A Systematic evaluation of blockchain-enabled contract administration in construction projects

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Abstract

Inefficient and ineffective Construction Contract Administration (CCA) is at the root of many of the sector challenges. Emerging digital technologies such as blockchain are revealing some capabilities with the potential for improving CCA. This paper addresses the research question of whether and where blockchain can contribute to improving CCA. The paper adopts a systematic review of studies in this domain and perform an analysis of its findings against a structured framework of CCA functions. Most applications were found to be centered on two CCA functions; the *financial management*, and the *document and record management*. CCA functions that embed complex contractual logics such as *claims and dispute resolution* have received scant attention. To advance blockchain applications in CCA, a structured roadmap of its key adoption challenges relating to technology, process, policy and society is proposed for future research. The results in this paper provide scholars, practitioners and policymakers, interested in construction contracts, with evidence about the current level of blockchain contribution to CCA and a structured set of recommendations for future research.

Keywords: Blockchain, Smart contracts, Intelligent contracts, Construction industry, Construction contracts, Contract administration functions, FIDIC 2017, digitalization.

1. Introduction

Construction contracts define the rights and obligations of contracting parties and allocate risks between them within a legal context using codified provisions [1]. In doing so, the construction contract administration (CCA) process performs various functions across the contract life cycle [2]. In fact, effective CCA is indispensable for achieving project success for all contracting parties, and poor CCA continues to be one of the biggest challenges encountered in the construction industry (CI) as evidenced by Arcadis' industry report [3].

Poor CCA can arise as a result of the individual or collective occurrence of misinterpretation, misapplication, negligence, or refusal to operate the contractual codified provisions and associated mechanisms [4]. This is normally accompanied by a proliferation of documentation, however, the information contained in the documentation often tends to be incomplete.

To tackle the aforementioned, researchers [5,6] have suggested adopting a digitally-enabled contract administration process for construction projects, given the emergence of sophisticated digital technologies. In particular, blockchain technology can act as the central core that supports and operates with other technologies, as well as concurrently with tasks manually performed by human agents. This central role of blockchain stems from its unique characteristics that support transactions and digital events recorded on its platform [7].

Blockchain's unique characteristics include immutability, instant traceability, decentralization of stored digital records, and self-execution coupled with irrevocability of outcomes generated by blockchain-based smart contracts (i.e., computerized coded protocols) [8]. As a result, auditability, accountability, transparency, and clearly defined roles and responsibilities of actors involved are achieved [9]. These blockchain characteristics offer potential solutions to the aforementioned causes of poor CCA.

Several studies undertaken in the construction domain have demonstrated the potential of blockchain-enabled solutions in preventing or reducing construction-related problems, including those related to contract administration. There exist two streams in these studies. One stream has developed frameworks and proof-of-concept simulations for particular issues. For example, a blockchain-based document management framework has been proposed to tackle document fragmentation and security [10]; an on-site quality management prototype to address quality-related records has been developed [11]; a blockchain-enabled payment system has been proposed for overcoming delayed payment to the supply chain [12]; and a blockchain-based system has been evaluated for schedule performance monitoring [13]. The second stream has focused on providing systematic reviews of the extant literature. For instance, studies conducted by [14,15] have identified that contract administration could be improved by exploiting blockchain technology. In a more recent study [16], it has also been reported that contract administration-related issues in the construction supply chain could be tackled by blockchain capabilities.

These studies have contributed to conceptualizing and operationalizing of blockchain and smart contracts in the construction research domain. However, no study has yet been published that evaluates the applicability of blockchain (and the 'smart contracts' associated with it) to CCA. The potential integration of CCA with blockchain and smart contracts to optimize the execution of contract provisions and mechanisms remains unclear [6]. Furthermore, an understanding coupled with an explanation of how current CCA practices can be enhanced by adopting this emerging technology has not been offered to academics and practitioners involved in construction contracts [8,17,18].

Hence, the overarching aim of this study is to classify and evaluate reported blockchain applications by mapping them against a multifunctional framework that represents the CCA process. The evaluation is enabled by using actual contractual provisions. These are taken from the International Federation of Consulting Engineers (FIDIC) Red Book 2017 edition [19], an internationally-accepted standard contract form that is used in construction projects procured through the design-bid-build route with the remeasurement payment mechanism. Hence, it is worth noting that the term "the employer" is used here to refer to the owner /client whereas "employer's personnel" refers to the consultant, project manager, or the engineer appointed by the employer to supervise the contractor's works and administer the contract. Interestingly, FIDIC has recently launched a digital transformation committee with the aim of futureproofing FIDIC contracts, including other services provided, given the emergence of enabling technologies to serve the construction industry and improve its performance [20]. It is therefore expected that the work presented in this paper will also contribute to achieving the mission of this committee.

Fig. 1 presents the structure and the logical flow of the rest of this paper as follows. The second section introduces a theoretical framework for understanding CCA functions, common causes of poor CCA, followed by a brief outline of blockchain and its smart contracts, previous systematic reviews and point of departure. In the third section, the research methodology is presented; namely, a systematic literature review (SLR) of the relevant literature. In the fourth section, the results of this review are classified according to the CCA functions and analyzed within the above contractual framework. Subsequently, commonly reported contractual challenges are formulated with future research questions in a separate section. The discussion section delineates the findings of the analytical results and the reported challenges. The paper concludes by outlining implications for policymakers, practitioners, and academics.

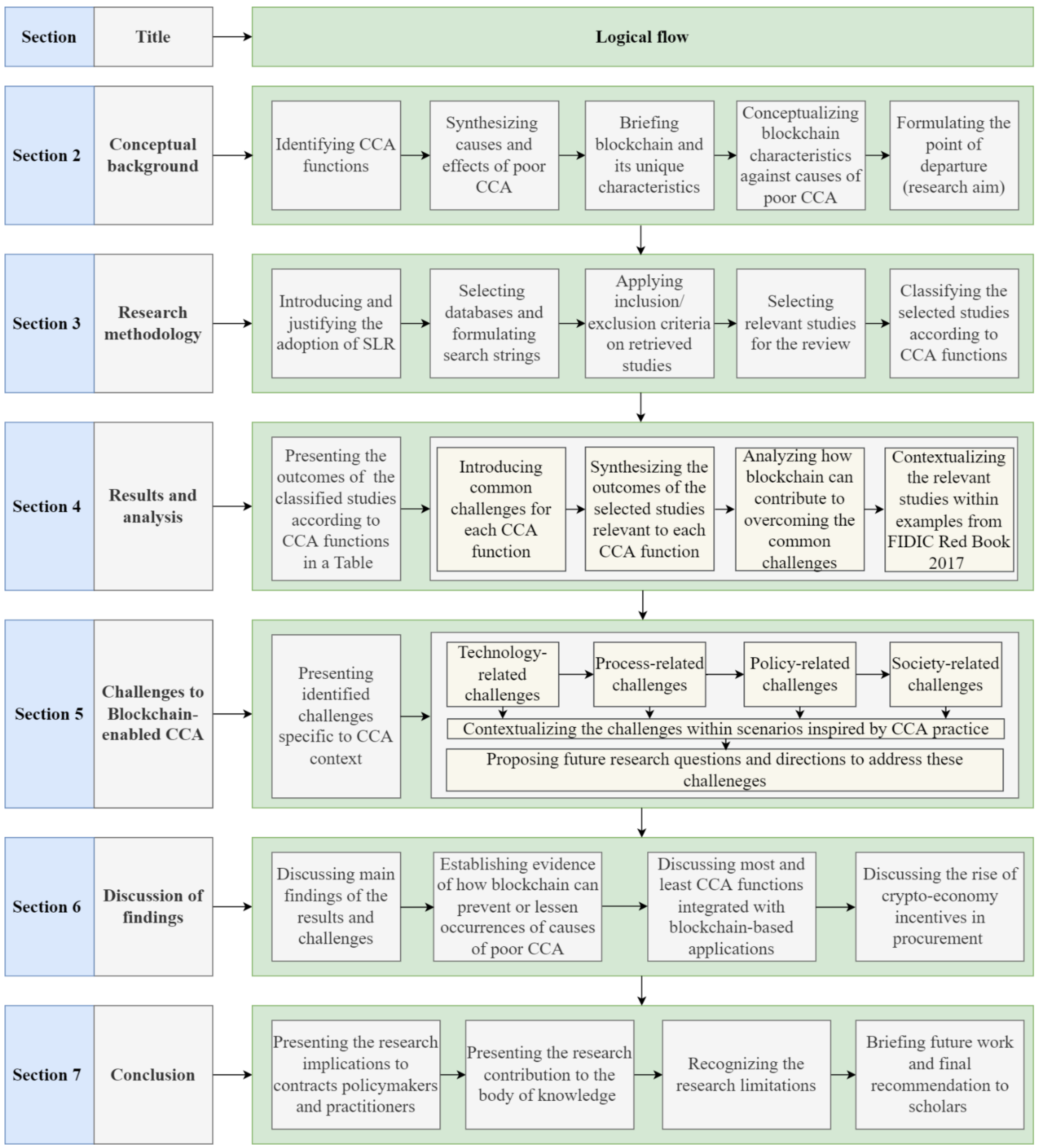

Fig.1. Structure and logical flow of the paper.

2. Conceptual background

2.1. Construction contract administration functions

FIDIC is one of a number of professional bodies that have produced standard forms of construction contract to cater for the risks and uncertainties inherent in construction projects. Such standard contracts offer a medium through which technical and legal perspectives are integrated [21]. Over the years, the interpretation of these standard forms has been complemented by the results of legal cases and they have subsequently been revised to reflect best practice [22]. For example, the evolution of the prescriptive claim and dispute resolution mechanisms in the 2017 edition of FIDIC contracts has been cited as such an improvement [23].

