ITcon
www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

DECENTRALIZED AND COLLABORATIVE INFORMATION MANAGEMENT SYSTEM IN CONSTRUCTION CONTRACT ADMINISTRATION: A CHANGE MANAGEMENT CASE STUDY

SUBMITTED: November 2024
REVISED: June 2025
PUBLISHED: July 2025
EDITOR: Yang Zou, Mostafa Babaeian Jelodar, Zhenan Feng, Brian H.W. Guo
DOI: 10.36680/j.itcon.2025.046

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SUMMARY: *Data quality and lack of reliable information about changes, claims, and risks are ongoing challenges in construction contract administration (CCA). These issues along with ineffective information management, can result in poor decision-making, and eventually, cost overruns and delays. The CCA processes involve complex communications and management of information flow among stakeholders. Blockchain and ontology have been widely studied for their capabilities to improve collaborative information management and foster decision-making, but their integration potentials are mostly unexplored within the context of CCA information management. This study aims to develop a contract information management system leveraging the benefits of blockchain and ontology. The system is demonstrated using change management as a representative CCA process, with two main objectives: (1) to overcome issues hindering trust and collaboration for the effective management of CCA-related information flow, and (2) to improve accessibility to reliable data for effective decision-making. A decentralized and collaborative contract information management (DCCIM) system was proposed encompassing two main layers of blockchain and ontology-based information management. Additionally, a novel framework was developed for designing the smart contract and blockchain network based on a standardized ontology and business process model. The system was evaluated using a change management process as a case study to demonstrate its applicability within CCA workflows. The blockchain infrastructure enables reliable, collaboratively managed information flow, while the ontology facilitates the development of smart contracts aligned with the management process and enhances access to information by supporting complex queries and automated reasoning over captured data. The proposed DCCIM system could be a promising building block for future developments and full automation of CCA processes.*

KEYWORDS: *Blockchain, Smart contract, Interoperability, Trust, Collaboration, Knowledge integration, Decentralization, Change management, Ontology.*

REFERENCE: *Navid Torkanfar, Ehsan Rezazadeh Azar & Brenda McCabe (2025). Decentralized and Collaborative Information Management System in Construction Contract Administration: A change management case study. Journal of Information Technology in Construction (ITcon), Special issue: 'Construction 5.0', Vol. 30, pg. 1123-1149, DOI: 10.36680/j.itcon.2025.046*

1. INTRODUCTION

Delays, cost overruns, and disputes that often result from poor construction contract administration (CCA) are common challenges in the successful delivery of projects (Memon et al., 2011, Gunduz and Elsherbeny, 2021, Pancoast et al., 2022). Construction contracts establish the legal framework by defining rights, obligations, and fair allocation of risks among parties (Hughes and Greenwood, 1996). CCA ensures safe and effective delivery of projects, proper management of disputes, and adherence to contractual obligations. Due to the critical role of CCA, various research explored the root causes of CCA issues, such as the lack of trust and collaboration among parties (Jaffar et al., 2011), poor record-keeping, loss and manipulation of critical information and documents (Ali et al., 2020, Abdul-Malak and Abdulhai, 2017), and unclear roles and responsibilities (Surajbali, 2016).

CCA encompasses a range of functions, including change management, claims processing, conflict resolution, and risk management. Among these, change management is particularly complex and critical, due to its direct influence on project scope, budget, and schedule (Chester and Hendrickson, 2005, Padala et al., 2022). While the challenges addressed in this study and the proposed methodological framework may be applicable to broader aspects of CCA, this research specifically focuses on change management as the representative use case.

Like many managerial processes, information management is a critical part of CCA. A successful CCA process optimizes the flow of information, effectively allocates resources, and establishes clear roles and responsibilities to ensure seamless information flow and efficient decision-making (Akanbi et al., 2019). In addition, the CCA process is inherently collaborative, as all parties should contribute to the management and exchange of information to enhance the availability and reliability of information. However, the fragmented nature of the industry and conflicting interests hinders effective collaboration and often leads to disputes (Faris et al., 2022). These issues are further compounded by technical challenges related to communication and information exchange, such as concerns over system security, data reliability and quality, and the interoperability and integration of systems, all of which make collaboration particularly challenging (Golzarpoor et al., 2018, Shen et al., 2010).

Digitalization and the use of technology have been a major focus for researchers and the industry to enhance communication and collaborative exchange of information in CCA (Msawil et al., 2022, Chong and Cheng, 2023, Jahanger et al., 2021). During the years 2000-2010, web-based applications received researchers' attention to address challenges such as lack of transparency, communication, integration, and knowledge transfer (Narayan et al., 2021). Various web-based applications were introduced to improve CCA related tasks, such as applications for information and knowledge management (Ahuja and Yang, 2006, Chassiakos and Sakellaropoulos, 2008), contract management (Kwok et al., 2007), claim management (Chau, 2007), document management (Forcada et al., 2007), risk management (Han et al., 2008), and change management (Charoenngam et al., 2003). The emergence of Building Information Modeling (BIM) further introduced new opportunities for enhancing collaboration in specific aspects of CCA, such as claim management (Al Shami, 2018, Marzouk et al., 2018), risk management (Zou et al., 2017) and performance management (Matthews et al., 2015).

Advances in blockchain and smart contracts applications have shown promise in improving efficiency and addressing persistent challenges in contractual administration tasks. Among these enhancements are the reduction of human errors and disputes, as well as the facilitation of legal processes and contract management automation (Msawil et al., 2022). Additionally, blockchain-based contract management can enhance transparency and traceability, reduce information asymmetry, and enable peer-to-peer collaboration, thereby improving overall information flow (Udokwu et al., 2021). Several solutions have been proposed to support CCA processes, including the automation of payments using smart contracts (Hamledari and Fischer, 2021a), construction quality management and inspection (Wu et al., 2021, Zhong et al., 2020), document management and version control (Das et al., 2022), risk assessment (Chung and Caldas, 2022) and the integration of smart contracts and blockchain with BIM to develop intelligent contracts (McNamara and Sepasgozar, 2021, Mason, 2017).

Blockchain technology represents a significant advancement in the digitalization of CCA processes. Blockchain technology was one of the core technologies that emerged and was further developed through Industry 4.0. While Industry 4.0 laid the technical foundations (Lasi et al., 2014), Industry 5.0 provides the construction industry with a roadmap toward enhanced efficiency by emphasizing human-centric approaches, sustainability, and resilience through the integration of people, processes, technology, and information (Xu et al., 2021, Ikudayisi et al., 2023). The technological principles of Industry 5.0 include collaboration, coordination, communication, automation, identification, and data analytics (Ivanov, 2023).

Blockchain, as one of the main enablers of Industry 5.0, can advance the digitalization of CCA toward the principles of Construction 5.0 by promoting transparency, trust, and accountability (Leng et al., 2022). However, several challenges continue to limit the practical utility and alignment of blockchain-based applications with Construction 5.0 principles in the context of CCA digitalization. These limitations include: (1) an overemphasis on automation as the primary outcome, often at the expense of fostering trust and collaborative information flow among stakeholders; (2) inability to achieve full automation due to complex contractual agreements, long-term and intricate communication, and human-centered decision-making based on the interpretation of stakeholder data; (3) limited accessibility to reliable, transparent, and trustworthy information captured on the blockchain, which constrains effective decision-making throughout the CCA process; and (4) inadequate integration of managerial processes, information flow, and clearly defined roles, which complicates access to critical information and contributes to delays in contract administration.

Given the persistent challenges in CCA, this research explores the potential of integrating blockchain and ontology technologies to address issues hindering trust and collaboration, enhance the management of CCA-related information flow, and improve access to reliable data for effective decision-making. While the proposed approach is applicable across various CCA functions, this study focuses specifically on change management, for the development, implementation, and evaluation of the proposed solution. Accordingly, this research proposes a decentralized and collaborative contract information management (DCCIM) system comprising three layers: (1) user interfaces to facilitate interactions with the system; (2) a blockchain-based foundational layer to handle communications and transactions among stakeholders; and (3) an ontology-based information management layer. The integration of ontology is intended to facilitate the development of smart contracts while enhancing information accessibility and decision-making through ontology-based information management throughout the CCA process and the execution of smart contracts.

The main steps toward achieving the objectives of this research are summarized as:

- Examine the root causes of poor collaboration in the exchange of information and knowledge during the CCA processes.
- Analyze the capabilities of blockchain in enhancing inter-organizational trust and collaboration.
- Explore the potential of ontology-based information management for improving information accessibility and decision-making based on high-quality and reliable data.
- Define a framework for designing blockchain and ontology layers of the proposed system.
- Develop the DCCIM's system architecture that effectively incorporates the main components.
- Evaluate the proposed framework and system architecture within the context of a CCA process.

2. LITERATURE REVIEW

2.1 Current Challenges in CCA

One of the initial phases of any construction project is the formation of a contract between the involved parties. The contract outlines the rights and obligations of each party within a legal framework (Gunduz and Elsherbeny, 2021). To ensure effective contract management and access to resources and expertise, the owner may enter into a separate contract with a third-party engineering consultant to assist the owner in tasks such as preparing plans and specifications, tendering, and contract administration. The CCA processes ensure that the contract is administered in accordance with its terms. The CCA team is authorized by the owner to make timely decisions regarding the performance of each party's obligation (Marston, 2019). The CCA team usually oversees change management, financial management, claim management, dispute resolution, risk management, as well as performance monitoring and reporting (Gunduz and Elsherbeny, 2021).

