BLOCKCHAIN TECHNOLOGY IN THE CONSTRUCTION INDUSTRY: IMPLICATIONS ON CONTRACT MANAGEMENT

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ABSTRACT

BLOCKCHAIN TECHNOLOGY IN THE CONSTRUCTION INDUSTRY: IMPLICATIONS ON CONTRACT MANAGEMENT

As digital transformation accelerates, innovation has become vital for enhancing organizational competitiveness in the construction industry. Despite this progress, contract management remains hindered by inadequate information sharing, payment delays, and supply chain inefficiencies. Blockchain technology offers a promising solution, introducing a transformative paradigm for managing construction contracts. This study investigates the impact of blockchain technology implementation on construction contract management and explores strategies to facilitate its implementation. Through a comprehensive literature review, the research identified critical factors influencing its integration including stakeholder commitment, regulatory issues, technological infrastructure and managerial aspects. Based on these insights, an initial framework is developed to illustrate the interactions among these factors. A questionnaire survey is then conducted with selectively targeted participants with relevant experience. The collected data is analyzed using Structural Equation Modeling (SEM) and a focus group study is conducted to validate the findings. The study culminates in a strategic roadmap designed to guide the adoption of blockchain technology in construction contract management which offers a comprehensive perspective and provides practical strategic recommendations. Its key novelty lies in its specific focus on blockchain-enabled construction contract management, distinguishing it from prior country-specific or use-case-limited roadmaps. Findings reveal that the immature industry does not deter motivated companies from implementing blockchain technology driven by the integration of advanced digital solutions. Blockchain technology primarily enhances data management, monitoring, and knowledge-sharing processes, enabling more informed decision-making which highlights its potential to improve overall industry efficiency. By exploring blockchain's potential and revealing the critical factors, this research provides valuable insights for organizations considering its implementation.

ÖZET

İNŞAAT SEKTÖRÜNDE BLOKZİNCİR TEKNOLOJİSİ: SÖZLEŞME YÖNETİMİ ÜZERİNE ETKİLERİ

Dijital dönüşümün hız kazanmasıyla birlikte, inşaat sektöründe kurumsal rekabet gücünü artırmak için inovasyon hayati bir önem kazanmıştır. Bu ilerlemeye rağmen, sözleşme yönetimi hâlâ yetersiz bilgi paylaşımı, ödeme gecikmeleri ve tedarik zinciri verimsizlikleri gibi sorunlarla engellenmektedir. Blokzincir teknolojisi, inşaat sözleşmelerinin yönetimi için dönüştürücü bir paradigma sunarak bu sorunlara umut vadeden bir çözüm teşkil etmektedir. Bu çalışma, blokzincir teknolojisinin inşaat sözleşme yönetimine etkisini incelemekte ve bu teknolojinin uygulamasını kolaylaştıracak stratejileri araştırmaktadır. Kapsamlı bir literatür taraması yoluyla, paydaşların kararlılığı, regülasyonlar, teknolojik altyapı ve yönetsel unsurlar gibi entegrasyonu etkileyen kritik faktörler belirlenmiştir. Bu bulgulara dayanarak, söz konusu faktörler arasındaki etkileşimleri ortaya koyan öncül bir çerçeve geliştirilmiştir. Ardından, ilgili deneyime sahip, özenle seçilmiş katılımcılarla bir anket çalışması gerçekleştirilmiştir. Toplanan veriler Yapısal Eşitlik Modellemesi (YEM) kullanılarak analiz edilmiş ve bulguların geçerliliğini sağlamak amacıyla bir odak grup çalışması yürütülmüştür. Çalışma, inşaat sözleşme yönetiminde blokzincir teknolojisinin benimsenmesini yönlendirecek stratejik bir yol haritası ile sonuçlanmakta; kapsamlı bir bakış açısı sunmakta ve uygulamaya yönelik pratik stratejik önerilerde bulunmaktadır. Çıktıların özgünlüğü, blokzincir destekli inşaat sözleşme yönetimine odaklanmasında yatmakta ve önceki ülke-odaklı ya da kullanım senaryosu sınırlı yol haritalarından bu yönüyle ayrılmaktadır. Bulgular, sektörün olgunlaşmamış olmasının, gelişmiş dijital çözümlerle entegrasyon motivasyonuna sahip şirketleri blokzincir teknolojisini uygulamaktan alıkoymadığını ortaya koymaktadır. Blokzincir teknolojisi, özellikle veri yönetimi, izleme ve bilgi paylaşımı süreçlerini geliştirerek daha bilinçli karar verme süreçlerine olanak sağlamakta ve bu sayede genel endüstri verimliliğini artırma potansiyelini ortaya koymaktadır. Blokzincir teknolojisinin potansiyelini ortaya koyarak ve kritik faktörleri analiz ederek, bu çalışma uygulamayı düşünen kuruluşlar için değerli içgörüler sunmaktadır.

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χ^2	Chi-square

LIST OF ACRONYMS / ABBREVIATONS

AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
AMOS	Analysis of Moment Structures
ANCOVA	Analysis of Covariance
AVE	Average Variance Extracted
BIM	Building Information Modeling
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
DAO	Decentralized Autonomous Organization
DBFT	Delegated Byzantine Fault Tolerance
DLT	Distributed Ledger Technology
DPoS	Delegated Proof of Stake
EDI	Electronic Data Interchange
FBA	Federated Byzantine Agreement
GDP	Gross Domestic Product
GIS	Geographic Information System
GPS	Global Positioning System
IoT	Internet of Things
IPD	Integrated Project Delivery
PBA	Project Bank Account
PBFT	Practical Byzantine Fault Tolerance
PoA	Proof of Authority
PoBr	Proof of Burn
PoC	Proof of Capacity
PoET	Proof of Elapsed Time
PoI	Proof of Importance
PoS	Proof-of-Stake
PoW	Proof-of-Work
RAFT	Reliable, Replicated, Redundant, and Fault-Tolerant
RFID	Radio Frequency Identification

RMSEA	Root Mean Square Error of Approximation
SEM	Structural Equation Modeling
SPSS	Statistical Package for Social Sciences
TLI	Tucker-Lewis Index

1. INTRODUCTION

As technological advancements and digitalization continue to evolve, innovation has become a crucial element to improve organizational competitiveness. Thus, organizations are integrating new technologies into their operations and digitizing traditional processes. During the past decade, the construction industry has embarked on its own digital transformation journey. As one of the world's largest industries, the construction industry still has numerous processes that remain to be digitized, presenting significant opportunities for digitalization (Wen *et al.*, 2025). Effective construction contract management is crucial in project management due to the interconnected tasks and diverse risks involved. This necessitates engagement with multiple stakeholders across various work processes. Blockchain technology, emerging as a transformative force in numerous industries, is also poised to revolutionize the construction industry.

This thesis aims to propose a strategic roadmap for integration of blockchain technology into construction contract management processes through examining how blockchain adoption influences construction contracts and the interplay among critical factors in this process. A comprehensive literature review identifies potential applications of blockchain in construction and key factors affecting its implementation. An initial model is developed to conceptualize the relationships among these critical factors. Subsequently, a questionnaire survey is administered to industry professionals and academics. Structural Equation Modeling (SEM) is employed to analyze survey data. Furthermore, the thesis proposes a roadmap for implementing blockchain technology in construction and validates its findings through a focus group study.

This research endeavors to uncover the potential of blockchain and offer insights to organizations planning to adopt this technology. The introduction chapter outlines the background, problem statement, related studies, research objectives, methodology, scope, limitations, and structure of the thesis.

1.1. Research Background

Blockchain technology is one of the emerging technologies that facilitate digital transformation and captures the attention of numerous industries, including the construction industry (Wen *et al.*, 2025). Blockchain, a type of digital distributed ledger technology (DLT), gained significant traction following its association with the cryptocurrency Bitcoin (Nakamoto, 2008). Despite blockchain being in its infancy stage of implementation within the built environment (Arup, 2019; Rathnayake *et al.*, 2022), it is anticipated to have a profoundly positive impact on the construction industry (Rugina, 2021). Tezel *et al.* (2020) argue that to fully harness the potential of blockchain technology, necessary adaptations in business models, procurement processes, and workforce upskilling are essential.

Although the number of research on blockchain applications within the construction industry is increasing constantly (Karacigan and Ozorhon, 2023), only a few studies have specifically analyzed the impact of blockchain on particular topics, such as construction contract management, and no study proposed a roadmap for companies in this regard. Thus, there is a great need to investigate blockchain technology in terms of construction contract management and to develop a roadmap for implementation.

1.2. Problem Statement

Traditional design and construction processes exhibit inefficiencies, prompting companies to enhance productivity through digitalization. Recently, the construction industry has been undergoing a digital transformation necessitating the integration of modern technological tools such as Building Information Modeling (BIM), the Internet of Things (IoT), and Blockchain into design and construction workflows (Karacigan and Ozorhon, 2023). According to a report by McKinsey & Company (2017), the construction industry lags behind other industries in terms of digitalization.

In addition, there is a critical need for the digitalization of contractual processes within the construction industry. The contract management procedures within the Architecture, Engineering, and Construction (AEC) industries are flawed with challenges, including inadequate information sharing (Liu *et al.*, 2023), delayed payments (Hamledari and Fischer, 2021), and a lack of a transparent and traceable supply chain (Tezel *et al.*, 2020). The implementation of blockchain technology holds promise in addressing these issues and can potentially reduce conflicts (Rugina, 2021).

Dispute resolution within the construction industry is very expensive and time-consuming, resulting in significant financial and temporal losses for companies (Younis *et al.*, 2008). Therefore, it is essential to prevent disputes or resolve claims before they escalate into intractable conflicts. In this context, blockchain technology offers a potential solution to contractual challenges and represents a prospective advancement in the management of construction contracts.

1.3. Related Studies

In recent years, blockchain technology has garnered significant attention from both academic and industrial perspectives in the context of digitalization. The literature presents various research focusing on potential applications of blockchain in construction (Li *et al.*, 2018; Shojaei, 2019; Rathnayake *et al.*, 2022) and explores challenges or barriers to its adoption (Wu *et al.*, 2022; Prabhakar *et al.*, 2023; Singh *et al.*, 2023). Other studies investigate the adoption process and identify drivers for implementation (Koc and Gurgun, 2020; Tezel *et al.*, 2020; Sun *et al.*, 2023).

Although the number of studies in terms of practical applicability is limited, a notable case study by Kang *et al.* (2023) presents a public infrastructure project where blockchain was applied across eleven core construction workflows including scheduling, daily operations, and payment systems. This workflow-based analysis not only highlights the technology's practical benefits, such as improved efficiency and communication among project teams, but also addresses real-world implementation challenges, including resistance to change and the persistence of traditional practices.

Predominantly, previous research has centered on examining blockchain's potential applications and its integration into areas such as supply chain management, document management, and BIM systems (Das *et al.*, 2022; Brandin and Abrishami, 2024; Liu *et al.*, 2024). Furthermore, Sun *et al.* (2023) investigated the critical success factors for implementing blockchain technology in construction in a review study. Finally, Zhang *et al.* (2023) conducted a systematic literature review and analyzed potential blockchain applications for construction contract management.

This study addresses a significant gap in literature by investigating the integration of blockchain technology into construction contract management, with a particular emphasis on elaborately identified critical factors and the complex interrelationships among key constructs. Furthermore, it contributes to the field by presenting a comprehensive and structured roadmap to guide the practical implementations.

1.4. Aim and Objectives

This research examines the potential impacts of blockchain technology on contract management in the construction industry. In this context, the study mainly aims to develop a strategic roadmap for integrating blockchain technology into construction contract management by analyzing the impact of blockchain adoption on construction contracts and exploring the interactions among key influencing factors throughout this process.

The other objectives of the study can be explained as follows; (i) determining the inputs and outputs of blockchain technology implementation in the construction industry, (ii) identifying the potential applications of blockchain technology in the construction industry, (iii) verifying the relationships between critical success factors through a focus group study, (iv) proposing a roadmap for the implementation of blockchain technology in the construction industry.

1.5. Research Methodology

Firstly, a comprehensive literature review was conducted to identify the potential applications of blockchain technology in the construction industry and the critical factors of the process. Following this, an initial model was developed that represents the relationships between these critical factors. An online questionnaire survey was then developed and distributed to industry professionals and academics, selected based on specific criteria. The data collected was analyzed using A SEM tool, and necessary tests were performed. Based on the analysis results, a roadmap was proposed for integrating blockchain technology into contract management practices within the construction industry. In the next phase, a focus group study with experts was conducted to validate the research findings.

1.6. Scope and Limitations

The scope of this research involves development of a framework for implementing blockchain technology in the construction industry, specifically for contract management. Additionally, within the scope of this research, a roadmap is proposed to facilitate the adoption of blockchain technology in the construction industry. Despite the comprehensive nature of this study, several limitations must be acknowledged. Firstly, the low adoption rate of blockchain technology results in survey responses that are largely perception-based, potentially introducing biases. Another limitation is the divergent opinions among participants due to the early stage of blockchain adoption in the construction industry. Furthermore, the conceptual framework developed in this study is primarily based on existing literature, reflecting the current state of knowledge on blockchain technology within the construction domain.

1.7. Organization of Research

This research is structured into six chapters. The first chapter outlines the research background, defines the problem, reviews related studies, states the research aims and objectives, details the methodology, specifies the scope and limitations, and describes the organization of the research. The second chapter introduces key concepts related to blockchain technology, including their definitions, main characteristics, and core technologies. It also mentions previous studies on blockchain technology in construction industry. The third chapter clarifies the research methodology, presents the initial framework, describes the questionnaire survey, and describes the SEM methodology. The fourth chapter reports the research results, including descriptive statistics and SEM analysis, which are then discussed in the fifth chapter. In the fifth chapter, the proposed blockchain roadmap is also presented and discussed in detail. The sixth chapter summarizes the conclusions, highlighting the main observations, and providing recommendations. The appendix includes the sample questionnaire survey.

2. KEY CONCEPTS & LITERATURE REVIEW

2.1. Blockchain Technology

Blockchain technology facilitates transparent information sharing among all network participants, ensuring that no single party has complete control over data (Penzes, 2018). The information is exchanged in a predefined, unalterable, and nearly instantaneous manner. Moreover, all data recorded on the blockchain is permanent and cannot be changed (Tezel *et al.*, 2021). Blockchain, a form of DLT, gained widespread attention nearly a decade ago as the foundational technology behind Bitcoin (Nakamoto, 2008).

2.1.1. Definition

The term "blockchain" is derived from its structural components: discrete records known as blocks, which are interconnected in a singular sequence referred to as a chain (Zeba *et al.*, 2023). Each block within a blockchain contains a timestamp, a hash value, and the hash value of the preceding block, which binds it to the previous block in the chain (Dib *et al.*, 2018). This architecture ensures the security and integrity of the blockchain, as its immutable nature prevents tampering, any alteration or modification is permanently recorded. Blockchain technology is used to record transactions on the system in a manner that makes it extremely difficult or virtually impossible to alter, hack, or commit fraud within the system (Paul *et al.*, 2021).

A distributed ledger is a basic database that possesses unique characteristics. It is distributed, which means that the database is spread across various locations in a shared manner (Penzes, 2018). This makes it somewhat similar to typical cloud systems or other shared internet storage solutions. However, unlike a single storage location with multiple access points, distributed ledgers consist of multiple stores that are updated simultaneously.

A distributed ledger can be described as a network that allows participants to interact or transact with each other directly in a peer-to-peer manner (Tezel *et al.*, 2021). This direct information exchange is facilitated by the DLT's highly resilient network protocol or consensus mechanism, eliminating the need for intermediaries (Li *et al.*, 2018). These interactions are cryptographically secured and added to, in the case of blockchain systems, an immutable chain of records. Encryption ensures that these transactions are indisputable (Xu *et al.*, 2023). Furthermore, since each block on the blockchain contains information from previous blocks, a highly resilient and trusted record is created. To modify one block, the entire chain must be altered, which is impossible without controlling the vast majority of the network (Penzes, 2018).

2.1.2. History of Blockchain and Distributed Ledger

The Distributed Ledger System has its roots in the double-entry bookkeeping system developed in the Middle East. In the early 1960s, the Electronic Data Interchange (EDI) system was introduced to automatically share ledger data among parties, allowing transactions to be recorded without human intervention (Penzes, 2018). Unlike EDI, which shares transactions between separate ledgers, DLT allows participants in a blockchain network to use a single, shared ledger that is entirely validated (Li *et al.*, 2018).

Haber and Stornetta (1991) were the first to define blockchain. They introduced the concept of timestamp-based digital documents that are secured and tamper-resistant through the use of cryptographic hashing. Subsequently, in 1998, computer scientist Nick Szabo developed "bit gold," a concept for a decentralized digital currency (Szabo, 1998). In 2000, Stefan Konst published his theory on cryptographically hashed and protected chains, along with its implementation theory (Zeba *et al.*, 2023). Developers made further advances after Nakamoto (2008) published a white paper introducing the blockchain model. Nakamoto implemented the first blockchain as a public ledger for transaction records through Bitcoin. In 2014, blockchain technology diverged from its association with currency, revealing its potential for various financial applications (Zeba *et al.*, 2023). This evolution led to the emergence of Blockchain 2.0, denoting its applications beyond digital currency.

2.1.3. Working Mechanism

The operational mechanism of the blockchain can be illustrated in five steps with a simple transaction example (Penzes, 2018).

i. A transaction is initiated between two parties.

ii. This transaction is then created as unique data and broadcast across the network for validation. During validation, it checks whether the sender and receiver are appropriate and ensures that the transaction is not duplicated.

iii. After the network consensus is reached, the transaction is validated and its hashed information is added to a "block," creating a tamperproof record.

iv. The blockchain is updated with the new block, ensuring that all network participants have an up-to-date copy of the blockchain.

v. Finally, the transaction is completed and the transferred digital asset, data, or order is received with an immutable record of its origin and transfer.

This process does not involve a centralized third party or accountant, as any changes or new transactions require consensus and validation from network stakeholders (nodes). The data sharing mechanism and the associated immutable uniqueness of information are made possible by robust cryptographic techniques (Sun *et al.*, 2023). These techniques ensure that the blockchain's embedded algorithm can verify that transactions are not duplicated. Each node on the network holds identical and updated copies of the blockchain simultaneously, with granted permissions and data accessibility (Yoon and Pishdad-Bozorgi, 2022). Figure 2.1. below has been designed to describe the working mechanism of blockchain technology when a transaction is requested.

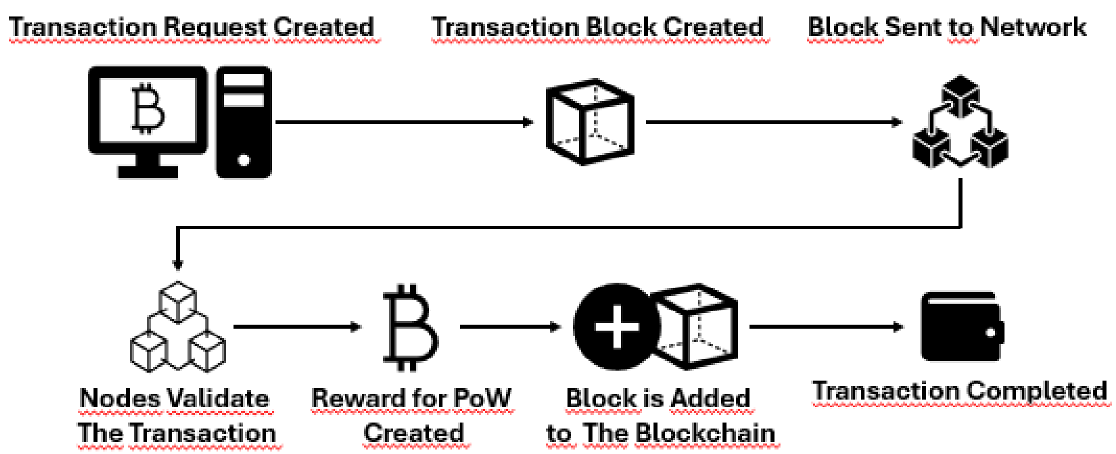

Figure 2.1. Working mechanism of blockchain technology.

In a construction project, every key stakeholder would be part of a blockchain-powered network governed by consensus and agreement among all stakeholders. Each participant would have their own copy of the blockchain, containing every interaction and transaction between parties (Li *et al.*, 2018). This information, whether private or fully disclosed, is recorded, tamper-proof, and cryptographically signed, creating a traceable record of every business interaction. This system can significantly reduce project control complexity, associated risks, and administrative costs (Penzes, 2018). Furthermore, smart contracts (self-executing conditions within blockchain-based systems) can further enhance process efficiency and traceability. This kind of system fundamentally improves trust and collaboration among all participants.

2.1.4. Types of Blockchains

Every blockchain comprises a network of computers, known as nodes, that perform transactions by appending new blocks to an existing chain. Although fundamental technology remains consistent, the configuration of these nodes and the routes they follow can differ across various implementations (Paul *et al.*, 2021). The architecture of a blockchain network is tailored to its specific application, necessitating distinct levels of access, processing capabilities, security, and privacy (Zeba *et al.*, 2023). Blockchains are categorized into two main modes: one focusing on network access control, which is further divided into four types as; public, private, consortium, and hybrid. The other mode focuses on network participants further divided into two types as; permissionless, and permissioned.

<u>2.1.4.1. Public Blockchain.</u> A public blockchain network is open and decentralized, allowing anyone with internet access to join as a node without approval (Martinovic *et al.*, 2017). Each participant holds an immutable copy of the ledger, ensuring transparency and security. The nodes have equal access rights, enabling full participation in the creation and validation of blocks through complex computations (Paul *et al.*, 2021). Public blockchains often use open source code, which allows users to inspect transactions, identify issues, and propose fixes. They are generally secure if users follow security protocols but can be vulnerable if not. They are commonly used for cryptocurrency mining and exchanges, utilizing proof-of-work (PoW) or proof-of-stake (PoS) consensus mechanisms for transaction security. Bitcoin is a good example for public blockchains.

The advantages of public blockchains include complete decentralization, fostering user independence from central authorities, and ensuring transaction legitimacy through consensus mechanisms (Zeba *et al.*, 2023). The distributed ledger enhances security by making it difficult for hackers to compromise the network. Public blockchains are transparent, with data accessible to anyone. However, they face challenges such as slow processing speeds, scalability issues, and high energy consumption, particularly with PoW systems, leading to high transaction fees (Randa, 2024).

2.1.4.2. Private Blockchain. A private blockchain is a compliant and restricted blockchain network designed for use within a closed association (Xu *et al.*, 2023). This type of blockchain is typically used within organizations or enterprises where only selected individuals participate (Martinovic *et al.*, 2017). The controlling entity of the private blockchain network dictates the levels of security, permissions, and transparency. While private blockchains share some similarities with public blockchains, they operate within a more restrictive framework. These networks are used for various applications such as internal voting, network storage management, automation, and asset ownership (Randa, 2024). Multichain, Hyperledger projects, and Corda are good examples of private blockchains.

Advantages of private blockchains include fast transaction processing, flexible rule changes, cost-effective transactions, and enhanced security due to limited access (Paul *et al.*, 2021). They are also adaptable, allowing companies to scale the network size as needed. However, private blockchains also have disadvantages. They are not fully decentralized, as a single entity controls the network (Zeba *et al.*, 2023). This centralization can lead to trust issues since the final decisions are made with a few central nodes. The limited number of nodes can compromise security if any of the nodes are compromised, thereby affecting the consensus mechanism.

2.1.4.3. Hybrid Blockchain. A hybrid blockchain combines elements of public and private blockchain systems, managed by a central entity. This type of blockchain uses a private, permission-based system alongside a public system. Although it restricts access, it gives the central authority control over the data that are accessible to the general public (Randa, 2024). Transactions and records are private, but can be verified by approved users through a smart contract system when necessary. However, the controlling entity cannot alter or change transactions on the blockchain. Hybrid blockchains are preferred by entities seeking the benefits of public and private systems. This type of blockchain is ideal for highly regulated industries, such as banking, and industries requiring transparency yet regulated access, like real estate, retail, and healthcare (Zeba *et al.*, 2023).