Several studies have used a multifunctional analysis approach to classifying construction contract provisions. One of these [24] identifies three CCA functions at an inter-organizational level, while another [2] proposes eleven functions at a project level. These eleven project level functions align with the CCA functions presented by Papajohn et al. [25] and those within the Royal Institution of Chartered Surveyors (RICS) practice standards for contract administration [26]. Table 1 maps these CCA functions (at both inter-organizational and project levels) against relevant contract provisions extracted from FIDIC Red Book 2017 edition [19].

Table 1. CCA functions with corresponding FIDIC 2017 provisions (Source: Authors).

CCA functions at inter-organizational level [24]	CCA function at project level [2]	FIDIC Red Book sub-clause	Extracted provision [19]
Coordination	Team management	*6.9* [Contractor's Personnel]	The Contractor's Personnel…shall be appropriately qualified, skilled... The Engineer may require the Contractor to remove any person employed on the Site.
	Communication and relationship management	*1.3* [Notices and Other Communications]	When a Notice ... is issued by a Party or the Engineer, the paper and/or electronic original shall be sent to the intended recipient and a copy shall be sent to the Engineer.
	Document and record management	*4.4.2* [As-Built Records]	The Contractor shall prepare, and keep up-to-date, a complete set of "as-built" records of the execution of the Works.
	Contract closeout management	*9* [Tests on Completion]	The Contractor shall carry out the Tests on Completion.

CCA functions at inter-organizational level [24]	CCA function at project level [2]	FIDIC Red Book sub-clause	Extracted provision [19]
Control	Project governance and start-up	*4.2* [Performance Security]	The Contractor shall deliver the Performance Security to the Employer…within 28 days after receiving the Letter of Acceptance.
		2.5 [Site Data and Items of Reference]	The Employer shall have made available to the Contractor for information, before the Base Date, all relevant data in the Employer's possession.
	Quality and acceptance management	*4.9.1* [Quality Management System]	The Contractor shall prepare and implement a QM System
		7.5 [Defects and Rejection]	If, as a result of … inspection, any Plant, Materials…workmanship is found to be defective …the Engineer shall give a Notice to the Contractor describing the item.
	Performance monitoring and reporting management	*4.20* [Progress Reports]	Monthly progress reports...shall be prepared by the Contractor and submitted to the Engineer.
	Financial management	*14.3* [Application for Interim Payment]	The Contractor shall submit a Statement to the Engineer after the end of the period of payment stated in the Contract Data (if not stated, after the end of each month).
		4.2.3 [Return of the Performance Security]	The Employer shall return the Performance Security to the Contractor.
	Changes and changes control management	*13.1* [Right to Vary]	The Contractor shall be bound by each Variation instructed ...the Engineer shall respond by giving a Notice to the Contractor cancelling, confirming or varying the instruction.
Adaptation	Claims and disputes resolution management	*20.2.3* [Contemporary Records]	The claiming Party shall keep such contemporary records as may be necessary to substantiate the Claim.
	Contract risk management	*18.2* [Notice of an Exceptional Event]	If a Party is or will be prevented from performing any obligations …due to an Exceptional Event…then the affected Party shall give a Notice to the other Party of such an Exceptional Event.

2.2. Causes and effects of poor CCA

It is likely that current standard forms of contract will continue to exist [27], but there is clearly a need for improved CCA since poor contract administration continues to be one of the biggest challenges encountered in construction projects [28]. Causes of poor CCA include: (*i*) misinterpretation, misapplication, neglect of contractual provisions or refusal to operate them [29], (*ii*) ineffective communication [30], (*iii*) a high volume of documents, many of them inaccurate [31], (*iv*) inaccessibility to contemporary records of events [32], (*v*) insufficient and incompetent contract administrators [33], (*vi*) unclear roles and responsibilities [34], and (*vii*) corruption [35].

The adverse effects of these reported causes on construction projects as well as the organizations and individuals involved tend to manifest themselves through various indicators which include: (*i*) ineffective control of performance [33], (*ii*) delayed completion of projects [32], (*iii*) unsubstantiated contractors' claims and disputes [36], (*iv*) unresolved claims which contribute to delayed payments and negative cash flow [37], (*v*) mental health-related issues (e.g., 'burnout') among construction professionals [38], and (*vi*) financial insolvency and bankruptcy of the supply chain [39,40].

These causes and effects of poor contract administration may unravel some of the reasons behind the adverse characteristics inherent in the construction industry (CI) being adversarial in nature, risk averse, opportunistic in behaviour [41], and sometimes corrupt [42]. Consequently, these inherent characteristics reduce transparency and create mistrust between construction contracting parties [40]. Therefore, it can be postulated that poor contract administration imposes significant adverse consequences on the performance of the CI.

Recognizing that improved contract administration requires solutions geared toward preventing, reducing, or mitigating the problems identified above, these solutions should offer, *inter alia*, a trusted source of information, transparency, immutability of records, and corruption-resistant mechanisms. These required features resonate with the innate characteristics of blockchain technology.

2.3. A brief overview of blockchain technology

2.3.1. *Blockchain technology*

Blockchain is the underlying distributed ledger technology (DLT) that underpins the operation of the Bitcoin cryptocurrency network [7]. A blockchain records transactions and validates digital events (e.g., information) conducted in the network in form of encrypted 'blocks' and 'chains' the entire recorded transactions chronology stored across multiple nodes [43]. Blockchain has been described [44] as operating on three core components: cryptography, consensus mechanisms, and decentralization. Cryptography (through hash values of blocks) ensures tamper-proof stored data; consensus mechanisms formulate protocols for endorsing the structure and correctness of data based on identity management; and decentralization refers to distributed data storage in form of ledgers stored in many nodes (i.e., actors' computers). These components support the innate characteristics of blockchain which are (*i*) traceability of data transactions, (*ii*) immutability of data records, (*iii*) disintermediation of overseeing transactions, and (*iv*) smart contracts execution.

A smart contract is an automated/computerized protocol of coded instructions that self-execute upon the fulfillment of certain conditions [8]. The automated execution of conditions is enabled by rules-based operations (e.g., If/Then/Else/Otherwise) that are consistent with the paper-based contractual rules [5]. In addition to automatic self-enforcement, smart contracts are irrevocable, that is, once executed, the outcomes for which the smart contract is encoded and subsequently triggered cannot normally be stopped or reversed [5].

2.3.2. *Blockchain types and common platforms*

Blockchain networks are generally categorized into two types based on identity management and permission to access the platform [7]. Permissionless platforms allow any actor to access the platform and create transactions: examples being the Bitcoin and Ethereum platforms. In contrast, permissioned platforms (such as Hyperledger Fabric) restrict access and hence the creation of transactions. Within this permissioned type, a network can be further categorized as public ('on-chain') and private ('off-chain').

Further discussion on the difference between blockchain types can be found elsewhere [45,46]. Decision trees on selecting an appropriate type for a given process in construction are proposed [9,47]. In terms of the pros and cons of dominant blockchain platforms, the study conducted by Hewa, Ylianttila, and Liyanage [45] serves as a point of departure for prospective research, and that of Nanayakkara et al. [48] offers a platform selection methodology that may be applied in construction projects at an inter-organizational level.

2.4. Related work and point of departure

The potential of blockchain applications to improve the performance of construction projects lies in the traceability and immutability that enhance trust in transactions, auditability, and accountability of information as data are digitally shielded against deletion and alterability while accessible to all actors registered to the blockchain network [47]. Meanwhile, disintermediation achieved through decentralization removes non-value-added activities from the process and provides data privacy; as a result, contractual and financial information flows improve [49]. In the same vein, smart contract protocols may be employed to enforce terms and conditions of contractual processes, such as interim payments [50] and record chronology of design information flow [51].

Blockchain-enabled digital contract administration has been advocated in several studies conducted [5,6,52]. This line of research coined the notion of “iContract” (Intelligent Contract) in which the CCA process is digitalized by exploiting blockchain as a single central platform with which other technologies (e.g., BIM and Artificial Intelligence) and individuals interact. This interaction allows blockchain-enabled smart contracts to be fed with necessary data/information needed to create digital events or return specific pieces of information. By the means of this theoretical notion, semi-automation or full automation of executing contract provisions and mechanisms can be achieved which could untimely lead to improved performance of construction projects.

This improved performance can be perceived by conceptually highlighting how blockchain technology unique characteristics can prevent or lessen the likelihood of the occurrence of the reported causes behind poor CCA as illustrated in Fig. 2. For instance, smart contracts can prevent misapplication of contractual provisions and eliminate the need for communication required to follow up the completion of a given contractual task. Furthermore, the instant traceability characteristic enables tracing the multiple versions of a particular drawing and identifying the individuals responsible for delaying an action or decision-making. Throughout the rest of this paper, greater clarity of this conceptualization will be emerging.