Poor CCA can result in claims, delays, and cost overruns, all of which have significant negative impacts on project delivery (Mansfield et al., 1994, Odeh and Battaineh, 2002). The most common causes of poor CCA include inadequate planning (Alzara et al., 2016), absence of robust systems, guidelines and procedures (Surajbali, 2016), lack of skilled personnel (Ahmed, 2015), and unclear roles and responsibilities (Surajbali, 2016). Other contributing factors include poor record-keeping (Ahmed, 2015), slow responses to inquiries (Cunningham, 2016), and insufficient use of information and communication technology (ICT) (Rotich, 2014).

Change management is a critical process within CCA, and its mismanagement can lead to delays, cost overruns, project failures, and disputes (Hao et al., 2008, Motawa et al., 2007). Unresolved or poorly managed changes often escalate into claims and disputes (Alzara et al., 2016, Park and Kim, 2018, Pancoast et al., 2022). Due to the inherent uncertainties in construction projects, unforeseen situations and resulting changes are common, leading to numerous change requests and claims that require timely and reliable decision-making to minimize their impacts on the project's cost and schedule (Chester and Hendrickson, 2005, Padala et al., 2022). As indicated by McKinsey's Productivity Science Center, delays in decisions on claims, often resulting from the accumulation of unresolved issues due to a lack of communication and accountability, can lead to construction delays and potentially cause a breakdown of trust between the owner and contractor (Changali et al., 2015).

2.2 Collaboration, Trust, and Information Management

Collaboration and trust among contracting parties are essential for improving project outcomes. Poor collaboration was identified as a main cause of low productivity in the construction industry (Laszig et al., 2020). To date, the enhancement of collaboration and trust has been tackled by ICT systems such as BIM and blockchain (Qian and Papadonikolaki, 2021, Lee et al., 2022), as well as relational contracting methods like alliancing and integrated project delivery (IPD) (Pishdad-Bozorgi and Beliveau, 2016, Davis and Love, 2011). Internally, organizational culture (Cheung et al., 2011) and transparency initiatives (Cheung et al., 2011) have contributed.

Collaboration among parties can occur at various stages of the project lifecycle, including contracting, contract administration, project execution, and project close-out. Depending on the nature of the process, the objective of collaboration may involve either facilitating the flow of materials and the delivery of physical objects or managing the flow of information (Akanbi et al., 2019). In information-oriented processes like CCA, effective practices and systems enhance communication, streamline information exchange, and foster collaboration for informed decision-making.

Information management is inherently a collaborative process that requires all parties to actively engage in the capture, storage, and maintenance of information and knowledge. Effective information management is fundamental to organizational success across all project stages, from initial planning to final delivery (Celoza et al., 2021, Bwalya and Saul, 2014). The information management process begins with the generation of new information and continues through its storage, sharing, and utilization. This cycle concludes when the information is no longer needed and is appropriately disposed (Celoza et al., 2021, Back and Moreau, 2001).

Advancements in technology and the use of ICT have improved communication and collaborative information management in CCA. However, the adoption of associated technologies also introduced challenges regarding the interoperability of information systems (Golzarpoor et al., 2018, Shen et al., 2010), inter-organizational trust (Selvanesan and Satanarachchi, 2023), knowledge integration capacities and information reuse (Dietrich et al., 2010), automated workflow processes (Chen et al., 2018), quality and reliability of data (Lee and Yu, 2012), and clarity of roles and responsibilities (Alreshidi et al., 2018).

One of the primary challenges of information systems is interoperability, which often arises from the proprietary nature of these systems, limiting their ability to interact with other systems and processes. More efficient collaboration can be achieved by enhancing interoperability among ICT systems (Golzarpoor et al., 2018). Interoperability can be addressed at both data and process levels to ensure seamless integration of data between organizations and a common understanding among systems regarding shared data and processes.

Ontology is a technology used in information systems to enhance the interoperability of data and processes. Ontology refers to machine-processable structures designed to define domain-specific knowledge (Studer et al., 1998, Borst, 1997). The ontology categorizes objects, delineates their properties, and defines their logical relationships (Chandrasekaran et al., 1999, Gruber, 1993). Structured representation of information in ontologies enhances information sharing and interoperability and minimizes data misunderstandings and omissions (Zhong et al., 2019). Another advantage of ontology-based information management is its support for collaboration by enhancing information reusability, as well as supporting knowledge integration (Rezgui et al., 2011).

In addition to interoperability concerns, the application of information systems comes with concerns around data security, intellectual property rights, and data reliability and quality, all of which can lead to inadequate communication, lack of collaboration, rework, and project failure (Yang et al., 2020, Svalestuen et al., 2017). These concerns negatively influence user trust and therefore collaboration. Building trust both in the system and among stakeholders is crucial for enabling effective collaboration (Oraee et al., 2019, Dodgson, 1993, Dietrich et al., 2010). It has also been demonstrated that while trust in communication technology does not directly affect inter-organizational trust, it significantly impacts obligatory collaboration, hence indirectly affecting inter-organizational trust (Lee et al., 2022).

Introducing decentralized systems such as blockchain for information management, where data are transparent, secure, and modification is prevented, can effectively address concerns around data security, trust, and transparency (Chung et al., 2022). Blockchain is a specific type of distributed ledger technology (DLT) that uses cryptographic techniques to offer unique attributes for utilization in information systems. It enables a transparent, immutable, traceable, and decentralized data management platform where users are accountable for their participation (Sunyaev, 2020). Smart contracts allow for the automation of process logic, reducing potential human errors, enhancing the reliability of process data and outcomes, and improvement of user trust in the system and data (Zheng et al., 2020).

2.3 Potentials for Integration of Blockchain and Ontology

Ontology has been proposed for integration with smart contracts across various stages of their lifecycle including creation, deployment, and execution (Dominguez et al., 2024). In this research, ontology is employed with two primary objectives. The first aim is to facilitate the creation of smart contracts that accurately reflect the underlying business processes and associated rules. In this context, CCA process rules, key concepts, and relationships can be semantically defined within the ontology, ensuring a consistent and robust transition from the CCA process logic to smart contract code. The second aim is to enable integration with the smart contracts during their execution phase to address key challenges in collaborative information management. While both blockchain and ontology have shown promise in overcoming these challenges, their cumulative advantages have yet to be established. When combined, the characteristics of blockchain and ontology can collectively enhance automation, information quality and reliability, interoperability, and the clarity of roles and responsibilities. Blockchain contributes to strengthening inter-organizational trust. Additionally, ontology plays a critical role in enabling effective knowledge integration and enhancing the accessibility, reusability, and management of transaction information.

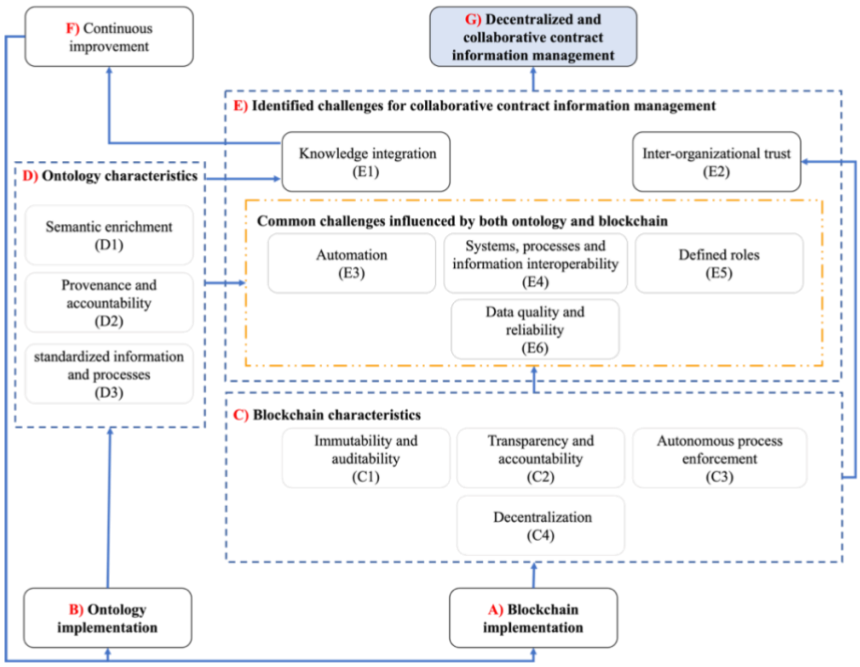

Figure 1: Mapping identified challenges in collaborative information management in CCA with technological characteristics of blockchain and ontology.

To improve the understanding of the complex interdependencies among the identified challenges and technological characteristics of ontology and blockchain, a causal loop diagram (CLD), shown in Figure 1, was developed. CLDs graphically represent the dynamic interactions between these elements by conceptualizing the problem factors as an interconnected whole (Senge, 2006). Based on Figure 1, blockchain characteristics are organized into four categories: (C1) immutable and auditable record of transactions and shared information (Celik et al., 2023, Sheng et al., 2020), (C2) enhancing transparency and accountability in sharing information (Zhong et al., 2022, Wu et al., 2022), (C3) autonomous business logic enforcement using smart contracts (Zhang et al., 2023, Torkanfar et al., 2023, Zhong et al., 2022), and (C4) decentralization and reducing third parties involvement (Saygili et al., 2022, Hamledari and Fischer, 2021b, Hunhevicz and Hall, 2020). Similarly, the characteristics of using ontologies in information management fall into three categories: (D1) semantic enrichment (Xue et al., 2021), (D2) data provenance and accountability enhancement (Castro et al., 2021, W3C, 2013, de Souza et al., 2024, Naja et al., 2021), and (D3) standardized information and processes (Fernández et al., 2011). A summary of the relationships and the articles supporting them is presented in Table 1.