The advantages of hybrid blockchains are notable. They offer flexibility, allowing customization to fit specific needs by combining public and private elements. They provide enhanced security by using the data integrity of private blockchains and the security of decentralized systems (Paul *et al.*, 2021). Hybrid blockchains also foster transparency, which builds trust among network participants. However, hybrid blockchains come with challenges. They can be more complex to manage and maintain compared to purely private or public blockchains. Since they are not fully decentralized, there might be concerns about potential censorship or manipulation due to the level of control exercised by the central entity (Zeba *et al.*, 2023).

2.1.4.4. Consortium (Federated) Blockchain. A consortium blockchain, also known as a federated blockchain, is managed collectively by multiple entities rather than a single central authority (Dib *et al.*, 2018). This collaborative approach among organizational members helps distribute governance and management responsibilities across the decentralized network, addressing the issues seen in centralized private blockchains.

Governance in a consortium blockchain is facilitated through consensus mechanisms controlled by predetermined centralized nodes (Paul *et al.*, 2021). These validator nodes initiate, receive, and validate transactions within the network (Randa, 2024). Participants collectively decide which nodes have the authority to validate transactions, ensuring secure and efficient operation (Zeba *et al.*, 2023). These networks are favored by organizations seeking greater control, security, and efficiency over their blockchain operations within a collaborative framework.

Consortium blockchains offer several advantages. They provide enhanced security and privacy as verified blocks are not visible to the public, reducing the risk of unauthorized access or data breaches (Dib *et al.*, 2018). In addition, they are more scalable and efficient compared to public blockchains because they operate under the control of a select few validator nodes. Access control in consortium networks is similar to that in private or hybrid blockchain systems, allowing participants to manage and regulate network permissions effectively (Randa, 2024). However, consortium blockchains also present challenges. They lack the transparency found in public blockchains since they are not open to the general public. Security vulnerabilities may arise due to the reliance on a single or limited number of validator nodes, potentially compromising the integrity of the entire network (Dib *et al.*, 2018).

2.1.4.5. Permissionless Blockchain. This decentralized system operates without gatekeepers or hierarchical access controls, distinguishing it from permissioned blockchains (Zeba *et al.*, 2023). Participants in a permissionless blockchain are equal, ensuring transparency, as all transactions are visible to everyone on the network. Users also benefit from a degree of anonymity, as they can interact with the blockchain without requiring special permissions (Randa, 2024).

The advantages of permissionless blockchains include high transparency, resistance to censorship, and robust security due to the distributed nature of the network (Zeba *et al.*, 2023). Since anyone can access and validate transactions, it becomes challenging to compromise the entire network simultaneously. However, these systems suffer from drawbacks such as slower transaction speeds due to increasing network usage, resource-intensive requirements for consensus mechanisms, and less privacy compared to permissioned blockchains (Randa, 2024).

2.1.4.6. Permissioned Blockchain. A permissioned blockchain restricts participation and transaction engagement to a predefined set of users authorized by a controlling entity (Randa, 2024). Unlike permissionless blockchains, permissioned systems require individuals to be invited or approved to join the network. This characteristic makes permissioned blockchains common in both private and sometimes public contexts, ensuring that only approved participants can access and interact with the blockchain. In permissioned blockchains, data is stored in a centralized repository accessible only to those with authorized permissions, ensuring privacy and control over sensitive information (Zeba *et al.*, 2023). Participants typically have designated permission levels that dictate their actions within the blockchain ecosystem, providing a structured approach to managing data and transactions securely.

Although permissioned blockchains offer advantages in terms of privacy, control, and regulatory compliance, their suitability depends on the specific requirements and security considerations of the organizations that use them (Randa, 2024). Permissioned blockchains face challenges such as increased complexity in managing permissions and the risk of collusion among authorized participants (Zeba *et al.*, 2023). They are not fully decentralized, as the controlling entity retains the authority to modify rules and permissions, potentially impacting the integrity of the blockchain network.

2.1.5. Consensus Algorithms

As a crucial element of blockchain technology, the consensus protocol is essential to the operation of blockchain networks within distributed environments (Nawari and Ravindran, 2019). It is particularly significant for managing the information flow among blockchain participants and ensuring the overall efficiency of the system (Salimitari *et al.*, 2020). A consensus protocol comprises a set of rules that facilitate the agreement among blockchain nodes on a value or state of the network, determining who, whether, and when a new block is added to the blockchain (Makhdoom *et al.*, 2019). Furthermore, by specifying the principles for creating valid blocks, the consensus mechanism influences the timing of new block generation and the acceptance of behaviors from honest or dishonest nodes. This, in turn, affects the blockchain's performance and security during operation. In the context of blockchain applications in the construction industry, where stakeholders come from various teams, the choice of consensus protocols is especially critical to ensure the safety of information transfer and meet operational requirements (Wu *et al.*, 2019). There are 12 different consensus protocols given below.

- Proof of Work (PoW)
- Proof of Stake (PoS)
- Delegated Proof of Stake (DPoS)

- Proof of Authority (PoA)
- Proof of Elapsed Time (PoET)
- Proof of Importance (PoI)
- Proof of Burn (PoBr)
- Proof of Capacity (PoC)
- Practical Byzantine Fault Tolerance (PBFT)
- Delegated Byzantine Fault Tolerance (DBFT)
- Federated Byzantine Agreement (FBA)
- Reliable, Replicated, Redundant, and Fault-Tolerant (RAFT)

2.2. Smart Contracts

2.2.1. Definition

The concept of smart contracts, first introduced by Szabo (1996) in the mid 1990s, involves the execution of contractual clauses through their integration into software as automated computer protocols (Karacigan and Ozorhon, 2023). A smart contract is a computerized protocol whose implementation is automated via executable code that operates on the blockchain (Ahmadisheykhsarmast and Sonmez, 2020). The fusion of smart contracts and blockchain technology heralded a new era where contractual clauses can be executed on the blockchain through automated computerized protocols. Moreover, smart contracts facilitate the automatic execution of contractual clauses on a secure and reliable platform, eliminating the need for a trusted third party or authority such as notaries, lawyers, or banks (Pinna *et al.*, 2020). They can improve efficiency and traceability (Penzes, 2018). As a result of these improvements a reduction in contractual disputes and saving in transaction fees, and administrative costs are expected (Crosby *et al.*, 2016).

Di Giuda *et al.* (2020) emphasized that the implementation of blockchain-based smart contracts addresses several barriers that have historically hindered the development and adoption of BIM. These include concerns related to data reliability, traceability, elimination of intermediaries, change tracking, and ownership of information. The integration of the BIM model with a decentralized ledger that encompasses comprehensive process data facilitates the establishment of a unified and dependable record system, thereby promoting collaboration among stakeholders. The concurrent evolution of the BIM environment and the execution of smart contracts enables the automation of various project delivery stages. Figure 2.2. illustrates the function of smart contracts within the context of blockchain integration in the construction industry.

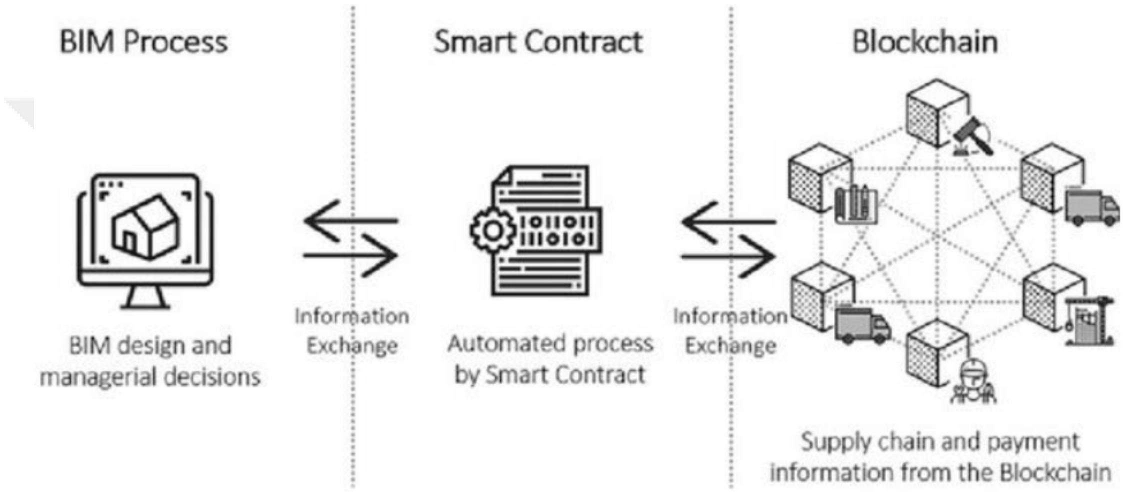

Figure 2.2. Integrating smart contracts into blockchain in construction industry (Di Giuda *et al.*, 2020).

2.2.2. Types of Smart Contracts

Morabito (2017) identified two types of smart contracts: deterministic and non-deterministic. A deterministic smart contract relies solely on information already available on a distributed ledger, whereas a non-deterministic smart contract requires additional information from a trusted third party.

2.2.2.1. Deterministic Smart Contracts. Deterministic smart contracts operate under a strict principle of predictability; given a specific set of inputs, they consistently produce the same outputs across all network nodes. This consistency is crucial for maintaining consensus in blockchain environments, especially within public blockchains like Ethereum, where uniform execution outcomes across nodes are essential (Alharby and van Moorsel, 2017;

Smith and Garcia, 2022). Deterministic smart contracts are particularly well-suited for automating clearly defined, rule-based processes such as milestone-based payments, compliance verification, or document authentication, where all variables can be pre-specified and encoded without ambiguity (Smith and Garcia, 2022).

2.2.2.2. Non-deterministic Smart Contracts. In contrast, non-deterministic smart contracts involve elements of uncertainty or rely on external inputs that may vary between executions. These contracts typically integrate off-chain data via oracles, enabling responsiveness to real-time information (Smith and Garcia, 2022; Arceri *et al.*, 2023). Use cases include dynamic pricing mechanisms, environmental condition-based scheduling, or any context requiring input from external databases. While this flexibility is advantageous, non-deterministic contracts also pose risks related to data authenticity, oracle reliability, and potential disruption of consensus mechanisms (Arceri *et al.*, 2023).

The applicability of each type of smart contract within construction project management depends on the specific context. Deterministic contracts are preferable in scenarios where predictability, auditability, and automation are critical—such as contractual compliance or payment execution. Conversely, non-deterministic contracts may be better suited for dynamic environments that require integration with real-time data, such as supply chain coordination or environmental monitoring (Morabito, 2017).

2.2.3. Benefits and Challanges

Smart contracts present a range of compelling advantages that distinguish them from traditional contract mechanisms, primarily due to their ability to execute specific contractual clauses automatically when predetermined conditions are fulfilled. This automation significantly reduces the potential for disputes and delays, particularly in financial transactions, as funds are only released upon the satisfaction of clearly defined criteria, thereby ensuring payment security and contractual compliance (Wang *et al.*, 2017). Moreover, the digital and algorithmic nature of smart contracts contributes to a higher degree of transparency, predictability, and precision in execution.

Unlike traditional contracts, which may be subject to interpretation and administrative inefficiencies, smart contracts operate on clearly coded logic, reducing ambiguity and enhancing the overall efficiency and effectiveness of contract administration processes. Furthermore, in the domain of supply chain management within the construction industry, smart contracts enabled by blockchain technology have demonstrated the potential to record critical logistics information, such as the exact delivery dates of materials to construction sites. This capability facilitates automated and timely release of payments based on actual delivery data, thereby improving coordination and trust among project stakeholders (Blycha, 2018).

The integration of smart contracts with blockchain technology introduces several significant advantages to construction project management. Primarily, smart contracts enable automatic and self-enforcing execution of contractual terms, thereby minimizing the likelihood of misapplication and reducing the necessity for follow-up communications regarding task completion. Their irrevocability ensures that, once activated, contractual obligations are executed without the possibility of reversal, enhancing reliability and accountability (Mason, 2017). Additionally, the real-time traceability feature facilitates the tracking of multiple document iterations, such as design drawings, and allows for the identification of responsible parties in cases of delay or inaction. The immutable nature of smart contracts, made possible through blockchain, further strengthens data integrity and security while eliminating the need for intermediaries in transaction validation.

Despite these advantages, certain challenges persist, particularly in the context of high-complexity and dynamic construction environments. The inflexibility of smart contracts, rooted in their immutability, can present difficulties when unforeseen conditions arise, such as modifications to payment structures or unexpected project requirements. In such scenarios, the rigid structure of smart contracts may hinder adaptability and responsiveness, which are often essential in dynamic construction processes (Wu *et al.*, 2022).

2.2.4. Decentralized Autonomous Organization (DAO)

One example of a smart contract structure is a DAO, which is an entity governed not by a single individual but by the consensus of its members. A DAO consists of a collection of smart contracts that, once deployed, cannot be altered and will always operate as programmed (Li *et al.*, 2020). Therefore, ensuring that the smart contracts constituting a DAO comply with regulations and function as intended is crucial, since they cannot be "turned off" once executed. Smart contracts provide the ability to automate tasks and activities throughout the built asset lifecycle while also serving as a mechanism to enforce regulatory compliance.

2.3. Construction Contracts, Claims & Disputes Management

The construction industry, despite being a major contributor to national economies, continues to rely heavily on traditional contractual frameworks and inefficient manual processes, particularly for payments and claims management (Hamledari and Fischer, 2020). These outdated practices are often associated with prolonged and cumbersome contract execution, leading to disputes and unresolved issues among project stakeholders. Such issues frequently evolve into formal construction claims, which are a significant cause of time and cost overruns in construction projects (Shaikh *et al.*, 2020).

Claims typically arise from various aspects of the contract, most notably from payment methods and project delivery systems. Conventional payment structures, such as lump sum, unit price, and cost-plus-fee, continue to dominate the industry, each carrying inherent risks that may trigger disagreements. Given the inherently complex, fragmented, and uncertain nature of construction projects, claims and disputes are virtually inevitable. They have become embedded in the standard operating environment of the industry. However, the resolution of such issues is often far from straightforward, demanding a high degree of contractual literacy and effective communication among project participants (Do *et al.*, 2022). A growing body of literature has aimed to analyze the frequency, typology, and root causes of construction claims to enhance dispute avoidance strategies.

Seminal studies, such as that of Diekmann and Nelson (1985), who reviewed 427 claims, identified project owners as a primary source of contract modifications and change orders. Zaneldin's (2006) research further categorized claims into six major types driven by 26 distinct causes, establishing a foundational typology of claim dynamics. In his more recent work, Zaneldin (2020) reinforced that project changes and delays remain the most dominant causes of construction claims today. Chaphalkar and Sandbhor (2015), through an analysis of 419 claims, found that variation orders were the most prevalent, followed by claims for extra work and cost escalation.

Understanding the root causes of claims is critical not only for dispute resolution but also for dispute avoidance. As Younis *et al.* (2008) argue, effective early identification of risks linked to unresolved claims enhances both preventative and mitigative strategies. Likewise, Ren *et al.* (2003) stress the importance of proactive measures aimed at avoiding disputes by analyzing claims trends to formulate targeted resolutions before they escalate into formal conflicts. The process of dispute resolution itself is notoriously time-consuming and costly. In response, researchers and practitioners alike have called for innovative approaches that align with the intent of contract parties and ensure compliance with obligations.

A report by McKinsey & Company (2017) revealed that construction lags behind other industries in technology adoption. A later report (McKinsey & Company, 2020) further noted that while digital transformation has enhanced productivity across industries by an average of 3.6%, the construction industry's productivity gains have stagnated at just 1% over the past two decades. These findings underscore a vast, untapped potential for digitalization within the construction industry.

A key area for digital innovation is contract management, which encompasses an array of interrelated tasks and considerable risk exposure (Greenhalgh, 2016). Effective contract administration requires coordination among multiple stakeholders across diverse project functions, including payments, procurement, and supply chain management. However, in the absence of integrated and secure data management systems, navigating these complexities becomes particularly challenging. Das *et al.* (2022) emphasize that industries such as healthcare, finance, and education have successfully addressed similar challenges through the implementation of blockchain-enabled platforms. Drawing from these industries, construction can likewise harness blockchain technology to create more reliable, collaborative, and efficient contract management processes.

The introduction of blockchain technology into these processes offers promising opportunities for mitigating the causes of such claims. It is anticipated that blockchain implementation will differentially impact claim occurrences depending on the type of payment method applied. For instance, Rugina (2021) highlights that blockchain's ability to enforce contractual terms transparently and immutably has the potential to substantially reduce disputes among parties by minimizing ambiguity and enhancing trust. Research indicates that improvements in contractual mechanisms and their digital transformation can lead to notable benefits. Specifically, advancements in contract management and digital integration are projected to yield up to 7% cost savings and a 10% increase in productivity McKinsey & Company (2017). These performance gains could translate into more efficient handling, or even prevention, of construction claims, thereby enhancing overall project delivery.

2.4. Application Areas of Blockchain Technology

Blockchain technology has been extensively adopted in various industries beyond construction, particularly in banking, healthcare, energy, and real estate. In the banking industry, blockchain facilitates secure and efficient cross-border payments, reduces reliance on intermediaries, and enhances the transparency of financial transactions (Zhang *et al.*, 2021). It is also used to streamline "know your customer" processes and improve anti-money laundering compliance through decentralized identity verification systems (Chen *et al.*, 2020). In healthcare, blockchain supports the secure exchange of electronic health records, enhances data privacy, and ensures the integrity of clinical trial data (Azaria *et al.*, 2016). These use cases highlight the technology's potential to address long-standing issues related to data silos and trust.

In the energy industry, blockchain enables decentralized energy trading, allowing prosumers to trade excess electricity directly with other users without centralized intermediaries (Andoni *et al.*, 2019). This promotes greater efficiency and transparency in energy distribution and consumption. Meanwhile, in the real estate industry, blockchain is applied to property registration, digital land titling, and smart contracts for automating lease agreements and transactions (Li *et al.*, 2019). These applications reduce fraud, enhance traceability, and lower administrative costs. Collectively, such implementations demonstrate blockchain's capacity to transform traditional processes across industries through improved transparency, automation, and data integrity.

Compared to other industries, the construction industry has been relatively slow in adopting blockchain technology, largely due to its fragmented structure, project-based nature, and resistance to digital transformation (Perera *et al.*, 2020). While industries like banking and healthcare have leveraged blockchain for well-defined and digitized processes, the construction industry faces challenges in integrating blockchain due to the lack of standardized data formats and interoperability across stakeholders. Moreover, whereas the energy and real estate industries have implemented blockchain to support decentralized trading and digital asset management, blockchain applications in construction are still in the exploratory phase, primarily focused on smart contracts for project delivery, supply chain transparency, and digital payment systems (Turk and Klinc, 2017).

The construction industry plays an essential role in national economic development, contributing significantly to Gross Domestic Product (GDP) (Ameyaw *et al.*, 2023). Despite this, many processes within the industry remain undigitized. The advent of the Construction 4.0 concept is expected to drive the digital transformation of companies, thus enhancing their productivity (Prabhakar *et al.*, 2023). Digitalization is regarded as a strategic response to the primary challenges faced by the construction industry, such as low productivity, substandard health and safety practices, and frequent disputes and claims (Linderoth, 2017; Lavikka *et al.*, 2018). Blockchain technology has recently emerged as a novel digital solution in various industries, including construction (Risso *et al.*, 2023).

2.5. Possible Application Scenarios in Construction Contract Management

As a disruptive technology, blockchain offers substantial opportunities for the digital transformation of construction companies (Li *et al.*, 2022). Although its adoption in the construction industry is still in the early stages (ARUP, 2019; Rathnayake *et al.*, 2022), blockchain is expected to revolutionize construction management practices (Perera *et al.*, 2020.). Construction contract management practices encompass the involvement of all project participants, and the integration of blockchain technology necessitates collaboration among various stakeholders based on the defined use cases. Figure 2.3. has been designed to illustrate the stakeholders in construction contract management.

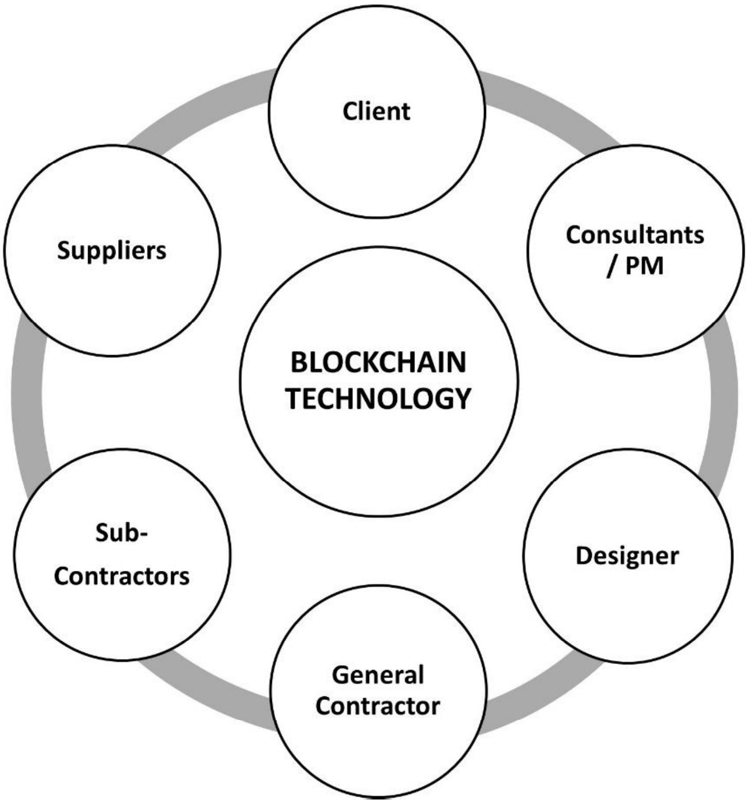

Figure 2.3. Stakeholders in construction contract management.

In a collaborative ecosystem, every participant in a construction project would be part of a blockchain-based network. Each stakeholder would possess an identical copy of the blockchain, with records created through consensus and agreement among all parties. Implementing such a system is expected to increase trust and foster a more collaborative environment among project stakeholders, potentially enhancing project success (Penzes, 2018). Contract management practices within the construction industry are particularly ripe for digitalization. As a crucial aspect of project management, contracts encompass interconnected tasks and a wide range of risks (Greenhalgh, 2016). Effective construction contract management requires coordination among multiple stakeholders for various processes, such as payments and supply chain management. Achieving this coordination is challenging without a secure and collaborative information management system (Das *et al.*, 2022).

Blockchain technology facilitates information sharing in a trustworthy, traceable, transparent, and storable manner among multiple parties (Penzes, 2018; Elghaish *et al.*, 2020). These features present an opportunity to integrate blockchain with construction contract management practices. Blockchain has the potential to digitalize construction contract management and address the issues faced by practitioners. According to the literature, the application of blockchain technology in construction contract management practices can be categorized into three main areas: payments, supply chain management, and information management (Zhang *et al.*, 2023).

2.5.1. Payment Management

Payments are a crucial component of construction project management. Delays in payments often cause a domino effect, generating numerous claims and resulting in project schedule delays (Matt, 2020). The existing payment system in the construction industry has significant flaws. Typically, the general contractor must first verify the completed work on site to apply for an interim payment from the client. Once the client agrees on the progress of the completed works, they make the payment to the general contractor, who then disburses payments to subcontractors based on their completed work. During these negotiations, significant schedule delays occur in terms of the percentage of completed work.

An alternative method, the Project Bank Account (PBA), involves direct payment by the client into a PBA, from which funds are automatically transferred to subcontractors and other parties. However, PBAs entail high management costs and require staff training (Ahmadisheykhsarmast and Sonmez, 2020), making them less attractive to clients (Das *et al.*, 2020).