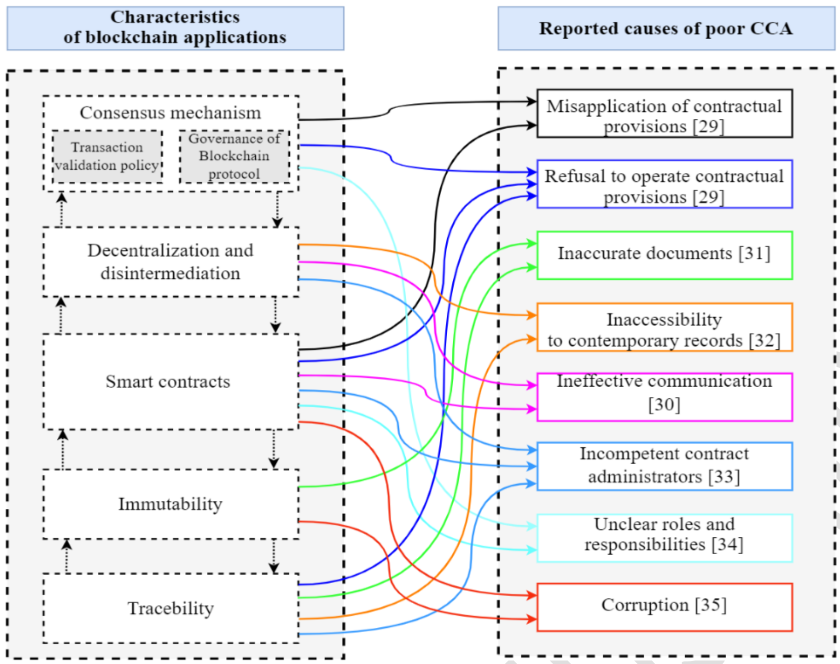

Fig.2. Conceptual demonstration of Blockchain characteristics against causes of poor CCA.

The body of knowledge contains a few valuable review studies that synthesize developed individual blockchain-based solutions to classify them across the various processes performed in the field of construction management and the built environment in general. Table 2 summarizes these reviews and identifies limitations of each one within the context of the present study. These tabulated studies focused on the broad application of blockchain in improving the performance of various processes associated with the domain. One such process was contract administration [14–16] from a high-level perspective.

This leaves the question of how the CCA process integrates with existing blockchain-based solutions proposed for construction projects. To this end, there is a need for a research study that is oriented toward: (*i*) classifying and evaluating the state-of-the-art of blockchain studies in the construction research landscape according to the recognized CCA functions by adopting a systematic review, (*ii*) identifying potential applications of the existing reviewed blockchain studies to provisions of a standard form of contract to provide contextualized examples, and (*iii*) reflecting on probable challenges that are likely to be facing the adoption and implementation of blockchain-based CCA. Hence, this study aims to bridge this knowledge gap by addressing these identified limitations, thereby contributing to a possible revolutionizing of construction contract administration through blockchain-enabled digitalization.

Table 2. Previous relevant review studies.

Reference	Focus of study	Limitation within the context of this study
[9]	Consolidating blockchain conceptual models and potential use cases in the built environment at large (including smart cities and transport) to support its adoption.	• No reference to an alignment between the CCA various functions and blockchain technology was offered. • The identified challenges were generic without specific examples in the CCA context.
[14]	Identifying six potential application areas in construction that can leverage blockchain applications.	• Blockchain application was suggested to be employed in subcontracts without a reference to its corresponding feasibility in the main contracts (which would be necessary). Shedding light on the latter would have added value to this study. • Although several challenges were identified, they were not specific to blockchain-based CCA.
[53]	Investigating evolvement of blockchain-related studies in the built environment across various areas.	• Blockchain-enabled CCA was not identified as a main subject area. • Identifying CCA as a potential area of blockchain application would have added value to the conclusion.
[15]	Classifying existing blockchain-based studies specifically to the construction sector.	• Contract administration was identified as a potential area that could leverage blockchain capabilities; however, this was not sufficiently covered at a granular level. Further investigation into blockchain-based CCA was required. • The reported challenges were generic to the construction sector without specific examples to the CCA context.
[16]	Exploring the applications of blockchain in addressing construction supply chain issues with respect to enhancing sustainability, promoting collaboration, and facilitating information sharing.	• This study reported benefits of blockchain solutions to critical problems in construction supply chain management (CSCM) research. • There was a need for further in-depth investigation into benefits offered by blockchain applications to problems caused by poor CCA.

3. Research methodology

The research methodology selection was inspired by the systematic literature review (SLR) multistage approach [54]. SLR methodologies are widely recognized to provide comprehensive and reliable sources for all existing studies according to the boundaries established by the researcher for a given phenomenon [55].The aim of SLR is to establish evidence of a given researched phenomenon based on aggregating primary studies in terms of research outcomes [56]. Fundamentally, the researcher has to formulate a narrowly specific research goal. From this research goal, key search terms are derived to enable searching relevant studies from database(s). Subsequently, the researcher applies inclusion and exclusion criteria at multiple stages according to the content and quality boundaries established for accomplishing the specific research goal. Following this approach, Fig. 3 illustrates a diagrammatic map of the five-stage process of the systematic review conducted.

At stage one, scoping and planning activities were carried out. Consequently, the selected academic databases to retrieve scientific primary studies were Scopus and ASCE Library. In the meantime, a parallel search was conducted on Google Scholar to ensure that the SLR would cover the greatest possible number of studies in the researched domain. The search string entered into Scopus is listed in Table 3, while the key terms selected for ASCE Library were simpler which included (“blockchain” OR ‘’smart AND contract*” AND “construction industry”). In addition, at this stage, the inclusion and exclusion criteria were developed to enable the authors to distill rigorous and relevant primary studies that serve the narrowed aim adopted in this study. It is worth pointing out that the exclusion criteria were applied sequentially at each stage. Table 4 illustrates these developed criteria along with reasons behind exclusion. It is worth noting that due to the narrowed exclusion criteria, the parallel search on Google Scholar did not return a single study that met the eligibility criteria of this current review.

Subsequently, the second stage (i.e., identification) took place by entering the specific search string and key terms in the databases which returned 179 articles. Since the rise of blockchain-related studies in construction research began in 2017 [9], only studies published between 2016 up to and including January 2022 were considered. Subsequently, the exclusion criterion concerning document type was applied at this stage. This step resulted in eliminating 106 articles and retaining 73 articles for the subsequent screening stage. At the third stage, the retained articles were screened by viewing the titles only, and those that were irrelevant to the construction phase were removed. In total, 29 articles were eliminated. For instance, titles included “Blockchain-enabled cyber security and circular economy” were discarded. Eligibility check was conducted at the fourth stage by applying two filters to the remaining 44 articles. The first filter subjected the abstract to exclusion criteria concerning the technical integration aspect of blockchain with other emerging technologies and articles resulted from conducting questionnaire or focus group studies. For example, abstracts pointed out to “blockchain-enabled BIM security and practitioners’ perceptions of smart contracts” were determined to be not eligible for this review study. Subsequently, the second filter assessed the remaining 27 articles by fully reading the content of each. By applying the exclusion criteria relating to replicated ideas published by the same authors in different journals and where blockchain was discussed in the conclusion, only 21 articles were included. At the final stage, these included articles were classified according to the CCA functions identified earlier. The classification of these 21 studies is presented and analyzed in the next section.

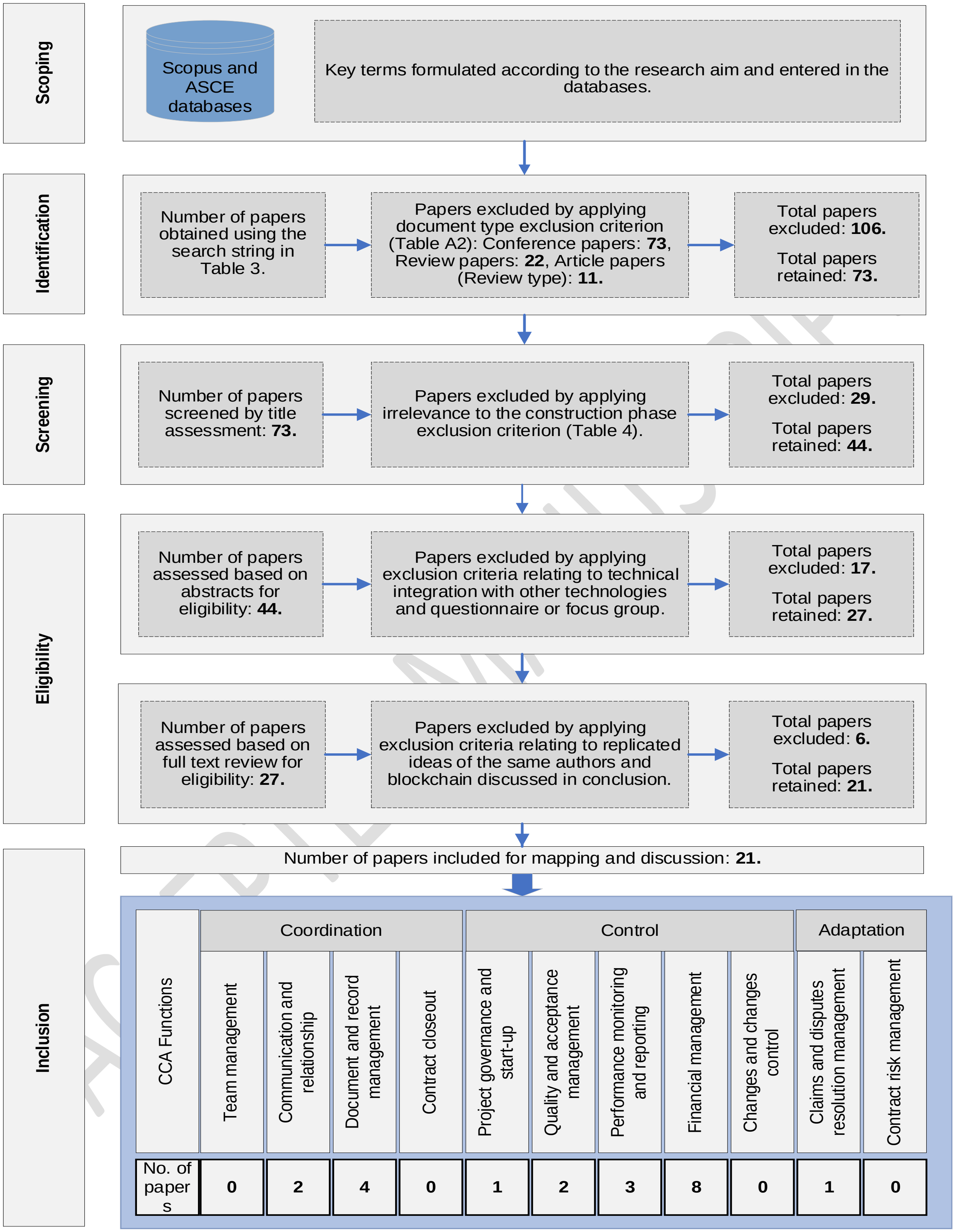

Fig.3. SLR process.

