is organized as follows. Section 2 introduces the definition and development of smart contracts. The research methodology is introduced in Section 3, and a descriptive analysis of the study results is addressed in Section 4. The results are further analyzed in Section 5, where the potential applications of smart contracts in the construction industry are discussed under eight domains and four integrated technologies. Section 6 discusses the applicability, benefits, and challenges of smart contracts in construction. Section 7 concludes the paper and points out future research directions.

2 Defining smart contracts in construction

2.1 Concept development

The term "smart contract" was first proposed in 1994 by Szabo as "a computerized transaction protocol that executes the terms of a contract" (Szabo, 1994). As a contract, this agreement should satisfy common conditions such as payment terms, liens, confidentiality, and even enforcement. For a smart technology, such a contract must minimize the need of trusted intermediaries such as banks, minimize both malicious and accidental exceptions, and reach economic goals such as lowering fraud loss, arbitration and enforcement costs, and other transaction expenses. In late 2013, smart contracts were implemented in the Ethereum blockchain as "systems which automatically move digital assets according to arbitrary pre-specified rules" (Buterin, 2014). Since then, smart contracts can be used to design specific logic based on the purpose of applications. With the flexibility of creation and enforcement, smart contracts can support complicated requirements that in turn enable developers to build powerful decentralized applications with integrated domain-specific functions. Through the design and implementation of domain-specific smart contracts, blockchain applications can store the domain-specific data in key-value format. Consequently, these contracts can be used in other areas, for example, manufacturing control, law enforcement, E-government, and healthcare (Ølnes et al., 2017; Agbo et al., 2019; Wang et al., 2019c; Kumar et al., 2021). After the widespread implementation of smart contracts, two concepts have emerged: Decentralized Application (DApp) and Decentralized Autonomous Organization (DAO). DApp is a computer application that runs on a decentralized peer-to-peer network (e.g., blockchain), and can be understood as an implementation of smart contracts with a front-end user interface. Once deployed in a blockchain, smart contracts can be operated in the DApp without the help of developers. Ideally, DApp can run without any human intervention, thereby forming a DAO (Cai et al., 2018). A DAO automatically operates decisions through rules coded by smart contracts, where all the management and rules are recorded on the blockchain. Using the DAO, a decentralized, transparent, efficient and autonomous operations can be achieved (Wang et al., 2019b).

Over time, the definition of smart contracts in the construction industry has evolved. In 2015, smart contracts were considered as self-enforcing digital agreements with embedded cryptocurrencies (e.g., blockchain) (Cardeira, 2015). Later in 2019, Nawari and Ravindran (2019a; 2019b) mentioned that smart contracts have two different definitions as the term is "used interchangeably for the written code and the binding contracts", specifically "smart contract codes" and "smart legal contracts". At present, the construction industry has no consistent definition of smart contracts. In literature, smart contracts are at times defined as "smart contract codes" (Hunhevicz and Hall, 2020; Li and Kassem, 2021), "smart legal contracts" (Darabseh and Martins, 2020; Götz et al., 2020; McNamara and Sepasgozar, 2021), or as both (Li et al., 2019a). Apparently, researchers in the construction field attach a strong expectation to the digitalization of construction contracts. Mason (2017) proposed to use "intelligent or automated contracts" as "the term used where the contract seeks to manage themselves". "Intelligent contract" or "iContract" was developed by McNamara and Sepasgozar (2021) as one step further than a smart contract in the digitalization of construction agreements, which can "manage itself through a hybrid legal clause/computer code framework". Later, "intelligent contract" is used by Li and Kassem (2021) as "an application of those smart contracts that aim to closely align with traditional contracts".

2.2 Point of departure

Regarding the different understanding of smart contracts in construction, this study emphasizes two connotations: 1) Smart contracts can promote the digitalization of construction agreements but are not the only technology or concept applied; and 2) Smart contracts can be applied beyond the digitalization of construction agreements, such as for quality compliance checking, supply chain tracing, and Common Data Environment (CDE) enhancing. Based on these two connotations, distinguishing smart contracts from "intelligent contracts" or "iContracts" is necessary to better understand the technical contribution and further apply smart contracts in relevant construction areas according to domain-specific demands. In this study, rather than focusing on the benefits originated from the blockchain, such as decentralized, transparency, and traceability, we address the technical contribution of smart contracts and consider the blockchain as a platform that provides a secure environment for their deployment and execution.

As mentioned above, smart contracts are not limited to the promotion of the digitalization of construction contracts. Smart contracts play a role in the progress of construction digital transformation. In this context, transience and lack of replication are argued as key barriers (Vrijhoef and Koskela, 2005; Sawhney et al., 2020). Construction projects are nearly always one-of-a-kind endeavors, with unique requirements that necessitate bespoke design and delivery approaches. However, the logic and mechanism in smart contracts (e.g., quality acceptance rules and payment requirements) can be easily reused and redeployed in multiple construction projects, thus lowering the barrier of low replication. Meanwhile, planning and design, production, management, and other processes, which occur in construction projects and companies, are more likely to be automated with increasing digital twins of the built environment (Opoku et al., 2021). Given the ability to activate and control data flows in a secured digital platform, smart contracts can first promote the generation and use of construction digital twins, which in turn can amplify the function of smart contracts due to its higher level of automation.

However, the adoption of smart contracts in the construction industry is still at an early stage. Whether the smart contract does make a difference or is merely a castle in the air is worthy of exploration. Identifying the benefits and pointing out the challenges in the adoption of smart contracts is essential. With this objective, this study presents three research questions:

1) Which potentials of smart contracts have been addressed in current research, including the domains that are frequently explored and technologies that can be integrated with?

2) What are the main benefits associated with smart contracts in the construction industry?

3) What are the main challenges associated with smart contracts in the construction industry?