Blockchain technology and smart contracts offer the potential to create an efficient and automated payment system for the construction industry. Several authors argue that construction contract terms can be embedded into a blockchain-based smart contract system, which would then execute automatically (Cecconi, 2020; Hamledari and Fischer, 2021; Li and Kassem, 2021). Luo *et al.* (2019) proposed a semi-automatic payment system, suggesting that combining a blockchain-based payment system with BIM could enhance the benefits of automation. Wang *et al.* (2017) noted that a blockchain-based automated payment system could reduce disputes related to late and unfair payments to subcontractors. Ahmadisheykhsarmast and Sonmez (2020) proposed another payment system which enables automated payments for both contractors and subcontractors through utilization of smart contracts. Figure 2.4. summarizes the proposed automated payment system through utilization of blockchain technology and smart contracts.

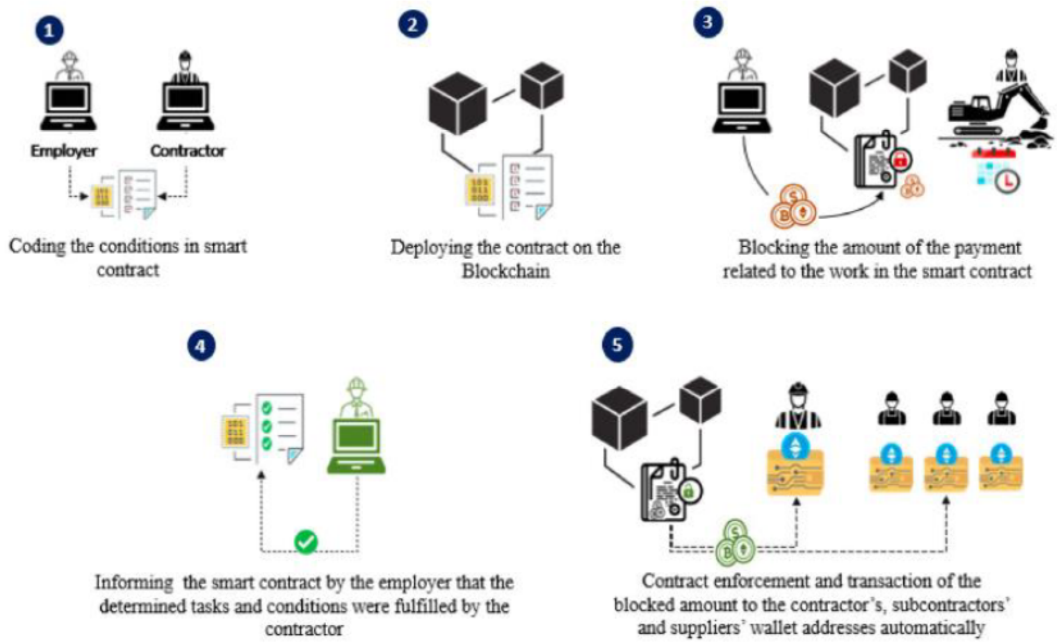

Figure 2.4. Automated payment system (Ahmadisheykhsarmast and Sonmez, 2020).

Despite these advantages, several challenges hinder the implementation of a blockchain-based automated payment system. First, there is general resistance to change, especially with regard to payment-related issues. Second, applying smart contracts to complex construction contracts may be difficult and time-consuming (Zhang *et al.*, 2023). Furthermore, choosing a suitable currency for payments can be problematic due to fluctuations in cryptocurrency. Das *et al.* (2020) argued that the cost of implementing a blockchain-based payment method would be higher than that of traditional payment systems

2.5.2. Supply Chain Management

Supply chain management is a crucial aspect of project management, involving a multitude of stakeholders, such as producers, vendors, warehouses, shippers, distributors, retailers and subcontractors (Zhang *et al.*, 2023). Managing these complex processes requires a systematic approach. The primary objectives of supply chain management systems are to enhance efficiency and optimize resource use, thereby reducing costs (Qian and Papadonikolaki, 2020).

Current supply chain management systems primarily utilize Global Positioning System (GPS) and Radio Frequency Identification (RFID) technologies. However, a significant issue with these systems is that each stakeholder maintains their own data within their respective systems, leading to interoperability problems and fragmented information (Wang *et al.*, 2020). This fragmentation makes it challenging to track and share sensitive information securely and transparently, often resulting in delays and increased supply chain management costs (Tezel *et al.*, 2020).

Blockchain technology offers the potential to improve supply chain management processes by providing secure real-time data storage and sharing (Tezel *et al.*, 2020). Wang *et al.* (2020) proposed a blockchain-enabled supply chain management system, and their case study demonstrated that blockchain technology facilitated real-time information sharing and monitoring. This improved the delivery process of precast components and allowed stakeholders to track the causes of disputes.

However, integrating blockchain technology with supply chain management presents several challenges. In environments with numerous stakeholders, resistance to change is a significant hurdle. Implementing a blockchain-enabled supply chain management system requires the participation of all stakeholders. Furthermore, integrating large volumes of GPS and RFID data can lead to limited storage capacity and time-consuming data transmission in a blockchain-based system (Wan *et al.*, 2020).

2.5.3. Information Management

Managing information in construction projects is both challenging and critical, necessitating meticulous attention. Effective data storage and timely sharing are often hindered by poor communication among stakeholders (Zhou *et al.*, 2020). Furthermore, concerns about information and data security impede the adoption of digital technologies such as BIM, Geographic Information System (GIS), or IoT within the construction industry (Hargaden *et al.*, 2019).

Blockchain technology, with its ability to keep and share transparent and secure information, has the potential to address these barriers to information management. Integrating a blockchain-based information management system with BIM can offer numerous advantages, including privacy, protection, and transparency (Safa *et al.*, 2019). This integration can safeguard BIM data from manipulation, which might otherwise lead to unresolved claims in the future (Liu *et al.*, 2019; Das *et al.*, 2021). Parn and Edwards (2019) argue that a blockchain-based data management system could enhance the security of the current common data environment.

Combining blockchain with BIM implementation allows project parties to reliably track data creation and modification history, resolving copyright and ownership issues (Turk and Klinc, 2017). Furthermore, integrating blockchain and IoT technologies facilitates the capture, sharing, and updating of real-time data in a transparent, secure, and accountable manner (Elghaish *et al.*, 2021; Lee *et al.*, 2021).

However, several barriers hinder the implementation of blockchain technology in information management. Lee *et al.* (2021) suggest that transaction processing times can be prohibitively long, especially when using a public blockchain. Given the large volumes of BIM data in construction projects, scalability is also a concern. In addition, because construction projects involve sensitive data such as design documentation, financial information, and legal contracts, private blockchains are more likely to be used. Nonetheless, private blockchains are more vulnerable to hacking if more than half of the users are controlled (Yli-Hummo *et al.*, 2016).

2.6. Blockchain Enabled Construction Contract Management

Blockchain technology has been recognized as a transformative innovation capable of significantly impacting global industries, including construction. It serves as an advanced database system that facilitates secure, transparent, and immutable information exchange among stakeholders. The system operates on predefined rules that ensure data reliability and permanence, offering an innovative approach to managing information within complex networks.

Early investigations into blockchain applications in the construction industry revealed its potential to enhance information reliability and secure data storage. For instance, Turk and Klinc (2017) highlighted the technology's ability to bolster data integrity and trust among stakeholders. Similarly, Safa *et al.* (2019) emphasized the integration of blockchain with BIM as a means to improve data transparency and sharing efficiency. Despite these promising applications, the adoption of blockchain has not yet met anticipated levels, largely due to various industry-specific challenges (McNamara and Sepasgozar, 2021).

Studies have explored diverse applications of blockchain, focusing on its integration with other digital tools and systems. Das *et al.* (2022) utilized hyperledger fabric to create a prototype for enhancing data integrity in document management systems, evaluating its scalability for construction projects. Liu *et al.* (2024) proposed a BIM-based blockchain framework for production management using open BIM standards, while Brandin and Abrishami (2024) developed a supply chain management model integrating IoT, BIM, and blockchain technologies. These studies illustrate the multifaceted applications of blockchain across construction processes.

The literature on blockchain in construction has primarily concentrated on specific applications, such as supply chain management, document management, and BIM integration. Li *et al.* (2018) categorized seven distinct use cases, ranging from smart cities to construction management. Shojaei (2019) further identified blockchain's potential to streamline project development processes and enhance information systems. Notably, Rathnayake *et al.* (2022) conducted a systematic review to investigate blockchain-enabled smart contracts, identifying implications like automated payments and logistics management.

Numerous studies have identified barriers to blockchain adoption in the construction industry. Singh *et al.* (2023) categorized these obstacles into organizational, technological, cultural, legal, security, and governmental factors, emphasizing the fragmented nature of the construction industry as a limiting factor. Wu *et al.* (2022) conducted a comprehensive review to outline technical and non-technical challenges, while Prabhakar *et al.* (2023) explored challenges related to unstructured innovation implementation, particularly in integrating blockchain with Artificial Intelligence (AI) and IoT.

While challenges persist, studies have also investigated the drivers and success factors for blockchain implementation. Koc and Gurgun (2020) identified key drivers, such as conflict and dispute reduction, through a fuzzy framework methodology. Sun *et al.* (2023) provided a systematic review of critical success factors, listing 22 elements essential for successful adoption. Moreover, Tezel *et al.* (2020) employed semi-structured interviews with industry experts to conduct a SWOT analysis, presenting a strategic overview of blockchain's potential for supply chain applications.

Despite the limited number of studies focusing on practical implementation, a significant contribution by Kang *et al.* (2023) showcases the application of blockchain technology in a public infrastructure project, encompassing eleven fundamental construction workflows such as scheduling, routine operations, and payment processes. This analysis, centered on workflow integration, emphasizes not only the tangible advantages of blockchain but also sheds light on key implementation barriers, including organizational inertia and the enduring reliance on conventional methods.

A number of prior studies have proposed several frameworks or roadmaps for incorporating blockchain technology into the construction industry. For example, Singh *et al.* (2023) developed a phased roadmap organized across five distinct stages for Indian construction industry. Similarly, Li and Kassem (2019) proposed a four-stage roadmap aimed at preparing the broader industry for the adoption of DLT. More recently, Jayarathna *et al.* (2025) employed the Delphi method through semi-structured interviews to design a roadmap that integrates circular economy principles with blockchain to improve construction waste management.

Although significant progress has been made, much of the existing research has focused on exploratory studies addressing specific blockchain components. Few studies have developed systematic frameworks or identified comprehensive performance indicators for implementation. This highlights the need for an integrative approach to guide blockchain adoption in the construction industry. Addressing this gap, the current research aims to propose a detailed framework and strategic roadmap, providing actionable steps to facilitate blockchain integration effectively.

This research makes a substantial contribution to academic discourse by targeting a critical gap in the existing body of knowledge namely, the underexplored integration of blockchain technology into construction contract management. Although there is a growing corpus of literature that investigates blockchain's potential applications within the construction industry, these studies often adopt fragmented or limited perspectives. While prior works have examined blockchain adoption in isolated contractual functions such as payment systems, procurement, or supply chain coordination, there remains a notable absence of research that takes a holistic view of blockchain implementation throughout the entire contract management lifecycle.

In response to this gap, the present study offers a comprehensive analysis of blockchain integration, emphasizing the identification of key critical factors and the intricate interdependencies among core constructs that influence implementation outcomes. Unlike existing investigations that often neglect the dynamic interactions among organizational, technological, and regulatory components, this research systematically unpacks these interrelationships. Through this approach, it enhances the understanding of how various determinants interact to either facilitate or hinder successful blockchain adoption in the contractual context of construction projects.

Moreover, a major novel contribution of this study is the development of a well-structured and practical implementation roadmap. This roadmap is not only informed by empirical data and theoretical grounding but also provides strategic, actionable steps for industry practitioners. Its purpose is to guide stakeholders through the complex process of integrating blockchain into existing contract management systems, thereby promoting more transparent, secure, and efficient project delivery methods.

Critically, this roadmap differs from existing conceptual models by spanning across all major phases of implementation, thus ensuring that the proposed guidance is comprehensive in scope. Importantly, the framework is context-independent and applicable across various national and organizational settings, which enhances its relevance and applicability for both academic inquiry and global industry practice.

By bridging the gap between theory and practice, and by constructing an implementation framework enriched with interrelated constructs and strategic insights, this study responds to the longstanding need for an integrated approach to blockchain-enabled contract management in the construction industry. It therefore serves not only as a scholarly advancement but also as a practical tool for transformation in an industry that has traditionally lagged in technological innovation.

3. METHODOLOGY

The methodology adopted in this research is structured into five distinct phases, which are sequentially executed to ensure a thorough and systematic approach: (i) the development of a conceptual framework, (ii) the administration of a questionnaire survey, (iii) the analysis of the collected data using SEM, (iv) the creation of a strategic roadmap, and (v) the validation of the findings through a focus group study, as depicted in Figure 3.1.

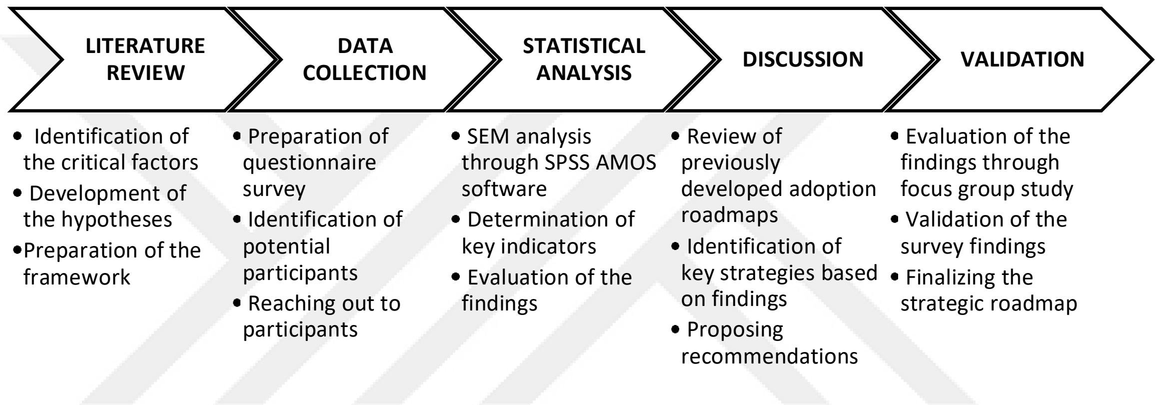

Figure 3.1. Flow of the research methodology.

In the first phase, an extensive and detailed review of the existing literature was carried out to understand the theoretical and practical foundations of blockchain technology in construction contract management. This review provided the necessary background to develop a robust framework representing the blockchain implementation process within this context. The framework was designed to capture the critical factors influencing the process, which were systematically identified and grouped into eight distinct constructs. Each construct was carefully defined to represent a significant dimension of the implementation process. To explore the interdependencies between these constructs, hypotheses were developed to model their interactions and form the basis for subsequent empirical analysis.

The second phase of the methodology focused on designing and conducting a comprehensive questionnaire survey. An online survey was chosen as the most effective tool for gathering data from a diverse group of stakeholders. The target population consisted of 286 industry professionals and academics with expertise in areas such as digital construction,

construction management, and blockchain technology. Recognizing the novelty of blockchain within the construction industry, the survey was purposefully designed to avoid overly complex or technically demanding questions, ensuring that respondents without advanced blockchain knowledge could also provide meaningful input. A purposive sampling strategy was employed to select participants with relevant experience and expertise, thereby enhancing the reliability of the data collected. The topic's innovative nature generated significant interest among the participants, resulting in a strong response rate and yielding a total of 155 completed surveys.

The third phase involved the rigorous analysis of the survey data using SEM, implemented through IBM’s statistical package for social sciences (SPSS) analysis of moment structures AMOS software. SEM was selected for its ability to simultaneously examine complex relationships between observed and latent variables. This phase included both direct and indirect relationship analyses among the variables, as well as extensive validity testing to ensure the robustness and reliability of the findings. The analysis provided critical insights into the factors driving blockchain adoption and their interactions within the broader framework.

Building on these insights, the fourth phase was dedicated to the development of a strategic roadmap aimed at guiding blockchain implementation in construction contract management. This roadmap was designed to be actionable, offering detailed and specific recommendations tailored to different stakeholder groups. The recommendations were categorized based on the roles and responsibilities of various action groups, providing a clear pathway for implementing blockchain technology effectively within the industry.

The fifth and final phase involved the validation of the research findings through a structured focus group study. This study was conducted as a two-hour session with a carefully selected panel of experts, each possessing substantial knowledge and experience related to blockchain technology and its application in construction. The focus group discussion provided an opportunity to critically evaluate the strategic roadmap and the overall findings of the study. Feedback from the participants was instrumental in refining the recommendations and ensuring their practical applicability.

This multi-phase approach combines qualitative and quantitative research methodologies which reflects a comprehensive and iterative approach to addressing the research objectives, combining theoretical development, empirical investigation, and practical validation to produce a robust and actionable roadmap for blockchain integration in construction contract management.

3.1. Development of the Initial Framework

The proposed framework was developed to holistically capture the process of blockchain implementation in construction contract management by encompassing three distinct phases: pre-implementation, implementation, and post-implementation. Within each phase, critical factors influencing blockchain integration were identified and organized into eight constructs: motivations, technological readiness, advanced technologies, emerging management methods, contractual process improvements, communication process improvements, short-term outcomes, and long-term outcomes.

In the pre-implementation phase, motivations refer to the driving forces and key enablers that stimulate interest and commitment toward adopting blockchain applications. Technological readiness pertains to factors associated with the maturity and preparedness of blockchain technologies, such as technical infrastructure and capability. These constructs set the foundational conditions necessary for blockchain implementation.

During the implementation phase, two constructs focus on the practical mechanisms enabling blockchain adoption. Advanced technologies represent widely utilized digital tools and platforms, such as cloud computing and IoT, that facilitate the integration of blockchain systems. Similarly, emerging management methods encompass contemporary management practices, such as agile and lean approaches, that act as enablers for blockchain applications. Contractual process improvements highlight specific ways in which blockchain can streamline and enhance the management of contractual agreements, while communication process improvements focus on expected advancements in information exchange and correspondence mechanisms enabled by blockchain's transparency and efficiency.

The post-implementation phase captures the impacts of blockchain integration. Short-term outcomes reflect the immediate effects observed following implementation, such as efficiency gains, cost savings, or enhanced trust among stakeholders. Meanwhile, long-term outcomes represent the broader and sustained impacts of blockchain adoption, including structural changes, improved collaboration, and enhanced industry competitiveness over time.

The initial framework postulates specific relationships between these constructs, hypothesizing that each construct exerts a direct and positive influence on another. These relationships, derived from a thorough literature review, are visually depicted in the framework using arrows that represent the corresponding hypotheses. This interconnected structure highlights the dynamic and interdependent nature of blockchain implementation, providing a comprehensive roadmap for understanding its integration within construction contract management.

3.1.1. Hypotheses Development

To examine the relationships between the constructs within the proposed framework, ten hypotheses were developed, each supported by a detailed rationale drawn from existing literature. These hypotheses establish the foundation for exploring the interconnections and influence pathways among key factors in blockchain adoption for construction contract management. The rationale for each hypothesis is as follows:

H1: "Motivations" have a direct and positive effect on "Contractual Process Improvements".

Motivational factors serve as essential catalysts for the adoption of innovative technologies, particularly in traditionally conservative industries such as construction. Ozorhon (2013) conceptualized motivations as key enablers in the innovation lifecycle, emphasizing their centrality in overcoming inertia and resistance to change. In the context of blockchain adoption, Li *et al.* (2022) underscored how intrinsic and extrinsic motivations, ranging from organizational innovation strategies to external regulatory pressures, directly influence the intent to implement blockchain solutions. Obidallah *et al.* (2024), through a technology acceptance model, further validated that motivational factors, such as perceived usefulness and strategic alignment, are among the most significant predictors of blockchain uptake. Wen *et al.* (2025) identified the lack of motivational impetus as a primary barrier in bridging the digitalization gap in the construction industry, while Prabhakar *et al.* (2023) highlighted financial motivation, particularly related to initial capital requirements, as a critical determinant for blockchain implementation success. These findings collectively affirm that well-aligned motivational drivers significantly enhance the efficiency and transparency of contractual processes in the construction industry.

H2: “Technological Readiness” has a direct and positive effect on “Contractual Process Improvements”.

Technological readiness encompasses the availability, maturity, and integration capacity of technologies within an organizational or industry-wide context. The adoption of blockchain in the construction industry is highly contingent upon such readiness. Singh *et al.* (2023) identified technological immaturity, including inadequate infrastructure and interoperability limitations, as a substantial impediment to blockchain integration. Li *et al.* (2018) emphasized that the presence of a supportive regulatory ecosystem and standardized frameworks is indispensable for unlocking the contractual efficiencies offered by distributed ledger technologies (DLT). Ameyaw *et al.* (2023) posited that the proliferation of successful case studies enhances technological readiness by providing replicable implementation models. Furthermore, Msawil *et al.* (2022) argued that resolving legal and compliance uncertainties is fundamental for increasing the industry’s preparedness for blockchain-based contractual innovations. Hence, higher levels of technological readiness directly support the transformation of contract management practices across the construction industry.

H3: “Advanced Technologies” have a direct and positive effect on “Contractual Process Improvements”.

The convergence of blockchain with advanced technologies such as BIM, AI, IoT, and RFID significantly amplifies its transformative potential within the construction industry. The Institution of Civil Engineers (2018) reported that BIM-blockchain integration can enhance transparency, accountability, and data integrity in contractual processes. Adel *et al.*

(2022) illustrated that AI integrated within blockchain ecosystems facilitates smart contract automation and predictive analytics, thereby enhancing contractual efficiency. Ciotta *et al.* (2021) emphasized the combined utility of RFID and blockchain in improving asset tracking and project oversight. Additionally, Sun *et al.* (2023) demonstrated how big data analytics supports blockchain by enabling real-time information governance and risk anticipation. Collectively, these technologies act synergistically to modernize and streamline contractual workflows in the construction industry.

H4: "Emerging Management Methods" have a direct and positive effect on "Contractual Process Improvements".

Innovative management methods, such as IPD, lean construction, and agile frameworks, play a crucial role in facilitating the implementation of blockchain technologies in contractual contexts. Dounas *et al.* (2021) observed that IPD, which prioritizes trust and stakeholder integration, is inherently compatible with blockchain's principles of decentralization and transparency. Tezel *et al.* (2022) highlighted a mutual reinforcement between lean construction and blockchain, wherein lean principles improve efficiency and blockchain ensures traceability and collaboration. The Institution of Civil Engineers (2018) advocated for the adoption of agile strategies to remain competitive amidst digital transformation. Pinna *et al.* (2020) further argued that agile methodologies are effective in guiding the development of blockchain-based solutions. These emerging management methods establish a robust foundation for reconfiguring traditional contractual practices across the construction industry.

H5: "Advanced Technologies" have a direct and positive effect on "Communication Process Improvements".

The deployment of advanced digital technologies, constitutes a critical enabler of effective communication across all stages of construction projects. These technologies facilitate real-time data exchange, reduce information asymmetry, and ensure consistency in project documentation. Karacigan *et al.* (2023) asserted that BIM enables seamless collaboration by providing a shared data environment accessible to all stakeholders, thereby eliminating traditional communication bottlenecks. Ozorhon (2013) linked technological innovation to enhanced inter-organizational communication and strategic alignment. Wu *et al.* (2022) demonstrated that IoT-enabled devices support automated data transmission, increasing the frequency, accuracy, and reliability of communication. Similarly, Gao *et al.* (2024) emphasized that integrating RFID, IoT, and BIM fosters a digitally connected ecosystem, enabling synchronized information flow among dispersed project teams. The convergence of these technologies thus acts as a digital infrastructure that significantly elevates communication processes within the construction industry.

H6: "Contractual Process Improvements" have a direct and positive effect on "Communication Process Improvements".

Improvements in contractual processes, particularly through the integration of blockchain technologies, play a significant role in optimizing communication within construction projects. Transparent, standardized, and automated contract administration reduces ambiguity, mitigates conflict, and enhances clarity in stakeholder interactions. Zhang *et al.* (2023) found that blockchain-driven contract management improves information traceability, fosters trust, and facilitates the real-time validation of contractual obligations. Gurgun *et al.* (2022) emphasized that immutable and transparent records support traceability, which is vital for consistent communication. Silva *et al.* (2024) emphasized the role of immutable records in ensuring the integrity and verifiability of shared information. These enhancements lead to more predictable and efficient communication channels, which are foundational to effective collaboration and decision-making in complex construction environments. Thus, optimized contractual processes act as a communication backbone, reinforcing transparency and operational coordination across project actors.