Table 3. Search string for Scopus.

TITLE-ABS-KEY (((blockchain OR dlt OR "distributed ledger" OR "hyperledger fabric" OR "smart contract*" OR chaincode*) AND (bim OR "building information model*" OR "building information manage*" OR "built environment" OR "construction procurement" OR "construction project*" OR "construction stage" OR "construction phase" OR "construction industry" OR "construction sector" OR aec OR "contract administration" OR "contract management" OR "construction manage*" OR "project manage*" OR "project lifecycle" OR "infrastructure project*" OR "civil engineering"))) AND (LIMIT-TO (DOCTYPE , "cp") OR LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (SUBJAREA , "ENGI")) AND (LIMIT-TO (LANGUAGE , "English")) AND (LIMIT-TO (PUBYEAR , 2022) OR LIMIT-TO (PUBYEAR , 2021) OR LIMIT-TO (PUBYEAR , 2020) OR LIMIT-TO (PUBYEAR , 2019) OR LIMIT-TO (PUBYEAR , 2018) OR LIMIT-TO (PUBYEAR , 2017) OR LIMIT-TO (PUBYEAR , 2016))

Table 4. Inclusion and exclusion criteria for the retrieved studies.

Inclusion Criteria	Exclusion Criteria	Reason behind Exclusion
Academic journal studies published from the year 2016 to date related to the research aim.	Academic review and conference studies.	Review studies provide aggregation and rigorous conference studies are converted into journal articles.
English language studies.	Studies in other-than-English language.	Unreadability and non-comprehensibility.
Studies that focus on the construction phase or performance of the built asset with regard to defects.	Studies that are irrelevant to the construction phase.	This review study focuses on construction contracts.
	Studies that focus on the technical integration of blockchain with other technologies (e.g., BIM, IoTs).	These studies do not contribute to the research aim.
Studies that have proposed at least a framework, and/or proof-of-concept simulation.	Studies that adopted questionnaires and/or focus groups without proposing at least a framework.	How accurate and well-informed the respondents are on a subject is questionable.
	Replicated studies the ideas of which are published by the same authors in different journals.	Considering identical ideas encapsulated in the same framework or simulation does not serve this study.
	Studies where blockchain is discussed in the conclusion.	These studies do not contribute to research aim.

4. Results and analysis

This section classifies and analyzes the outcomes of the resultant 21 studies according to the CCA functions identified earlier. Table 5 summarizes these studies which can act as points of departure in future research or professional discussions that revolve around the integration of blockchain with CCA functions.

Table 5. Summary of retrieved studies according the CCA functions.

CCA function at project level	Reference	Research method	Blockchain type	Blockchain platform	Oracles (human/other technology)	Application
Document and Record Management	[57]	Proof-of-Concept	Permissionless	Ethereum	Human	Information flow of BIM structural models.
	[51]	Prototype Simulation	Permissionless	Ethereum	Human	Traceability of records and BIM models revisions.
	[58]	Proof-of-Concept	Permissioned	Hyperledger Fabric	Human/IPFS	Document management.
	[10]	Proof-of-Concept	Permissioned	Hyperledger Fabric	Human/IPFS	Security of documents.
Communication and Relationship Management	[59]	Case Study	Permissioned and Permissionless	Ethereum/ Hyperledger Fabric	Human/BIM	Business process streamlining and communication.
	[60]	Virtual Case Study	Permissioned	Azure	Human/IoTs	Data communication.
Financial Management	[43]	Framework	Permissionless	Ethereum	Human	Security of interim payments.
	[12]	Case Study	Permissionless	Ethereum	Human	Security of payment.
	[18]	Prototype	Permissionless	Ethereum	Human	Payment system for projects regulated by PBAs.
	[61]	Case Study	Permissioned	Hyperledger Fabric	BIM	Security of Payment.
	[8]	Case Study	Permissionless	Ethereum	Reality captures and BIM	Automated payment.
	[17]	Case Study	Permissionless	Ethereum	Reality captures and BIM	Automated payment.
	[62]	Proof-of-Concept	Permissioned	GoQuorum	BIM	Payment process management and automated payment.
	[50]	Proof-of-Concept	Permissioned	Hyperledger Fabric	BIM	Financial system for IPD projects.
Performance Monitoring and Reporting Management	[13]	Proof-of-Concept	Permissioned	Hyperledger Fabric	Human	Real-time control of scheduling.
	[44]	Prototype	Permissioned	Hyperledger Fabric	Human	Accessibility to off-site records for reporting purpose.
	[63]	Prototype	Permissionless	Ethereum	Sensors	Thermal performance monitoring during post construction.
Quality and Acceptance Management	[64]	Prototype	Permissioned	Hyperledger Fabric	Human	On-site quality records management.
	[11]	Case Study	Permissioned	Hyperledger Fabric	Human	On-site quality reports management.

CCA function at project level	Refer ence	Research method	Blockchain type	Blockchain platform	Oracles (human/other technology)	Application
Project Governance and Start-up	[65]	Framework	Permissioned	Hyperledger Fabric	Human/BIM	Obtaining building permits.
Claims and Disputes Resolution Management	[66]	Proof-of-Concept	Permissionless	Ethereum	Human	Managing payment-related disputes.

To clarify what each of these recognized functions serves in construction projects and reported common challenges associated with each, a brief description is introduced for each of them. Following this step, the outcomes of relevant blockchain studies are described. If no direct application/study could be mapped to a given CCA function, other relevant studies are indirectly referred to. Next, the potential applicability of the mapped studies to relevant examples extracted from FIDIC 2017 [19] is introduced and analyzed as appropriate

4.1 Classifying blockchain applications against coordination-oriented functions

4.1.1. Document and record management

Documents and records carry information that enables the execution of construction activities and support the rights and obligations of contracting parties [67]. It has also been pointed out [31] that information availability supports the decision-making process and encourages responsiveness between actors involved in a construction project. However, construction projects are widely recognized as suffering from unstructured or absent information in the form of documents and records. Four studies that demonstrated potential of blockchain in combating document and information-related issues in construction are identified here.

A proof-of-concept has been developed for structural documents related to buildings to be stored across multiple stakeholders to prevent exchanging incorrect versions of files [57]. In this approach, the communication between Dropbox hosts, adopted as document containers, and the blockchain was enabled via encoded smart contracts created based on a defined workflow process. Similarly, a prototype has been developed and evaluated to facilitate traceability (both during and after construction) of exchanged design information [51]. During construction, the prototype ensured a unified blockchain-enabled RFI (request for information) workflow where all involved documents were immutably recorded on the blockchain platform. To assist parties to disputes arising from defects during post construction, a simulated scenario demonstrated the fast traceability of the responsible party for neglecting to provide a correct specification document to the contractor.

To overcome challenges arising from the limited capacity of blockchain to store large-size files, such as BIM models and prescriptive specifications, Tao et al. [58] integrated blockchain with the Interplanetary File System (IPFS). IPFS is an innovative protocol that builds an addressable and peer-to-peer file storage system without a centralized server [58]. Furthermore, current document management systems, such as cloud-based Aconex, Dropbox, and Oracle Unifier, adopted in construction projects, lack required characteristics to prevent alterability, deletion, accessibility denial, and incorrect revision history. To address these document security concerns for construction projects, Das et al. [10] developed a blockchain-based decentralized document management prototype. By integrating Hyperledger Fabric as a blockchain platform with IPFS as a cloud-based database system, a request for information (RFI) workflow process was modeled and deployed on the developed system. The researchers demonstrated the prototype's technological ability to prevent alterability, accessibility denial, and incorrect revision history of documents.

Based on the above-described studies, it can be inferred that blockchain can significantly improve the CCA function of *document and record management* both during and post construction. For example, blockchain addresses the issue of separate documents (e.g., emails, minutes of meetings, confirmation of verbal instructions) involved to conclude a response to an RFI and its subsequent execution. It also reliably facilitates information retrieval and document relocation without the need for reverification. Such platforms can also overcome data manipulation and accessibility denial resulting from the centralized document containers being owned and controlled by various stakeholders of existing BIM platforms [68]. From FIDIC 2017's perspective, a blockchain-enabled document and record management platform could support governing sub-clauses *4.4.2* [As-Built Records] and *7.3* [Inspection] both of which demand a relatively high volume of documents and record exchange with signatures from multiple actors involved in the contract execution. To implement such a blockchain-based platform, the exact contractual workflow process stipulated in the contract needs to be designed and agreed upon by the parties. This can be achieved by considering the contractual requirements with regard to documents for each sub-clause as well as by consulting the tacit knowledge possessed by practitioners.