Table 1: Summary of references supporting relationships identified in Figure 1.

Relationship code	Relationship description	References
A-C1	Blockchain improving immutability and auditability	(Celik et al., 2023, Sheng et al., 2020, Li et al., 2019)
A-C2	Blockchain improving transparency and accountability	(Wu et al., 2022)
A-C3	Blockchain enabling autonomous process logic enforcement	(Zhang et al., 2023, Torkanfar et al., 2023, Zhong et al., 2022)
A-C4	Blockchain enabling decentralization	(Saygili et al., 2022, Hamledari and Fischer, 2021b, Hunhevicz and Hall, 2020)
B-D1	Ontology improving semantic enrichment	(Xue et al., 2021)
B-D2	Ontology improving provenance and accountability of information	(Castro et al., 2021, W3C, 2013, Naja et al., 2021)
B-D3	Ontology enabling standardized information and process	(Fernández et al., 2011, Zhong et al., 2019)
C-E2	Blockchain enhancing inter-organizational trust	(Qian and Papadonikolaki, 2021, Yoon and Pishdad-Bozorgi, 2022, Hijazi et al., 2021, Lu et al., 2023, Jing et al., 2019, Selvanesan and Satanarachchi, 2023)
C-E3	blockchain enabling automation	(Hamledari and Fischer, 2021a, Chung and Caldas, 2022, Zhong et al., 2022, Hunhevicz et al., 2022, Kifokeris and Koch, 2020)
C-E4	Blockchain improving integration of systems, information and systems	(Yang et al., 2020, Teisserenc and Sepasgozar, 2021, Khawaja and Javidroozi, 2023, Hewavitharana et al., 2024, Lawal and Nawari, 2023)
C-E5	Blockchain establishing defined roles and responsibilities	(Kim et al., 2023, Gupta and Jha, 2023)
C-E6	Blockchain enhancing data reliability and quality	(Wu et al., 2021, Pradeep et al., 2020)
D-E1	Ontology implementation enhancing knowledge integration capabilities	(Husáková and Bureš, 2020, Chungoora et al., 2013)
D-E3	Ontology enabling automation	(Hong et al., 2019, Lu et al., 2015, Zhang and El-Gohary, 2017)
D-E4	Ontology improving integration of systems, information and systems	(Zhou et al., 2016, Farghaly et al., 2024, Rezgui et al., 2011, Pandit and Zhu, 2007)
D-E5	Ontology establishing defined roles and responsibilities	(Guévremont and Hammad, 2021, Zheng et al., 2021)
D-E6	Ontology enhancing data reliability and quality	(Rasmussen et al., 2019, Pauwels et al., 2017, Liaw et al., 2013)
E1-F	Knowledge integration driving continuous improvement	(Kamara et al., 2002, Dietrich et al., 2010)

3. METHODOLOGY

This research proposes the DCCIM system as a solution to the challenges associated with collaborative information management in CCA. The study focuses on change management to demonstrate the implementation and evaluation of the DCCIM system. As illustrated in Figure 2, three main steps were undertaken for the development, implementation, and evaluation of the system. First, a framework was developed to provide researchers and practitioners with a systematic approach for designing the ontology, blockchain network, and smart contracts, which constitute the core components of the DCCIM system. These components were subsequently integrated into a comprehensive system architecture, which outlines the flow of information among parties, blockchain-based communication mechanisms, and ontology-based information management processes. Throughout the implementation and evaluation, the proposed framework and system architecture were implemented on change management as one of the most important CCA processes. Finally, the developed DCCIM was evaluated through a case study involving three typical change scenarios in a construction project. Section 4.2 provides details of these scenarios and the system implementation, followed by a discussion of the results.

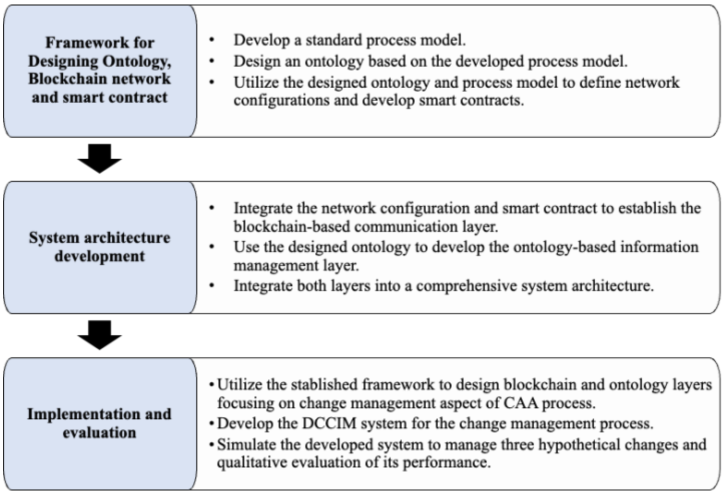

Figure 2: Research methodology workflow.

3.1 Proposed Framework for Designing Blockchain and Ontology Layers

A standard framework was established for designing the DCCIM's main components including ontology-based information management, blockchain network and its associated smart contracts. As shown in Figure 3, the framework consists of four stages. The first stage involves collecting information about the CCA function's process, corresponding contractual obligations, and organizational procedures. CCA at the project level encompasses functions such as change management, financial management, risk management, claim management, quality control, and performance monitoring (Msawil et al., 2022).

In the second stage, three categories of definition are established: 1) the workflow tasks along with their associated roles and responsibilities; 2) core concepts of the process and information flow and their interrelationships; and 3) rules and constraints necessary for the effective sharing and management of information. During the third stage, a standard business process and ontology are developed. The standard business process modeling outlines the flow of information between parties. In this study, the modeling of CCA processes is carried out utilizing the graphical representation of Business Process Model and Notation (BPMN) (Chinosi and Trombetta, 2012). The ontology is designed in web ontology language (OWL) (W3C, 2012) using Protégé, an open-source ontology editor and knowledge management system (Musen, 2015).

After establishing the ontology and the business process model, the blockchain network and corresponding smart contracts are developed. The design of the blockchain network and smart contracts are based on the previously established business process model and ontology. This approach ensures that the blockchain complies with the requirements for the CCA information flow, while also guaranteeing process and information interoperability and integration across all stakeholders. The blockchain network and smart contracts are developed utilizing Hyperledger Fabric V2.5 (Hyperledger, 2023). Hyperledger's network consists of policies and processes that govern the interactions between organizations. Smart contracts are used to encode the CCA process information management requirements in an executable code to manage inter-organizational transactions within the network. In Hyperledger, smart contracts can be written in Go, JavaScript, or Typescript and are packaged into chaincode and deployed to the blockchain network (Hyperledger, 2023). In this study, the Go language is used for writing and deployment of smart contracts.

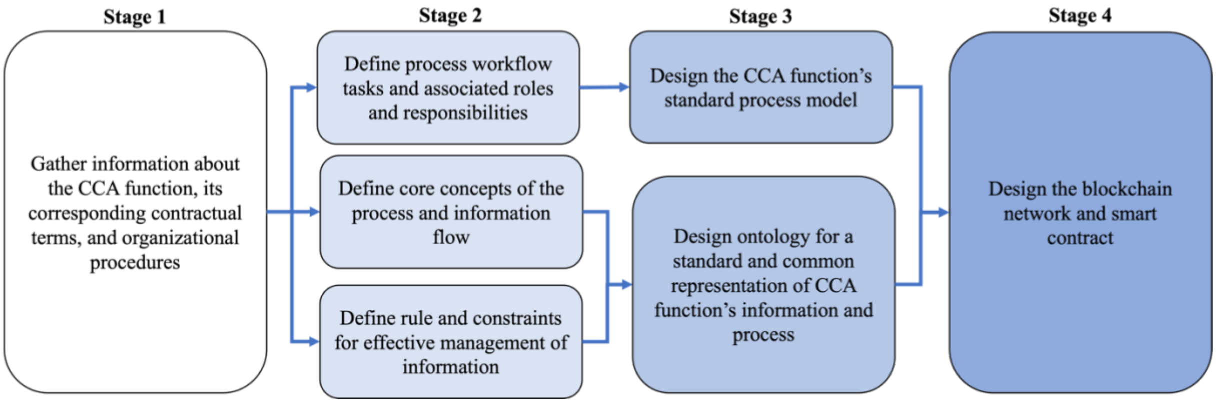

Figure 3: Proposed framework for designing the main components of DCCIM.

3.2 DCCIM System Architecture

A system architecture was developed to demonstrate the main components of the DCCIM, their interactions, and the flow of information. As shown in Figure 4, the system architecture encompasses three main layers. The user interface layer provides customized user interfaces for each stakeholder. The blockchain layer contains the network for secure, decentralized and transparent management of transactions. Finally, the ontology-based information management layer establishes storage and retrieval architecture for storing, retrieving and sharing of CCA information.

The system architecture is developed for a typical design-bid-build (DBB) project with three stakeholders: Owner (R1), engineer (R2), and contractor (R3), each interacting with their respective client application interface A1, A2 and A3. The client applications serve two main functions, enabling parties to interact with the blockchain and submit transactions, and to retrieve information by running complex queries.