H7: "Emerging Management Methods" have a direct and positive effect on "Communication Process Improvements".

Emerging management approaches fundamentally reshape the communication culture within construction projects by promoting collaboration, shared responsibilities, and continuous feedback loops. Ozorhon *et al.* (2022) demonstrated that agile practices facilitate open and iterative communication cycles, which improve responsiveness to change and stakeholder engagement. Liu *et al.* (2023) emphasized that IPD fosters a relational contract environment, wherein communication is both structured and trust-based, enabling the proactive resolution of issues. Kifokeris and Tezel (2023) underscored how lean principles encourage daily communication rituals that enhance situational awareness and team alignment. These management methods institutionalize communicative routines and cultural norms that are critical for navigating the complexities of modern construction projects. Therefore, the adoption of these innovative management frameworks leads to substantial improvements in both the frequency and quality of communication processes.

H8: “Communication Process Improvements” have a direct and positive effect on “Short-term Outcomes”.

Enhanced communication processes are a decisive factor in realizing short-term project efficiencies, including faster decision-making, reduced rework, improved coordination, and timely task completion. Blockchain-based systems, which underpin improved communication, contribute to operational transparency, expedited information flow, and consensus-building among stakeholders. Zhang *et al.* (2023) identified that effective communication facilitated by blockchain minimizes payment delays and enhances supply chain coordination. Xu *et al.* (2023) emphasized that consistent and accurate information sharing reduces the risk of miscommunication, dispute escalation, and schedule slippage. Li *et al.* (2018) asserted that blockchain-driven communication infrastructure streamlines workflow management, directly impacting cost, time, and quality metrics. Improved communication enhances project responsiveness and resilience during early execution phases, yielding measurable short-term benefits that align with project performance goals.

H9: “Communication Process Improvements” have a direct and positive effect on “Long-term Outcomes”.

Robust communication systems not only yield immediate advantages but also create the institutional conditions necessary for sustained long-term value creation. Effective communication promotes organizational learning, strategic alignment, and digital innovation over extended time horizons. Ye *et al.* (2022) demonstrated that blockchain-enabled communication, via smart contracts and transparent data exchanges, cultivates a culture of collaboration and accountability that reduces disputes and enhances project continuity. Ozorhon *et al.* (2015) and Kifokeris and Tezel (2023) argued that consistent knowledge sharing and cross-organizational communication are critical enablers of innovation diffusion and digital transformation in construction. Qian and Papadonikolaki (2020) further highlighted the role of transparent communication in informed decision-making and stakeholder trust-building. Therefore, improvements in communication processes extend beyond project-level interactions to influence broader organizational capabilities and industry-wide digital maturity, serving as a cornerstone for long-term competitive advantage.

H10: “Short-term Outcomes” have a direct and positive effect on “Long-term Outcomes”.

Short-term project gains function as critical precursors to sustainable long-term outcomes. These immediate results accumulate over time, contributing to organizational learning, strategic resilience, and reputation building. Caglayan and Ozorhon (2023) asserted that repeated short-term project successes strengthen an organization’s capability to manage complexity, thereby enhancing its long-term positioning in the industry. Karacigan *et al.* (2023) confirmed that BIM-enabled short-term benefits, such as improved coordination and information quality, lay the foundation for enduring operational excellence. Safa *et al.* (2019) argued that blockchain supports long-term knowledge retention and innovation scaling by enabling secure data repositories and traceable workflows. Thus, the compounding effect of short-term improvements creates a reinforcing feedback loop that facilitates long-term strategic transformation, resilience, and industry leadership.

These hypotheses collectively provide a theoretical foundation for exploring the interactions among the constructs within the blockchain implementation framework, offering valuable insights into the mechanisms driving its adoption and impact in construction contract management. The developed framework is illustrated in Figure 3.2.

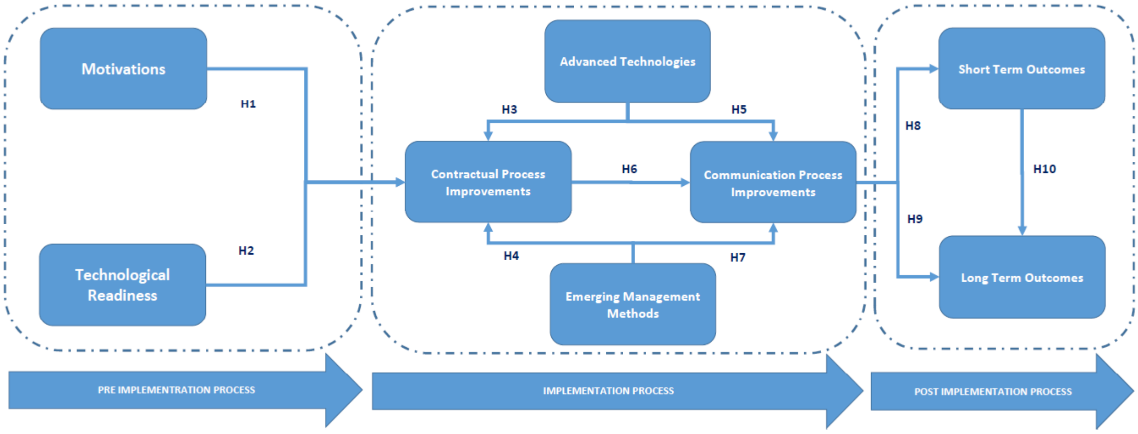

Figure 3.2. Initially developed framework.

3.1.2. Determination of the Critical Factors

To identify and refine the factors influencing blockchain adoption in the construction industry, an initial list was curated through an extensive review of the existing literature. This preliminary framework was subsequently validated and refined through consultations with three academic experts and two experienced industry professionals. Their insights led to modifications such as the elimination of redundant factors, reclassification of some elements, and consolidation under new, more coherent categories. The result was a streamlined and well-structured final list that better reflects the practical and theoretical considerations surrounding blockchain implementation.

3.1.2.1. Motivations. A total of six factors have been categorized under motivations cluster as below.

i. Competence of Project Staff (MT1): MT1 pertains to the level of technical expertise in blockchain possessed by the project team and the organization as a whole. According to Ozorhon *et al.* (2015), having sufficient engineering competence is a critical determinant for the successful implementation of innovative technologies within an organization. This perspective is supported by Sharma and Kumar (2020), who assert that a lack of blockchain knowledge can present significant challenges in its adoption, potentially leading to reduced stakeholder engagement and demotivation. Consequently, enhancing the technical capabilities of project staff is essential to overcome these barriers and ensure a smoother transition to blockchain integration.

ii. Willingness of Project Parties (MT2): MT2 reflects the level of enthusiasm demonstrated by all stakeholders toward the adoption of blockchain technology. Li and Kassem (2019) recommend establishing a dedicated task force for blockchain adoption, consisting of members from diverse project groups. Successful implementation hinges on the active involvement of all project parties, fostering a decentralized or distributed network that optimizes the potential benefits of blockchain technology (Li and Kassem, 2021). This collective engagement is crucial for driving innovation and aligning project goals with the broader vision of blockchain adoption.

iii. Company Experience (MT3): MT3 encompasses the extent of a company's accumulated knowledge and practical experience with digital construction applications, specifically in relation to blockchain technology. Ozorhon *et al.* (2015) contend that a company's prior involvement with similar technological advancements significantly influences its capacity to adopt new innovations. Building on this, Sharma and Kumar (2020) highlight that the depth of a company's experience with digitalization plays an important role in shaping its willingness to integrate blockchain, underscoring the importance of learning from past technological implementations to navigate the challenges of adoption effectively.

iv. Top Management Support (MT4): MT4 emphasizes the critical role of top management in providing unwavering support for the adoption of blockchain technology. Obidallah *et al.* (2024) identify management support as a key motivational factor that helps mitigate resistance to change during the implementation process. Furthermore, Li *et al.* (2022) argue that top management's active involvement is essential within the organizational framework to facilitate the successful adoption of blockchain within the construction industry. This leadership is necessary to guide and align organizational efforts, ensuring a smooth transition to innovation.

v. Budget and Investments (MT5): MT5 refers to the allocation of financial resources for the integration of blockchain technology within construction projects. Tezel *et al.* (2020) highlight that substantial investment is required to harmonize existing legacy digital systems with blockchain, presenting a challenge that often hinders adoption. Similarly, Prabhakar *et al.* (2023) emphasize that insufficient initial funding is a significant barrier to the successful implementation of blockchain applications. Adequate financial support is therefore critical for overcoming these obstacles and fostering innovation in digital construction practices.

vi. Competitive Pressure (MT6): MT6 illustrates the level of industry competition driving the adoption of blockchain technology, as well as the expectation of gaining a competitive advantage from its implementation. Fernando *et al.* (2021) suggest that intense industry rivalry compels organizations to adopt innovative solutions to maintain their competitive edge and ensure sustained relevance. Additionally, Li *et al.* (2022) have developed a framework that underscores competitive pressure as a pivotal environmental factor influencing blockchain adoption, highlighting how market dynamics shape the urgency for technological advancement.

3.1.2.2. Technological Readiness. A total of six factors have been categorized under technological readiness cluster as below.

i. Level of Industry Awareness (TR1): TR1 reflects the construction industry's understanding and perception of blockchain technology. Singh *et al.* (2023) identified limited industry awareness as a significant barrier to blockchain adoption, noting that insufficient knowledge regarding its potential hinders efforts to enhance productivity through technological integration. Similarly, Forcael *et al.* (2020) argued that the construction industry struggles to capitalize on innovative technologies due to a lack of awareness, which prevents firms from recognizing the full scope of blockchain's benefits.

ii. Availability of Guidelines and Standards (TR2): TR2 pertains to the development of industry-wide frameworks that provide guidance for blockchain implementation. Singh *et al.* (2023) underscored the necessity of structured guidelines to support informed decision-making and mitigate challenges associated with blockchain adoption. Caglayan and Ozorhon (2023) further emphasized that the presence of clear protocols and guidelines can foster companies' alignment with technological advancements, reducing uncertainty and enhancing the feasibility of blockchain implementation.

iii. Applicability of Technology (TR3): TR3 reflects the adequacy of technical infrastructure and the interoperability of blockchain with other technologies within the construction industry. Li *et al.* (2018) identified interoperability as a critical challenge for blockchain adoption, stressing the need for compatible systems to ensure seamless integration. Li *et al.* (2022) also pointed out that the technical compatibility of blockchain systems with existing infrastructures is a fundamental concern, requiring careful planning to ensure successful implementation.

iv. Availability of Benchmarks (TR4): TR4 refers to the presence of exemplary case studies and success stories that provide organizations with valuable insights into effective blockchain implementation. Ameyaw *et al.* (2023) emphasized the importance of case studies in identifying potential challenges, fostering trust, and guiding firms toward replicating successful blockchain applications. These benchmarks serve as educational tools, helping organizations navigate blockchain adoption by learning from proven experiences.

v. Feasibility of Pilot Trials (TR5): TR5 denotes the ease of conducting pilot projects that serve as a precursor to broader blockchain adoption. Li *et al.* (2022) identified trialability as a critical factor, highlighting the value of small-scale trials for evaluating blockchain's compatibility with practical industry needs. Ameyaw *et al.* (2023) further noted that pilot trials allow organizations to test blockchain in real-world settings, providing crucial feedback to refine its implementation before wider deployment.

vi. Convenience of Legal Infrastructure (TR6): TR6 refers to the alignment of blockchain technology with legal frameworks and regulatory requirements in the construction industry. Li and Kassem (2019) emphasized that legal uncertainties pose a major obstacle to blockchain adoption, particularly in areas such as contract management and compliance. Msawil *et al.* (2022) further supported this view, arguing that overcoming legal challenges is essential to enable blockchain-based solutions in contract management and other key applications.

3.1.2.3. Advanced Technologies. A total of seven factors have been categorized under advanced technologies cluster as below.

i. Building Information Modeling (BIM) (AT1): BIM refers to a digital modeling technology that integrates a comprehensive database containing project-related information, encompassing both the physical and functional characteristics of structures. Celik *et al.* (2023) highlighted that the integration of BIM with blockchain significantly improves the sharing of documents and project-related information, thereby amplifying the overall benefits of BIM. Ciotta *et al.* (2021) further emphasized that the combination of BIM and blockchain has become a central focus in current research, contributing to the advancement of more efficient and transparent project workflows.

ii. Geographic Information System (GIS) (AT2): GIS is a computer-based system designed to collect, analyze, and visualize geospatial data related to construction projects. Yoon and Pishdad-Bozorgi (2022) suggested that integrating blockchain with GIS facilitates the efficient collection and sharing of logistical data, thus streamlining supply chain operations and improving the accuracy of spatial data management in construction projects.

iii. Internet of Things (IoT) (AT3): IoT refers to a network of interconnected devices that facilitate the exchange of data among systems. Li *et al.* (2019) highlighted the potential for significant improvements by integrating blockchain with IoT, particularly in enhancing data transparency and security in construction projects.

Heiskanen (2017) and Wu *et al.* (2022) further pointed out that the combination of IoT and blockchain can optimize productivity by enabling more reliable data collection, monitoring, and automation of various construction processes.

iv. Radio Frequency Identification (RFID) (AT4): RFID utilizes radio waves to detect and identify tagged objects, providing real-time tracking capabilities. Lanko *et al.* (2018) introduced a framework for integrating RFID with blockchain, arguing that this combination enhances logistics management by improving the accuracy and traceability of supply chain operations. Ciotta *et al.* (2021) also highlighted RFID and blockchain integration as a prominent topic within existing research, emphasizing its role in enhancing operational efficiency.

v. Artificial Intelligence (AI) (AT5): AI involves the simulation of human intelligence in machines designed to mimic cognitive functions. Adel *et al.* (2022) proposed that decentralizing AI applications via blockchain represents a critical step toward advancing construction technologies. Li *et al.* (2018) further emphasized that combining AI with blockchain and smart contracts enables the automation, certification, and verification of complex processes, resulting in more efficient and high-quality outcomes.

vi. Big Data (AT6): Big Data refers to the analysis of large, complex datasets to identify patterns and correlations that support data-driven decision-making. Li *et al.* (2022) noted that large construction firms are increasingly leveraging big data analytics to gain a competitive advantage, which also facilitates the adoption of blockchain technology. Sun *et al.* (2023) reinforced this view, highlighting big data's potential in supporting blockchain-based solutions in the construction industry by enhancing data management and driving innovation.

vii. Robotics (AT7): Robotics refers to machines that perform tasks traditionally carried out by humans, often operating autonomously. The adoption of construction robotics has become increasingly prevalent, with many large firms conducting pilot projects. Robotics plays a key role in data capture, generating large volumes of real-time progress data that can be securely stored and shared within decentralized blockchain networks. Ye *et al.* (2022) noted that robotics, along with blockchain-enabled smart contracts, enhances project processes by facilitating data transparency and automation.

3.1.2.4. Emerging Management Methods. A total of three factors have been categorized under emerging management methods cluster as below.

i. Lean Construction (EM1): Lean construction is a project delivery methodology centered on maximizing stakeholder value while minimizing waste through optimized processes. Tezel *et al.* (2022) examined the intersection of lean construction and blockchain, proposing a conceptual framework that identifies 22 key points of interaction between the two concepts. Kifokeris and Tezel (2023) further noted that lean construction principles—particularly in areas such as management, procurement, and toolsets—can facilitate the integration of blockchain technology by promoting efficiency, reducing waste, and fostering collaboration.

ii. Integrated Project Delivery (IPD) (EM2): IPD is a collaborative approach that brings together people, systems, business structures, and practices to form a unified process. Hall *et al.* (2022) argued that blockchain technology has the potential to transform the construction industry by enabling Industry 4.0-compliant IPD applications. Kifokeris and Tezel (2023) further emphasized that blockchain can enhance trust and transparency in multi-party collaborations, which are characteristic of IPD systems, ultimately leading to more streamlined and efficient project execution.

iii. Agile Construction (EM3): Agile construction is a project management approach focused on adaptability, collaboration, and continuous improvement to respond to dynamic project environments. Institution of Civil Engineers (2018) highlighted that blockchain is integral to the digital transformation of the construction industry, necessitating agile strategic thinking to remain competitive. Pinna *et al.* (2020)

advocated for the use of agile methodologies in designing blockchain-enabled software systems, emphasizing their role in fostering flexibility and rapid response to technological advancements. Ozorhon *et al.* (2022) also reinforced that adopting agile construction enhances the industry's ability to manage change, which is critical for successfully integrating emerging technologies like blockchain.

3.1.2.5. Contractual Process Improvements. A total of six factors have been categorized under contractual process improvements cluster as below.

i. Automated Progress Tracking (CT1): CT1 involves the use of blockchain-based data infrastructures to track construction progress on-site automatically. Hamledari and Fischer (2020) conducted a comprehensive case study that demonstrated how integrating robotics and BIM with blockchain-enabled smart contracts enhances real-time progress tracking. The study emphasized that data collected during construction is timestamped and securely stored on a blockchain, ensuring its immutability and preventing unauthorized modifications by stakeholders. This feature improves the accuracy and reliability of project monitoring, offering enhanced transparency and reducing the potential for data discrepancies or manipulation.

ii. Automated Payment (CT2): CT2 refers to the automation of monthly progress payments to contractors and subcontractors via blockchain-based transaction systems. In the case study by Hamledari and Fischer (2020), payments were executed automatically based on the recorded progress data, ensuring that payments were made efficiently and without delays. Smart contracts with predefined conditions facilitated seamless payment transfers to the appropriate contractors or subcontractors, eliminating the need for manual intervention and reducing financial bottlenecks. This automation improves cash flow and reduces administrative overhead, enhancing overall payment efficiency and accuracy.

iii. Automated Material Tracking (CT3): CT3 pertains to the use of blockchain-based data infrastructures to track materials across the entire construction supply chain. Blockchain ensures secure and accurate tracking of materials, from raw material sources to factories, vendors, subcontractors, contractors, and project sites (Shojaei, 2019). Qian and Papadonikolaki (2020) noted that blockchain's ability to provide a reliable platform for supply chain management enhances the accuracy and transparency of material tracking. By preventing discrepancies and ensuring secure data transmission, blockchain helps improve inventory management and reduces delays in material procurement, ultimately leading to more efficient project execution.

iv. Improved Vendor Management (CT4): CT4 refers to streamlining the payment and transaction processes for vendors within a construction supply chain through blockchain-based systems. Nanayakkara *et al.* (2021) emphasized that blockchain technology reduces project delays caused by vendor-related issues by providing a transparent and efficient mechanism for vendor management. Blockchain-integrated supplier management systems enable vendors to showcase certifications and credentials, facilitating trust-based transactions without the need for traditional forms of verification. This reduces administrative burdens and enhances vendor accountability, contributing to smoother project operations.

v. Improved Data Management (CT5): CT5 signifies the secure and transparent storage and sharing of project data using blockchain-based infrastructures. Cheng *et al.* (2021) highlighted that data management is a critical area where blockchain offers substantial benefits, particularly in the construction industry. Hijazi *et al.* (2021) further demonstrated, through a case study, that storing BIM data on a blockchain network enhances the efficiency and accuracy of project data management. This not only ensures data integrity but also facilitates real-time access to accurate information, improving decision-making, collaboration, and reducing errors.

vi. Improved Change Management (CT6): CT6 refers to the use of blockchain-based systems to manage design changes efficiently, ensuring transparency and traceability throughout the project lifecycle. Ernst & Young (2018) noted that blockchain-enabled smart contracts reduce uncertainties related to project scope, allowing for more effective resolution of change orders and claims. This improvement in change management practices helps enhance project efficiency by ensuring that all stakeholders have access to real-time, verifiable data, reducing conflicts and delays associated with design modifications.

3.1.2.6. Communication Process Improvements. A total of seven factors have been categorized under communication process improvements cluster as below.

i. Advanced Data Traceability (CM1): CM1 primarily focuses on supply chain management and logistics, but its scope extends beyond these areas to include various phases of project development, such as design modifications, as-built documentation, manufacturer details, installation records, and scheduled maintenance or replacements (Li *et al.*, 2020). Gurgun *et al.* (2022) suggest that blockchain technology significantly enhances traceability in construction projects by providing an immutable and transparent record that ensures the integrity of information across the entire lifecycle of a project.

ii. Advanced Data Reliability (CM2): CM2 pertains to the accuracy, consistency, and trustworthiness of information exchanged among project stakeholders. Blockchain technology creates a secure and trustworthy environment for data exchange, fostering reliability in project information (Silva *et al.*, 2024). Tezel *et al.* (2020) further argue that decentralized autonomous organizations powered by blockchain offer reliable mechanisms for conducting transactions and managing information, reducing the likelihood of discrepancies and inaccuracies.

iii. Advanced Data Consistency (CM3): CM3 emphasizes the uniformity and synchronization of data across various systems and databases, ensuring that all instances of data are identical. The decentralized nature of blockchain guarantees that participants maintain immutable and synchronized records, contributing to data consistency within construction projects (Penzes, 2018). Blockchain-based applications ensure that shared data remains accurate and consistent, reducing potential conflicts due to differing data versions (Xu *et al.*, 2023).

iv. Enhanced Information Transparency (CM4): CM4 is critical for fostering trust among stakeholders by ensuring the availability and accessibility of relevant information to all parties involved. The decentralized structure of blockchain technology enhances information transparency by providing a shared, immutable record accessible to all stakeholders, facilitating more effective communication and decision-making (Rathnayake *et al.*, 2022).

v. Enhanced Information Security (CM5): CM5 refers to the protection of project data from unauthorized actions such as modification, disruption, or unauthorized access. Blockchain technology enhances information security by establishing secure, decentralized systems that prevent data tampering and unauthorized access (Nanayakkara *et al.*, 2021). Gurgun *et al.* (2022) also note that blockchain's role in securing payment transactions adds another layer of security, reducing the risk of fraudulent activities.

vi. Improved Trust Among Stakeholders (CM6): CM6 is essential as trust plays a crucial role in reducing disputes and fostering smoother project processes. The decentralized and distributed nature of blockchain technology addresses trust-related challenges by offering transparent, verifiable, and immutable records, thereby enhancing stakeholder trust compared to conventional systems (Nanayakkara *et al.*, 2021).

vii. Improved Collaboration Among Stakeholders (CM7): CM7 focuses on the importance of collaboration among project stakeholders, which is vital for the successful implementation of innovative technologies. Blockchain technology supports enhanced collaboration by facilitating real-time communication and establishing robust, transparent networks. Silva *et al.* (2024) argue that blockchain improves collaborative communication within projects, while Dounas *et al.* (2021) highlight its role in enhancing design collaboration within BIM environments.

<u>3.1.2.7. Short Term Outcomes.</u> A total of six factors have been categorized under shoert term outcomes cluster as below.

i. Reduced Number of Claims and Disputes (SO1): The construction industry has long grappled with the challenge of numerous claims, which often escalate into disputes if left unresolved, impacting project efficiency and stakeholder relationships (Rugina, 2021). Blockchain technology offers a promising solution for reducing such claims and disputes by enabling greater transparency, traceability, and automated processes (Gupta and Jha, 2023). Hamledari and Fischer (2021) further emphasize that blockchain's role extends to construction law informatics, dispute resolution, and enhancing overall contractual performance, thereby reducing the likelihood of claims and disputes.

ii. Eliminated Payment Issues (SO2): Payment disputes have historically posed significant challenges within the construction industry, often leading to project delays and financial conflicts. Blockchain technology, through the automation of payment systems and smart contracts, offers a means to resolve such disputes efficiently (Hamledari and Fischer, 2021). Gupta and Jha (2023) also propose that blockchain-based automated payment systems can ensure timely and secure payments, reducing the occurrence of payment-related conflicts.

iii. Reduced Risks (SO3): Minimizing risks is critical for stakeholders in construction projects, and blockchain technology plays a significant role in this regard by facilitating the sharing of risks and enabling risk mitigation through smart contracts (Silva *et al.*, 2024). According to Rathnayake *et al.* (2022), the adoption of blockchain-based systems helps reduce risks across the network, contributing to greater confidence among project participants and improving overall project outcomes.

iv. Accelerated Project Schedule (SO4): Timely project completion is a key performance indicator in the construction industry, and blockchain-enabled smart contracts offer mechanisms to automate workflows and expedite processes

(Rathnayake *et al.*, 2022). Li *et al.* (2018) further suggest that blockchain enhances workflow efficiency, which contributes to reduced project timelines and improved schedule performance.

v. Reduced Costs (SO5): Although the initial investment required for blockchain adoption may be significant, its long-term benefits in process automation and efficiency lead to substantial cost savings (Li *et al.*, 2022). Blockchain reduces transaction costs by eliminating the need for intermediaries, thus reducing overhead and fostering financial efficiency (Li *et al.*, 2018).

vi. Improved Client Satisfaction (SO6): Client satisfaction is a crucial factor for the success of construction projects, particularly when innovative technologies are integrated. Ozorhon *et al.* (2015) argue that the adoption of blockchain can enhance transparency, trust, and overall project efficiency, leading to improved client satisfaction through better service delivery and performance.