4.1.2. Communication and relationship management

CCA governs written and unwritten communication and regulates the transactional relationship between the employer's personnel (e.g., the engineer and the project manager) and the contractor. However, communication breakdown and poor working relationship management are widely recognized as problems in construction [30]. It is believed that blockchain-based systems can enhance both communication and working relationship management as identified in the following two studies. In the first [59], a permissioned blockchain was employed in a cladding material approval process for a building project. Their study demonstrated transparent communications among stakeholders as a result of immutable and accessible records to all stakeholders at any time during the project life-cycle. In the second, enhanced efficiency was reported in communicating decisions for essential actions among dispersed project participants [60].

Both studies reveal that blockchain-based platforms streamline stakeholder management and remove communication barriers at both inter-organizational and inter-personal (project) levels. The blockchain-enabled smart contracts receive, verify, update, and record information in form of immutable and transparent transactions. In turn, the recorded transactions are directly and automatically communicated to all stakeholders registered on the blockchain network according to pre-defined communication protocols.

It is worth noting that sub-clause *1.3* [Notices and Other Communications] of FIDIC 2017 recognizes digital records as contractual. Further, it states that a digital communication system can be established. Hence, this sub-clause can be relied upon to contractually introduce binding blockchain-based communication systems to construction projects governed by FIDIC 2017. To design such a system the above studies can be used as a point of departure.

4.1.3. Team management

Team management is an essential function of a successful CCA to resolve personal conflicts, assign accountability, and define roles and responsibilities, for example. No example was identified of a blockchain study that directly matched this function. However, blockchain-based systems are believed to directly result in enhanced accountability and auditability required to resolve personal conflicts [15,47]. This enhancement is achieved through consensus mechanism protocols, which explicitly define roles and responsibilities, and immutable traceability of transactions demonstrating team members' actions and responses with metadata (e.g., digital signatures and timestamps). Both sub-clauses *2.3* [Employer's Personnel and other Contractors] and *6.9* [Contractor's Personnel] of FIDIC 2017 give rights to both parties to request removal of a team member from the other party team due to malpractice. A blockchain governance system can support both sub-clauses by providing evidence of delayed action or inaction of an individual team member.

4.1.4. Contract closeout management

At the closeout phase, both parties perform a series of tasks to ensure that the project has accomplished its intended purpose and that parties have executed their obligations and received their rights. For example, according to clause *9* [Tests on Completion] of FIDIC 2017, the contractor carries out tests upon completion to ensure functional and structural stability during the operation phase whereas the employer's personnel inspect the completed works to prepare for their take over pursuant to sub-clause *10.1* [Taking over the Works or Sections]. This whole process needs a high volume of documentation together with its coordination by key staff. The elaborated needs for this phase resonate with the capabilities of blockchain. Implementing a blockchain-governed construction project would arguably contribute to more successful contract closeout, however, no evidence could be found in the literature for a blockchain-based study for this purpose.

4.2. Classifying blockchain applications against control-oriented functions

4.2.1. Financial management

This CCA function serves and performs the contractual payment-related clauses and provisions dealing with both the rights and obligations of both parties [69]. However, parties tend to either misinterpret or misapply, deliberately neglect, or refuse to operate these mechanisms to improve their financial position [29]. Despite the availability of legal frameworks to enforce and manage payments in construction, the issue has persisted [8,70]. In this review, eight studies were identified that proposed blockchain-based frameworks and proof-of-concept simulations with the aim of improving financial management and securing timely payment to contractors and their supply chains.

In the first [43], a blockchain-based framework was developed to execute contractual provisions at various stages in the payment cycle by incorporating a mixture of manual and smart contract-based processes. The proposed framework was proposed to facilitate interim payment cycle and secure timely payment but required further evaluation and assessment by practitioners. Another study [12] proposed and evaluated a smart contract-based system to automatically transfer booked cryptocurrency from the employer's wallet to the contractor and subcontractors' wallets according to agreed terms. The evaluation revealed that current concerns about delayed payment may decrease while concerns about employer's direct payment to subcontractors may result in the contractor's loss of control over its supply chain. These perceptions align with findings reported by [18] who translated the payment mechanism governed by the Project Bank Account (PBA) arrangement into a blockchain prototype which was run in parallel with existing processes to assess its viability. The resulting focus group proposed its streamlining and integration with BIM.

In line with the aforementioned suggestion, BIM was exploited to provide progress data of installed construction elements to a blockchain network that triggered smart contract-based payment to subcontractors [61]. In this case study, the blockchain-based framework not only provided security of payment to the supply chain but also enabled employers to certify completed works without the time-consuming need for constant verification of related information. The effectiveness of integrating blockchain with BIM was further demonstrated in research studies undertaken by Hamledari and Fischer [8,17]. Their real-life project-based research focused on integrating reality capture technologies (i.e., robots, sensors, machine intelligence, and BIM) with smart contracts to automate a cryptocurrency payment to supply chain actors upon completion of their obligations. Unlike the semi-automated approach [61], the need for payment submission was eliminated as it was triggered by reality capture technologies that connected on-site progress data with smart contracts.

In the same vein of integrating BIM as a digital oracle to feed the blockchain with data for payment purposes, in [71] a semi-automated model was demonstrated that connected BIM containers with blockchain-based smart contracts for payment from employers to contractors. In this model, BIM containers were deployed off-chain and linked to a blockchain network. Unlike earlier described studies that disregarded the procurement route, there is an example [50] of a permissioned blockchain-based financial framework that was developed specifically for construction projects that were procured through the Integrated Project Delivery (IPD) approach. In this semi-automated framework, BIM tools interacted with the blockchain network to provide the information required to trigger the smart contract functions for payment.

The approaches reported in the above studies have the potential to revolutionize current payment practices in the construction industry. For example, the proposed applications allow automatic execution of selected payment-related provisions and self-execution of payment via smart contracts. Therefore, blockchain-enabled smart contracts for payment will likely prevent or lessen misinterpretation and misapplication of relevant contractual-related provisions. This is because these provisions are encoded, verified, and agreed upon during the initiation phase of a contract before deployment to the blockchain system. Further, failure to process and certify a contractor’s payment would be readily visible since the blockchain system provides transparent and accessible information concerning responsiveness. Eliminating refusals to pay and delayed payments would be one of the most tangible benefits of such a system, as smart contracts self-execute payments to registered actors. FIDIC 2017’s payment-related sub-clauses can benefit from such a blockchain-based system to support the execution of both sub-clauses *14.3* [Application for Interim Payment] and *14.9* [Release of Retention Money] by reducing the volume of human effort.

4.2.2. Performance monitoring and reporting management

Performing this CCA function with satisfactory results and in a timely manner is challenging when it is conducted manually, but digital technologies may overcome this challenge [72]. Although BIM-based project performance monitoring tools as well as Enterprise Resources Planning and reporting systems (e.g., Primavera) have been introduced to the industry, the full intended benefits with regard to this CCA function have remained unrealized [73,74]. This is because of a reluctance to share information and the frequent discrepancies of chronological records, as well as the lack of traceability of inputted data, immutability, transparency, and trust. Blockchain may tackle these issues. Three blockchain-based studies are classified under this function.

In [13], a blockchain-based information model was produced by using real-world project data and revealed that blockchain could facilitate updating a schedule of precast operations. In this model, timely accessibility demonstrated a reliable comparison between planned and actual progress coupled with traceability of the original causes for the late delivery of precast units. As a response to both the resistance to information sharing (e.g., due to data privacy) and inefficient performance reporting for off-site modular housing production, Li et al. [44] developed a Two-layer Adaptive Blockchain-based Supervision (TABS) model using on-chain and off-chain networks. The model allowed each stakeholder to access traceable and immutable records relevant to monitoring and reporting, while data irrelevant to the project were kept unshared. Another recent study [63] leveraged the potential of blockchain-based smart contracts to serve this CCA function during post construction. The use case was a performance-based procured building project in which the thermal performance was monitored during the building occupancy period. A smart contract directly executed payments from the contract bank account to the contractor and facility manager for delivering the performance levels stipulated in the contract.

The above studies demonstrate that blockchain-based systems could provide instant monitoring and reporting on off-site construction activities executed as well as performance of the built asset post construction. This evidential demonstration could be extended to perform this CCA function by leveraging blockchain capabilities for on-site construction activities, thereby eliminating the need for waiting for the monthly progress reports to detect a performance-related problem. The contractual execution of both FIDIC 2017 sub-clauses *4.20* [Progress Reports] and *8.7* [Rate of Progress] could be enhanced by adopting such systems.

4.2.3. Quality and acceptance management

Substandard execution of work during construction has adverse consequences during the operation phase materialized in defects [75]. To prevent or lessen the severity of these defects, contracts place obligations on the contractor to conform with contract specifications. If a nonconformance occurs, contracts give rights to the employer to reject completed works and issue nonconformances (NCRs). However, recording and documentation of quality-related issues have been consistently reported as a problem on construction projects [76]. In this review, two studies were identified that could offer improvements to this CCA function.

The first [64] presented a blockchain-based conceptual framework to improve on-site quality management. In this study, the researchers argued that the solution presented could secure and automate quality inspection records respectively through the immutability feature of blockchain and its related smart contracts. In contrast to this theoretical study, in [11] a prototype was deployed for a project quality management information system to the inspection of cast-in-situ bored pile in an actual project. The validation of the prototype demonstrated that blockchain immutability and smart contracts together tackled the fragmentation inherent in the information flow of quality acceptance and associated NCRs.