3 Research methodology

3.1 Systematic review

Considering that research in construction can be seen as a combination of multiple disciplines, both technical and managerial, this review carried out a comprehensive search of the applications of smart contracts in the construction industry. A systematic review approach was adopted to identify and assess the significant outputs of smart contract research in English peer-reviewed journals, international conferences, and book chapters. A systematic review is a defined and methodical means of identifying, assessing, and analyzing published primary studies to investigate specific research questions (Staples and Niazi, 2007). As an assessment tool for early-stage research on smart contracts, a systematic review is an effective exploratory method. Figure 1 illustrates the entire process. First, data were collected based on the clarification of the definition of the smart contract. Collected articles were limited to qualified construction-related studies. Research type categorization and domain codification were further carried out to provide a basis for analysis. The applicability, benefits, and challenges of smart contracts were discussed based on the results of the

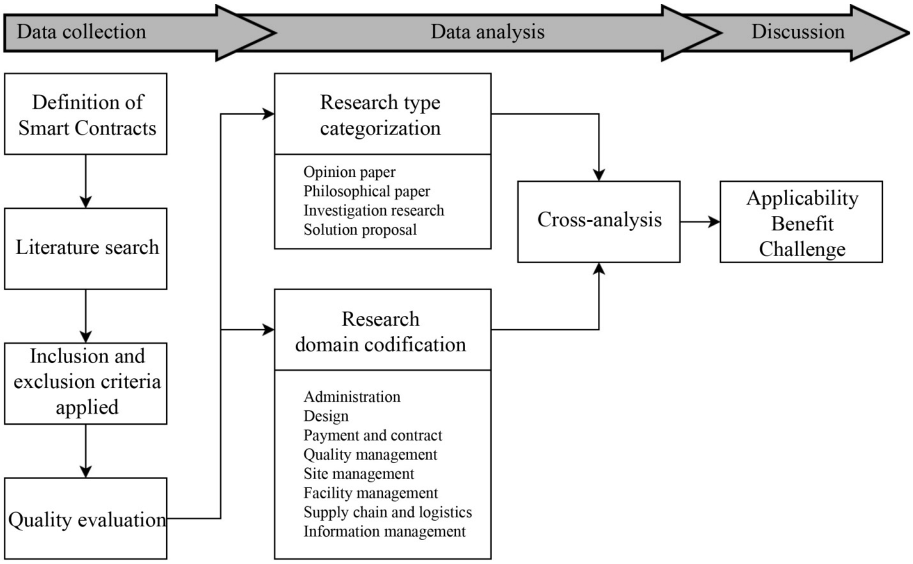

Fig. 1 Overview of research methodology.

research type and domain cross-analysis.

Figure 2 shows the data collection and search rules in detail. This study followed the primary goals of systematic review set out by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Liberati et al., 2009). First, a comprehensive exploratorion was carried out by using the following search engines: 1) Scopus, 2) Web of Science, 3) Science-Direct, 4) IEEE Xplore, 5) SpringerLink, 6) Semantic Scholar, and 7) Google Scholar. In the article title/abstract/keyword fields, the following phrases were used for the search: (“smart contract” OR “intelligent contract”) AND (“construction” OR “AEC”). In addition to the database search, the reference lists of retrieved studies were viewed to identify additional relevant studies to be included in this review. The data used in this review were retrieved on 17 April, 2021, and the search timeline included the years within 2014–2021. The search yielded 827 studies, which were subject to further inclusion and exclusion criteria as mentioned in the selection step.

The selection of relevant articles had two stages, namely, data screening and quality evaluation. In the data screening stage, several articles were excluded for the following reasons (see Table 1): 1) duplication, 2) not available in English, 3) without full availability, 4) unsuitable type, such as thesis or review, and 5) not about the construction field. Removal of all unqualified articles according to the screening criteria yielded 122 articles. In the quality evaluation stage, each article was downloaded and read. The content was checked on whether the smart contract in construction is the primary focus to assure selection quality. For quality evaluation, the question was proposed: Does the article provide clear findings or specific applications of adopting smart contracts? All 122 qualified articles must address this aspect, and are classified into three categories according to the quality evaluation criteria. In total, 81 articles are deemed acceptable for further analysis.

3.2 Research type categorization

Research type analysis are carried out for all qualified articles. To systematically analyze the technology applications, we use the classification principles proposed by Wieringa et al. (2006) and divided technical articles into six research types: 1) conceptual paper, 2) investigation research, 3) solution proposal, 4) validation research, 5) opinion paper, and 6) experience paper (see Table 2). The categorization aims to provide evidence and foundations for further analysis combined with the results of research domain codification. The type of solution proposal aims to provide sufficient details for smart contract applications. However, not all research domains contain this type of article. We also pay attention to works that offer ideas and models at the conceptual level (conceptual and opinion papers) and those that reflect practical problems and provide empirical implications (investigation research).

3.3 Research domain codification

To aggregate findings across studies, we developed a list of first- and second-level codes and their descriptions are shown in Table 3. Creating the list was an iterative process and required coding of each article multiple times, beginning with all three authors independently coding all the technical articles. Research themes for each article are identified as first-level codes, which were

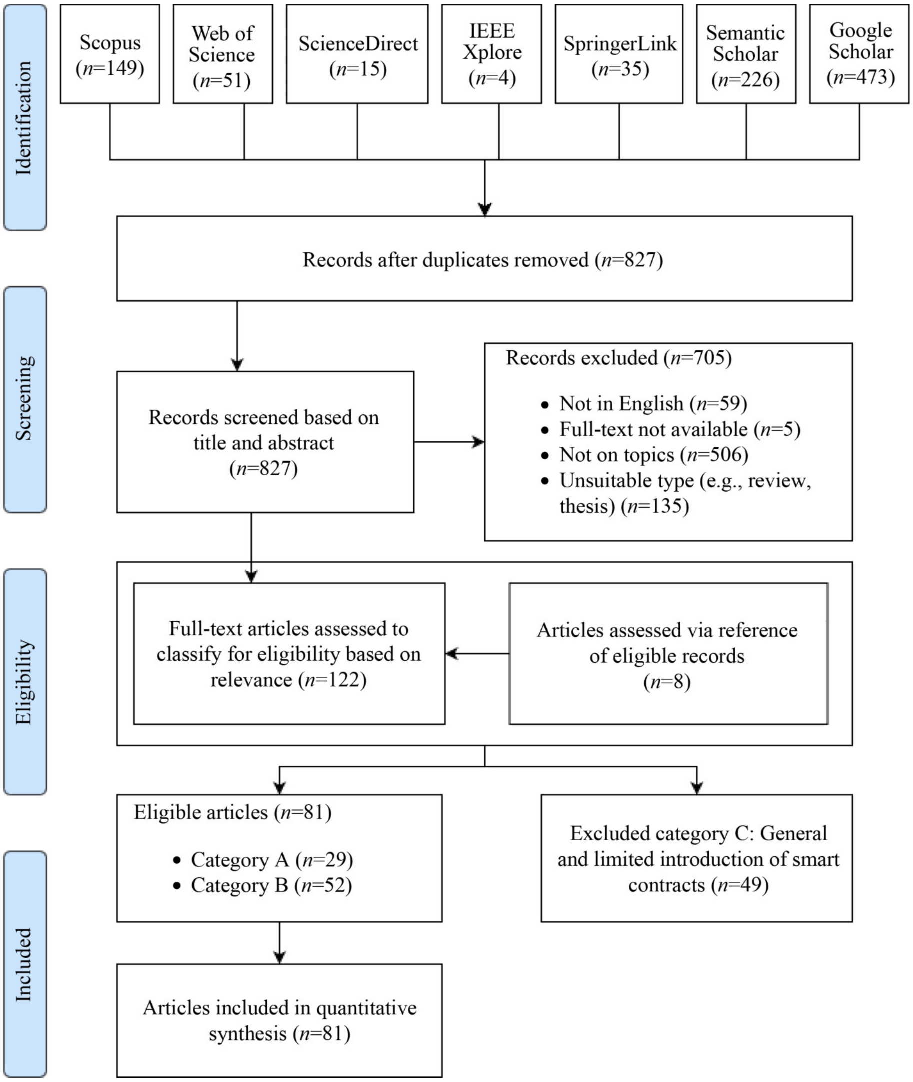

Fig. 2 Data collection flow diagram based on PRISMA.