<u>3.1.2.8. Long Term Outcomes.</u> A total of six factors have been categorized under long term outcomes cluster as below.

i. Fostered Innovation and Digitalization (LO1): The adoption of new innovations in the construction industry often faces resistance due to a lack of supportive environments for change and inadequate collaboration (Ozorhon, 2013). Blockchain technology, by enhancing collaboration and facilitating effective knowledge management, provides a critical mechanism for fostering innovation and digitalization within the industry (Ozorhon *et al.*, 2015; Kifokeris and Tezel, 2023). Blockchain serves as a catalyst for transforming traditional practices and promoting the widespread adoption of innovative solutions, contributing to the digitalization and modernization of the construction industry.

ii. Automated Processes (LO2): Automation is a key advantage of blockchain technology, particularly in areas such as supply chain and payment management. Blockchain-enabled smart contracts automate various processes, reducing human intervention and enhancing efficiency (Rathnayake *et al.*, 2022). By streamlining operations, blockchain technology contributes to cost reduction, improved accuracy, and greater control over project workflows.

iii. Improved Decision-Making (LO3): Reliable, consistent, and transparent information is fundamental to effective decision-making. Blockchain technology enhances communication, providing stakeholders with accurate and trustworthy data, thereby supporting informed decision-making (Qian and Papadonikolaki, 2020). The adoption of blockchain in construction helps improve the quality and transparency of data, leading to better strategic decisions and project outcomes.

iv. Improved Brand Value (LO4): The adoption of blockchain technology can enhance a company's brand value by demonstrating a commitment to innovation and cutting-edge solutions. As Ozorhon *et al.* (2015) point out, integrating advanced technologies contributes to a positive corporate image, positioning companies as leaders in the adoption of new and disruptive innovations. Blockchain adoption reflects a company's forward-thinking approach, which can be a competitive advantage across industries.

v. Improved Sustainability (LO5): Sustainability extends beyond environmental concerns to encompass social and economic dimensions (Elkington, 1998). Blockchain technology promotes automation, transparency, and trust, which are integral to achieving sustainability goals (Pinna *et al.*, 2020). By fostering data integrity and reducing inefficiencies, blockchain enables more sustainable practices that benefit both environmental and social outcomes.

vi. Enhanced Knowledge Management (LO6): Blockchain technology provides secure, transparent, and traceable data storage, making it a powerful tool for effective knowledge management (Safa *et al.*, 2019). By enabling the secure sharing and access of critical information, blockchain supports improved knowledge management, both within organizations and across project networks, leading to long-term knowledge retention and dissemination.

3.2. Quantitative, Qualitative and Mixed Research Methods

Quantitative data is represented numerically, whereas qualitative data is conveyed through textual or verbal expressions (Abuhamda *et al.*, 2021). The integration of quantitative and qualitative methods enables researchers to capitalize on the strengths inherent in each approach while mitigating their respective limitations. Employing a mixed-methods design facilitates a more nuanced and holistic comprehension of the research domain. Accordingly, this study adopted a combined methodological framework comprising: (i) SEM as the quantitative component, and (ii) a focus group study as the qualitative component.

3.2.1. Quantitative Research Methods

Quantitative research is employed to quantify phenomena by generating numerical data or information that can be transformed into statistically analyzable formats (Tavakol and Sanders, 2014). This approach primarily seeks to understand the nature and extent of variation in phenomena, often through the application of statistical models and techniques. It facilitates the production of objective, generalizable insights by examining the relationship between independent variables and outcome or dependent variables, typically through descriptive and inferential statistical analyses (Abuhamda *et al.*, 2021).

One of the principal advantages of quantitative research lies in its efficiency. The use of statistical methods enables researchers to interpret and present findings in a time and cost effective manner, minimizing the need for extensive narrative explanation (Abuhamda *et al.*, 2021). Furthermore, the methodological rigor and standardized data collection techniques employed in quantitative research support the generalization of findings to broader populations. An additional strength of this approach is its replicability; due to its structured and transparent procedures, studies can be reproduced across different settings and timeframes, often yielding consistent results (Shank and Brown, 2007).

However, despite its strengths, quantitative research is not without limitations. A notable critique concerns the detachment between the researcher and the research participants (Shank and Brown, 2007). The method emphasizes objectivity to such an extent that it discourages interaction, potentially overlooking the subjective experiences and contextual nuances of the participants. Moreover, the linear and rigid structure of quantitative research constrains flexibility, limiting opportunities for participants to contribute beyond predefined parameters (Abuhamda *et al.*, 2021). As a result, the approach may restrict the scope for innovative, interpretive, and creative exploration, given its reliance on predetermined instruments and analytical frameworks.

3.2.2. Qualitative Research Methods

Qualitative research is characterized as exploratory in nature and is designed to uncover patterns in perceptions, experiences, and viewpoints (Abuhamda *et al.*, 2021). This methodological approach employs a variety of data collection techniques; including participant observation, in-depth interviews, document analysis, and focus group discussions to investigate complex social phenomena (Randall *et al.*, 2011). Like its quantitative counterpart, qualitative research is rigorous, systematic, and methodologically robust, offering a meaningful alternative for exploring topics that require contextual depth and interpretive insight. Its inherent flexibility enables researchers to pursue more open-ended and adaptive modes of inquiry.

Through direct observation and participant engagement, particularly in focus group settings, qualitative research facilitates a nuanced understanding of human behavior. This methodological orientation yields rich, contextually grounded data that reflects real-life conditions and experiences (De Vaus, 2014). The qualitative approach enables an in-depth exploration of human actions, encompassing interactions, cognitive processes, beliefs, and social norms. In this framework, data collection is highly contextual and individualized, with the researcher serving as the primary instrument for gathering non-numerical, narrative-based primary data (Abuhamda *et al.*, 2021). As such, qualitative research is particularly suited for generating detailed, descriptive insights.

Nonetheless, this approach is subject to certain criticisms. One primary concern relates to its perceived limitations in terms of replicability and generalizability (De Vaus, 2014). Critics argue that the interpretive and constructivist underpinnings of qualitative inquiry often diverge from the standardized procedures typically associated with the scientific method (Abuhamda *et al.*, 2021). The subjective orientation of qualitative research is criticized regarding the reliability and validity of its findings (De Vaus, 2014). The absence of numerical data further complicates efforts to generalize or simplify outcomes, leading some scholars to challenge the methodological rigor and empirical consistency of qualitative approaches.

3.2.3. Mixed (Combined) Research Methods

Quantitative and qualitative methodologies may be integrated through various strategies to leverage the respective strengths of each while mitigating their individual limitations (White, 2009). Among the commonly employed approaches to methodological integration are triangulation, sequencing, and cross-analysis.

<u>3.2.3.1. Triangulation.</u> Triangulation entails examining data from multiple perspectives, this may involve employing diverse data collection techniques, engaging different participant groups, or utilizing multiple researchers or evaluators. The primary aim of triangulation is to enhance the depth, reliability, and validity of the research findings. A frequent application of this approach includes juxtaposing data derived from both quantitative and qualitative methods to reinforce interpretive robustness (Simister and James, 2020).

<u>3.2.3.2. Sequencing.</u> Sequencing refers to the systematic arrangement of research phases, wherein one methodological approach informs or complements the other, rather than being conducted concurrently (Simister and James, 2020). A preliminary quantitative study might serve to delineate focal points for a subsequent, more context-sensitive qualitative inquiry. Illustrative examples include:

- Using qualitative data to formulate hypotheses subsequently tested through large-scale quantitative surveys;

- Analyzing quantitative findings at the population level and conducting in-depth qualitative investigations within specific subgroups or contexts;

3.2.3.3. Cross-analysis. Cross-analysis involves the synthesis of qualitative and quantitative data through reciprocal interpretive techniques. For instance, qualitative interpretation of quantitative outputs, such as tables or graphical representations, can enhance contextual understanding. Conversely, qualitative data can be systematically coded and transformed into quantifiable metrics, thereby facilitating statistical examination (Simister and James, 2020).

3.3. Questionnaire Survey

To collect empirical data and explore the relationships among the constructs outlined in the conceptual framework, a questionnaire survey was developed. To ensure accessibility and clarity, the questions avoided the use of complex terminology, given the relatively recent introduction of blockchain technology within the construction industry. The survey was further refined through feedback from three academic experts and two industry practitioners during preliminary trials, leading to a finalized version consisting of two distinct sections. The first section gathered demographic details from participants, while the second required respondents to evaluate the identified factors within the framework based on their personal perceptions, using a five-point Likert scale. The complete set of the questionnaire survey is provided in Appendix A.

Given that blockchain technology remains a novel concept, particularly within the construction industry, potential survey participants were identified through a targeted sampling approach. This strategy focused on individuals possessing relevant knowledge, expertise, and interest in the subject. The survey was distributed over a two-month period to 286 participants who met the specified criteria. The target group comprised both academics and practitioners with expertise in digital construction, construction management, or blockchain technology. Contact information for these individuals was sourced from industry databases and distributed via direct email or professional networking platforms such as LinkedIn. In cases where direct contact information was unavailable, the survey was disseminated through professional associations.

Many participants expressed strong interest in the survey, indicating that the topic aligned closely with their professional experience and areas of interest. A total of 155 fully completed questionnaires were received, yielding a response rate of 59%. This high level of engagement can be attributed to the use of personalized communication strategies and the growing prominence of blockchain technology, both of which contributed to increased participation compared to generic mass-distribution methods.

3.4. SEM Analysis

3.4.1. Definition & Characteristics

SEM is a widely utilized multivariate statistical technique that adopts a confirmatory approach to evaluate theoretical frameworks associated with specific phenomena (Byrne, 2012). This method enables the examination of complex structural relationships within a model, incorporating both observed and latent variables (Bollen and Long, 1993). SEM is also referred to as "Simultaneous Equation Modeling," "Analysis of Covariance (ANCOVA) Structures," and "Confirmatory Factor Analysis (CFA)" (Kline, 2015). By integrating CFA and path analysis, SEM facilitates the assessment of latent constructs using multiple observed indicators, making it a preferred analytical method in various disciplines (Bowen and Guo, 2011). Furthermore, SEM effectively mitigates bias by addressing measurement errors associated with observed variables and allows for the simultaneous testing of multiple hypotheses (Werner and Schermelleh-Engel, 2009).

SEM is characterized by two fundamental aspects: (i) causal relationships are expressed through a system of structural equations, and (ii) these relationships can be visually represented to facilitate a clearer understanding of the theoretical framework (Byrne, 2016). SEM primarily involves hypothesizing the definition of constructs based on a set of variables and examining the relationships among those constructs. This method supports both the development and empirical validation of theoretical models by illustrating interactions between observed and latent variables while simultaneously testing the formulated hypotheses (Schumacker and Lomax, 2016).

A critical distinction in SEM is made between observed and latent variables. Observed variables represent collected data that are recorded in a dataset, whereas latent variables refer to theoretical constructs that cannot be directly measured. Observed variables may take categorical or continuous forms, whereas latent variables are always continuous within the SEM framework. Unlike conventional statistical approaches, which are limited to analyzing only observed variables, SEM has the unique capability to incorporate both observed and latent variables in its analysis (Kline, 2015).

The construction of an SEM model necessitates the specification of causal directions among variables to align with the proposed hypotheses, making it a confirmatory analytical approach. However, if empirical data fail to support the theoretical model, modifications may be required (Kline, 2015). When a theoretical model is not validated by the sample data, researchers may either revise the existing model or propose and test an alternative theoretical framework (Schumacker and Lomax, 2016).

According to Kaplan (2009), conducting SEM analysis requires adherence to several key statistical assumptions:

- The data must follow a normal distribution.
- There should be no missing values in any of the variables.
- The structural equation model must include all relevant variables, ensuring that no essential variable is omitted from any equation.
- Independent variables should not be influenced by dependent variables.

The characteristics of various SEM software tools are summarized in Table 3.1. A total of eleven software tools are identified, categorized based on whether they function as standalone programs or as components, procedures, or commands within a broader statistical environment. Notably, only three of these SEM tools are available free of charge. The software packages are associated with different statistical environments, including R (sem, lavaan, lava, systemfit, OpenMx), SAS/STAT (CALIS), Stata (Builder, sem, gsem), STATISTICA (SEPATH), and SYSTAT (RAMONA).

Table 3.1. Structural equation modeling tools (Kline, 2015).

Computer Tool	Batch (Syntax)	Wizard (Template)	Drawing Editor
AMOS	X	X	X
EQS	X	X	X
LISREL	X	X	X
Mplus	X	X	X
Ωnyx			X
sem, lavaan, lava, systemfit	X		
OpenMx	X		
CALIS	X		
Builder, sem, gsem	X	X	X
SEPATH	X	X	
RAMONA	X		

This study employed SEM as the primary analytical tool for evaluating the relationships within the developed conceptual framework. The AMOS tool within IBM's SPSS software was used to conduct SEM analysis. The initial model was designed to represent the blockchain implementation process in construction contract management, illustrating the structural relationships among key constructs. Ten hypotheses were formulated to explore the interconnections among these constructs.

A crucial consideration in SEM application is the sample size, as an adequate number of responses is necessary to ensure statistical reliability. Bagozzi and Yi (2012) recommend a minimum sample size of 100 for SEM to yield valid results. Additionally, Xiong *et al.* (2015) conducted an analysis of 84 SEM applications in the construction industry, revealing that 26 models used fewer than 100 samples, 39 models were based on sample sizes ranging from 100 to 200, and 19 models relied on more than 200 samples. Given this precedent, the adoption of SEM in this study was deemed methodologically appropriate for assessing the proposed framework and deriving meaningful insights from the collected data.

3.4.2. Modeling Steps

The process of model development in SEM consists of several key stages: model specification, model estimation, model testing, and model modification.

In SEM, models represent a series of statistical assertions regarding the relationships between observed and latent variables. These relationships are generally linear, similar to other linear modeling techniques (Hoyle, 2012). The specification of measurement and structural models is guided by prior research and theoretical foundations. In a measurement model, observed variables are linked to an underlying latent variable, whereas a structural model defines the relationships among latent variables.

SEM model estimation is broadly categorized into two approaches: single-equation methods and simultaneous methods. Single-equation methods assess individual equations independently without requiring the assumption of multivariate normality. However, they do not facilitate an assessment of overall model fit, as they focus on evaluating local model fit. Conversely, simultaneous methods estimate all free model parameters concurrently, prioritizing global model fit assessment (Kline, 2015).

Model testing in SEM involves the evaluation of model fit using multiple fit indices. (i) Chi-square (χ^2); This statistical test assesses whether a significant discrepancy exists between observed and expected values in the model. A chi-square value of zero signifies a perfect model-data fit (Kline, 2015). (ii) Comparative Fit Index (CFI); This incremental fit index assumes no correlation among latent variables and compares the sample covariance matrix against a null model. Its values range from 0 to 1, with a threshold of 0.90 indicating an acceptable fit and values above 0.95 representing a good fit (Hooper *et al.*, 2008; Bowen and Guo, 2011). (iii) Tucker-Lewis Index (TLI); Originally introduced by Tucker and Lewis (1973) for factor analysis and later extended to SEM, the TLI compares a specified model to a null model. Like the CFI, TLI values close to 0.90 or 0.95 indicate a well-fitting model (Schumacker and Lomax, 2016). (iv) Root Mean Square Error of Approximation (RMSEA); This index quantifies model misfit per degree of freedom, allowing researchers to assess the extent of model misspecification. RMSEA values below 0.080 or 0.100 are generally considered acceptable (Hoyle, 2012).

If a model fails to adequately fit the data, modifications may be necessary. However, researchers are discouraged from arbitrarily altering the structural model by adding or removing paths unless such changes are theoretically justified. A practical approach to improving model fit is to introduce an error covariance term between observed variables in the measurement model (Schumacker and Lomax, 2016).

3.4.3. Validity of Measures

The validity of measurement instruments is evaluated using two primary concepts: content validity and construct validity. (i) Content Validity; This aspect assesses whether the test items adequately represent the domain they are intended to measure. Unlike other validity measures, content validity is established based on expert judgment rather than statistical analysis. (ii) Construct Validity; This evaluates the extent to which a hypothetical construct is accurately measured by a given test or experiment. Since no single definitive test can confirm construct validity, it must be demonstrated through multiple sub-tests, including scale reliability, discriminant validity, and convergent validity.

- Scale Reliability: This measures the internal consistency of a scale, reflecting the uniformity of responses across different items within the same measure. Cronbach's alpha is commonly used to assess this reliability.
- Discriminant Validity: This ensures that measures intended to be unrelated do not exhibit significant correlation. Discriminant validity is supported when the inter-correlation among these measures is low.
- Convergent Validity: In contrast to discriminant validity, convergent validity verifies that measures expected to be related are indeed correlated. This is typically assessed through overall model fit indices and factor loadings.

3.4.4. Model Development

The developed model, illustrated in Figure 3.3., consists of both observed and latent variables. In the model, eight latent variables are depicted within larger circles, each comprising a set of observed variables represented as squares. Additionally, all latent and observed variables are associated with residual (error) variables, which are indicated by smaller circles.

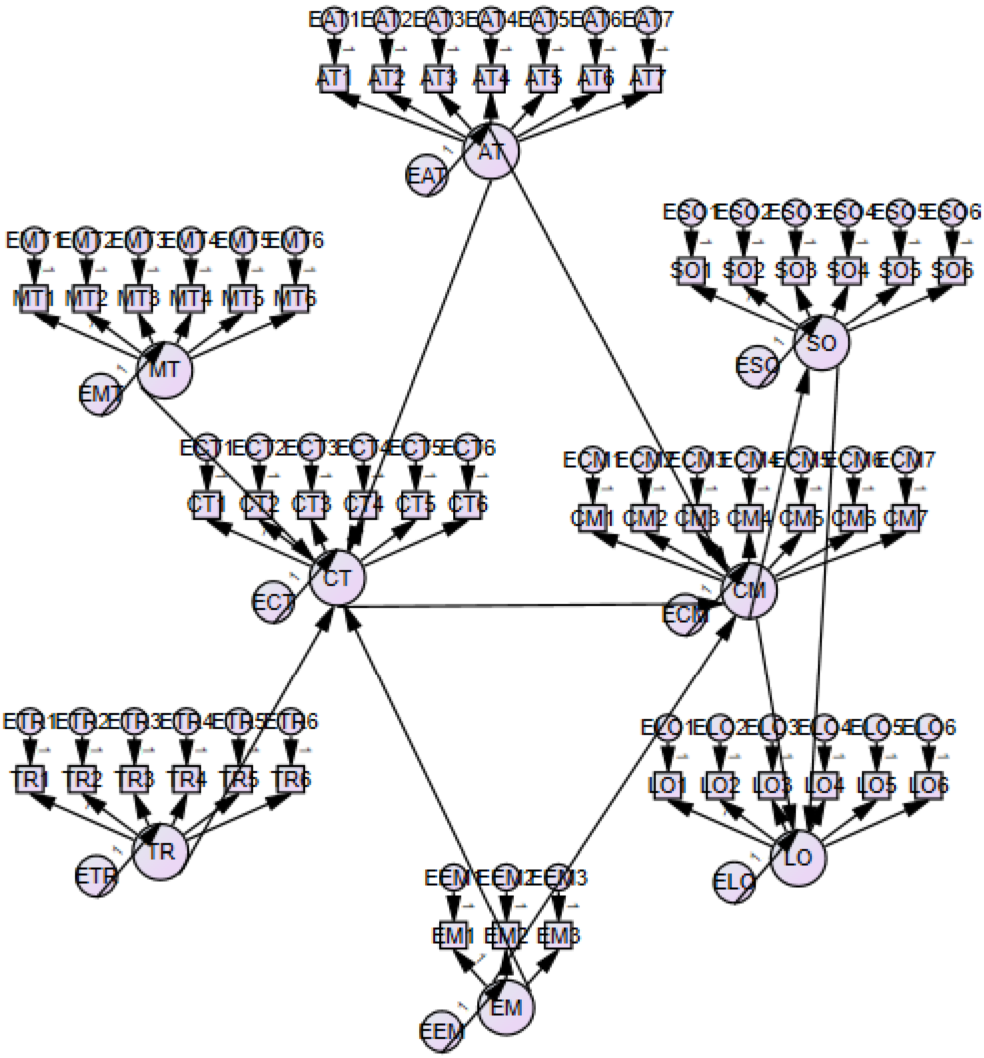

Figure 3.3. Model developed in IBM SPSS AMOS.

3.5. Development of the Strategic Roadmap

The development of a structured roadmap for the adoption of emerging technologies serves as both a strategic and operational framework that guides organizations and industries toward successful integration and long-term sustainability (Daim and Oliver, 2008). A well-defined roadmap not only provides a clear trajectory for implementation but also facilitates the identification of key challenges, enablers, and necessary interventions at various levels.

Several studies in the existing literature have proposed roadmaps for the integration of blockchain technology into construction projects. Singh *et al.* (2023) examined the barriers to blockchain adoption within the Indian context and developed a roadmap comprising short-, medium-, and long-term recommendations structured across five distinct stages to address these challenges. Similarly, Li and Kassem (2019) formulated a four-stage roadmap aimed at fostering macro-level readiness for the adoption of DLT in the construction industry, with an emphasis on facilitating the diffusion of DLT for specific application scenarios as presented in Figure 3.4.

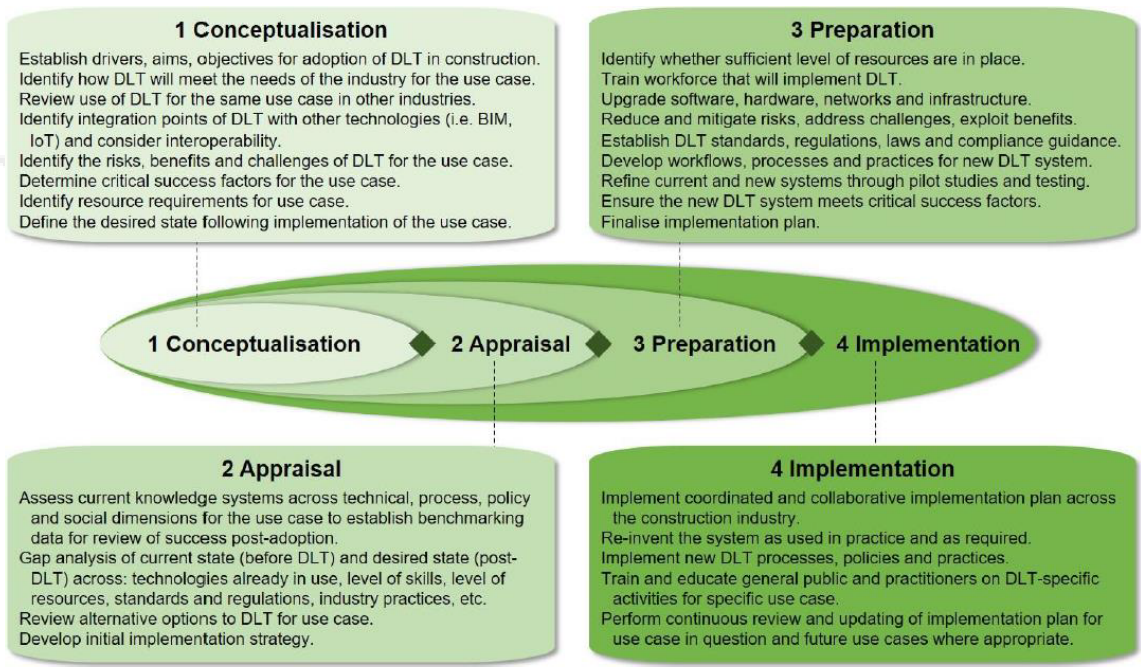

Figure 3.4. Li and Kassem's (2019) DLT roadmap.