Both the above studies provide initial evidence to demonstrate that blockchain could be promoted and applied in construction projects with the aim of enhancing the *quality management* function of CCA. For instance, sub-clause *4.9* [Quality Management and Compliance Verification] of FIDIC 2017 places an obligation on the contractor to prepare and implement a robust system to comply with quality assurance management requirements. Another sub-clause that could benefit from such a system is *7.5* [Defects and Rejection] which deals with obligations of the employer’s personnel and interaction with the contractor regarding defective works.

4.2.4. Project governance and start-up

During the project initiation phase, this function legally connects a given construction project with its ecosystem. This connection is achieved through obtaining building permits prior to executing the contract plans on the site [77]. For example, the employer provides access to the construction site whereas the contractor applies for building permits from local authorities. Only one blockchain-based study [78] could be directly linked to this function. In that study, a blockchain-based plan review and building permit conceptual framework is proposed to enable contract parties to apply for approvals of revised construction plans from local authorities after the occurrence of a natural disaster event. The framework relied on the creation of a BIM to feed data into the blockchain-based smart contracts. Upon receipt of the application, the system performs an automated code check and compliance using smart contracts deployed to the blockchain. If authorities’ pre-determined conditions are met, the smart contract triggers the coded function allocated for generating the building permit, or otherwise notifies the applicants of necessary requirements and reapplications.

Such frameworks are believed to be employable to new projects to accelerate administrative processes while providing timely notification of necessary technical requirements demanded by relevant authorities. They could, for example, alleviate the time impact on project schedules caused by authorities which entitle a contractor to time extension under sub-clause *8.6* [Delay Caused by Authorities] of FIDIC 2017. Further, such systems could enhance the operability of sub-clauses *1.13* [Compliance with Laws] and *2.2* [Assistance] both of which place obligations on both contract parties to assist each other to comply with local laws.

4.2.5. Changes and changes control management

It important for both the employer and the contractor to control changes so that they have minimal impacts on cost, time, and quality of the project [79]. A blockchain-based system can streamline the process of FIDIC 2017 sub-clause *13.3* [Variation Procedure] which describes the mechanisms for managing changes. Within the context of this review, no direct research was identified to address *change management* by exploiting blockchain features. Since changes and accepted change orders rely on *documents* and *communication*, it can be argued that the studies identified earlier under these respective functions can be indirectly mapped against this CCA function.

4.3. Classifying blockchain applications against adaptation-oriented functions

4.3.1. Claims and disputes resolution management

Construction contracts generally allow the contractor to submit claims for time extension and/or reimbursement of additional costs and the employer to raise claims against the contractor [4]. Claims can evolve into disputes if they are not settled or if the decision outcome conflicts with the expectation of the party raising the claim [30]. The efficient and effective application of this CCA function necessitates the need for identifying and operating the relevant clauses and provisions for a given claim [27]. To achieve this application and settle a submitted claim, a multistep approach coupled with the involvement of multiple team members from contracting parties is generally adopted. However, a challenge facing *claims and disputes management* stems from the insufficiency of documentary evidence coupled with the occasional departure from the project of key staff who have tacit information that relates to a claim. A system that addresses such problems would be beneficial.

Only one recent study [66] was found that applied blockchain to claims or dispute resolution. This offered a blockchain system as an alternative dispute resolution method which was reported to prevent payment-related disputes and manage the dispute resolution process transparently. According to this system, if a dispute arises as a result of a rejected payment, it can be referred to independent registered construction professionals (blockchain-based jurors) in the blockchain network who are allocated randomly. This is enabled via triggering a smart contract function to call for a decision on the dispute from multiple jurors. A majority decision is then taken through a designed consensus mechanism. This construction-specific blockchain-based system is believed to facilitate the assessment of dispute cases by people who understand construction workflow and are incentivized by cryptocurrency reward to act in the system.

The use of blockchain for other CCA functions can indirectly ameliorate the *claims and disputes management* function; in particular, those described under *communication and relationship management* and *document and record management* functions. On FIDIC 2017 level, blockchain-enabled *claim and dispute management* can support both the employer and the contractor in various ways. For example, contemporary records (stipulated under FIDIC sub-clause *20.2.3*) can be chronologically and immutably recorded on a blockchain platform to serve establish causation and provide evidence to subsequently enable fair and efficient quantification of a disruption claim event. Furthermore, the traceability feature of blockchain technology could assist forensic schedule delay analysis significantly. This will likely result in determining quantification of extension of time within a shorter period compared to the current conventional manual process. Hence, execution and enforcement of FIDIC sub-clauses *3.7* [Agreement and Determination] and *8.5* [Extension of Time for Completion] could be achieved more effectively and benefit the contracting parties and the employer's personnel. If disputes do proceed to arbitration or other external dispute forum, the recorded documents and chain of evidence underpinned by blockchain and smart contracts could serve the proceedings without the need to re-verify, compile, and cross-reference the documents again.

4.3.2. Contract risk management

Risks are identified and allocated between contracting parties via the conditions of the contract that they have agreed upon, the provisions of law, or both [80]. This lays the foundation for the course of action when a given risk materializes [81]. Such provisions appear across a variety of clauses in the contract. They can occur in the form of compensation (for either time or cost or both) to the contractor. For example, when differing site conditions are encountered on site, the contractor may be entitled to both time extension and additional payment pursuant to sub-clause *4.12* of FIDIC 2017. Likewise, if an exceptional event arises and prevents the employer from performing its obligations, both sub-clauses *15.5* [Termination for Employer's Convenience] and *18.5* [Optional Termination] may entitle the employer to terminate the contract. Like the previous adaptation-oriented function, this CCA function can be indirectly mapped to other studies reviewed under *communication and relationship management* and *document and record management* functions, thereby leveraging the same reported benefits offered by blockchain.

5. Challenges to blockchain-enabled CCA

The previous section systematically classified and evaluated the applicability of the retrieved blockchain studies according to recognized CCA functions within contextualized examples of provisions from the FIDIC Red Book (2017 edition). In the construction research space, there is a scarcity of scholarly investigations that identify specific challenges that may decelerate the adoption and implementation of blockchain-based construction contract administration (CCA) [6].

Hence, this section sheds light on the challenges that have emerged. It offers a description of each challenge within contextualized scenarios inspired by CCA practice along with implications for future research in the field of blockchain-based CCA. It is worth noting that not necessary all of these reported challenges in this study to have been explicitly stated in the referenced studies; some of them are present because of reasonable inferences.

To assist in the identification of the consequences of each particular challenge, the DLT Four-Dimensional Model proposed in the study undertaken by Li, Greenwood, and Kassem [9] is adopted in this paper. This model consists of four dimensions: *technology*, *process*, *policy*, and *society*. To this end, Table 6 summarizes ten challenges that have been mapped to their most relevant corresponding dimensions including the expected consequence of each challenge if not addressed. Additionally, potential future research questions are suggested in this Table.

Table 6. Challenges to blockchain-enabled CCA.

Dimension	References inspired the identification of the challenge	Identified challenge	Expected consequences	Potential future research question
Technology-related challenges	[5,12,18]	Risk of malfunction	Delayed execution of blockchain-based contractual processes (e.g., payment processing).	How can manual temporary actions completed during malfunctioning be subsequently incorporated into a blockchain-based payment system?
	[17,44,60,63]	Authenticity of oracles	Potential inaccuracy and error (coupled with mistrust) of oracle-enabled data entry.	Who verifies and validates the data before being added to a blockchain network and what happens if the entered data turns out to be incorrect?
	[8,18]	Blockchain platform lifecycle	Missed opportunities to extract necessary transactional records needed for dispute resolution arising during the operation phase.	How can records executed through permissioned blockchain-enabled smart contracts be transferred to another sustainable digital or otherwise format/system?
Process-related Challenges	[8,11,63]	Contractual logic	Undefined/uncaptured terms of the contractual logic that hinders encoding smart contracts and subsequently the production of outcomes identical to the ideal paper-based CCA.	How can contractual provisions and subjective terms contained therein be translated into encoded smart contracts? What are the language modifications required in a given standard form of contract (e.g., FIDIC) to enable encoding its provisions to smart contracts?
	Authors	Detailed cost breakdown	Compromised accuracy of automated payment amount to the subcontractors involved in re-measurement contracts.	How can compatibility between subcontract payment mechanism/unit rates and main contract unit rates in a blockchain-based payment system be achieved to enable the automation of correct amount payment?
Policy-related Challenges	[15,18]	Procurement route and contractual frameworks	Decelerated adoption of blockchain-based governance by policy makers and employers.	How to align blockchain-based governance and applications with existing procurement routes and standard forms of contracts and are the least changes required to enable successful blockchain-enabled governance?
Society-related Challenges	[12,18]	Contracting parties' acceptance	Disregarding the acceptance of main contracting parties forms a barrier to adoption.	What are the factors influencing the attitudes of the main contracting parties to adopt blockchain-based CCA? How can the effectiveness of a blockchain-based CCA be assessed in comparison to traditional-based CCA using qualitative and quantitative metrics?
	[8]	Cash farming	Main contractors' attitudes to payment by employers to their supply chain.	What are the alternatives offered to main contractors for short-term working capital generated through cash farming when employing blockchain-enabled payment oriented toward the supply chain?
	Authors	Delayed and defective work	Non-processing of due payment to supply chain actors by the employer's finance department in case of delayed and defective work.	What flexibility and rigidity does a blockchain-enabled payment system pose in case of delayed and defective work caused by one actor in a construction project?
	Authors	Accessibility to dispute resolution boards	Refusal to engage with such a technological system and interpret its contents.	How are the accessibility to and admissibility of blockchain-based contractual records dealt with under various dispute resolution mechanisms?