Table 1 Inclusion and exclusion criteria

No.	Screening criteria	Result (article number)
1	Duplicate articles	Excluded (126)
2	Articles that are not available in English	Excluded (59)
3	Articles without full availability	Excluded (5)
4	Articles with unsuitable type (thesis, review, and report)	Excluded (135)
5	Articles that are not about the construction field (e.g., computer science)	Excluded (506)
No.	**Quality evaluation criteria**	**Result (article number)**
1	Clear findings or specific applications of smart contracts	A: Included and focused (29)
2	Introduction of application of smart contracts	B: Included (52)
3	General and limited introduction of smart contracts	C: Excluded (49)

identified without any preconceived ideas of the final research domains to ensure the original landscapes of the literature rather than fitting articles into predefined categorizations. In the next stage, all the first-level codes were examined and discussed and then merged into several second-level codes that represent the research domains. Finally, we identified 8 research domains for smart contract applications in the construction field based on the codification of 81 technical articles: 1) administration, 2) design, 3) contract and payment, 4) quality

Table 2 Definitions of different research types

Research type	Description
Conceptual paper	Explorations of new perspectives or conceptual frameworks
Investigation research	A study that investigates a problem in smart contracts practice; causal properties are studied empirically, such as by case study, field study, field experiment, or survey
Solution proposal	A study that proposes a novel method or technique and argues for its relevance; a proof-of-concept may be offered
Validation research	Investigations of the properties of a solution proposal that has not yet been implemented in smart contracts practice; the solution may have been proposed elsewhere
Opinion paper	A study that reflects an author's opinions about what is wrong or good about smart contracts in construction
Experience paper	The experience may concern one or many projects, but must be from the author's personal experience; a study must contain a list of lessons learned

Table 3 First- and second-level codes for research domain codification

First-level code	Second-level code	First-level code	Second-level code
Administration	Administration	Quality information management	Information management, quality management
Administration risk		Real-time information	Information management
Employee		Cash flow	Contract and payment
BIM-based design	Design, information management	Contract	
Design liability	Design	Crypto asset	
Smart construction object		Digital currency	
Facility management	Facility management	Financial supply chain	Contract and payment, supply chain and logistics
As-built information	Information management	Financial system	Contract and payment
BIM		Interim payment	
BIM change contract		Payment	
Common data environment		Payment security	
Data flow		Progress payment	
Data security		Transaction	
Digital twin		Quality inspection	Quality management
File system		Quality management	
Fog computing		Safety	Site management
Information exchange record		Site management	
Information flow		Worker management	
Information management		Integrated project delivery	Supply chain and logistics
Information redundancy		Logistics	
Information sharing		Prefabricated supply chain	
Information traceability		Production	
Interoperability		Supply chain management	
Internet of Things (IoT)		Supply chain traceability	

management, 5) site management, 6) supply chain and logistics, 7) facility management, and 8) information management.

The objective of a systematic review is to identify all empirical evidence that fits the predefined inclusion criteria to answer a particular research question or examine a specified hypothesis (Snyder, 2019). However, the systematic review has several limitations, such as publication bias, sample selection bias, and inconsistent coding or data interpretation. To deal with the publication bias, we carried out the search in the most comprehensive databases for relevant papers. The consistency of sample selection was ensured by carrying out a pilot search and discussing all the inclusion and exclusion criteria with experts in the construction and computer science fields. As for the data screening, coding, interpretation, and analysis, all researchers worked collaboratively through timely information sharing and discussion. A comprehensive analysis was conducted on the 81 articles, and critical issues are reported in the following sections.

4 Descriptive analysis

Figure 3 shows the annual distribution of the published articles from 2014 until 2020. The last four years show an increase in the number of publications on smart contract applications in the construction industry, indicating that this technology is still a new research topic in this field. The first paper on smart contracts in the construction industry was published in 2015. Then, since 2019, the publication of both conference and journal papers has increased significantly due to the increasing awareness of and developments in smart contract applications, along with their scalability that makes them suitable for adoption in the construction industry. Smart contract research in the construction industry is thus expected to increase in the near future.

According to the collected 81 articles, smart contract applications in the construction industry can be analyzed by dividing them into four groups with specific aspects: Types of publication, countries, research domains, and integrated technologies (Fig. 4). The included publication types were journal papers, conference papers, and book chapters. Most of the selected articles were published as conference papers (50.6%) and journal papers (46.9%), and only two (2.5%) were published as book chapters. The four major countries of publication were UK (19.8%), China (17.3%), USA (14.8%), and Australia (12.3%), which accounted for 64.2% of the publications. Based on the classification stated in Section 3.3, the research domains were divided into eight categories. The major domains are contract and payment (34.9%), supply chain and logistics (18.6%), and information management (14.0%). Several articles also considered integrating smart contracts with other concepts or technologies, in particular with BIM (65.5%). The second major integrated technology was Internet of Things (IoT) (22.4%), followed by robotics (6.9%) and Artificial Intelligence (AI) (5.2%).

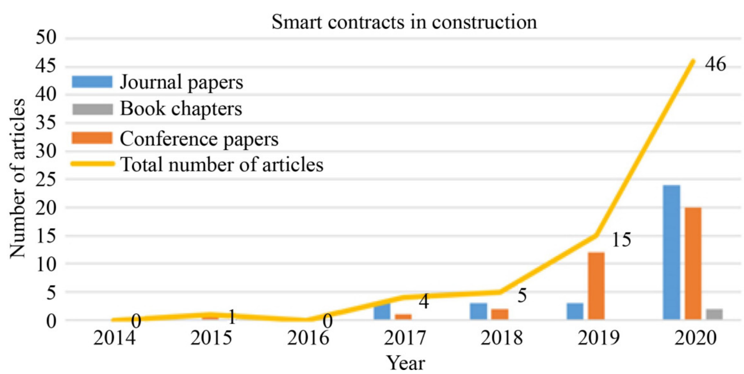

Fig. 3 Year and type distribution of the selected articles.