Furthermore, Jayarathna *et al.* (2025), utilized the delphi method through semi-structured interviews and introduced a roadmap that integrates circular economy principles with blockchain to enhance construction waste management practices. Different than the existing roadmaps, this research adopts a broader perspective that spans from pre-implementation to post-implementation phases. It offers granular, strategically oriented recommendations and is not constrained to a specific national context as presented in Figure 3.5.

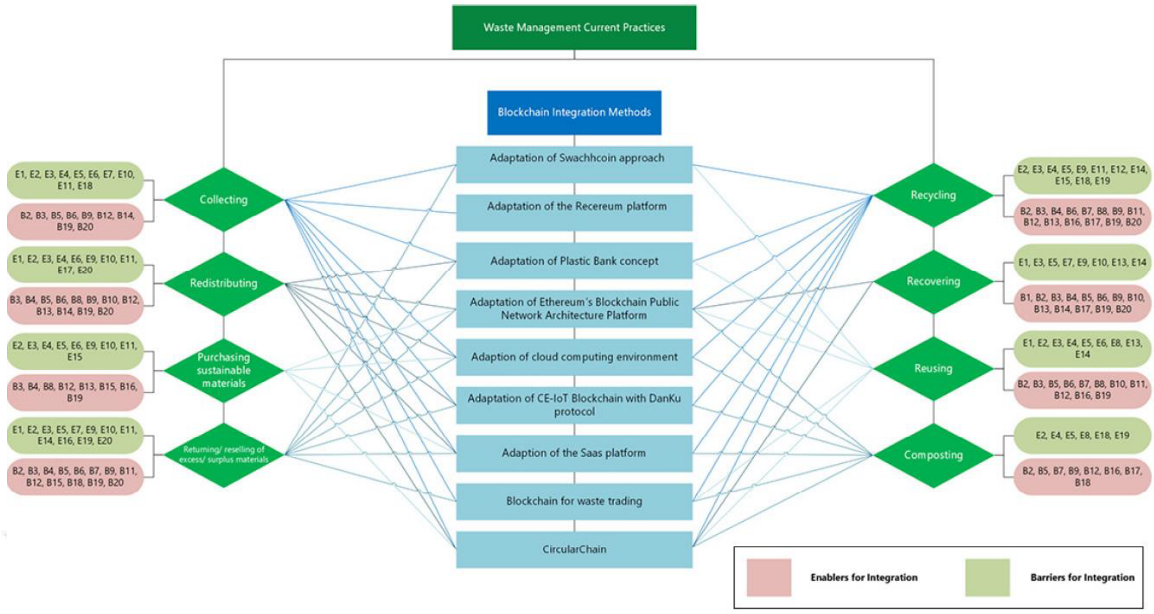

Figure 3.5. Roadmap for blockchain enabled construction waste management (Jayarathna *et al.*, 2025).

A comparative analysis of blockchain implementation in other industries such as finance and logistics reveals key success factors applicable to the construction industry. These include the establishment of standard protocols, early engagement of stakeholders, and alignment with regulatory frameworks. For instance, the logistics industry has demonstrated "GS1 protocol" as a global standard for blockchain network users to scale enterprise adoption which could enhance construction supply chain coordination (Clohessy, 2023). Similarly, the finance and banking industries' adoption of blockchain enabled smart contracts underscores the importance of legal and institutional readiness (Javaid *et al.*, 2022). Early engagement with legal bodies is crucial for adoption. By incorporating these cross-industry insights, the proposed roadmap is not only grounded in industry-specific analysis but also informed by proven strategies from adjacent domains, thereby strengthening its practical relevance and applicability.

Within the scope of this research, a comprehensive roadmap was developed to facilitate the construction industry's adoption and implementation of blockchain-based applications in contract management. The initial conceptualization of this roadmap was carried out by a group consisting of three academic experts and two industry practitioners, leveraging their combined knowledge of blockchain technology, construction management, and digital transformation. Following its initial development, the roadmap underwent further refinement through a focus group study, where additional insights were incorporated to enhance its applicability and effectiveness.

The final roadmap is structured into distinct phases, each representing critical stages in the adoption process. Within these phases, specific recommended actions are outlined at three hierarchical levels: project, organizational, and industry-wide. At the project level, the roadmap highlights key implementation steps necessary for integrating blockchain solutions into construction contracts and workflows. At the organizational level, it provides strategic guidance on capacity building, stakeholder engagement, and infrastructure readiness. Lastly, at the industry level, the roadmap underscores broader systemic changes required, such as regulatory adaptations, standardization efforts, and collaborative initiatives to drive widespread blockchain adoption.

By providing a phased and multi-tiered approach, this roadmap serves as a structured guide to support stakeholders in navigating the complexities of blockchain implementation in construction contract management, ensuring that both immediate operational needs and long-term strategic objectives are effectively addressed.

3.6. Focus Group Study

A focus group study was conducted as a supplementary qualitative approach to validate the findings derived from the SEM analysis and to further refine the strategic roadmap. The primary objective of the focus group was to achieve a consensus on the research findings by critically assessing key insights, validating the relationships identified in the SEM analysis, and enhancing the proposed roadmap for blockchain implementation in construction contract management.

Focus group is a widely recognized qualitative research method, typically involving six to twelve participants to facilitate in-depth discussion and collective analysis (Guest *et al.*, 2006). In this study, the focus group session lasted for two hours and included ten participants, comprising four industry practitioners and six academics. This diverse composition ensured a balanced representation of both theoretical and practical perspectives, thereby enriching the discussion with insights from both academic research and industry experience.

The session commenced with a brief presentation by the research team, outlining the study's objectives, methodology, and key findings from the SEM analysis. Following this introduction, the participants engaged in an interactive discussion guided by open-ended questions designed to evaluate the critical factors within each construct of the proposed framework. In the subsequent phase, the focus shifted toward analyzing the implications of the findings, with participants providing feedback on the relationships identified through SEM.

A key component of the session involved a structured review of the strategic roadmap. Participants were encouraged to critically examine the roadmap's structure, feasibility, and practicality. Their insights and recommendations were recorded to refine the proposed strategy. To enhance collaboration and allow for extended engagement beyond the in-person session, an online collaborative platform was utilized. A shared board page was developed, granting participants access for one week after the focus group session. This enabled them to contribute additional insights, refine key points, and suggest further modifications.

The iterative nature of this process allowed for a more comprehensive and well-informed strategic roadmap, integrating a broad spectrum of expert opinions and practical considerations. As a result, the final roadmap presents a more robust and actionable guide for the adoption of blockchain-based solutions within construction contract management. Figure 3.6. below provides an illustration of the structured flow of the focus group study, depicting its key phases and discussion points.

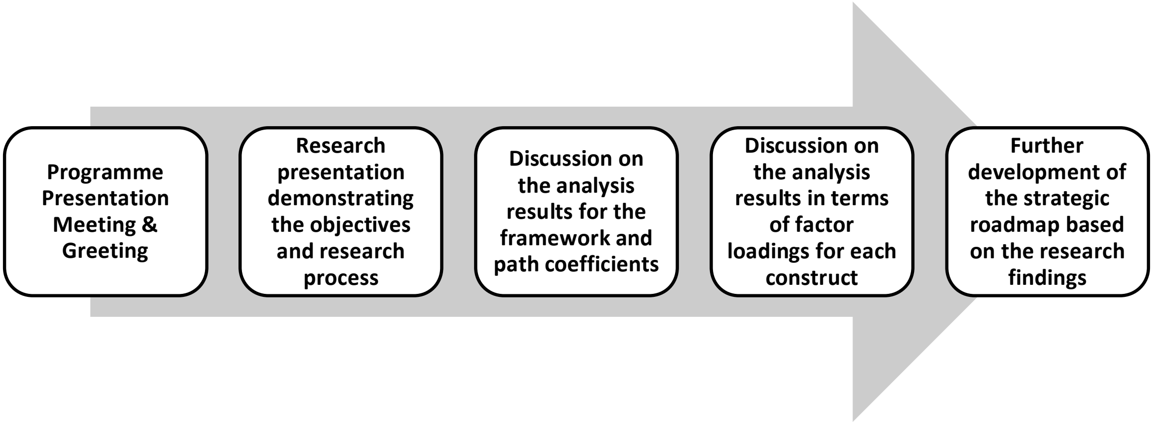

Figure 3.6. Organization of the focus group study.

4. RESEARCH RESULTS

4.1. Demographics of Survey Participants

4.1.1. Respondent Profiles

As per the followed targeted sampling strategy, survey respondents were consisting of individuals possessing relevant knowledge, expertise, and interest in blockchain technology and construction contract management. A total of 155 fully completed questionnaires were collected, with participants including both academics and practitioners specializing in digital construction, construction management, or blockchain technology. The targeted sampling strategy ensured that the participants possessed relevant expertise, leading to an average blockchain familiarity of nearly five years. Furthermore, the respondents have an average of 16 years of experience in the construction industry, with most professionals having between 10 and 25 years of industry experience. Additionally, respondents are familiar with the construction contracts for an average of 11 years.

The survey findings reveal a well-distributed representation of professionals across various positions within the construction industry. 29% of the respondents are working either as an engineer or architect whereas 23% are working as managers, 9% as directors and 8% are a part senior management. Additionally, 6% of the respondents consisting of owners and board members and 18% are academicians. Below Figure 4.1. shows the distribution of respondents' positions.

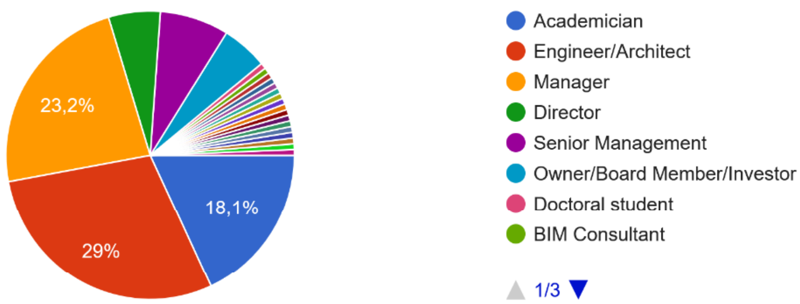

Figure 4.1. Respondents' positions.

The professional roles of the respondents indicate a strong managerial presence, with approximately 45% occupying senior management, director, or managerial positions. Engineers and architects constitute 30% of the respondents, further reinforcing technical expertise within the participant pool.

Respondents are also well distributed in terms of the role of their companies within the construction industry. Specifically, 28% of respondents are employed in consultancy firms, whereas 27% are employed in contractors, 18% are affiliated with academic institutions and 8% are working for designer companies. Below, Figure 4.2. shows the distribution of respondents' employment.

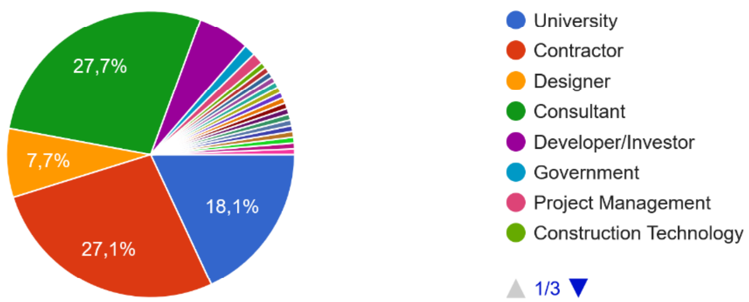

Figure 4.2. Respondents' employment.

Regarding geographic distribution, nearly half of the survey participants are based in Turkey, while 12% of respondents are from United States followed by the United Kingdom and European Union each with 11% of the participants. Additionally, Arab Countries constitute almost 7%. This global representation provides a broad perspective on blockchain adoption trends in the construction industry. Figure 4.3. shows the geographic distribution of the participants.

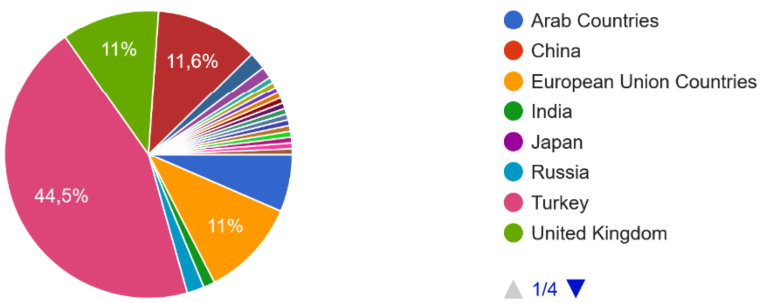

Figure 4.3. Respondents' geographic distribution.

4.1.2. Company Information

Research results indicate that most of the companies participating in the research are well established and highly experienced organizations. Almost 20% of the respondents' companies have over 100 years of experience whereas 40% have 11 to 50 years of experience. Additionally, 20% of them have less than 11 years of experience. Below Figure 4.4. shows the overall distribution regarding company experience.

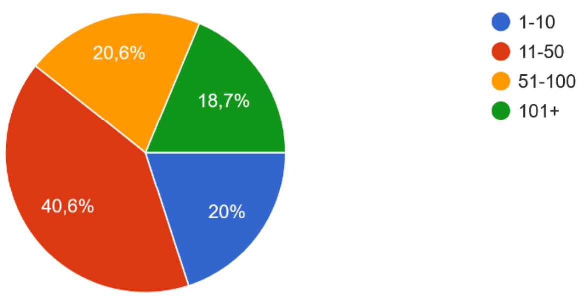

Figure 4.4. Distribution of company experience.

Company size and financial scale were also considered in the analysis. Over half of the survey respondents are employed by organizations with more than 1,000 employees and annual revenues exceeding 100 million USD. This finding also suggests that large-scale enterprises, which are more likely to invest in innovative technologies, are well-represented in the study. Figure 4.5. and Figure 4.6. below show the distribution of employee numbers and annual revenues of the companies respectively.

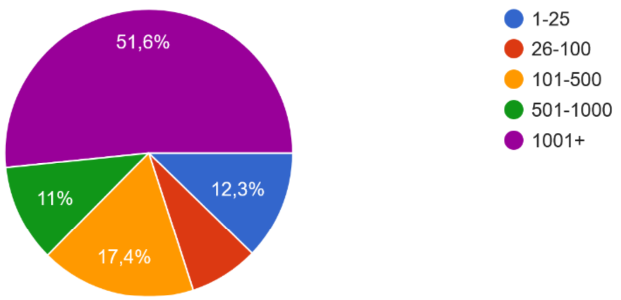

Figure 4.5. Distribution of employee numbers.

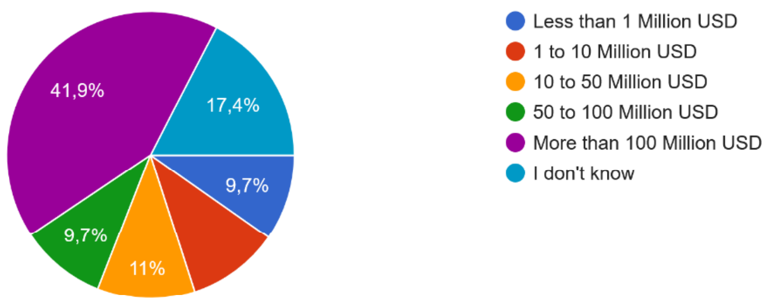

Figure 4.6 Distribution of annual revenues.

Findings show that companies are mostly expertized in commercial and residential building projects followed by infrastructures projects, industrial projects and airport projects. Finally, 57% of participants expressed confidence in the widespread adoption of blockchain in the construction industry, while 30% remained uncertain and 13% expressed skepticism.

4.1.3. Utilization of the Blockchain Technology

Research results indicate that 10% of the participants reported direct involvement in pilot blockchain implementations within construction projects, demonstrating firsthand experience with blockchain applications. Among them, 50% work for contractors and 30% work for consultancy companies. This finding shows that blockchain trials are mostly engaged via participation of contractors and consultants. To mitigate potential biases associated with perception-based responses, particularly given the infant stage of blockchain adoption, a targeted sampling strategy was employed. Participants were carefully selected based on their demonstrable experience and expertise in related subjects to ensure informed and relevant contributions.

In a multiple-choice and open-ended combined question, it is revealed that pilot trials of blockchain technology are mostly utilized for information management which is followed by payment management and supply chain management. Below, Figure 4.7. shows the distribution of trial utilizations for blockchain technology.

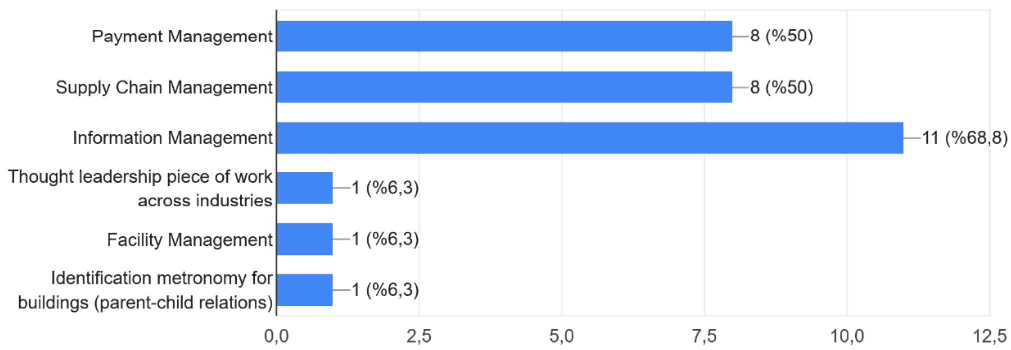

Figure 4.7. Distribution of trial utilizations for blockchain technology.

4.2. Demographics of Focus Group Experts

A focus group session was conducted to further examine the findings and refine the strategic roadmap. The session lasted for two hours and included ten participants, comprising four industry practitioners and six academics, ensuring a balanced blend of theoretical and practical insights. A moderator facilitated the discussion to ensure structured engagement and comprehensive evaluation of key topics. Table 4.1. presents detailed information regarding the focus group participants, providing an overview of their professional backgrounds and areas of expertise.

Table 4.1. Details of the focus group participants.

Code	Experience	Expertise	Title/Profession
P1 (Mod)	10+	Contract Management, Digitalization	Consultant
P2	10+	Contract Management	Contract Manager
P3	15+	Blockchain Technology, Digitalization	Academic
P4	20+	Innovation, Technology Adoption	Academic
P5	15+	Digital Construction	Academic
P6	15+	Blockchain Technology, Law	Founder & CEO
P7	15+	Project Management	Academic
P8	10+	Contract Management, Digitalization	Contract Manager
P9	10+	Digital Construction	Academic
P10	15+	Digital Construction	Academic

4.3. Descriptive Statistics

Descriptive statistics refer to a set of summary measures that utilize descriptive coefficients to provide an overview of specific characteristics within a data set. Among them, the central tendency indicators are namely the mean and median.

Central tendency represents the extent to which data points cluster around a central value, effectively summarizing an entire data distribution with a single representative figure. Among the key measures of central tendency, the mean and median are widely employed. The mean is derived by summing all values within the dataset and dividing the result by the total number of observations. This measure is often regarded as the most reliable estimate of central tendency (Tabachnick and Fidell, 2012).

Table 4.2. presents the mean values of factors categorized under the "Motivations" cluster. The results indicate that Top Management Support (MT4) and the Willingness of Project Parties (MT2) are the most highly rated factors, each achieving an average score above 4.00. This finding aligns with the general understanding that internal motivations serve as primary drivers for technological innovation. Conversely, Competitive Pressure

(MT6) and Company Experience (MT3) received the lowest scores, with mean values below 3.50. Given the relative novelty of blockchain technology in the construction industry, relying on organizational experience or competitive forces as catalysts for adoption may not be particularly relevant at this stage.

Table 4.2. Mean values of motivational factors.

No	Factors	Mean Values
MT4	Top Management Support	4.34
MT2	Willingness of Project Parties	4.02
MT5	Budget and Investments	3.93
MT1	Competence of Project Staff	3.82
MT6	Competitive Pressure	3.44
MT3	Company Experience	3.39

Table 4.3. illustrates the mean values of factors within the "Technological Readiness" cluster. Among these factors, the Applicability of Technology (TR3) received the highest mean value of 4.10, suggesting that respondents acknowledge the importance of clearly defining blockchain's application areas to highlight its potential benefits and compliance with legal frameworks. In contrast, Availability of Benchmarks recorded the lowest score, falling below 3.50. This result may indicate skepticism among participants regarding the utility of cross-industry benchmarking, given that the application of blockchain in construction is highly project-specific and depends on distinct project needs and conditions.

Table 4.3. Mean values of technological readiness factors.

No	Factors	Mean Values
TR3	Applicability of Technology	4.10
TR6	Convenience of Legal Infrastructure	3.90
TR2	Availability of Guidelines and Standards	3.84
TR1	Level of Industry Awareness	3.76
TR5	Feasibility of Pilot Trials	3.71
TR4	Availability of Benchmarks	3.48

Table 4.4. provides an overview of the mean values of factors grouped under the "Advanced Technologies" cluster. The findings suggest that Big Data (AT6) and BIM (AT1) are the most influential factors, both achieving mean values above 4.00. This result is consistent with the notion that blockchain technology enhances the security and integrity of

BIM-based project data, making the management of this process through big data technologies particularly vital. On the other hand, Robotics (AT7) recorded the lowest mean value, falling below 3.00, which may indicate that its integration with blockchain technology is not yet a primary concern for industry professionals.

Table 4.4. Mean values of advanced technologies.

No	Factors	Mean Values
AT6	Big Data	4.08
AT1	Building Information Modeling (BIM)	4.01
AT5	Artificial Intelligence (AI)	3.80
AT3	Internet of Things (IoT)	3.74
AT2	Geographic Information System (GIS)	3.30
AT4	Radio Frequency Identification (RFID)	3.14
AT7	Robotics	2.92

Table 4.5. outlines the mean values of factors classified under the "Emerging Management Methods" cluster. Among the factors, IPD (EM2) stands out with a mean value exceeding 4.00. This finding underscores the necessity of collaborative engagement among all project stakeholders for the successful implementation of blockchain technology in construction projects. The remaining factors in this cluster received relatively lower ratings, implying that while various management methods may facilitate blockchain adoption, the IPD approach is perceived as particularly crucial.

Table 4.5. Mean values of emerging management methods.

No	Factors	Mean Values
EM2	Integrated Project Delivery System	4.02
EM3	Agile Management Techniques	3.52
EM1	Lean Construction	3.41

Table 4.6. displays the mean values of factors within the "Contractual Process Improvements" cluster. Most factors in this category have mean values exceeding 4.00, suggesting that participants strongly believe contractual advancements are likely to accompany the adoption of blockchain technology. Notably, factors related to Data Management Applications received the highest scores, reinforcing the idea that blockchain's

core functionality revolves around establishing a robust and secure data management infrastructure.

Table 4.6. Mean values of contractual process improvements.

No	Factors	Mean Values
CT5	Improved Data Management	4.24
CT1	Automated Progress Tracking	4.24
CT2	Automated Payment	4.19
CT6	Improved Change Management	4.00
CT3	Automated Material Tracking	3.98
CT4	Improved Vendor Management	3.76

Table 4.7. summarizes the mean values of factors categorized under the "Communication Process Improvements" cluster. Similar to the contractual process improvements, most factors in this category received mean values above 4.00, indicating a consensus among participants that blockchain technology will significantly enhance communication processes. However, Improved Collaboration Among Stakeholders (CM7) received the lowest score (3.83). This result suggests that collaboration may be perceived more as a prerequisite for blockchain implementation rather than a direct outcome of its application.