The blockchain network is structured with one communication channel (C1) facilitating secure, decentralized, and transparent transactions among parties, and includes peer nodes P1, P2, and P3, representing the owner, engineer, and contractor, respectively. Smart contract S is installed on each peer, with each maintaining a copy of ledger L. Channel configurations CC1 assign rights and permissions to stakeholders through *policies* that define the rules for governing the network and making decisions. In this structure, all three parties hold the same authority over the channel configuration. The network configuration policy NC1, managed by the owner, sets the rules for the overall network, including which parties can participate and under what conditions. The ordering service (O1), configured by NC1, is a single node managed by the owner. This node orders transactions into blocks, ensuring that all transactions are processed sequentially and consistently across the network. The certificate authorities (CAs) are instrumental in assigning verifiable digital identities to the network participants. CA1, CA2, and CA3 correspond to the owner, engineer, and contractor, respectively. These identities are critical for transaction security, enabling digital signatures that verify the authenticity of the transactions and endorsements that confirm agreement among the parties before any addition to the ledger.

The ontology-based information management layer facilitates structured storage and retrieval of information. An application written in typescript was used to monitor the Fabric network and receive the block data when transactions are confirmed and validated by network peers. Using the listener application, the block events are extracted and stored in an off-chain data storage. For ontology-based storage of blockchain's ledger data, an automated mapping application was developed. The application automatically maps the ledger data to the relevant classes and object properties based on the defined ontology for the CCA function. After the information is mapped, the associated data are stored in a resource description framework (RDF) repository. The RDF repository serves as an off-chain storage system for capturing structured information related to transactions throughout the CCA process. For instance in change management process, this includes data ranging from the initial identification of a change to its evaluation and negotiation phases. Both blockchain transaction metadata and process-specific information are semantically structured using the ontology.

The RDF repository, also referred to as triplestore, is a graph database for storing semantic data. A triple is a statement in the form of subject-predicate-object, which represents an entity, subject property, and the subject entity. For example, the project (subject), hasOwner (predicate), the project's owner (object). One of the advantages of ontology-based storage of information is its ability to run complex queries using SPARQL, a powerful language for querying data stored in RDF format. SPARQL users can query the RDF repository to extract relevant information for effective and reliable decision-making throughout the CCA process.

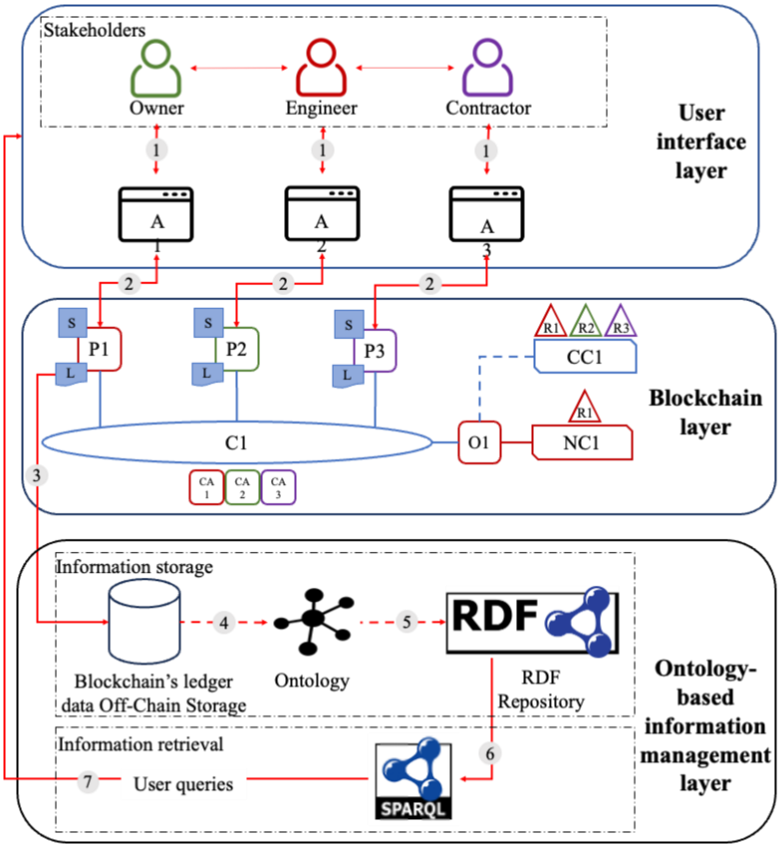

Figure 4: Detailed system architecture for the DCCIM. ❶ users' interactions with user interfaces, ❷ user interfaces link to blockchain network peers, ❸ blockchain network ledger automatically recorded off-chain using a listener application, ❹ mapping the stored information to the defined knowledge structure within the ontology, ❺ storing the structured knowledge in an RDF repository, ❻ running complex queries and retrieving information using SPARQL, ❼ connecting the user interfaces with SPARQL queries.

4. RESULT AND DEMONSTRATION

The proposed DCCIM system was implemented for change management to evaluate its potentials and limitations. Unpredicted changes are common in CCA, which can lead to disputes, delays, cost overruns and project failures if not managed effectively (Hao et al., 2008, Motawa et al., 2007). As a result, the potential advantages of the proposed system to enhance collaboration and efficiency of change information management can positively influence project success.

4.1 Implemented Case Study on Change Management

The proposed framework, as depicted in Figure 3, was followed to design the blockchain and ontology layers of DCCIM system architecture for managing changes. After understanding the contractual terms and common business processes for managing changes, a standard ontological representation of change management and a standard change management process model needs to be created. The ontology and standard change management process model are used to design the blockchain and smart contract.

To understand the contractual obligations and common business processes for managing changes, two sources were used: 1) Canadian construction document committee stipulated price contract (CCDC 2) (CCDC, 2020), and 2) current literature to determine typical change management processes. CCDC 2 is for design-bid-build projects with a fixed price and is widely used in the Canadian construction industry. Table 2 summarized the key contractual terms utilized in this study.

Table 2: Change management contractual requirements from CCDC stipulated price contract (CCDC, 2020).

Document	Section	Clause
CCDC 2	GC 6.1	1) The owner, through the consultant, can make changes to the work (additions, deletions, or revisions) by issuing a change order or change directive without invalidating the contract.
	GC 6.2	1) When a change in the work is proposed or required, the consultant provides a written description of the proposed change to the contractor. 2) The contractor must promptly present a method of adjustment or an amount of adjustment for the contract price and time for the proposed change. 3) Agreements on adjustments are effective immediately and recorded in a change order, and the value of the work performed as a result of a change order is included in progress payments.

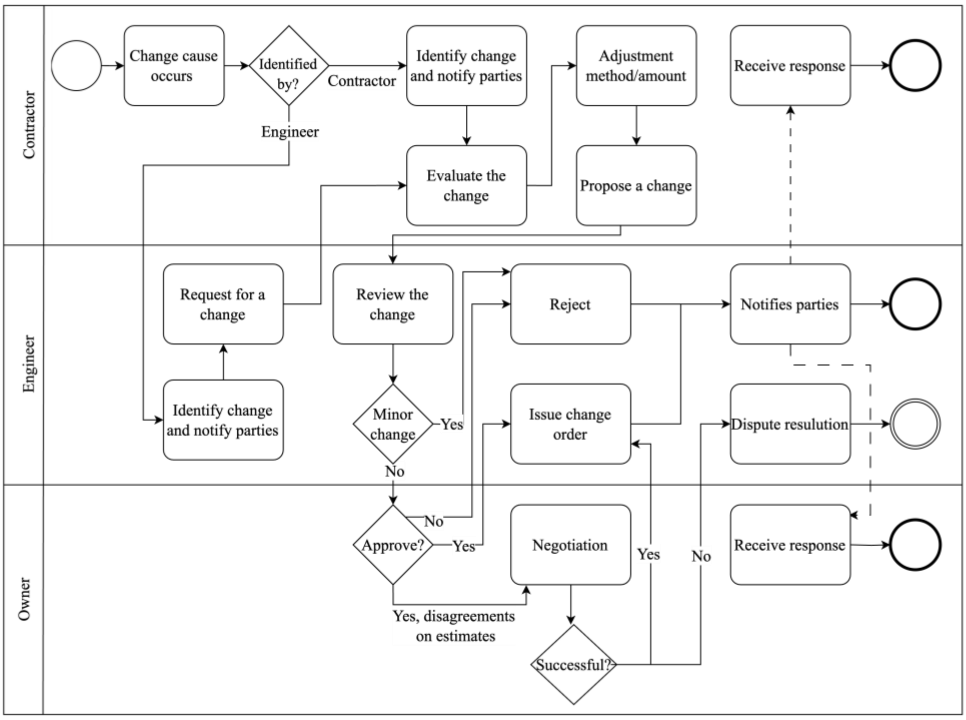

Figure 5: A standard change management process modeled using BPMN for the development of the system.

The required information on the common change management process, roles, and information flow was obtained from previous studies (Hao et al., 2008, Motawa et al., 2007). The change management process begins with the identification of a potential change, arising from various sources such as project scope change, design change, supply chain issues, or unforeseen circumstances. As depicted in Figure 5, a change can be identified by either the engineer or the contractor. Once a change is formally documented, the appropriate parties are notified. The change is then subjected to an initial review to identify and assess existing options and their impact on the project's scope, schedule, and cost. A change proposal outlining necessary adjustments to the project plan is developed by the contractor. This proposal is then reviewed by the design team to ensure it aligns with the project's objectives and it is not a minor change or internal design change. If the team deems it viable, the proposal is presented to the project owner for approval. If the owner approves the proposal, the change is implemented, and the project plan is updated accordingly. However, if the owner disagrees with the proposed budget estimation, schedule, or approach, negotiations with the contractor may ensue. Successful negotiations result in an official change order being issued to the contractor. The process is accurately documented to maintain a clear record of decisions and modifications made throughout the project lifecycle.