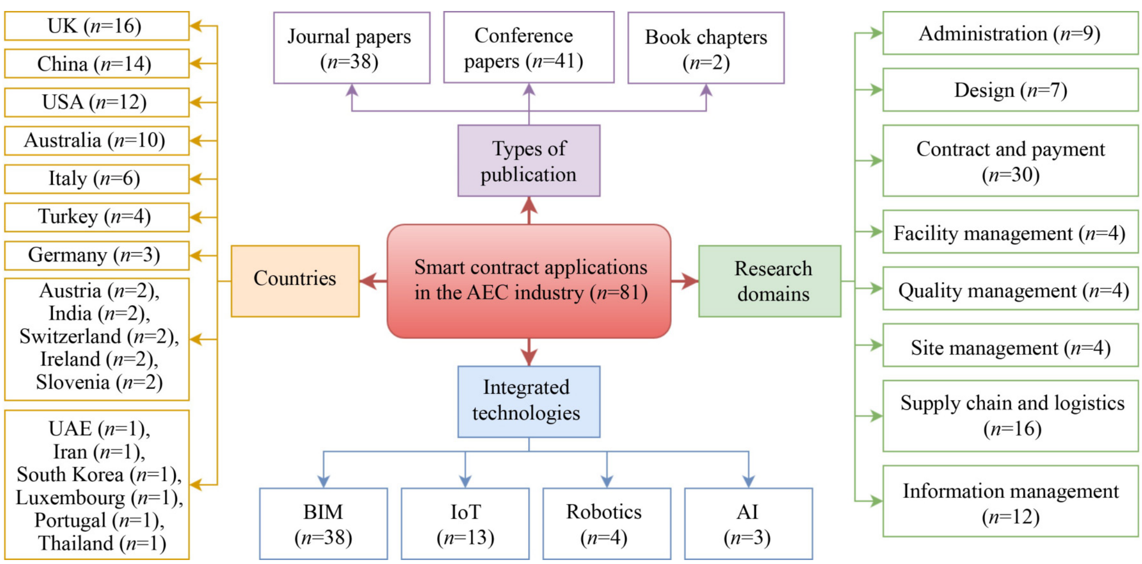

Fig. 4 Classification of smart contract applications.

5 Potential smart contract applications in the construction industry

5.1 Research domains

Figure 5 shows the research phases and eight research domains of smart contracts in construction as identified per the abovementioned iterative coding process and thematic analysis. Planning and design, construction, and operation were recognized as three key phases, which essentially reflect the life cycle of construction project development. The domain of supply chain and logistics extends that of construction management. Information management was identified as a central domain that has high interaction with the others.

Figure 6 shows the research types distributed in the 8 domains. The collected articles included 20 opinion papers, 22 conceptual papers, 17 investigation research, and 29 solution proposals. Research on administration and facility management stayed at the theoretical level, while most smart contract-related solutions were proposed in articles on contract and payment, quality management, and information management. In the following sections, we carried out a research types and domains cross-analysis for further content clarification.

5.1.1 Administration

All administration-related studies had no technical solution using smart contracts, but explored the determinants, drivers, and risks of adopting smart contracts in the construction industry. Badi et al. (2021) drew experience from investigations of UK practitioners, and then suggested four factors that significantly influence the adoption of smart contracts: Supply chain pressure, competitive pressure, top management support, and observability. Koc and Gurgun (2020) applied fuzzy technique-based analysis and determined the top five drivers in implementing smart contracts: Simple layout to read, reduction in clients' risks, clarity in responsibility and risk allocation, ease of comprehension for various stakeholders, and conflict, claim, and dispute reduction. From the opposite perspective, Gurgun and Koc (2021) further identified the top five administrative risks that

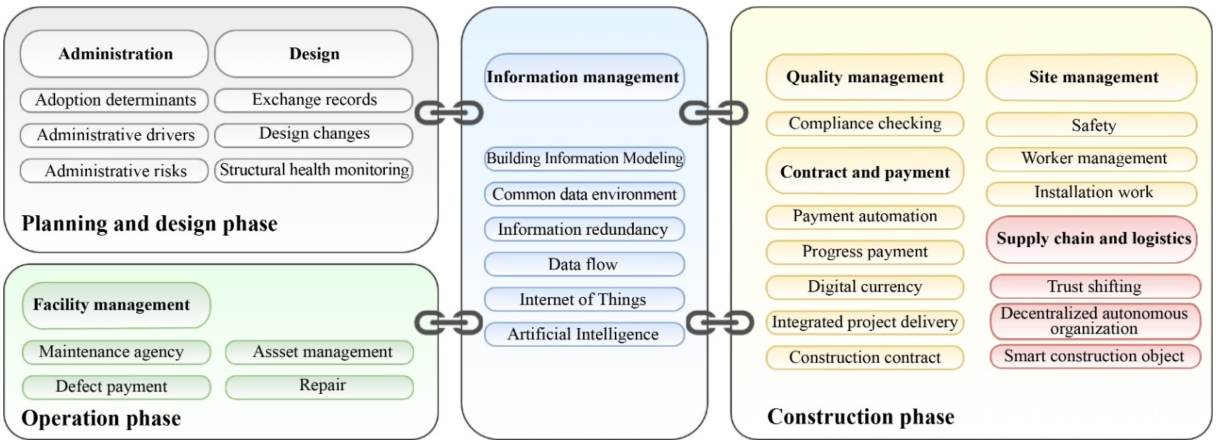

Fig. 5 Research domains of smart contracts.

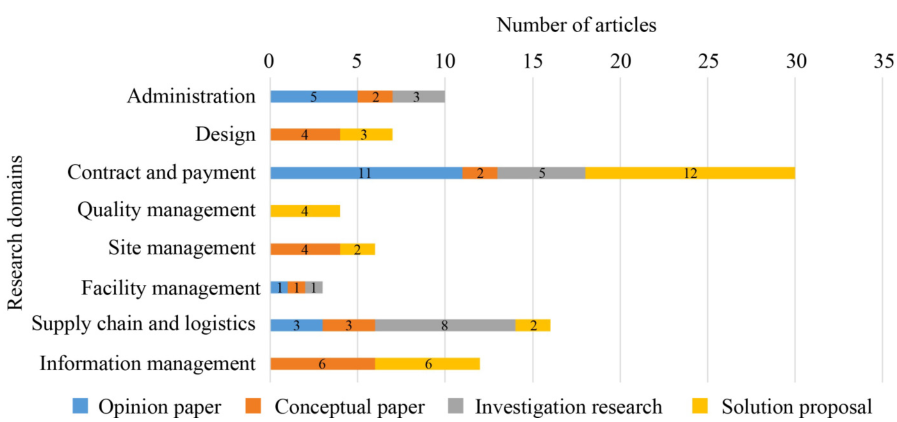

Fig. 6 Distribution of research domains and types.

challenge construction companies to implement smart contracts: Regulation change, lack of a driving force, works not accounted in planning, shortcomings of current legal arrangements, and lack of dispute resolution mechanism. The latter study recommended future research on the necessities and differentiation of smart contracts in agreements between different parties.