5.1. Technology-related challenges

5.1.1. Risk of malfunction

Malfunction of digital platforms is not uncommon and could result in adverse contractual consequences to both parties [5,12,18]; an example being where a contractor submits the payment application on the platform, but the employer's personnel cannot certify it because of a malfunction. Such an incident would lead to delayed payment to the contractor and potential financial losses to the employer due to a subsequent contractor's claim for financing charges. Challenges of this nature might be addressed by specifying corrective 'back-up' measures ahead of implementing a blockchain-based system. One such measure may be to revert to the conventional paper-based payment processing mechanism on a temporary basis [5]. However, how the actions completed through this temporary measure would be subsequently incorporated into the system after solving the digital malfunction remains uncertain, and an area to be explored.

5.1.2. Authenticity of oracles

The relevant reviewed studies reported the reliance on 'oracles' in the form of human intervention and/or other digital technologies (e.g., BIM) to feed the blockchain network with data [17,59–61,63]. This is required to trigger the self-execution of functions encoded in smart contracts based on data entered by these oracles off-chain. This poses the question of who verifies and validates the data before being added to a blockchain network and what happens if the entered data turns out to be incorrect [17,44,60,63]. Records on the blockchain are immutable and transactions executed through smart contracts are irreversible [5]. A future research effort might be directed at developing a protocol that tackles such challenges by regulating the data entries at the intersection between the off-chain and on-chain networks. Provision of such as an allowance for an inverse transaction to correct previous incorrect block data might be included in the protocol.

5.1.3. Blockchain platform lifecycle

The blockchain system and its associated smart contracts lifecycle has not been considered in the reviewed studies given the embryonic nature of this research domain. But disregarding the lifecycle design brings a contractual challenge that may hinder the adoption of blockchain in construction projects [8,18]. This challenge stems from the latent defects liabilities that demand retention of documents and records for many years after the completion of a project. This retention of information is required to produce evidence to support or counteract claims arising from defects during the operation phase. The availability of records on the permissioned blockchain networks for years and the executability of smart contracts to return a specific piece of information may be a challenge. This challenge will likely be more pronounced where off-chain and on-chain intersect. Future research is needed to tackle this challenge, especially in construction projects procured through public–private partnerships (PPP) arrangement where 25-30 years long contracts are the norm.

5.2. Process-related challenges

5.2.1. Contractual logic

Converting the logic of a given contractual mechanism and provisions into a self-executing smart contract will probably be the most pronounced challenge [8,11,63] as demonstrated in the following simplified example. Contractual provisions forming a single specific mechanism are generally dispersed throughout the conditions of contract and other contract documents (e.g., specifications). Examples of such dispersal can be found in the payment-related provisions stipulated in the FIDIC Red Book, where the payment cycle stipulated under sub-clause *14.3* [Application for Interim Payment] includes multiple stages. The first stage involves measuring the completed works, pursuant to sub-clause *12.1* [Works to be Measured], in accordance with the bill of quantities (BoQ) which refers to the method of measurement and payment in the specifications pursuant to sub-clauses *12.2* [Method of Measurement] and *12.3* [Valuation of the Works]. The second stage includes adding or deducting amounts to account for: (*i*) changes in laws,(*ii*) retention, (*iii*) recovery of the advance payment, and (*iv*) payment for on-site materials, respectively, pursuant to sub-clauses *13.6* [Adjustments for Changes in Laws], *14.9* [Release of Retention Money], *14.2* [Advance Payment], and *14.5* [Plant and Materials intended for the Works]. The third stage deals with certifying provisional amounts for determined claims and variations which are still under negotiations pursuant to sub-clause *3.7* [Agreement or Determination]. This complicated cycle further compounds when contracts are terminated or when previously paid amounts need to be deducted as offsetting. To execute these highlighted stages multiple sub-clauses and provisions interact and complement one another. Thus, defining the contractual logic is indispensable to enable the contractual operation of a blockchain-based payment system; yet it is challenging. However, ensuring that the encoded smart contracts will produce the exact contractual outcomes over the whole payment cycle (from the advance payment to the final payment) is still a valuable and worthwhile ambition.

5.2.2. Detailed cost breakdown

In order to implement the proposed blockchain-enabled payment systems, a detailed cost breakdown of the work items needs to be in place. Breaking down the components of construction cost into their basic constituent parts would be a challenging process, especially, in contracts where the specified payment mechanism is re-measurement, such as in the case of FIDIC Red Book. The reason behind this challenge is that many unit rates for work items are composite, and, for example, may include elements for temporary activities and testing. Furthermore, it is not uncommon for specific work items to be completed by multiple actors. For example, in a pipeline project, the excavation and backfilling work packages may be awarded to a subcontractor while the main contractor may carry out the pipeline supply and installation. In projects of this nature, whole sets of work items might be priced under one BoQ item. Thus, agreeing on the relative proportion of these two work packages and how they would be paid for in a blockchain-based payment system remains unclear. This could be clarified by adopting the Institute of Civil Engineers' Civil Engineering Standard Method of Measurement [82].

5.3. Policy-related challenges

5.3.1. Procurement route and contractual frameworks

A challenge to adopting and implementing these reviewed blockchain-based applications with the aim of improving CCA is the complication of the variety of procurement and contractual frameworks available [15,18]. Few of the reviewed studies had mentioned this and few had defined which framework they were considering: an exception being the work in [50]. It was, however, frequently suggested that policymakers need to reform current practices and standard forms of contracts to align with the requirements of blockchain technology. In contrast, in [83] it is argued that construction contractual objectives should drive the technology objectives and not the reverse. To overcome this challenge, it is suggested that research efforts are needed to explore how to align blockchain-based applications with existing procurement routes and standard forms of contracts. Construction projects are generally governed by conditions of contracts (e.g., those of FIDIC) that have evolved and developed over time and are unlikely to be readily discarded.

Aligning blockchain applications as much as possible to current practice, rather than vice-versa would make its adoption more likely. The interplay between blockchain opportunities and procurement and contractual policies would be a valuable future research area.

5.4. Society-related challenges

5.4.1. Acceptance of the contracting parties

Under most contractual arrangements there are two parties to the main contract for execution of the works: the Employer (or Owner) is one; the other is the Contractor. Implementing a blockchain-based platform needs the acceptance of both [12,15,18]. This may be a challenge as blockchain is still in its exploratory stage in the construction domain. To accelerate acceptance, both employers and contractors must be consulted, persuaded, and involved in the development of such systems. Among the twenty-one reviewed studies, only two studies, i.e., those undertaken in [12] and in [18] evaluated the attitude of practitioners, including contractors, to the developed blockchain-based prototypes, while other studies evaluated the proposed frameworks and prototypes in controlled environments. Thus, extending future research to a more thorough evaluation of the attitudes of the main contracting parties is crucial to understanding challenges to adoption.

5.4.2. 'Cash farming'

Main contractors often exploit prolonged payment periods with their supply chain partners [8]. The delayed payment enhances main contractors' cashflow at the expense of those further down their supply chains, in a practice that has been referred to as 'cash farming' [84]. Therefore, the implications of a system that enables the supply chain to be paid more automatically, unequivocally, and transparently may be resisted by many main contractors. It remains to be seen how such disincentives can be overcome. A point of departure could be developing a blockchain-based payment methodology that satisfies balanced working capital needs of main contractors and their supply chain.

5.4.3. Delayed and defective work

It is not uncommon for construction projects to exceed the contractual time for completion without the contract works being fully or properly completed. The contractual responsibility may lie with the employer or the contractor, or it may be due to the occurrence of an 'external' event. A disagreement often follows, and it is common for the employer's financial department to stop processing contractor's payment applications pending settlement. A similar scenario often emerges with disagreements over defective work. In a fully automated blockchain-based payment system scenario, this cannot be done without refining the consensus mechanism. On the other hand, if the consensus mechanism allows a payment to be withheld, downstream subcontractor payments would not be processed despite the subcontractor's works having no relevance to the disagreement between the employer and contractor (see Table 6 for a potential future research question).

5.4.4. Accessibility to dispute resolution boards

In construction, contractual disputes may arise due to many reasons, and it is important for contracts to include accessibility to external dispute resolution processes (e.g., mediation, adjudication, arbitration, and ultimately, the courts). Ignoring, for the moment, the possibility of the blockchain technology itself being a source of dispute, the ability of a blockchain platform to maintain the parties' accessibility to dispute resolution mechanisms has not been considered in the current research literature. For example, those responsible for the various dispute resolution processes (e.g., adjudicators and arbitrators) may refuse to engage with such a technological system and interpret its contents due to disharmony with the conventional systems with which they are familiar. In an optimistic scenario, a board may appoint an expert to access the system and extract information relevant to the dispute. However, the mechanism allowing accessibility to this expert coupled with the admissibility of the blockchain records without further verification needs to be closely examined in future research. To this effect, a blockchain consensus mechanism protocol with a focus on accessibility and admissibility could be developed for construction projects that adopt blockchain technology.

6. Discussion of findings

The overarching aim of this study was to evaluate the feasibility and establish evidence of how blockchain can contribute to improving CCA. Unlike earlier review works [14–16], this paper has shifted focus from a high-level analysis of blockchain applications in construction management to the granular/micro level represented by CCA. To achieve this, the reviewed studies have been classified according to an adopted set of recognized CCA functions while contextualizing them within examples from a commonly-used standard form of contract, the FIDIC Red Book (2017 edition). Subsequently, the challenges identified have been specifically set in CCA context and a series of potential research questions was established within scenarios inspired by CCA practice. The following discussion revolves around the multiple findings of this study.