Table 4.7. Mean values of communication process improvements.

No	Factors	Mean Values
CM1	Advanced Data Traceability	4.37
CM2	Advanced Data Reliability	4.25
CM4	Enhanced Information Transparency	4.25
CM3	Advanced Data Consistency	4.20
CM5	Enhanced Information Security	4.10
CM6	Improved Trust Among Stakeholders	4.05
CM7	Improved Collaboration Among Stakeholders	3.83

Table 4.8. presents the mean values for factors within the "Short Term Outcomes" cluster. Among the examined factors, Eliminated Payment Issues (SO2) emerged as the highest-rated, signifying the widespread expectation that blockchain will automate and streamline progress payment processes, thereby mitigating payment-related disputes. In contrast, Accelerated Schedule (SO4) and Reduced Costs (SO5) recorded the lowest scores.

This suggests that while blockchain may offer numerous efficiency gains, its impact on construction schedules and overall cost reduction is perceived as less immediate.

Table 4.8. Mean values of short term outcomes.

No	Factors	Mean Values
SO2	Eliminated Payment Issues	3.82
SO6	Improved Client Satisfaction	3.75
SO1	Reduced Number of Claims and Disputes	3.68
SO3	Reduced Risks	3.48
SO5	Reduced Costs	3.31
SO4	Accelerated Schedule	3.29

Table 4.9. provides an overview of the mean values of factors within the "Long Term Outcomes" cluster. The results indicate that Automated Processes (LO2) and Fostered Innovation and Digitalization (LO1) are the most highly rated, each scoring above 4.00. This highlights the expectation that blockchain will contribute to process automation and drive digital transformation in the long run. Conversely, Improved Sustainability (LO5) received the lowest mean score, possibly reflecting concerns regarding blockchain's well-documented high energy consumption, which may counterbalance its sustainability benefits in certain contexts.

Table 4.9. Mean values of long term outcomes.

No	Factors	Mean Values
LO2	Automated Processes	4.27
LO1	Fostered Innovation and Digitalization	4.22
LO6	Enhanced Knowledge Management	3.95
LO3	Improved Decision Making	3.92
LO4	Improved Brand Value	3.70
LO5	Improved Sustainability	3.57

4.4. Model Results

The SEM method was utilized to analyze the collected data, focusing on an initial model composed of eight constructs and ten hypotheses. The SEM analysis was conducted using IBM's SPSS AMOS software, a widely recognized tool for structural modeling and path analysis.

The preliminary results revealed that two hypotheses, H5 and H7, did not exhibit statistically significant relationships. Specifically, no meaningful connection was identified between the cluster of advanced technologies and communication process improvements, nor between emerging management methods and communication process improvements. As a result, these two non-significant pathways were removed to enhance the model's accuracy and reliability.

Following these refinements, a re-analysis of the modified model was undertaken to validate its revised structure and improve its overall model fit. This iterative approach ensured that the final model was both statistically robust and methodologically sound, accurately reflecting the relationships between the key constructs in the study.

4.4.1. Validity and Reliability of The Model

In the application of SEM, ensuring both validity and reliability is fundamental to the robustness of the proposed model. While statistical methods cannot directly assess content validity (Garver and Mentzer, 1999), it is instead established through expert judgment and systematic evaluation. To uphold content validity, a structured approach was adopted in the formulation of constructs and their relationships. This process commenced with an extensive literature review, followed by multiple discussion sessions with a panel of three academics and two industry professionals. These sessions facilitated the refinement of factors, leading to the consolidation or exclusion of certain elements. Ultimately, careful attention was devoted to verifying the selected factors, constructs, and their interconnections to ensure the conceptual integrity of the model.

Construct validity, a critical component of model assessment, encompasses scale reliability, convergent validity, and discriminant validity. Model reliability pertains to the strength of direct relationships within the structural model (Bollen and Long, 1993). Scale reliability was evaluated using two established statistical methods: Cronbach's Alpha, which measures internal consistency, and composite reliability, which is derived from reliability coefficients. In this study, Cronbach's Alpha values exceeded the widely accepted threshold of 0.70 (Nunnally, 1978), confirming internal consistency. Similarly, composite reliability was validated, with coefficients surpassing 0.60 (Ahmad *et al.*, 2016). The Cronbach's Alpha and composite reliability values for all constructs are presented in Table 4.10.

Table 4.10. Test results for reliability and convergent validity.

Latent Variables	Cronbach's Alpha	Composite Reliability	AVE
Motivations	0.808	0.810	0.647
Technological Readiness	0.901	0.901	0.776
Advanced Technologies	0.847	0.848	0.668
Emerging Management Methods	0.749	0.764	0.726
Contractual Process Improvements	0.849	0.851	0.700
Communication Process Improvements	0.901	0.905	0.763
Short Term Outcomes	0.888	0.888	0.756
Long Term Outcomes	0.873	0.874	0.733

Convergent validity determines whether observed variables adequately represent a single latent construct. This is typically assessed using Average Variance Extracted (AVE), which should ideally be greater than 0.50. However, if AVE values fall below this threshold, convergent validity can still be deemed acceptable provided that composite reliability exceeds 0.60 (Fornell and Larcker, 1981). In the current model, all AVE values met the required criteria, confirming convergent validity, as detailed in Table 4.10.

Discriminant validity, another crucial aspect, ensures that observed variables distinctly measure separate constructs rather than capturing overlapping elements. This is evaluated by comparing the correlations between constructs against the square root of the AVE for each construct (Byrne, 2012). The developed model successfully met these discriminant validity requirements, with all corresponding values reported in Table 4.11. Moreover, inter-correlations between the measures of the constructs need to be checked to satisfy discriminant validity (Byrne, 2016). The inter-correlations should be less than 0.90 to ensure that there is no multicollinearity (Hair *et al.*, 2010).

Table 4.11. Test results for discriminant validity.

Constructs	MT	TR	AT	EM	CT	CM	SO	LO
MT	0.805							
TR	0.800	0.881						

AT	0.569	0.521	0.817					
EM	0.466	0.455	0.578	0.852				
CT	0.649	0.593	0.712	0.526	0.837			
CM	0.601	0.540	0.529	0452	0.807	0.873		
SO	0.370	0.326	0.626	0.688	0.516	0.485	0.870	
LO	0.588	0.481	0.643	0.548	0.749	0.642	0.768	0.856

Additionally, the structural model's overall goodness-of-fit was assessed using multiple fit indices, including Cronbach's Alpha, the Chi-square statistic divided by degrees of freedom, the CFI, the TLI, and the RMSEA. These indices provide insight into how well the hypothesized model aligns with the observed data. Kline (1998) established threshold values for these fit indices, which serve as benchmarks for evaluating model adequacy. The corresponding fit indices for both the initial and finalized models, alongside their respective Cronbach's Alpha coefficients, are provided in Table 4.12. Notably, after refining the initial model by removing non-significant paths, the goodness-of-fit indices demonstrated significant improvements, ensuring that the finalized model conformed to the recommended statistical criteria.

Table 4.12. Goodness of fit indices.

Index	Recommended Value	Initial Model	Finalized Model
Cronbach's Alpha	>0.70	0.958	0.958
χ^2/dof	<3.00	2.103	1.770
CFI	0 (no fit) to 1 (perfect fit)	0.745	0.885
TLI	0 (no fit) to 1 (perfect fit)	0.731	0.852
RMSEA	<0.10	0.085	0.071

4.4.2. Path Coefficients

Upon completing the SEM analysis of the finalized model, all null hypotheses were supported, indicating statistically significant relationships between the constructs, albeit with varying degrees of strength. The path coefficients, which measure the magnitude and significance of these relationships, are presented in Table 4.13. To interpret these coefficients, the classification framework proposed by Murari (2015) was applied: values between 0.1 and 0.3 indicate a weak relationship, coefficients ranging from 0.3 to 0.5 suggest a moderate relationship, and values exceeding 0.5 represent a strong relationship.

Table 4.13. Results of the SEM analysis for path coefficients.

Hypothesis	Relationship	Path Coefficient
H1	Motivations -> Contractual P. Improvements	0.344
H2	Technological Readiness -> Contractual P. Improvements	0.225
H3	Advanced Technologies -> Contractual P. Improvements	0.479
H4	Emerging M. Methods -> Contractual P. Improvements	0.187
H5	Advanced Technologies -> Communication P. Improvements	Rejected
H6	Contractual P. Imp. -> Communication P. Improvements	0.786
H7	Emerging M. Methods -> Communication P. Improvements	Rejected
H8	Communication P. Improvements -> Short-Term Outcomes	0.469
H9	Communication P. Improvements -> Long-Term Outcomes	0.356
H10	Short-Term Outcomes -> Long-Term Outcomes	0.587

In the finalized model, Contractual Process Improvements demonstrated weak relationships with both Technological Readiness and Emerging Management Methods, suggesting that while these factors influence contractual improvements, their impact is limited. Conversely, moderate relationships were identified between Contractual Process Improvements and both Motivations and Advanced Technologies, indicating a more substantial yet not dominant influence.

Further, the analysis revealed moderate relationships between Communication Process Improvements and both Short Term and Long Term Outcomes, underscoring the role of enhanced communication in achieving project and organizational benefits over different time horizons. Notably, a strong relationship was observed between Contractual Process Improvements and Communication Process Improvements, highlighting the interconnected nature of these constructs improvements in contractual mechanisms are closely tied to enhancements in communication processes. Finally, another strong relationship was identified between Short Term Outcomes and Long Term Outcomes, affirming that the successful realization of short-term objectives positively contributes to achieving long term strategic goals.

4.4.3. Factor Loadings

A factor loading quantifies the strength of the relationship between an observed variable and its corresponding latent construct, serving as an essential indicator of how well each observed variable represents the underlying theoretical concept. Higher factor loadings suggest a stronger association, reinforcing the validity of the observed variable as a reliable measure of the construct.

Table 4.14. Results of the SEM analysis for factor loadings.

Construct	No	Observed Variable	Factor Loading
Motivations (MT)	MT1	Competence of Project Staff	0.676
	MT2	Willingness of Project Parties	0.747
	MT3	Company Experience	0.651
	MT4	Top Management Support	0.715
	MT5	Budget and Investments	0.602
	MT6	Competitive Pressure	0.450
Technological Readiness (TR)	TR1	Level of Industry Awareness	0.752
	TR2	Availability of Guidelines and Standards	0.801
	TR3	Applicability of Technology	0.783
	TR4	Availability of Benchmarks	0.756
	TR5	Feasibility of Pilot Trials	0.781
	TR6	Convenience of Legal Infrastructure	0.779
Advanced Technologies (AT)	AT1	Building Information Modeling (BIM)	0.667
	AT2	Geographic Information System (GIS)	0.704
	AT3	Internet of Things (IoT)	0.796
	AT4	Radio Frequency Identification (RFID)	0.674
	AT5	Artificial Intelligence (AI)	0.562
	AT6	Big Data	0.583
	AT7	Robotics	0.665
Emerging Management Methods (EM)	EM1	Lean Construction	0.722
	EM2	Integrated Project Delivery System	0.542
	EM3	Agile Management Techniques	0.875
Contractual Process Improvements (CT)	CT1	Automated Progress Tracking	0.673
	CT2	Automated Payment	0.575
	CT3	Automated Material Tracking	0.606
	CT4	Improved Vendor Management	0.561
	CT5	Improved Data Management	0.727
	CT6	Improved Change Management	0.639
Communication Process Improvements (CM)	CM1	Advanced Data Traceability	0.814
	CM2	Advanced Data Reliability	0.800
	CM3	Advanced Data Consistency	0.818
	CM4	Enhanced Information Transparency	0.749
	CM5	Enhanced Information Security	0.688
	CM6	Improved Trust Among Stakeholders	0.599
	CM7	Improved Collaboration Among Stakeholders	0.546

Short Term Outcomes (SO)	SO1	Reduced Number of Claims and Disputes	0.714
	SO2	Eliminated Payment Issues	0.640
	SO3	Reduced Risks	0.767
	SO4	Accelerated Schedule	0.816
	SO5	Reduced Costs	0.806
	SO6	Improved Client Satisfaction	0.728
Long Term Outcomes (LO)	LO1	Fostered Innovation and Digitalization	0.642
	LO2	Automated Processes	0.680
	LO3	Improved Decision Making	0.749
	LO4	Improved Brand Value	0.697
	LO5	Improved Sustainability	0.747
	LO6	Enhanced Knowledge Management	0.771

In the SEM analysis of the finalized model, as presented in Table 4.14., the factor loadings for the observed variables were evaluated to ensure their adequacy in representing their respective latent constructs. The results indicate that all observed variables exhibited factor loadings greater than 0.5, demonstrating a sufficient level of correlation between the indicators and their constructs. The only exception was MT6 – Competitive Pressure, which had a factor loading below the 0.5 threshold.

A factor loading below 0.5 suggests that the respective variable may have a weaker contribution to explaining the latent construct, which may necessitate further investigation. Despite this exception, the overall model retained its integrity, as the majority of observed variables displayed sufficiently high factor loadings, reinforcing the reliability of the measurement framework used in the study.

5. DISCUSSION

5.1. Evaluation of the Model Framework and Path Coefficients

The successful adoption of emerging technologies within the construction industry requires the development of strategic, well-informed implementation frameworks rooted in a comprehensive understanding of underlying processes (Ozorhon, 2013). A key factor in this process is recognizing the dynamic interactions among various elements that shape the effectiveness of technological integration. Without a thorough analysis of these interconnections, organizations may struggle to maximize the potential benefits of novel solutions.

5.1.1. H1: "Motivations" have a direct and positive effect on "Contractual Process Improvements"

The results of this study indicate that motivational factors significantly influence the improvement of contractual processes in blockchain adoption, aligning with Li *et al.* (2022), who emphasized motivation as a core determinant of implementation success. The path coefficient of 0.344 underlines that companies with strong motivations are more inclined to initiate digital transformation efforts. This reinforces the view of Ozorhon (2013), who contended that successful innovation requires a strategic alignment between organizational will and implementation capacity. The focus group discussions reinforced this perspective, with participants asserting that highly motivated firms tend to proactively overcome adoption barriers, regardless of technological challenges. This underscores that organizational motivation is not only a prerequisite but also a critical enabler of blockchain-driven contractual enhancements, capable of compensating for broader technological or institutional immaturity. This observation aligns with the conclusions drawn by Obidallah *et al.* (2024), who emphasized the crucial role of motivation as a catalyst for blockchain adoption.

5.1.2. H2: "Technological Readiness" has a direct and positive effect on "Contractual Process Improvements"

Although technological readiness positively affects contractual process improvements, the relatively modest coefficient (0.225) suggests its role is enabling rather than determinative, which partially aligns with Ozorhon (2013)'s framework that emphasized the infrastructural prerequisites of innovation. However, when compared with the stronger effect of motivation (H1), these findings suggest a deviation from technology-push narratives that assume readiness alone leads to adoption. Li *et al.* (2022) similarly observed that technological capacity must be activated by strategic intent, without which it remains underutilized. Hence, technological readiness is best understood as a necessary but insufficient condition, requiring alignment with broader motivational and strategic drivers to effect contractual transformation. Specifically, the findings suggest that construction companies driven by strong motivations are more likely to adopt blockchain-based solutions, even in an environment characterized by industrial immaturity and technological uncertainty.

5.1.3. H3: "Advanced Technologies" have a direct and positive effect on "Contractual Process Improvements"

Advanced digital technologies represent the most influential factor in driving contractual improvements (0.479), highlighting the importance of technological complementarity. This finding aligns strongly with Qian and Papadonikolaki (2020), who demonstrated that blockchain, when integrated with BIM and IoT, delivers measurable gains in transparency and supply chain coordination. It also reinforces Li *et al.* (2022)'s assertion that blockchain's potential is maximized when embedded within a digital ecosystem. Focus group discussions further supported this, with Participant P3 indicating blockchain, combined with RFID, allowed real-time material tracking that reduced disputes and shortened delivery schedules. These insights collectively affirm that advanced technologies act as strategic accelerators, enhancing the contractual value proposition of blockchain through automation, traceability, and real-time control.

5.1.4. H4: “Emerging Management Methods” have a direct and positive effect on “Contractual Process Improvements”

Although emerging management methods contribute positively to contractual process improvements, their effect is marginal (0.187), suggesting a supportive rather than primary role. This finding challenges the assertion by Tezel et al. (2022) that lean methodologies and IPD approaches can independently foster blockchain adoption. Instead, the results imply that such methods create a collaborative and process-oriented culture, which may facilitate implementation but does not guarantee it. During the focus group study, P6 stated that lean and IPD just help to create a culture that supports blockchain. These findings nuance previous claims by Ozorhon (2013) by highlighting that management innovations require technological or motivational scaffolding to generate an impact. Thus, blockchain integration is more effectively facilitated when aligned with existing technological infrastructures rather than relying solely on new management practices. The present study indicates that management-based innovations alone may not exert a direct influence on blockchain adoption. Instead, their impact is likely to be mediated indirectly through other critical factors.

5.1.5. H5: “Advanced Technologies” have a direct and positive effect on “Communication Process Improvements”

Interestingly, despite the recognized importance of technological advancements, the rejection of Hypotheses H5 suggests that advanced technologies do not directly contribute to communication process improvements. This finding deviates from Ozorhon’s (2013) assertion that innovation plays a key role in enhancing communication processes. Instead, it indicates that technological advancements may influence communication only indirectly, primarily through their impact on contractual processes. This discrepancy can be explained by the mediating role of contractual mechanisms, as supported by the qualitative data. This perspective was further reinforced by Participant P9 in the focus group discussions, who argued that while advanced technologies provide supportive frameworks, their real impact on communication processes emerges through contractual improvements rather than direct intervention. Thus, while Qian and Papadonikolaki (2020) emphasized the integrative power of technology, this study refines their argument by identifying contractual architecture as the critical pathway for activating those capabilities.

5.1.6. H6: "Contractual Process Improvements" have a direct and positive effect on "Communication Process Improvements"

One of the most critical findings of this study is related to Hypothesis H6, which serves as a critical link between process inputs and outputs in the proposed framework. The SEM analysis revealed that the strongest direct relationship exists between contractual process improvements and communication process enhancements (0.786), validating Zhang *et al.* (2023)'s claim that smart contract systems enhance transparency, traceability, and accountability, all of which improve communication efficiency. This finding directly supports Ozorhon's (2013) assertion that effective innovation depends on the alignment of internal processes and information flows. The focus group participants reached a unanimous consensus on the central role of H6, emphasizing that the successful implementation of blockchain solutions is highly dependent on their ability to enhance contractual and communication mechanisms. Thus, the results demonstrate that contractual digitization is the central conduit through which blockchain enhances organizational communication.

5.1.7. H7: "Emerging Management Methods" have a direct and positive effect on "Communication Process Improvements"

The rejection of hypothesis H7 shows that despite their conceptual alignment with collaboration and transparency, emerging management methods did not directly affect communication processes, contradicting earlier findings by Ozorhon (2013) and Tezel *et al.* (2022). The focus group offered an explanation rooted in practice: management approaches lack enforcement mechanisms unless integrated with digital or contractual systems. This supports the idea that management methodologies must be embedded within enforceable process structures. Therefore, while theoretically aligned, emerging management methods function more as contextual enablers than as direct levers of communicative improvement.

5.1.8. H8: "Communication Process Improvements" have a direct and positive effect on "Short-term Outcomes"

In examining the broader implications of blockchain adoption, the study also highlights the temporal nature of its benefits, with focus group participants agreeing that the most immediate advantages are realized in the short term. Improved communication processes are shown to significantly impact short-term project outcomes (0.469), confirming the argument by Zhang et al. (2023) that blockchain streamlines workflows and accelerates contractual transactions. These findings align with Li et al. (2018), who noted that digital traceability facilitates dispute resolution and reduces operational delays. Thus, communication efficiency emerges as a key tactical enabler of short-term project success, influencing contract execution, payment mechanisms, supply chain coordination, and information management.

5.1.9. H9: "Communication Process Improvements" have a direct and positive effect on "Long-term Outcomes"

Communication improvements also exert a positive, though moderately strong, influence on long-term outcomes (0.356), suggesting that sustained, structured communication underpins broader organizational benefits. This supports the work of Ye et al. (2022), who posited that communication maturity contributes to trust building and institutional resilience. Qian and Papadonikolaki (2020) similarly noted that interoperable communication systems help scale digital transformation across project portfolios. Therefore, communication enhancement is a strategic asset, gradually shaping long-term capabilities such as reputation, compliance, and innovation readiness.

5.1.10. H10: "Short-term Outcomes" have a direct and positive effect on "Long-term Outcomes"

Finally, the strong relationship between short term and long term outcomes (0.587) underscore the cumulative nature of blockchain benefits, validating Caglayan and Ozorhon's (2023) assertion that successful short-term project execution serves as a precursor to broader long-term benefits, as early gains in process efficiency, risk mitigation, and financial transparency contribute to sustained organizational growth and industry-wide transformation. Zhang et al. (2023) further argued that initial efficiency gains build trust and commitment among stakeholders, reinforcing the adoption cycle. Further validated during the focus group, these findings collectively suggest that short term wins are not only operationally beneficial but also strategically formative, laying the groundwork for sustained industry impact.

The most novel and consequential finding reveals that motivational factors outweigh technological readiness in driving blockchain integration within contractual processes. This insight challenges prevailing assumptions that prioritize technological maturity and instead positions organizational intent and drive as crucial enablers of innovation adoption. Furthermore, the study identifies the integration of advanced technologies, not management innovations, as a more potent catalyst for successful implementation, underscoring the importance of aligning blockchain solutions with existing digital infrastructures. The validation of Hypothesis H6 further refines the proposed implementation framework, establishing the enhancement of communication processes as a central mechanism through which blockchain delivers value, mediated primarily via contractual improvements. Importantly, the study also challenges traditional models by rejecting the direct influence of both technological and managerial innovations on communication efficacy, thereby offering a reconfigured perspective on process interdependencies. Finally, the research underscores the temporal stratification of blockchain benefits, with immediate process-level gains serving as a strategic foundation for long-term organizational advancement. Collectively, these findings present a robust, empirically grounded contribution to implementation theory and offer practical insights for guiding the strategic deployment of blockchain in complex construction environments.

5.2. Evaluation of the Observed Variables

5.2.1. Motivations

The motivations cluster encompasses a range of factors that play a significant role in the initial phase of blockchain adoption, particularly informational, financial, and intrinsic motivations. The results of the analysis emphasize the critical importance of two primary motivational factors: MT2, the willingness of project stakeholders, and MT4, the support from top management. These elements, characterized as internal motivations, reflect a sense of commitment that is fundamental for the successful integration of blockchain technology into construction processes. This aligns with the findings of Obidallah *et al.* (2024), who highlighted the significant role of organizational commitment in the adoption of emerging technologies, including blockchain. The focus group discussions further validated this by emphasizing the central role of commitment from all parties involved in ensuring a smooth and effective adoption. Participant P8 specifically underscored that top management support acts as a clear manifestation of an organization's commitment to embracing technological advancements. This assertion is consistent with Li *et al.* (2022), who argued that top management involvement is a critical success factor in driving blockchain adoption within organizations. Moreover, P3 pointed out that client demand, including government regulations, can significantly influence stakeholders' motivation to adopt blockchain technology, which resonates with previous findings by Caglayan and Ozorhon (2023), who identified the commitment of project teams as a key driver for the adoption of other emerging technologies like BIM.

On the other hand, the analysis also revealed that MT6, competitive pressure, was the least significant factor in motivating blockchain adoption. Competitive pressure represents an external motivator that currently holds less weight in the decision-making process compared to internal motivations. During the focus group discussions, P2 noted that blockchain is still a novel technology within the construction industry, and as such, competitive pressure is not yet a strong enough driver for its adoption. This observation is consistent with Rathnayake *et al.* (2022), who acknowledged that the adoption of blockchain in the construction industry is still in its early stages, and therefore, competitive pressure is likely to gain prominence only as blockchain becomes more widely adopted and recognized across the industry. In contrast, competitive pressure serves as a significant driving force for blockchain adoption within the banking and finance industries, largely due to the relatively higher technological maturity and widespread implementation in these fields (Chen *et al.*, 2020).