5.1.2 Design

For architectural and construction design, the focus is to shift from improving paper-based designs to better handling the digital design information exchange, because such information can be already exchanged digitally (e.g., via BIM) but with little regard to their governing contracts. Erri Pradeep et al. (2021) proposed a system that can improve the design liability control for contributing stakeholders and the auditability of exchange records. A web-based integrated development environment, called Remix, was used for coding the smart contract to facilitate the storage of transactional records on the Ethereum public blockchain. The deployed smart contract is the key component for ensuring design information security, and can verify secure login based on credentials stored on the blockchain.

BIM-enabled information management is a widely discussed topic. Tao et al. (2021) applied smart contracts in developing a distributed CDE (DCDE) for BIM-enabled collaborative design, and addressed both security and decentralization for changes (i.e., transactions). A smart contract was developed to share and query design changes to support the collaboration, and related smart contract functions were identified based on design activities in DCDE. “UPLOAD” and “INQUIRE” functions were developed in a smart contract to satisfy the requirements in BIM model updating, recording of design issues, document sharing, and design information querying. Project members can carry out necessary design activities by invoking different smart contract functions. A pilot experiment was then carried out to evaluate a DCDE with six peers for nine design transactions. The authors called for future research on network optimization solutions for a large-scale application with tens of peers and thousands of transactions. Dounas et al. (2019; 2021) proposed a smart contract-based framework connected with BIM tools for the decentralized architectural design phase to enhance collaboration among designers. On the basis of the integration of BIM with smart contracts, Srećković et al. (2021) introduced another conceptual framework in the design phase to determine possible roles in a workflow, and thus either pass the responsibilities to the next actor or approve the completed steps. Liu et al. (2019) explored the use of smart contracts to aid BIM for sustainable building design information management. Dounas et al. (2020) presented a prototype using smart contracts for handling BIM change records in architectural design practice. Xue and Lu (2020) proposed another approach by using smart contracts to minimize information redundancy between architects and clients by only handling and storing BIM change information in the design phase.

5.1.3 Contract and payment

According to the review results, contract and payment is a major research domain that includes investigations of problems in smart contracts practice and proposals of a novel method or technique. Most of the articles (76.7%) in this research domain either presented opinions (36.7%) or proposed solutions (40.0%).

For the use of smart contracts in the contract and payment domain, researchers mainly hold a positive opinion. As Mason (2017) pointed out, construction agreements and payments can be automatically executed through smart contracts once the clauses were satisfied and work was completed. Badi et al. (2021) carried out a survey among the UK construction practitioners about the views of using smart contracts. The majority of survey participants believed that smart contracts can reduce payout time, lower transaction costs, provide secured payments, reduce the occurrence of disputes and increase trust among contracting parties, and meet the contract management needs of their organization.

The benefits and potentials of adopting smart contracts in construction are likewise widely investigated. Palachuk (2020) pointed out that using smart contracts can improve the drafting and navigating of construction agreements. McNamara (2020) listed the benefits of using smart contracts in the construction industry, including optimizing its formulation and negotiation, improving administration efficiency, and improving communication, collaboration, and trust. Moreover, the combination of BIM and smart contracts can automate the execution phases, including design, commissioning, construction, and asset management (Di Giuda et al., 2020b; Pattini et al., 2020). Shojaei et al. (2020) stated that smart contracts were valuable for managing construction project agreements in any form of dispute resolution, because of its ability to automate the consequences of each transaction and maintain a tamper-proof record of the project progress. In addition, given the complexity, fluidity, and high uncertainties involved in each project, translating all the traditional contract clauses into smart contracts was not necessary. The smart contract adoption for construction administration was analyzed in two surveys, with the first analyzing its reasons for use among construction stakeholders (Koc and Gurgun, 2020) and the second pointing out its risks (Gurgun and

Koc, 2021).

In this domain, the benefits and solutions regarding payment security are highly discussed. In Australia, as a form of performance security, smart contracts can improve the security of the payment framework and be an alternative to a Project Bank Account (PBA) to address financial fragility in the construction industry (Wang, 2018). As Di Giuda et al. (2020a) pointed out, smart contracts can be used with BIM for payment execution in the design phase. Chong and Diamantopoulos (2020) proposed a data-flow-diagram framework for payment security and considered smart contracts as a solution. Ahmadisheykhsarmast and Sonmez (2020) presented a smart contract system using DApp with a blocked process for securing the payment of construction contracts. Another framework was introduced combining BIM and payment data with smart contracts for automating the payment, where the construction agreement stored the hashes of both smart contracts and payment data (Ye et al., 2020; Ye and König, 2021). To realize secured payment automation in the construction supply chain, Hamledari and Fischer (2021a; 2021b; 2021d) presented a solution using decentralized smart contracts with robotic visual data. For the automation and security of interim payments in construction projects, a smart contract framework (Luo et al., 2019; Das et al., 2020) was presented where the terms and conditions are automatically checked at different stages of payment cycles.

5.1.4 Quality management

In this research domain, all articles belong to the type of solution proposal. Several technical solutions using smart contracts have been developed for quality information management, focusing on compliance checking. Sheng et al. (2020) applied smart contracts to standardize the management of quality information and avoid certain processing violations (e.g., an unauthorized signature). Zhong et al. (2020) and Wu et al. (2021) used automated compliance checking based on smart contracts to assure that construction products meet regulatory requirements and for quality inspection associated with IoT system-based on-site data, respectively.

The quality traceability of precast components principally influences the extensive adoption of pre-fabricated buildings. Therefore, Zhang et al. (2020) proposed a quality traceability system for precast components using three types of smart contracts to automate certain operations, such as certification, classification, and multiple traceability. The first smart contract authenticates all edge nodes to ensure the data accuracy while the second classifies all precast component information. Then, the third one, the multiple traceability smart contract multi-directionally tracks the current problem, performs multi-directional mesh tracking on the manufacturing, transport, and construction of the precast components, and identifies the key points that may have issues.

5.1.5 Site management

For this construction domain, most studies apply smart contracts to develop systems or solutions for safety and worker management. Kochovski et al. (2019) developed a blockchain-based fog computing platform for site safety monitoring. Kochovski and Stankovski (2021) further used smart contracts for access management to AI models to satisfy data security and privacy standards, thereby achieving a safe and smart construction site. Pinna et al. (2020) developed a construction worker management system and defined two main smart contracts, namely, “OSPManager” and “JobManager”, to satisfy security requirements by using a “contract diagram”, a graphical description of on-chain elements for solidity-based smart contracts.