Based on the gathered information, a standard change management process was modeled using the BPMN tool. Figure 5 depicts the standard change management process, which provides a reference framework to manage changes.

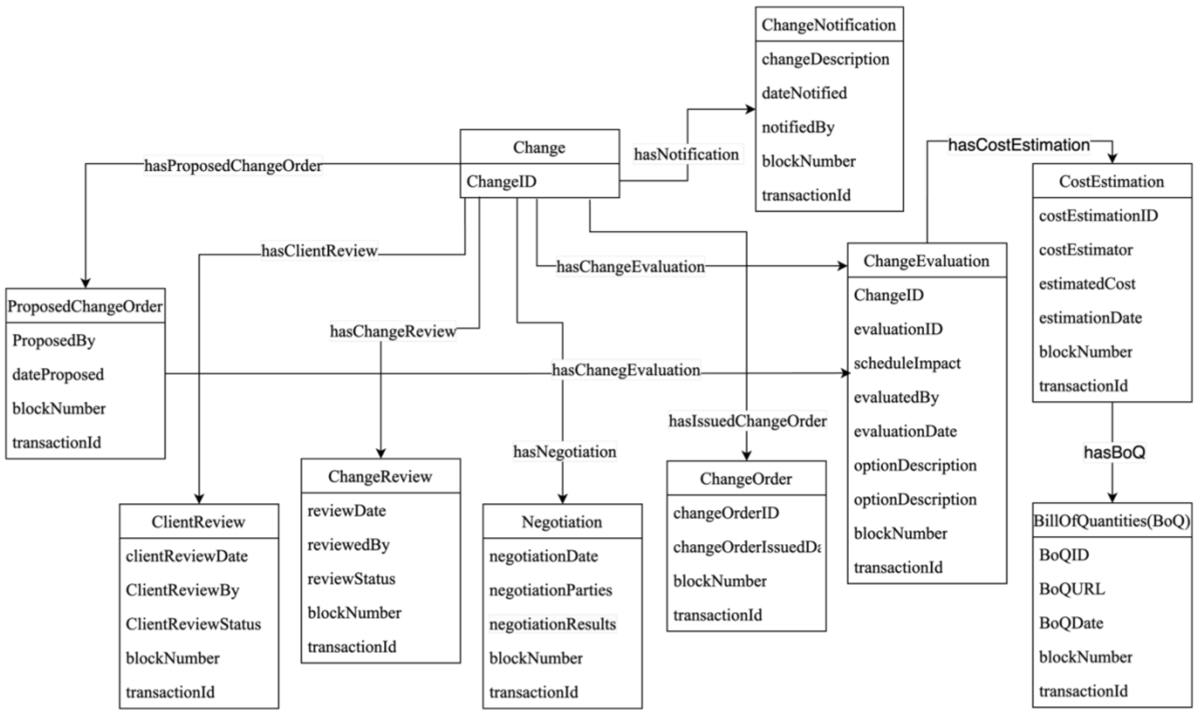

Figure 6: Snapshot of the developed change management ontology.

4.1.1 Ontology Development

A structured methodology was followed to develop an ontology for the change management process (Uschold and Gruninger, 1996). The first step in designing an ontology is defining the competency questions. These questions clarify the ontology's scope and ensure that the ontology addresses all relevant aspects of the domain. The scope of the designed ontology in this study is focused on covering the concepts and relationships specified by the developed change management process model. Examples of the competency questions considered for this ontology include:

1. What changes have been approved by the engineer and have initiated a negotiation process?
2. What are the blockchain transaction IDs of changes that were notified within the last month?
3. What is the total cost of approved change orders to date?
4. What changes have been notified within the past ten days and are still waiting for response from the contractor?

With no pre-existing change management ontologies found in this field, the development process proceeds with defining the essential terminology. Figure 6 shows the classes and the associated object and data properties. For example, *Change* has a data property of *changedID* and has object properties such as *hasProposedChangeOrder*, *hasChangeEvaluation*, and *hasChangeRevie*w. The precise semantics of these terms are then established through axioms that define the terms and ensure internal consistency. The development of the ontology was conducted in Protégé software (Musen, 2015). The ontology was evaluated to ensure consistency among the identified classes and relationships using HermiT reasoner (Glimm et al., 2014). HermiT is commonly used to check ontologies for consistency and to identify subsumption relationships between classes. As indicated in Figure 7, the reasoner was successfully activated without any errors, confirming the structural integrity and applicability of the ontology for this project.

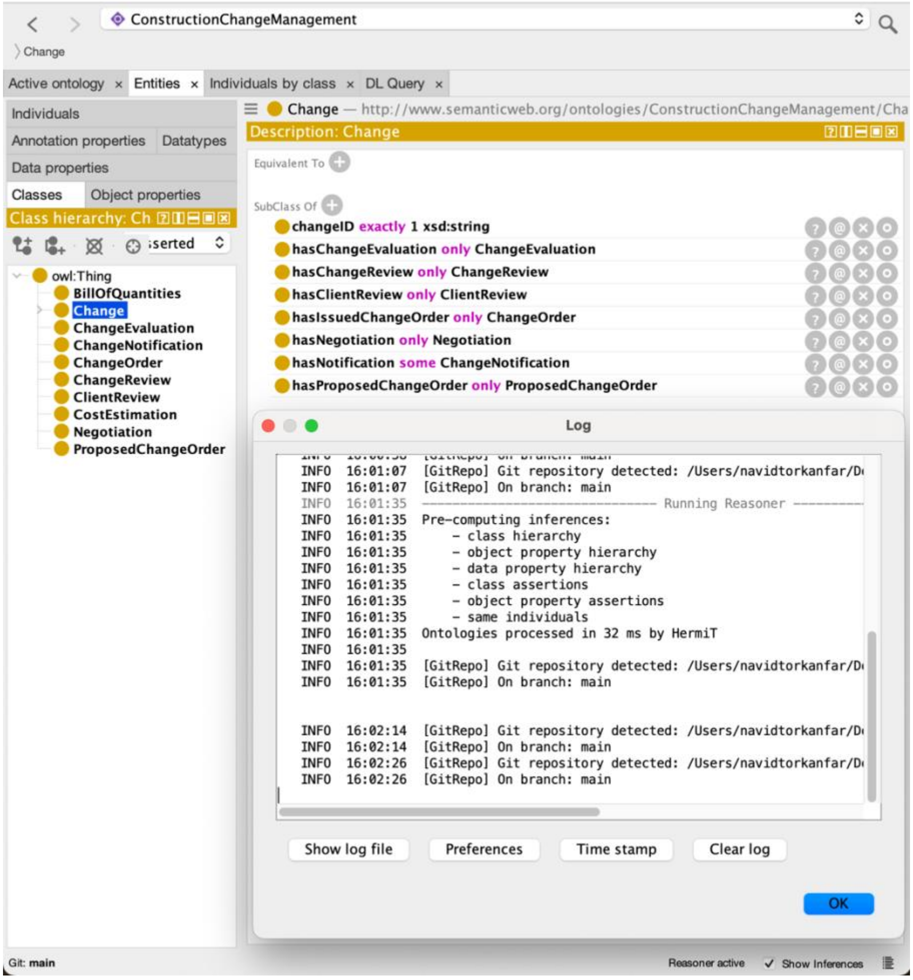

Figure 7: Screenshot of designed ontology in Protégé with active reasoner running using HermiT.

4.1.2 Blockchain Network and Smart Contract Development

A blockchain network lays the foundation for secure and decentralized transactions among stakeholders throughout the change management process. Following the designed system architecture shown in Figure 4, Hyperledger Fabric network is used for managing changes in a contract between the three stakeholders. The network's smart contract design begins with defining the ledger state and variables for storing, updating, and tracking changes by the blockchain network's users. This is achieved by using the ontology along with the change management process model.

The developed ontology ensures that required business concepts and relationships are defined in the ledger state and directly correlate to the components of the change management. The process model outlines the roles and information flow. The functions in the smart contract are defined to update or query the state of the ledger based on user inputs. When a transaction is issued calling a specific function, the application sends a transaction proposal to the network through a peer node. The peer executes the transaction for simple call functions or forwards it to the appropriate parties for endorsement based on the defined policy. The policy designates which parties must approve a transaction before it can be considered valid and added to the ledger. The endorsed transaction is then forwarded to the initial node, which orders it with other endorsed transactions, and packages them all into a block. Table 3 summarizes the eight functions defined in the smart contract. Figure 8 illustrates an example of the workflow for defining appropriate ledger state objects and functions based on the ontology for *EvaluateChange*, which is designed for the contractor to submit their evaluation information of a change. The same process is undertaken for defining other functions to achieve a comprehensive smart contract that covers all aspects of the change management process.

Table 3: Main functions used to design the smart contract for the change management process.

Smart contract Function	Description
ChangeExists	Checks that the given change ID does not already exist in the world state.
NotifyChange	Issues a new change to the world state with given details.
IssueBoQ	Issues the Bill of Quantities (BoQ) corresponding to the scope of work related to the notified change.
EstimateCost	Records the estimated cost associated with the proposed change, based on the corresponding BoQ.
EvaluateChange	Records the evaluation of the identified change by including the change option, the cost and schedule impact.
ProposeChangeOrder	Submits a proposed change order for an identified change including the evaluation options and impacts.
ReviewChange	Records the results of the change review by engineering team.
ClientReviewChange	Records the results of the change review by the owner.
NegotiateChange	Records the details through the negotiation process when negotiation for a change is triggered.
IssueChangeOrder	Issues the official change order for the identified change.