The potential of eliminating or lessening the likely occurrence of reported causes of poor CCA and ultimately the severity of their adverse effects (see subsection 2.2) was readily evident in the reviewed blockchain-based applications. The following paragraphs relate this evidence to the identified challenges.

Misapplication and/or refusal to execute contract provisions can both be prevented by agreeing on a blockchain consensus mechanism (e.g., endorsement policies in the case of the Hyperledger Fabric permissioned blockchain) and codifying smart contracts to reflect the corresponding provisions in the paper-based contract. The consensus mechanism and automated execution of contractual provisions by means of smart contracts without human involvement, while ensuring immutability coupled with traceability of the executed process, are the main characteristics that differentiate blockchain technology from other computerized systems. In this way, the blockchain system prevents the two problems in question when it is fully automated (i.e., without human involvement), or, when employed in a semi-automated mode (i.e., with limited human involvement) lessens the occurrence or minimises their effects. The latter is achieved due to the blockchain traceability feature that makes visible the inactions of any actor responsible for the execution of a contractual function.

In the same vein, causes of poor CCA that stem from inaccurate documents, inaccessibility of records, and corruption can all be tackled by using features offered by blockchain technology. Notably, traceability, immutability, and decentralization collectively pose a digital shield to any inadvertent or intentional deletion or changes to document versioning and contemporary records, while ensuring their distributed state in a unified manner across the nodes of registered actors. As pointed out earlier, current computerized and cloud-based systems are unable to provide these features since deletion of any document or record in their digitized workflow can be exercised without notification.

In terms of enhancing the efficiency and effectiveness of CCA functions, the review of current literature has revealed that out of the eleven identified CCA functions only seven received attention. Notably, among the twenty-one classified studies, eight focused on the payment aspects of the financial management function while other CCA functions have either received scant attention or were absent (see Table 5 in Section 4). The possible reason behind this focus on financial management is that blockchain has already demonstrated promising results in resolving financial-related issues in other industries. Hence, scholars in the construction domain have been encouraged to translate those results into construction to address its chronic non-payment and delayed payment issues. This finding regarding the financial management aligns with findings reported in [14] and in [53].

There has been no previous study that models the whole payment cycle (i.e., from the advance payment to the final payment) of a given standard form of contract using a blockchain system. The one exception is [50] which related to projects procured through an IPD framework based on cost reimbursement payment (a system that is a comparative rarity in construction). The absence of such a study is explained by the difficulty encountered in encoding the contractual logic of corresponding provisions and sub-clauses which tend to be dispersed across the conditions of contract (see subsection 5.2.1). In future research directed toward this type of application, contract experts can be consulted to validate the contractual logic. Moreover, there is still a need for further efforts to be devoted to overcoming the challenge of 'cash farming' practised by main contractors to their evident advantage (see subsection 5.4.2).

The *claims and disputes resolution management* CCA function has received attention in only one recent study [66] though on closer examination the focus was on payment-related disputes rather than the wider management off claims events (including extension of time as well as payment-related claims). Interestingly, evidence presented in reviewed literature suggests that claims management can leverage the benefits offered by blockchain applications classified under other CCA functions.

The findings suggest that in a blockchain-based claim management scenario the system can instantly notify a delay event by signaling schedule deviations in advance (instead of, for example, waiting for monthly progress reports to notify the same). It can also ensure that schedule performance-related records remain unaltered. In turn, blockchain-based CCA governance could revolutionize claims management by offering a readily streamlined chronological versioning of documents and records necessary for establishing evidence for a given claim event and performing forensic schedule delay analysis. These could all be recorded on unified ledgers that are accessible to all actors involved. As such, issues arising from frequent manipulation and discrepancies of schedule updates along with confused or inadequate evidence of the origins of delays would be eliminated. Interestingly, ideal blockchain-based smart contracts could be programmed to automatically serve notices of claims and determine quantification of entitlement to extensions of time and compensation for additional costs in line with the mechanisms stipulated in the paper-based conditions of contract. As a result, the efficiency and effectiveness of CCA functions that deal with *communication and relationship management*, *document and record management*, *performance monitoring and reporting management*, *changes and changes control management*, *claims and disputes resolution management* could be substantially improved in comparison with current manual practices. All these functions intersect with one another in a dynamic manner in a claim-based system. Having said that, the realization of blockchain-based claim management system would be confronted by challenges. As with a blockchain-based payment system, the codification of smart contracts to exactly simulate the contractual logic for the corresponding contract provisions and sub-clauses will be the most pronounced challenge. Moreover, authenticity of oracles (see subsection 5.1.2), blockchain platform lifecycle (see subsection 5.1.3), and accessibility to dispute resolution boards (see subsection 5.4.4) may challenge the adoption and implementation of such a system.

In contrast to blockchain-based payment, it can be assumed that a blockchain-based claim management system may be more complicated to achieve and operationalize in practice. The reasons include: (*i*) the greater involvement of and intersection with other functions, (*ii*) the fact that various claim types demand different documents and records, and (*iii*) the requirement for multilayer communication among the actors involved. These reasons may explain why the reviewed studies do not contain a specific blockchain-based claim management system despite its attraction.

However, it is readily evident how the core components and unique characteristics of blockchain technology presented here might prevent or lessen the occurrence of the most common causes and effects of poor CCA (as conceptualized earlier in Fig.2 in Section 2). It can reasonably be inferred that integration of these isolated reported applications would result in realizing a digitally- based CCA, underpinned by blockchain technology.

Nonetheless, because of the identified and scenario-based challenges explained in Section 5, the benefits of adopting and implementing blockchain-based CCA applications and the alignment between blockchain-based applications and conventional procurement routes requires further in-depth investigation. Adoption of blockchain may give rise to innovative procurement methods through the use of cryptocurrencies as observed in [63]. In this study, the use of blockchain-based crypto-economic incentives to procure performance-based building projects was proposed. The rationale behind this innovative line of thought was to align contractual thermal performance targets with actual results with the aim of meeting end users' needs while reducing the environmental impacts of heating systems. Such an approach could be adopted in highway or rail projects procured through PPP to monitor the corresponding performance indices which reflect the rideability and safety of the surface over time. Future in-depth investigations into the role of blockchain-based crypto-economic incentives for procuring performance-based building and infrastructure projects are worth conducting. However, given the likely longevity of traditional procurement routes there is a need for research efforts toward designing blockchain architectures that can be accommodated within them.

One technical observation has emerged during this study is that a particular blockchain-based solution to a typical problem within the same CCA function was developed using permissionless as well as permissioned platforms (see Table 5 in Section 4). This suggests an absence of a consensus among researchers with respect to the selection criteria for a blockchain type or platform. Future technically-orientated research efforts are encouraged to address this.

7. Conclusions

This paper has established initial evidence that demonstrates how current blockchain-based applications proposed within the construction research domain can contribute to improving CCA functions. It also proposes a set of potential research questions to address the challenges identified specifically to CCA context.

This paper carries implications for contract drafting bodies and policymakers (e.g., FIDIC Task Groups and digital transformation committee) as well as practitioners. It has classified state-of-the-art blockchain applications in the construction research domain according to the multifunctional approach of CCA while providing contextualized examples from FIDIC Red Book 2017 edition. This is expected to raise awareness about the applicability of blockchain technology in addressing specific issues arising from a given CCA function. In practical terms, the study provides an up-to-date reference point for enhancing the knowledge of contracts policymakers and practitioners with respect to the feasibility of blockchain in CCA.

Contribution to the academic body of knowledge was realized in three ways. Firstly, it is hoped that the classification of blockchain applications according to the multifunctional approach of CCA may serve as a response to calls in [5,6] for further work that enables incremental progression towards a digital CCA. This analytical review contributes to the conceptual understanding of the tasks and processes that could be automated (partly or fully) by referring to the relevant contractual mechanisms and provisions of a specific (and widely used) form of contract. Secondly, it is expected that the proposed future directions to tackle the ten identified challenges would encourage scholars in the field to continue research efforts with the aim of realizing a blockchain-enabled CCA. Thirdly, it has mapped a large number of disparate research efforts against a framework of CCA functions to demonstrate that causes of poor CCA can be addressed with the adoption of blockchain technology.

Despite the contributions as discussed, some limitations are recognized. Firstly, the systematic literature review applied narrowed exclusion criteria to distill the most relevant studies to CCA. In the process, some insightful and valuable studies might have been missed. However, those retrieved are believed to represent a sufficient sample of the state-of-the-art that revolves around the researched theme. Secondly, the contextualization and analysis of the classified studies took place within the context of a single standard form of contract: the FIDIC Red Book. Future studies might investigate how contractual provisions of other standard forms can be mapped to blockchain applications. In this way, the necessary modifications needed for encoding the contractual logic of existing standard provisions to programmable smart contracts could be recognized. Thirdly, the challenges presented which emerged as a reflection from reviewing the literature were not verified by interviewing practitioners or consideration of legal challenges. However, these potential challenges may be addressed in future research when they spark scholars' interests to explore or debate them.

In future research, the authors intend to develop a blockchain-based claim management prototype and evaluate its suitability across a variety of claim types while addressing some of the identified challenges. This could subsequently be applied to different procurement routes.

Last but not least, this paper has highlighted that the roles played by policymakers of standard forms of contract and main contractors were rarely considered in the literature review of blockchain-based applications. It is therefore proposed that the perspectives of both these parties should be included in future research efforts. This may help to drive adoption levels by achieving balanced benefits for all actors involved, while improving the operationalization of procurement and contractual frameworks devised by policymakers.

Declaration of Competing Interest

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

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