For installation, Baek et al. (2020) proposed a system for using smart contracts to check the adequacy of on-site scaffolding. An application was developed to allow general contractors and suppliers to enter information about scaffolding ordering and procurement. Such necessary core installation information was stored in a non-modifiable form using the distributed ledger storage technology. Combined with smart contracts, simulation and BIM were also applied for installation work. Li et al. (2019b) provided a smart contract-based demonstration that included a simulated installation activity in a BIM-based project.

5.1.6 Supply chain and logistics

Industrial surveys and investigations were carried out to explore the potentials of smart contracts in the construction supply chain and logistics, and half of the reviewed articles (50%) in this domain were investigation research. Nanayakkara et al. (2019) investigated the stakeholders’ perspective on smart contracts in the construction supply chain and highlighted quality, confidence, fairness, protection, transparency, accountability, enforcement, and standardization as the primary perspectives. On the basis of results of semi-structured interviews, Tezel et al. (2020) suggested using smart contracts to support procurement and supply chain activities via automated payments, provenance tracking, contract administration, disintermediation, data ownership, and redefining trust. Tezel et al. (2020) and Shemov et al. (2020) addressed the use of smart contracts to form a DAO in construction supply chains. Qian and Papadonikolaki (2021) studied trust shifting in the construction supply chain via blockchain, and addressed the use of smart contracts in contracting and cash flow transfers. Their findings indicated that improving smart contracts and strengthening the enforcement through mandatory external mechanisms can help reduce the need for trust among construction supply chain participants.

Information sharing is critical in the construction supply chain to promote decision making, accelerate the schedule, reduce costs, and improve the project's final quality. Pishdad-Bozorgi et al. (2020) presented three logical scenarios in information-sharing systems for the application of blockchain technology, which aids in the establishment of a trust-enhanced ecosystem for secure information sharing while minimizing counterfeiting and reducing the bullwhip effect. However, the application of blockchain in construction supply chains generally involves legal issues. Ma (2020) proposed solutions to three main legal problems emerging from the use of blockchain technology: 1) limiting the use of smart contracts to predetermined results, 2) questions on access to and control of a decentralized blockchain network, and 3) multi-jurisdictional concerns about which laws apply.

Conceptual models related to construction supply chain and logistics were also developed and analyzed, and 18.75% of the reviewed articles in this domain were conceptual papers. Kifokeris and Koch (2020) proposed a digital business model for construction logistics consultants and Tezel et al. (2021) presented three models of payment, finance, and tendering. Data flow was analyzed in different supply chain scenarios using smart contracts to prove its necessity and feasibility. Among the supply chain and logistics-related research, only one study from Lu et al. (2021) explored the technical solution development stage. A smart construction object-enabled supply chain management framework was developed to address the implementation of four smart contracts, namely, for blockhain oracle, aggregator, reputation, and service.

5.1.7 Facility management

The adoption and application of smart contracts were rarely explored in the research domain of operation and maintenance. Only one prototype using smart contracts was proposed by Tiwari and Batra (2021), who sought smart contracts with the cyber–physical system (CPS) in facility management. In their system, the sensor-detective device can communicate with the maintenance agency via the smart contract in real-time. The smart contract also facilitates immediate payment on the closure of the defect. A self-activating and self-supervising scenario was elaborated using smart contracts and CPS. Two challenges applying smart contracts in facility management were identified as the unique digital identification of devices and inconvenience caused by updating the necessary tools (i.e., Solidity).

Meanwhile, reliable and relevant data is lacking for the construction project life cycle and the in-use process. Raslan et al. (2020) created a framework for assembling asset information models using smart contracts, enabling the owner, consultant, contractor, and supplier to upload and visualize data from any location at any point during the building's life cycle. As an asset class, infrastructure has a high capital intensity, a long return on investment cycle, and substantial social spillover effects, and is illiquid and dynamic. Tian et al. (2020) showed that infrastructure asset tokenization using smart contracts can increase liquidity, transaction efficiency, and transparency across intermediaries.

5.1.8 Information management

In this domain, the smart contract research were divided between conceptual papers (50%) and solution proposals (50%), mainly with a focus on two aspects, information processing and compliance checking. Li et al. (2020) proposed a framework to automate existing processes during the operation and maintenance of built assets, where the information is processed and checked by a non-deterministic smart contract in the DAO.

For information processing, smart contracts can be applied to different kinds of information, such as construction documents (Das et al., 2021), quality information (Sheng et al., 2020), delivery information (Wang et al., 2020), and BIM change data (Xue and Lu, 2020). Das et al. (2021) designed a construction document management system using smart contracts as a process orchestrator and a sub-process executor; the former orchestrates the calls to different functions according to the requirements of the document approval workflow, and the latter carries out the individual processes such as document creation, document updating, document endorsement, and feedback.

Compliance checking was also emphasized in construction projects to ensure the correctness of execution order, selection, automation payment, and BIM model. Beach et al. (2020) systematically analyzed obstacles to automated compliance checking, such as lack of shared open standards for regulation clauses, inability of brief and regulatory requirements to be contractually enforceable, and lack of requirements stipulating the use of designed and as-built structured asset information (e.g., BIM). Hunhevicz et al. (2020) designed smart contract logic to control the execution order of construction for different stakeholders. Yang et al. (2020) investigated two cases by using smart contracts for complication checking. Case 1 lies in the design phase for checking the complication of selecting cladding, while case 2 is in the procurement phase for checking the equipment complication for automating payment. Recently, Nawari (2021) proposed a framework using the smart contract to check the compliance of the BIM model over the project life cycle.

5.2 Technology integration

This section reviews the integration of smart contracts with other technologies, namely, BIM, IoT, robotics and AI. Given the importance of BIM in the construction industry, smart contracts are integrated to assist in workflow execution and change information management. In addition, the integration of smart contracts with other technologies, namely, IoT, robotics and AI, can aid applications in physical data capture, decision making, and progress detection.