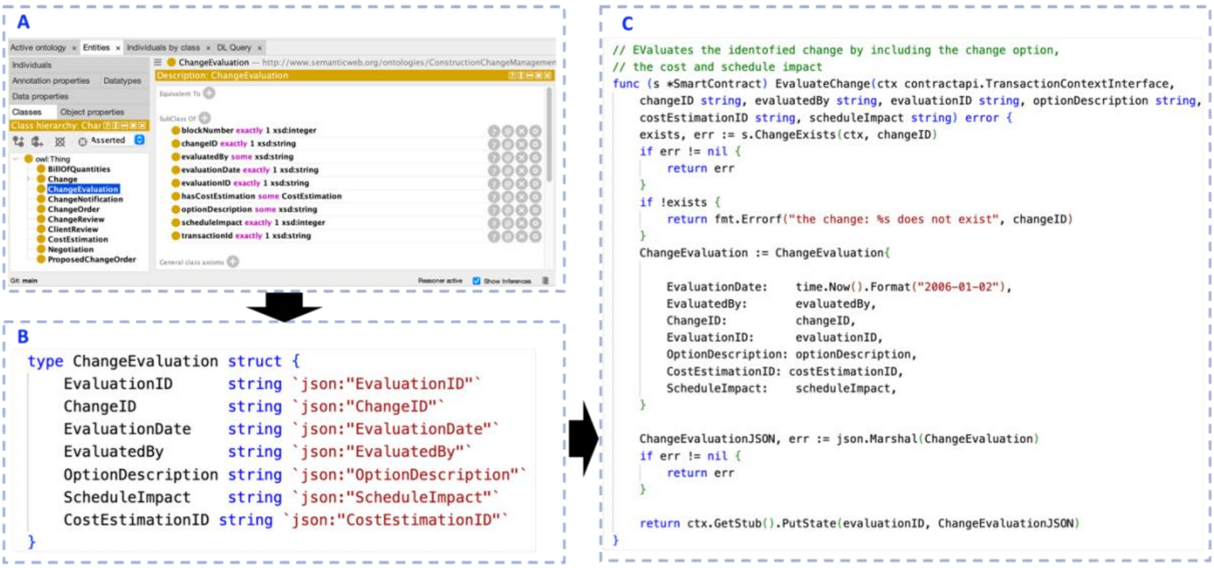

Figure 8: The steps in mapping the designed ontology (A) to appropriate ledger states objects (B) and designing functions to update the ledger accordingly (C).

4.2 Simulated Change Scenarios

Three commonly occurring changes were identified to evaluate and discuss the potential and limitations of the proposed DCCIM system in change management.

1. The contractor encounters hard rock during excavation, necessitating extra resources. A proposal for extra excavation work is submitted with cost and time estimates. Upon engineer and owner approval, a change order is issued for the additional work.

2. A protected species is discovered at the construction site. The contractor proposes an eco-friendly construction alternative with detailed additional costs and time. After approval of the engineer, the owner disagrees with the estimated price. After negotiations that result in a reduction of the cost, the contractor receives the official change order.
3. New local traffic regulations disrupt the original construction plan. The contractor adjusts the schedule and costs and submits a proposed change. The change is reviewed by the engineer and is still waiting for owner approval.

The changes and communications among parties were simulated using the developed system. Hyperledger Explorer, a web application for viewing Hyperledger Fabric network information, was used to monitor data related to blocks, transactions, smart contract, network status, and nodes. As shown in Figure 9, thirty transactions were recorded within thirty blocks during the simulation. To demonstrate the flow of information and its relationship with the smart contract, Table 4 provides a step-by-step description of the transactions that occurred between the contractor, owner, and engineer throughout the management of the first two change scenarios.

The main nodes of the network include one ordering node and peer nodes Org1, Org2 and Org3, representing the owner, engineer, and contractor, respectively. The network contains one smart contract that was deployed through a chaincode. Figure 9 also depicts an example of a transaction initiated by the contractor (i.e. Org3) for notifying the parties about “change002”. Details, such as transaction value, timestamp, transaction ID, and endorser parties are visible in the transaction tab. The endorsers of the transaction are Org1, Org2, and Org3 indicating the requirement for validation of all three parties for transactions under the defined endorsement policy for the network.

Table 4: A step-by-step breakdown of transactions conducted among stakeholders during the simulated change scenarios 1 and 2.

Change ID	Transaction description	Issuer	Smart contract function
Change001	Contractor encounters hard rock during excavation.	Contractor	NotifyChange
	A transaction is submitted to issue the BoQ for the identified change, including the BoQ ID (Change001BoQ001), issue date, and the URL of the corresponding document.	Contractor	IssueBoQ
	The contractor estimates a cost of $100,000 based on the issued BoQ.	Contractor	EstimateCost
	Contractor evaluates the change, proposing additional resources with an added cost of $100,000 and an extension of 90 days, impacting the schedule.	Contractor	EvaluateChange
	Contractor submits the evaluated change proposal for review by the engineer.	Contractor	ProposeChangeOrder
	Engineer reviews and approves the proposed option, including the cost and schedule impact.	Engineer	ReviewChange
	Owner reviews the proposed change and engineer's assessment, subsequently approving the change.	Owner	ClientReviewChange
	Engineer issues the change order instruction for the additional work to be conducted.	Engineer	IssueChangeOrder
Change002	Contractor discovers a protected species at the construction site.	Contractor	NotifyChange
	A transaction is submitted to issue the BoQ for the identified change, including the BoQ ID (Change002BoQ001), issue date, and the URL of the corresponding document.	Contractor	IssueBoQ
	The contractor estimates a cost of $20,000 based on the issued BoQ.	Contractor	EstimateCost
	Contractor identifies an eco-friendly alternative to avoid removal of the species, estimating an additional $20,000 with a 60-day schedule impact.	Contractor	EvaluateChange
	Contractor submits the evaluated change proposal for review by the engineer.	Contractor	ProposeChangeOrder
	Engineer reviews and approves the proposed option, including the cost and schedule impact.	Engineer	ReviewChange
	Client reviews and disagrees with the estimated cost for the alternative work.	Owner	ClientReviewChange
	Client initiates the negotiation process, requesting a reduction in cost, to which the contractor agrees to a $10,000 reduction.	Owner	NegotiateChange
	Engineer issues the change order instruction for the additional work to be conducted.	Engineer	IssueChangeOrder

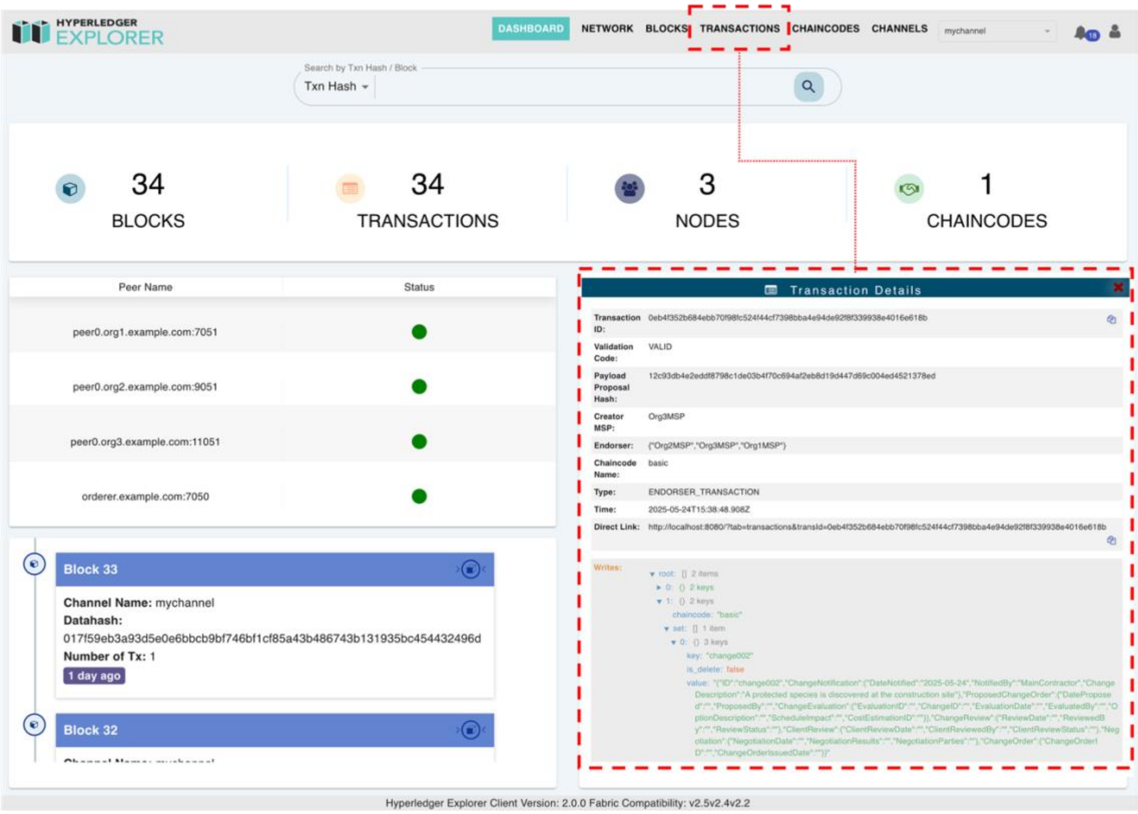

Figure 9: Explorer's user interface for monitoring the transaction status and checking the ledger state, and a sample transaction issued by the contractor (Org3) is included.