Research on the integration of smart contracts with BIM mainly lies in the design, contract, and payment domains. Liu et al. (2019) pointed out that the adoption of smart contracts allows BIM to declare obligations and create clear contractual relationships, which are beneficial to current sustainable design practices. Dounas et al. (2021) introduced a decentralized architectural design using DAO to shift trust from the people to the underlying infrastructure and optimize BIM integration via smart contracts. Another possibility was to develop a decentralized BIM using a smart contract for the design phase (Dounas et al., 2020) to handle the connection rules with off-chain storage and the transaction for decentralized hosts. Srećković et al. (2021) also proposed the use of smart contracts in their BIMd.sign project to analyze, model, and execute BIM workflows in the design phase. Di Giuda et al. (2020a) stated three main benefits that can be obtained through the integration of BIM and smart contracts in contract management: 1) a collaborative environment with clear definitions of responsibilities and duties, 2) storage and tracing of information as intellectual property, and 3) automated delivery and payment. Pattini et al. (2020) provided an execution framework enabled by smart contract-based BIM while Elghaish et al. (2020) applied 5D BIM to cost management for all Integrated Project Delivery (IPD) core participants. Xue and Lu (2020) proposed a BIM change contract, a smart contract-like protocol for integrating distributed semantic differential transaction records from different participants to calculate the important semantic BIM changes and reduce the information redundancy. A BIM-based billing model was also used as the input data to smart contracts for payment automation and contract management (Ye et al., 2020; Ye and König, 2021). Chong and Diamantopoulos (2020) designed a conceptual framework using IoT, BIM, and smart contracts for payments, where self-executing smart contracts enables automated transactions based on both as-built (from sensors) and as-designed (from BIM) information.

The integrations with IoT, robotics, and AI were mainly used for physical data capture, decision making, and progress detection in smart contract applications, which have automated data collection and processing for a better process or payment automation. IoT devices can be used to capture the physical data on the construction site and automatically track each delivery step as inputs to verify requirements coded in smart contracts (e.g., installation tasks or payments) (Li et al., 2019b; 2020). Zhong et al. (2020) presented a smart contract-based framework with an IoT module (including sensors) to automatically collect construction quantity information of labor, equipment, or materials on construction sites. Another quality traceability system for prefabricated buildings used IoT devices for automatic data collection to aid smart contracts in operation automation (Zhang et al., 2020). The collected data were authenticated, classified, and traced by smart contracts to ensure the accuracy, performance, and traceability. Robotics can be used in capturing real-time construction progress at job sites as inputs to trigger smart contracts for progress payments in the construction supply chain, which was proposed by Hamledari and Fischer (2021a; 2021b; 2021c; 2021d). AI is quite useful in decision-making (Kochovski et al., 2019; Calvetti et al., 2020) and progress detection (Hamledari and Fischer, 2021c) for smart contract applications. In worker management, AI can be used for automation of data analysis and decision making regarding craft workforce monitoring, performance assessment, and post-processing. The processed data serve as the input to smart contracts for information sharing, monitoring, and automated execution (Calvetti et al., 2020). For a secured worker management, Kochovski et al. (2019) used IoT devices for data capture, AI to analyze video footage to detect safety violations (e.g., a construction worker without a helmet), and smart contracts for further results processing and trusted cloud storage. Hamledari and Fischer (2021c) proposed to use AI for progress detection based on robot-captured images to aid smart contracts in automated progress payment at the concept level.

6 Discussion

6.1 Applicability of smart contracts in construction

The applicability of smart contracts in construction is influenced by various factors, such as domain-specific requirements, frequency of information updates, and the capacity of information. For smart contracts, the clarification of the application context is essential for design and implementation. Figure 6 shows that all the reviewed articles in the quality management domain reached the technical solution development level due to clear requirements clarification. For example, in the research from Sheng et al. (2020), the main objectives, key participants, workflows, and data exchange requirements of construction quality control were clearly defined. Thus, sufficient information can be provided for smart contracts design and deployment. By contrast, administration objectives are comprehensive and related scenarios are hard to define, therefore, all smart contract-related researches in the administration domain remain theoretical (see Fig. 6). For further application of smart contracts in construction, clarifying domain-specific requirements and building well-defined application scenarios are essential.

Another aspect of smart contract applicability is the determination of which data are stored on-chain (i.e., on the blockchain) or off-chain (i.e., on other databases). Smart contracts can be coded differently based on different storing rules. In these applications, not all data are sensitive or require a high level of security. Such data can be stored off-chain to save more capacity in the blockchain, thereby increasing transaction speed and reducing transaction costs. For example, given the large storage demand of 3D BIM models, storing them all on-chain is unreasonable. Instead, the entire BIM file can be stored off-chain, and only the BIM change information is stored on-chain. In the contract and payment domain, data has low information update frequency, low data capacity demand, and fewer recording needs. In this case, off-chain storage may not be necessary and smart contracts can be used more on process automation and compliance checking. Given the fixed nature and validity of construction contracts, the updating of contract information caused by design or engineering changes has relatively low frequency, but each modification of contract terms is critical and must be recorded. Payments are executed once a month or even once during the entire construction period based on contract type, and thus have a low update frequency. However, payment information has such high importance and needs secure recording. At the same time, the information carriers of these contracts and payments are commonly in text and digital forms, which require limited capacity and can be stored on-chain.

The use of DApps can lower the barriers of applying smart contracts for construction project stakeholders by providing a user-friendly interface. Trust and organizational issues have persisted in the administration and supply chain domains, which can be reduced by using DAO, wherein trust is shifted from the people to the underlying infrastructure. The application of smart contracts brings change not only in method but also in consciousness. In a flat and transparent organization, work efficiency and effectiveness can be greatly improved. Thus, in terms of changing the organizational model and enhancing trust, smart contracts play a very vital role.

6.2 Benefits of smart contracts in construction

Smart contracts play a role in the entire life cycle of the construction project. In the design stage, the benefits of applying smart contracts include enhanced collaboration among designers, efficient recording of BIM changes, and automated design phrases. In tendering, bidding, and contracting, smart contracts can help automate the contractual clauses, increase transparency and trust among contracting parties, reduce disputes, and enhance contract management. In the construction stage, smart contract applications can verify the adequacy of the installation work and manage, check, and trace quality information. Meanwhile, worker data can be stored and managed with accountability, integrity, and immutability. As for the payments, using smart contracts can reduce payment time, lower transaction costs, and provide secure cash flow. Finally, in the demolition stage, smart contracts can improve waste management by tracking the waste generation, processing, and elimination.

In the construction industry, a significant benefit associated with smart contracts is its technical extensibility, which allows the blockchain to store data beyond digital currencies (Lamb, 2018). Stakeholders can design smart contracts based on their own demands. Smart contracts are fostered via a strong assurance of reliability and resilience, which enables their safe applications in all suitable domains of the construction industry. Moreover, smart contracts are automated by code instead of humans, which can simplify the manual approval process. Cryptographic transactions remove the need to trust a third-party middleman, given that transactions are completed securely based on network verification of consensus algorithms as opposed to people or organizations. Moreover, the integration of smart contracts with other concepts or technologies (e.g., BIM) can further extend the benefits of using smart contracts.

Another essential benefit lies in addressing payment and cash flow issues (Hamledari and Fischer, 2021d). For example, the cash flow problems of the contractor and lower tiers (e.g., subcontractors and suppliers) resulting from late payments can be significantly solved via a direct payment transfer from the owner's wallet to the subcontractors' and suppliers' wallets in a smart contract application. Smart contracts eliminate the need for a trusted third party to verify the location or ownership of funds or to guarantee a master copy to clear transactions. Payments can be integrated and processed through the Internet without the need for a merchant account or passing through any banking infrastructure.

Preventing and solving contract disputes were also recognized as major benefits of using smart contracts (Badi et al., 2021). Such disputes between clients and contractors can be minimized because the smart contract carries out the contractual and payment clauses based on automated protocol, leaving no chance for the parties to disobey, reinterpret, or alter the agreed conditions. Thus, the need for a costly and time-consuming arbitration for dispute resolution for contractual and payment issues can be reduced. Given that contractual and payment conditions are flexible, they can be coded in the smart contract based on the agreements between the clients and contractors. Smart contracts can also be used globally as an alternative for the PBAs of both public and private projects.

6.3 Challenges of smart contracts in construction

For different research domains, the challenges of applying smart contracts in construction also vary, as shown in Table 4. For the contract and payment domain, the feasibility and potentials of smart contracts have been explored, such as for payment automation and contract security (Ahmadisheykhsarmast and Sonmez, 2020; Das et al., 2020). Future related studies can move forward from the conceptual framing stage to develop technical solutions, and thus may face more technical challenges or problems, such as advanced underlying logic design for payment automation and deployment of compound smart contracts for complex management systems. For some less-ready research domains, such as administration, design, and site management, exploring the domain-specific requirements and defining possible application scenarios are the main challenge. Once these scenarios are well defined, a series of conceptual frameworks can be further developed with related technical solutions. As for the research domain of information management, a challenge lies in integrating other ICTs, such as IoT, BIM, and AI. Extant research has taken the first step to propose visions for combing ICTs but without technical details or with a low integration level. For example, smart contracts can enhance the CDE for automated multidimensional information management (Tao et al., 2021), however, sufficient solutions and use cases still remain lacking.

To date, research on smart contracts have focused mainly on the challenges associated with technical issues. Hamledari and Fischer (2021d) highlighted security concerns for smart contracts. Given that the calculation and execution results are irreversible, an incorrect code may jeopardize the integrity of the project data or cause financial losses. Project participants must ensure the soundness of the computerized code before its deployment. One of the challenges faced by the construction industry is the lack of standardized design of the widely used protocol to ensure the consistency and security. In addition, machine-readable code cannot capture all the complexity of the contracts, resulting in the need for a hybrid model that encompasses both human-based interpretation of agreements and autonomous execution of formalized relationships.

Managerial risks can be identified from contractual, cultural, planning and relational perspectives: 1) lack of a driving force, 2) lack of dispute resolution mechanism, 3) regulation change, 4) shortcomings of current legal arrangements, and 5) difficulties in defining unforeseen conditions (Gurgun and Koc, 2021). First, a common problem encountered in the adoption of new technologies is the lack of a driving force, which may be caused by ignorance of technology and disapproval of changing the existing habits. In construction projects, the owner may become the source of driving force by including the application of smart contracts into the bidding requirements. Another major managerial challenge is the instability and changes in the external environment, such as in regulations and laws (Gurgun and Koc, 2021). For example, the application of smart contracts in contract management requires a good and consistent legal environment to exert its binding force. Turk (2021) pointed out that in the context of open data and BIM, a lack of guidance for technical and legal aspects leads to difficulties on communicating on national and international levels. Especially for international construction projects, the smart contracts can be more difficult to execute because of inconsistent legal systems among countries, which thus poses a significant challenge.

7 Conclusions

This study aims to discover the unique contributions and

Table 4 Main challenges of smart contracts in construction

Research domains	Main challenges	
	Technical challenges	Managerial challenges
Contract and payment	Advanced underlying logic design	Regulation change
	Compound smart contracts deployment	Inconsistency of legal systems
	Integration with BIM	Difficulties in defining unforeseen conditions
	Lack of standardization in protocol design	
Administration, Design, Site management	Define possible application scenarios	Explore domain-specific requirements
Information management, Quality management	Integration of other ICTs (IoT, BIM, AI)	Lack of a driving force
	Lack of standardization in protocol design	
Supply chain and logistics, Facility management	Development of DAOs	Explore domain-specific requirements
	Integration of other ICTs (IoT, BIM, AI)	

value of smart contracts in the construction industry, which was achieved by presenting a comprehensive review of 81 research articles on relevant applications from 2014 to 2021. The review results were categorized and analyzed based on research types and domains, which were used to explain the potentials of smart contracts in construction and technology integration. Eight research domains were identified, namely, administration, design, contract and payment, quality management, site management, supply chain and logistics, facility management, and information management. For technology integration, BIM was the most discussed. The applicability of smart contracts in construction depended on the characteristic of research domains, storage of information (i.e., on-chain or off-chain), and DAO for trust and organizational issues. The benefits of using smart contacts in construction include flexibility, security, automation, transparency, reliability, and traceability. Technical and managerial challenges were identified, which can serve as guide for future applications.

Smart contracts have carved a place in the digital transformation of construction, or namely Construction 4.0 (Perrier et al., 2020). This industry is lagging behind in the trend of digital innovation, and can gain experience or learn from other industries, such as manufacturing. The smart contract-enabled network was recognized as one of the most promising technologies to achieve the Smart Factories in the Industry 4.0, wherein decentralization, security, authenticity, and transparency are highlighted (Fernandez-Carames and Fraga-Lamas, 2019). In the future, transferring smart contract-related applications from the manufacturing industry can prove essential to achieve the concept of Smart Construction.

Although this study provides a knowledge contribution by clarifying the contributions and reporting the potentials of smart contracts in construction, the following limitations are similarly noted. First, manual screening and coding may still cause publication bias, sample selection bias, and inconsistent coding or data interpretation. The accuracy can be improved by collecting more related publications and enhancing collaborative group work. Second, implications and conclusions from this review can be limited due to current low level of technology readiness for smart contracts. In most of the reported research domains, applications of smart contracts were still theoretical, including conceptual model building and framework development. More empirical studies are needed in the future. Further evidence can be collected from real cases and scenarios to evaluate the applications of smart contracts and explore improvements from technical and managerial perspectives. On the one hand, the adoption of smart contracts can be considered in booming domains such as the digital twin. On the other hand, analyzing the integration of smart contracts with other innovative concepts and advanced ICT technologies, such as BIM, IoT, and AI, is likewise of value to build a transparent, safe, and smart construction environment in the future.

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