5. DISCUSSION

The capabilities of the proposed DCCIM system were evaluated in overcoming the challenges of collaborative exchange and management of information, focusing on change management to prove the concept. The desired objectives include the ability to enhance automation, interoperability of systems, information and processes, clarifying roles and responsibilities, enhancing quality and reliability of data, improving information retrieval and knowledge integration capacities, and enhancing inter-organizational trust.

5.1 Automation

Blockchain and ontology-based information management layers of the proposed system provided capabilities for enabling automation through the change management process. The smart contract facilitated automated and decentralized enforcement of information flow requirements, data quality requirements, and contractual obligations. Once a transaction was validated, it ensured that all preceding steps had been properly executed and that all necessary information and user validations were in place. For instance, when a change evaluation was validated, it confirmed that the necessary approvals had been obtained.

One notable example of enforcing contractual requirements through the implemented case study was the application of a time constraint between the notification of a change and the submission of a proposed change order. This time constraint was implemented to comply with the CCDC contract requirement for timely responses to the identified changes by the contractor. In this example, a two-week period was encoded into the smart contract. This automation ensures that the ledger's state adheres to the contractual requirement without the need for manual inspection. If the response does not meet the specified two-week timeframe, the transaction is deemed invalid and not stored on the ledger.

The ontology-based information management enhanced automation from two main perspectives: automated inference of new information; and checking compliance and consistency with data quality requirements and ontology rules. The off-chain storage of ledger data in the RDF repository provided the capability for automated inference. To illustrate this, a class was defined within the ontology to identify changes that have been approved by the engineer but have not yet been approved by the owner. An equivalent class was defined to facilitate this query, as depicted in the Figure 10. Running the HermiT reasoner on the off-chain data enables the automatic inference of such cases. For example, the change labeled "change003" is automatically inferred and highlighted in yellow, indicating that it should be categorized within this class. This inference was not explicitly defined in the ontology; rather, it was deduced by the reasoner based on the defined relationships and properties. This capability underscores the power of ontology-based systems to enhance understanding and ensure compliance by automatically deriving new insights from existing data, reducing the need for manual oversight.

The automation capabilities provided by the ontology-based information management and blockchain layers promote collaboration and availability of information. The automation reduces potential human errors, and the time and effort required for manual work, which in turn allows the team to focus on more critical tasks.

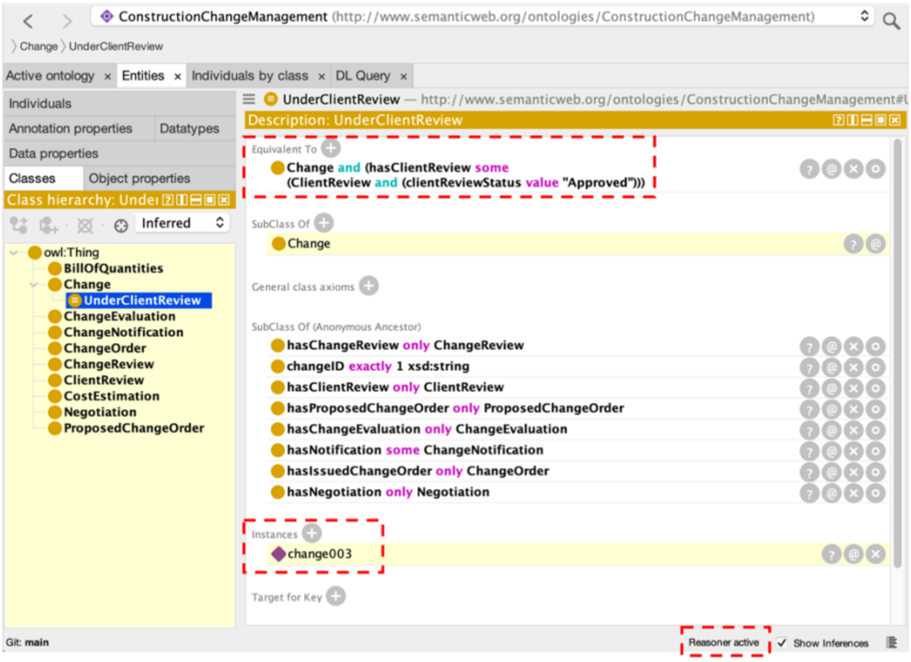

Figure 10: Automated inference of new information by reasoning the ontology in Protégé.

5.2 Information Retrieval and Knowledge Integration

The implementation of ontology-based information management within the change management DCCIM system showed promising results in improving information reuse and enhancing knowledge integration. The ontology provided a structured and machine-readable representation of change management knowledge within the DCCIM system. Knowledge integration capacity helps parties to transform information and knowledge into actionable insights. In addition, the enhanced collaboration and information sharing lead to more frequent contributions of knowledge and a wider understanding of the project. This is an important aspect of creating a shared understanding of the CCA process and achieving successful collaboration.

The use of SPARQL enabled the execution of complex queries over the RDF repository, facilitating better access to information, enabling insightful knowledge about the change management process, and enhancing decision-making capabilities. Two example queries that can leverage the power of SPARQL to extract useful insights from the RDF repository are provided.

1. Retrieve the transaction ID and change ID of changes with a schedule impact less than 60 days.
2. Find the identification date for changes that initiated negotiations and resulted in a change order being issued.

Apache Jena Fuseki, a free and open-source application for querying RDF data using SPARQL was used to address these two questions. Figure 11 and Figure 12 show the SPARQL queries and responses for questions one and two, respectively. Figure 12 also indicates the corresponding transaction in the blockchain, which was checked through explorer with the transaction number. This transaction was issued by the contractor for notifying the Change002 and was endorsed by all parties. The transaction information was also retrieved directly from Protégé connected to the off-chain repository.

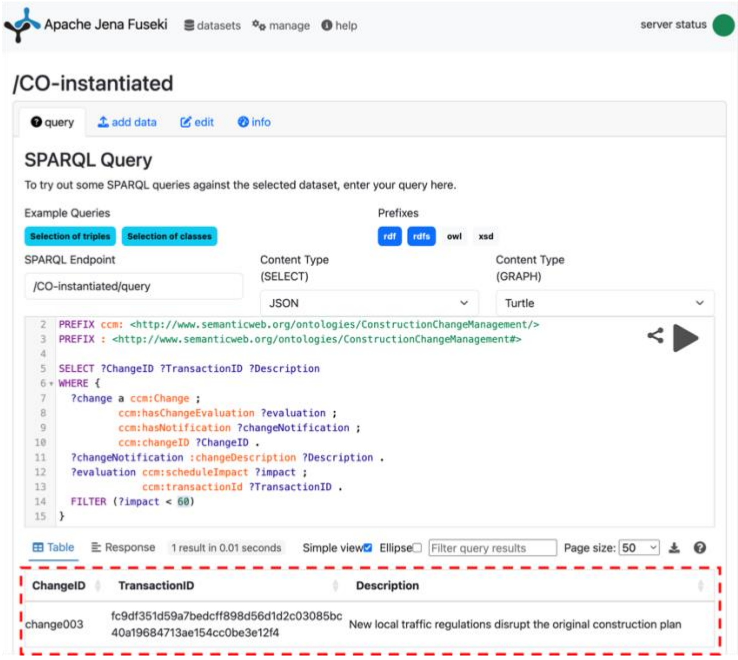

Figure 11: SPARQL query using Fuseki and retrieved information from off-chain RDF repository for the question#1.

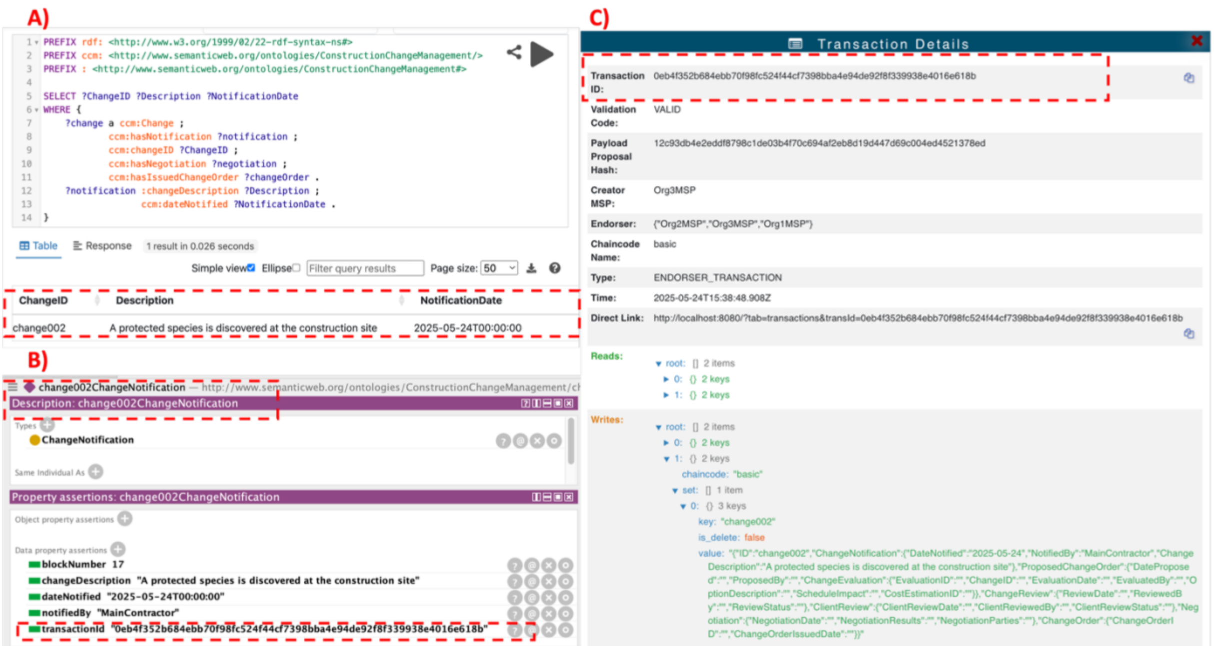

Figure 12: Retrieved information related to question#2 (A) A SPARQL Query and the retrieved information from RDF repository in Fuseki, (B) the corresponding information related to the change notification in Protégé, and (C) the transaction information in explorer.

5.3 Data Quality and Reliability

The quality and reliability of managed data within an information system can influence the collaboration among parties (Lee and Yu, 2012). In traditional contract administration practices, data are often handled manually across fragmented systems, leading to issues such as incomplete, inconsistent, or outdated information, which undermine trust and collaborative decision-making. In contrast, the implementation of the proposed DCCIM system demonstrated improvements in data quality across multiple dimensions, such as accuracy, timeliness, completeness, and consistency (Wand and Wang, 1996, Hazen et al., 2014).

The ontology-based information management layer enabled a structured representation of change management information, ensuring that data adhered to a defined semantic structure. During the case study simulations, information related to each change request—such as proposed cost, schedule impact, evaluation details, approvals, and negotiations—were consistently captured and stored in an ontology-compliant format. This standardization ensured accurate, consistent, and complete representation of the real-world state in a coherent manner. Since the entire domain knowledge was initially modeled into an ontology, it reduced errors associated with incomplete or inaccurate information, which is common in manual processes. Furthermore, automated reasoning in ontology ensured that data are consistent and comply with the ontology, reducing the risk representing different states for the same real-world situation.

The blockchain layer further enhanced reliability by enforcing data quality requirements and rules defined within the ontology and securely storing timestamped transactions on the ledger. This provided an immutable audit trail of all communications and decisions throughout the management of simulated change scenarios. In traditional systems, tracking the status and source of information across parties is time-consuming and error-prone; however, in DCCIM, the decentralized ledger ensured that information was verifiable and jointly validated by stakeholders through endorsement policies.

5.4 Interoperability of Information, Processes and Systems

The developed DCCIM system demonstrated potential for seamless integration of systems, processes, and information. Traditional contract management systems are often characterized by data silos and heterogeneous systems, which contribute to the unavailability of information, data loss, and the inability to access the necessary information for decision-making at the right time by the right person (Rezgui et al., 2011, Farghaly et al., 2024). The DCCIM system contributed to resolving these challenges by adopting an ontology-based approach for representing and managing change management information. This semantic representation ensured that information and processes are uniformly structured and understood across diverse systems and platforms, enabling greater integration between stakeholders' tools and workflows. The ontology provided a shared vocabulary and logic that standardized data exchange, allowing different organizations and systems to interact without loss of meaning or structure.

The integration of blockchain further reinforced interoperability by providing a decentralized environment where structured information could be shared securely and consistently, without dependence on centralized intermediaries. In the implemented case study, three organizations with distinct roles were able to interact effectively using the DCCIM platform. The use of a shared ontology allowed each organization to interpret and contribute to the information system using a consistent data model, while the blockchain ensured integrity and coordination across transactions and updates.

5.5 Inter-organizational Trust

One of the main components of the developed DCCIM system is the blockchain layer, which plays a pivotal role in enhancing inter-organizational trust and collaboration (Hijazi et al., 2021, Lu et al., 2023). As demonstrated through the change management case study, the blockchain infrastructure enabled secure and transparent recording of transactions related to each change scenario. Key characteristics of blockchain such as transparency, tamper-resistance, timestamped transaction records, and decentralized validation contributed to improving the reliability and security of information shared among project stakeholders. This is especially valuable in the context of CCA, where information asymmetry and concerns about manipulation or loss of data often hinder trust between parties.

Compared to traditional contract administration processes, where trust is often dependent on manual documentation, fragmented systems, or intermediaries, the DCCIM system established a shared, verifiable ledger of actions and decisions. In the simulated scenarios, every step of change initiation, evaluation, negotiation, and approval was traceable and mutually visible across stakeholders, eliminating ambiguity and reducing the risk of opportunistic behavior.

Furthermore, the smart contract within the DCCIM was used to enforce process logic and ensure compliance with defined roles and workflows. This automated enforcement showed potential for reducing human error, increasing consistency, and minimizing disputes arising from miscommunication or deviations from agreed processes. The immutable record of validated transactions served as a reliable and auditable source of evidence, which can be instrumental in claim resolution and dispute management—processes that are often time-consuming and contentious under traditional methods.

The case study scenarios illustrated how blockchain-enabled automation and traceability can expedite decision-making and change management process compared to conventional workflows. Thus, the DCCIM system not only enhances technical trust in the data but also strengthens inter-organizational trust among parties by providing a transparent and equitable platform for collaboration.

5.6 Clarification of Roles and Responsibilities

Well-defined roles and responsibilities are key to reducing friction and enhancing cooperation during CCA processes. In traditional CCA processes, role ambiguity and inconsistent documentation often lead to confusion, duplicated efforts, or delayed decision-making. In contrast, the DCCIM system provided a clear and formalized structure for role definition and enforcement through its blockchain-based network configuration and smart contract logic.

In the implemented DCCIM system, developed using Hyperledger Fabric, permissioned network access ensured that only authorized stakeholders among owner, contractor, and engineer can participate in specific transactions. Endorsement policies were designed to assign validation responsibilities to appropriate parties at each stage of the change management process. For example, the smart contract required joint endorsement from all three parties for specific actions such as change approvals and negotiations. These configurations ensured that each participant's role was encoded within the system, thereby reducing the risk of role ambiguity.

Moreover, roles and permissions were mapped directly to the smart contract functions—such as NotifyChange, EvaluateChange, and IssueChangeOrder. This ensured that only designated parties could initiate or respond to transactions. During the case study simulations, this design allowed efficient and accountable task execution. Each transaction could be traced back to the individual responsible, supporting better oversight and eliminating common issues in manual systems, such as unauthorized changes or delays due to unclear responsibilities. In contrast to traditional methods where roles may not be effectively enforced or tracked during execution, the DCCIM system operationalized and enforced roles at the system level, creating a robust foundation for accountability and process integrity.

5.7 Future Works and Limitation

This research introduces a novel approach for developing a collaborative information management system for CCA process to enhance collaboration, trust, and the utility of information. The proposed system was focused on the change management function of CCA to demonstrate the feasibility of an integrated blockchain and ontology-based system. However, the advantages of the system are likely to be more pronounced when its scope is expanded to a holistic system that encompasses all CCA functions. Additionally, our system was evaluated using common change requests in the field. However, this model shall be tested on a broader range of real-world change management scenarios prior to transitioning to industrial application. The implemented change management process in this study primarily emphasized transactional communications. However, in addition to information exchange, CCA processes also involve the communication of various documents, models, and reports. While this study focused on managing information flow, future advancements of the system should incorporate mechanisms for the exchange and tracking of documents and files. Permissioned blockchain networks offer strong potential for supporting such document management and traceability, and should be further explored in this context. Future research should explore other applications of blockchain integration with ontology-based data structures and communication channels to enhance information management, decision-making, and project efficiency. The integration of semantic web technologies with blockchain, or 'semantic blockchain' (Mikroyannidis et al., 2020), represents a cutting-edge area of research aimed at promoting interoperability and trusted data on a web scale. Thus, more research is necessary to explore the advantages and limitations of semantic blockchain for the construction industry. Moreover, advancements in the field of large language models (LLMs) have provided opportunities for automation in construction. One such opportunity involves exploring the use of LLMs to further enhance the efficiency of the proposed system. For example, through automated recognition, classification, and notification of potential changes from communication channels outside the blockchain network, such as emails. Finally, the implemented case study was based on DBB projects, and the approach might have greater potential in more collaborative contract settings, such as integrated project delivery (IPD).

6. CONCLUSION

Inter-organizational collaboration and trust are pivotal for efficient contract administration and overall project success. This research presents a novel decentralized and collaborative information management system aimed at overcoming existing challenges in collaborative information management within the CCA process. The identified challenges were analyzed against the advantages of the two technologies of interest, blockchain and ontology, to show their capabilities against these challenges. This novel combination was evaluated through a change management case study. Three common change scenarios in construction projects were simulated, and the results highlight the potential of the developed system in driving collaborative information sharing throughout the change management process. Blockchain and smart contract components were designed using Hyperledger Fabric, enabling secure and reliable transactions handling and information flow and enforcing the process logic. Ontological modeling of the change management process enabled the development of semantically enriched smart contracts and ontology-based information management. The use of ontology also enhanced the retrieval and reuse of information by enabling semantic storage of blockchain transaction data, supporting automated reasoning, and allowing complex querying necessary for informed decision-making. The integration of blockchain and ontology in this manner offers a novel approach to designing communication and information management systems in CCA and has the potential to improve efficiency, transparency, and collaboration in contract administration workflows.

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