5.2.2. Technological Readiness

The technological readiness cluster reflects the adequacy of technological infrastructure and industry maturity required to support blockchain adoption. The study found that TR2, the availability of guidelines and standards, emerged as the most crucial factor, followed by TR3, the applicability of technology, TR5, the feasibility of pilot projects, and TR6, the convenience of legal infrastructure. The focus group participants reached a consensus that a strategic roadmap is necessary for companies to successfully integrate blockchain into their operations, ensuring its compatibility with existing business practices. Participant P6 emphasized the importance of achieving a shared understanding among industry stakeholders, which can be facilitated through the establishment of clear guidelines and standards. This observation is in line with Li and Kassem (2019), who noted that the lack of industry-wide standards can act as a significant barrier to blockchain adoption. The need for clear, actionable roadmaps was echoed by several focus group participants, who agreed that having a well-defined path forward is essential to overcome the uncertainties associated with blockchain integration.

Additionally, Participant P8 highlighted the critical importance of TR6, convenience of legal infrastructure, emphasizing that the absence of clear legal frameworks poses a significant barrier to blockchain adoption. P8 noted that stakeholders are understandably reluctant to engage in activities that may conflict with existing legal norms, reinforcing the notion that regulatory uncertainty undermines confidence in implementation. As such, the participant stressed the urgent need for the development of robust and adaptive regulations to provide legal clarity, ensure compliance, and foster a secure environment for the integration of blockchain technologies within the construction industry.

5.2.3. Advanced Technologies

The advanced technologies cluster refers to the most current technological tools being used in the construction industry. The analysis revealed that AT3 IoT, is considered the most critical tool for integrating blockchain technology, followed by AT2 GIS, AT4 RFID, AT1 BIM, and AT7 robotics. In the focus group discussions, P3 highlighted that the IoT generates large amounts of data that can be effectively used by facility managers in digital twin operations, with blockchain providing a secure infrastructure for managing and sharing this data. This finding is supported by Tezel *et al.* (2020), who argued that IoT-based blockchain applications hold significant potential for the development of digital twins in construction. Additionally, blockchain based digital twins can boost information management in several dimensions (Teisserenc and Sepasgozar, 2021). Moreover, P10 noted that the choice of technology to integrate with blockchain largely depends on the specific goals of the implementation. For instance, RFID may be more suited for supply chain applications, while BIM and GIS may be more applicable for payment systems or progress tracking. This perspective aligns with the work of Yang *et al.* (2020), who identified RFID, IoT, and BIM as essential components for effective blockchain integration in the construction industry.

The adoption of advanced technologies tends to be highly dependent on the specific characteristics of each industry and the intended application. For instance, in the banking and finance industry, blockchain can be integrated with various financial instruments to enhance the efficiency of know your customer procedures and improve compliance with anti-money laundering regulations (Chen *et al.*, 2020). Similarly, the healthcare industry applies blockchain in conjunction with tailored information management systems designed for hospital environments (Azaria *et al.*, 2016). Consequently, the configuration and outcomes of advanced technology clusters are likely to differ according to the particular industry under investigation.

5.2.4. Emerging Management Methods

The analysis of emerging management methods revealed substantial variation in the effectiveness of different managerial approaches, with agility being the most impactful for the integration of blockchain technology. According to a report by Institution of Civil Engineers (2018), blockchain is poised to play a crucial role in the digital transformation of the construction industry, which necessitates agile strategic approaches to project management. Consistent with this, Ozorhon *et al.* (2022) emphasized that agile construction practices are essential for adapting to the dynamic nature of emerging technologies like blockchain. This focus on agility aligns with the broader industry trend of adopting flexible, responsive management approaches to deal with the rapidly evolving technological landscape. Participant P6 expressed surprise at the extent of variation among the factors influencing emerging management methods, particularly drawing attention to the unexpectedly low score of EM2, IPD. Given IPD's collaborative nature and its theoretical alignment with blockchain's decentralized principles, P6 had anticipated a higher level of significance attributed to this method.

5.2.5. Contractual Process Improvements

The contractual process improvements cluster refers to the potential applications of blockchain in enhancing the management of construction contracts. The findings suggest that CT5, which involves enhanced data management, and CT1, automated progress tracking, are the most critical areas for improvement. Focus group participants confirmed that blockchain adoption is expected to significantly improve data management and monitoring processes, with blockchain's secure infrastructure playing a central role in this improvement. Turk and Klinc (2017) similarly emphasized that blockchain technology enhances data reliability and secure data storage. While automated payments and improved vendor management (CT2 and CT4) were considered important, participants pointed out that resistance to change, especially in payment systems, might slow down the adoption of these features. However, this resistance may diminish over time as new financial regulations are introduced, as noted by Ahmadisheykhsarmast and Sonmez (2020).

Similar to advanced technologies, contractual process improvement are also context-dependent and may differ across industries according to the specific use case requirements. Unlike other industries that have adopted blockchain technology, the construction industry is characterized by a fragmented structure and a project-based operational model, both of which pose significant challenges to implement permanent changes within traditional workflows (Perera *et al.*, 2020).

5.2.6. Communication Process Improvements

In the communication process improvements cluster, the analysis revealed that CM3 advanced data consistency, CM1 advanced data traceability, and CM2 advanced data reliability were the most significant communication-related improvements expected from blockchain adoption. The focus group participants agreed that blockchain technology, as a data-sharing and storage infrastructure, would enhance the consistency, traceability, and reliability of communication processes among project stakeholders. Ye *et al.* (2022) similarly noted that blockchain integration addresses key challenges in construction communication, facilitating more transparent, reliable exchanges. P7 pointed out that while improved collaboration was rated lower, it may function as more of an enabler for blockchain adoption rather than a direct outcome.

Additionally, Participant P4 emphasized that enhancing trust and collaboration within the construction industry is a long-term endeavor that cannot be achieved solely through the adoption of new technologies such as blockchain. P4 noted that while technological solutions may provide tools to support transparency and accountability, the cultivation of trust and collaborative culture requires sustained organizational effort, behavioral change, and interpersonal engagement. This observation highlights the socio-technical complexity of digital transformation, where technological implementation must be complemented by parallel shifts in organizational mindset and stakeholder relationships.

Participant P6 emphasized that building trust within the construction industry necessitates openness and transparency, suggesting that increased openness could yield significant benefits for industry practices. However, P6 also questioned whether the industry is truly prepared to embrace such a cultural shift toward transparency. Expanding on this concern, Participant P8 observed that the construction industry has traditionally been resistant to full transparency, often perceiving it as a potential risk or negative outcome rather than a value-enhancing attribute. In contrast, Participant P3 offered a more optimistic perspective, arguing that this challenge can be addressed through the flexible design of blockchain systems. Specifically, P3 noted that different blockchain configurations—such as permissioned networks or customizable access controls—can balance the need for transparency with the industry's desire for confidentiality, thus offering a tailored solution to accommodate varying levels of openness.

5.2.7. Short Term Outcomes

The short term outcomes cluster represents the immediate benefits expected from blockchain implementation. Findings suggest that blockchain can significantly enhance project timelines, resulting in faster completion and lower costs. P3 mentioned that accelerated project timelines could be achieved due to the continuous flow of resources and funds facilitated by blockchain technology. Similarly, P8 pointed out that cost reductions could be achieved by eliminating the need for trusted intermediaries. Participants agreed that these short-term outcomes depend on effective project management. Li *et al.* (2018) also highlighted that blockchain reduces transaction costs by eliminating third-party intermediaries. Additionally, risk management was identified as a key driver for adopting blockchain-enabled smart contracts (Koc and Gurgun, 2020). P2 observed that while blockchain mitigates certain risks, it also introduces new challenges, which explains the moderate importance placed on (SO3) reduced risks. P6 emphasized the importance of developing a well-defined business case in future research to accurately capture and reflect the practical realities of blockchain implementation.

5.2.8. Long Term Outcomes

Finally, the long term outcomes cluster reflects the sustained benefits of blockchain adoption. The most significant long-term outcome was identified as LO6, which involves enhanced knowledge management. P8 noted that blockchain proficiency enables construction companies to improve their knowledge management capabilities, leading to more informed decision-making. This is consistent with findings by Qian and Papadonikolaki (2020), who argued that the integration of digital technologies, including blockchain, strengthens the decision-making process. Additionally, Safa *et al.* (2019) highlighted that blockchain offers significant opportunities for improving knowledge management, a critical component for fostering organizational growth and strategic foresight in the construction industry. The participants reached a consensus that blockchain adoption has the potential to accelerate digitalization in the construction industry by eliminating key barriers related to data and information management. They agreed that blockchain's secure, transparent, and immutable nature could streamline data sharing and reduce inefficiencies, thereby enhancing the overall management of information throughout the project lifecycle.

This could serve as a catalyst for broader digital transformation within the industry, improving both operational efficiency and collaboration among stakeholders.

In comparison with existing literature, the findings of this study are unlikely to vary significantly across national contexts. For instance, Sun et al. (2023) examined critical success factors for the implementation of blockchain technology in the construction industry by synthesizing data from studies conducted in over 20 countries, while Singh et al. (2023) concentrated specifically on the Indian construction industry. Despite the geographical differences, both studies identified a set of critical factors that closely align with the findings of the present research, particularly in relation to comparable use cases. This consistency suggests a degree of universality in the key determinants influencing blockchain adoption in the construction industry.

A key novel contribution lies in the identification of internal motivational factors, specifically stakeholder willingness and top management support, as the most influential drivers in the early stages of adoption, eclipsing external pressures such as competitive dynamics. This finding reorients traditional diffusion models by emphasizing the primacy of organizational commitment and leadership engagement. Equally significant is the study's demonstration that technological readiness, particularly the availability of guidelines and standards, is foundational for integration, highlighting the necessity for structured industry roadmaps. Within the advanced technologies cluster, the prominence of IoT as a catalyst for blockchain-enabled digital twins advances the discourse on synergistic tech ecosystems. The research also introduces agility as the most effective emerging management method, offering a nuanced perspective on how responsive managerial frameworks can facilitate technological integration. On the process level, the findings underscore that data management and automated progress tracking are critical contractual improvements, while data consistency, traceability, and reliability are central to communication process enhancements. Notably, the study differentiates between the short-term operational benefits, such as cost and time efficiency, and long-term strategic gains, with knowledge management emerging as a vital area of impact. By mapping these clusters through both statistical analysis and qualitative insights, this study not only refines existing adoption frameworks but also contributes a holistic model of blockchain integration that captures both the immediate and enduring transformations in construction project delivery.

6. CONCLUSIONS

6.1. Research Summary

The integration of blockchain technology into construction contract management practices presents substantial advantages for construction projects and industry stakeholders. The success of such an implementation is highly dependent on the guidance provided by a well-structured strategic roadmap. This research proposes a strategic roadmap following an in-depth analysis of the constructed framework and its key components. A comprehensive framework was developed to represent the blockchain implementation process by identifying, categorizing, and organizing critical factors into distinct constructs. A targeted questionnaire survey was designed and distributed to selected participants, with the collected data analyzed using SEM. Based on the analysis results, a preliminary strategic roadmap was drafted. To further validate the findings, a focus group meeting was conducted with industry experts, which enabled refinement of the initial roadmap by incorporating expert insights and practical considerations. Major research findings can be summarized as:

- Motivational factors have a greater impact on blockchain adoption than technological readiness.
- Advanced technologies exert a stronger influence on blockchain integration than emerging management methodologies.
- H6 showed the strongest direct relationship, indicating blockchain significantly enhances communication through contractual improvements.
- H5 and H7 were rejected, suggesting that technological and managerial advancements influence communication indirectly, primarily via contractual process enhancements.
- MT2 (Stakeholder willingness) and MT4 (Top management support) are the most critical motivational drivers.
- MT6 (Competitive pressure) is the least influential, reflecting the early stage of blockchain adoption in construction.

- TR2 (Availability of guidelines/standards) is the most crucial readiness factor.
- The need for a strategic implementation roadmap and shared industry understanding was emphasized.
- IoT (AT3) is the most critical technology for blockchain integration, followed by GIS, RFID, BIM, and robotics.
- Technology choice should align with project-specific goals (e.g., RFID for supply chain; BIM for payment systems).
- Agile strategies help organizations adapt to the dynamic nature of emerging digital technologies.
- CT5 (Enhanced data management) and CT1 (Automated progress tracking) are key areas improved by blockchain.
- Resistance to change, particularly in payment systems, may slow adoption, but could be mitigated by regulatory evolution.
- CM3 (Advanced data consistency), CM1 (Traceability), and CM2 (Reliability) are the most significant expected communication improvements.
- Blockchain can accelerate project timelines and reduce costs by ensuring uninterrupted resource flow and removing intermediaries.
- SO4 (Accelerated schedule) and SO5 (Reduced costs) are the most significant short-term benefits, as blockchain enables continuous resource and fund flow, expediting project timelines and reducing costs by eliminating trusted intermediaries.
- Risk mitigation is a moderate benefit, as blockchain reduces some risks but introduces new challenges.
- LO6 (Enhanced knowledge management) is the most significant long-term benefit.
- Blockchain facilitates better organizational decision-making and strategic foresight, strengthening long-term industry competitiveness.

Based on the above findings, the main observations concluded from the research are indicated as:

- Despite the nascent state of blockchain adoption within the construction industry, motivated companies are not deterred from exploring its potential. However, organizational commitment is essential for successful implementation, as blockchain may not be feasible without the development of guidelines and standards to ensure compatibility with existing business operations.
- Advanced technologies act as the primary enabler of blockchain integration, while innovative management techniques play a comparatively less influential role. The integration of complementary advanced technologies significantly enhances the efficiency of data management and monitoring processes.
- Blockchain technology facilitates consistent, traceable, and reliable communication within construction project workflows, leading to both direct and indirect benefits. These improvements have the potential to accelerate project completion timelines, reduce costs, and enhance firms' ability to manage knowledge and make informed decisions.

6.2. Contributions

The proposed framework advances the existing body of knowledge by (i) identifying the core components essential for blockchain adoption in construction contract management, (ii) outlining the interrelationships among these components, and (iii) uncovering the foundational factors that influence their interaction.

This research makes a novel contribution to the literature by systematically exploring the integration of blockchain technology into construction contract management. By meticulously identifying critical factors and analyzing the intricate interdependencies among key constructs, the study advances theoretical understanding. Moreover, it offers a rigorously developed and structured roadmap, providing valuable guidance for the practical deployment of blockchain in construction contract processes. Distinct from existing roadmaps, this study adopts a holistic perspective encompassing the entire lifecycle of implementation. It provides detailed, strategically grounded recommendations that transcend specific national contexts. The primary contribution lies in the roadmap's innovative focus on blockchain-enabled practices in construction contract management, marking a significant departure from prior context-specific and narrowly scoped approaches.

The strategic roadmap structured into three distinct phases: pre-implementation, implementation, and post-implementation. This roadmap articulates tailored strategies for each phase and includes actionable recommendations to support the effective execution of each stage. Collectively, it offers valuable guidance for construction industry stakeholders aiming to incorporate blockchain technology into their contract management processes.

The pre-implementation phase focuses on raising industry awareness, establishing legal frameworks and standardized guidelines, demonstrating organizational commitment, and showcasing use cases to facilitate a smooth adoption process. The implementation phase involves identifying project-specific needs, tailoring strategies for various contract management applications such as payment processing, supply chain management, and information management, integrating advanced technologies, engaging relevant stakeholders, and ensuring alignment of decentralized systems with existing business operations. The post-implementation phase emphasizes sustaining innovation, establishing feedback loops to address challenges, leveraging outcomes to optimize benefits and industry reputation, and creating case studies to serve as best-practice references for future initiatives.

6.3. Recommendations and The Strategic Roadmap

During the focus group study, the initially developed preliminary roadmap underwent further refinement based on participant discussions. The finalized version of this strategic roadmap is illustrated in Figure 6.1. The roadmap delineates targeted strategies across different implementation phases, complemented by specific recommended actions to ensure the effective execution of each strategic step.

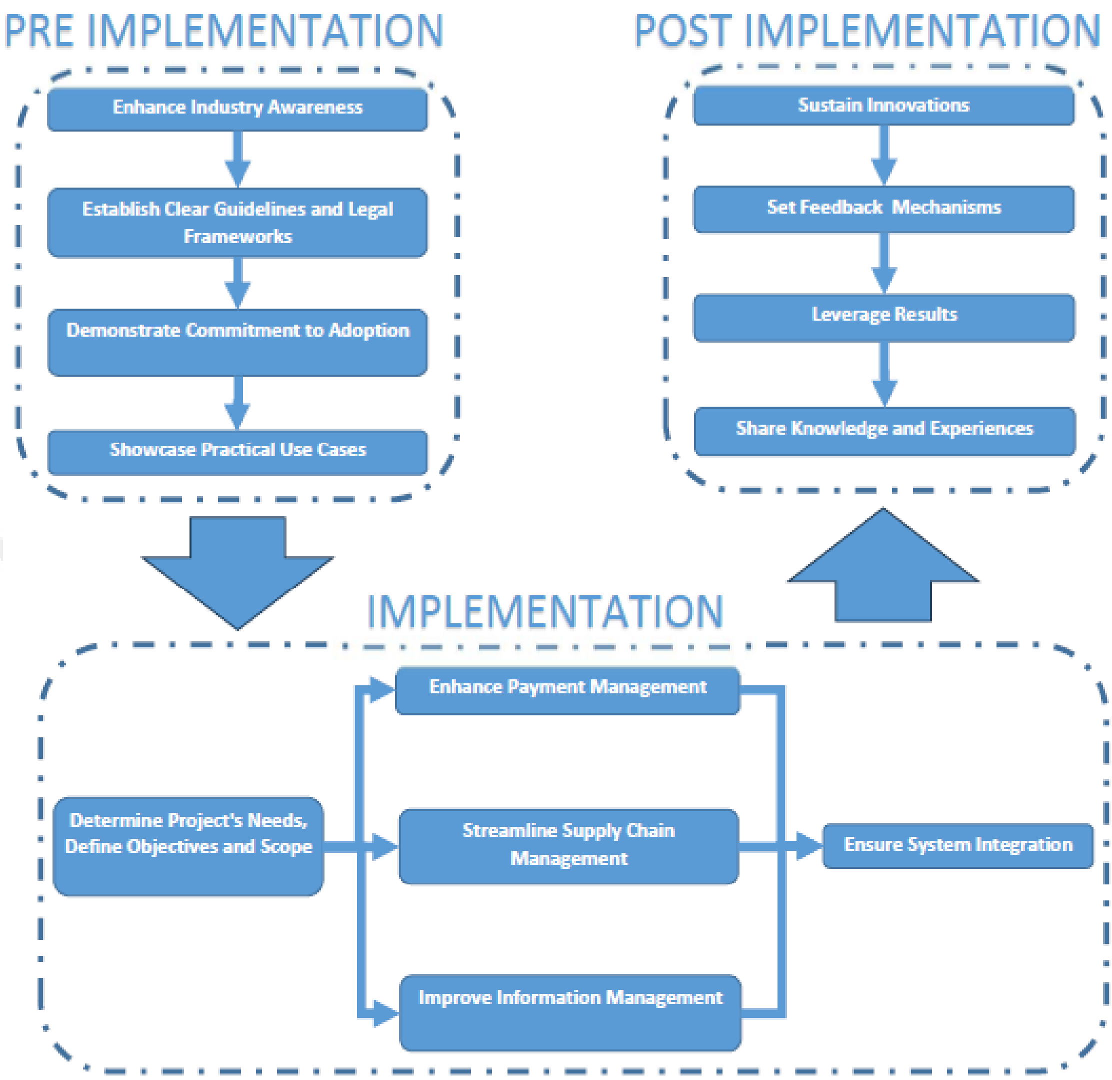

Figure 6.1. The strategic roadmap.

The primary objective of the strategic roadmap is to systematically address the critical factors identified through the comprehensive analysis of the developed framework. Accordingly, the strategic initiatives and corresponding recommendations are meticulously aligned with these findings, while also incorporating the valuable insights and perspectives shared by focus group participants. Over time, the efficacy of these strategies can be further evaluated and validated by industry professionals. This strategic roadmap offers essential guidance for construction industry stakeholders seeking to integrate blockchain technology into contract management practices.

In the pre-implementation phase, four fundamental strategic actions are recommended to facilitate a smooth and successful blockchain adoption process. The first step involves enhancing industry awareness by actively engaging with key stakeholders and professional communities. This serves as a foundational measure, ensuring that industry players are well-informed about blockchain technology and its potential benefits. Complementary to this, the publication of standardized guidelines and the establishment of regulatory frameworks are imperative for fostering a common understanding among stakeholders and providing clear direction for practitioners. Demonstrating a strong commitment to the adoption process represents another critical strategic action at this stage, as organizational dedication plays a pivotal role in technology's successful deployment. Lastly, showcasing practical use cases is essential for demonstrating real-world applications, helping industry professionals recognize potential opportunities, and preparing them for a seamless transition to blockchain-enabled workflows.

The implementation phase is initiated by the identification of project-specific requirements, ensuring that realistic and achievable objectives are established from the outset. At this stage, tailored strategies are designed based on the desired use cases, which may include payment automation, supply chain optimization, and information management enhancement. Each of these use cases requires distinct implementation methodologies, particularly in relation to the integration of advanced technologies, as the specific advantages of blockchain differ depending on the application. Regardless of the chosen use case, the involvement of relevant stakeholders is crucial to maintain alignment, foster collaboration, and ensure a smooth adoption process. The final step in this phase involves the development of a decentralized system that seamlessly integrates with existing business operations, ensuring compatibility and functionality within the established industry framework.

In the post-implementation phase, four strategic actions are recommended to ensure the long-term sustainability and effectiveness of blockchain integration within the construction contract management domain. The priority is to maintain an innovative mindset, which is critical for preserving the relevance and adaptability of the system over time. Secondly, establishing a feedback loop is essential for continuously monitoring progress, addressing emerging challenges, and providing actionable insights for system improvements. The third action focuses on leveraging blockchain outcomes to enhance organizational performance, increase operational efficiency, and elevate the company's industry reputation. Finally, the creation of case studies is proposed as a valuable strategy for documenting lessons learned, serving as reference points for future implementations, and establishing benchmarks for best practices in blockchain-enabled construction contract management.

Table 6.1. provides a detailed categorization of these recommendations according to their scope of application, distinguishing between project-level, company-level, and industry-wide strategies. Given that blockchain technology's primary applications in construction contract management are centered on payments, supply chain management, and information management, the proposed strategies are specifically tailored to optimize these key areas.

Table 6.1. Recommended strategic actions.

Strategies	Recommended Strategic Actions
Enhance Industry Awareness	1) Engage with blockchain communities to host conferences aimed at expanding industry knowledge. *
	2) Collaborate with academic institutions to provide training for professionals and introduce graduate-level courses.*
	3) Offer specialized training programs for employees and collaborate with experienced consultants. **
	4) Dedicate part of projects to pilot trials to foster experiential learning. ***
Establish Clear Guidelines and Legal Frameworks	1) Publish comprehensive guidelines, including integration strategies for legacy IT and accounting systems.*
	2) Develop legal frameworks to ensure compliance with regulatory requirements.*
	3) Create industry-specific standards. **
	4) Incorporate blockchain-specific clauses into diverse contract forms. **
	5) Define organizational protocols tailored to blockchain use cases. **
Demonstrate Commitment to Adoption	1) Provide incentives or bonuses for projects implementing blockchain technology. *
	2) Mandate the use of blockchain for specific applications. *
	3) Identify and implement project delivery models that facilitate blockchain adoption.*
	4) Support ongoing research and development efforts. *
	5) Define clear company objectives and expectations for blockchain use. **

	6) Form internal blockchain study groups to encourage collaborative learning.**
	7) Establish a rewards system to promote blockchain integration in projects. ***
Showcase Practical Use Cases	1) Assess project-specific needs and identify potential blockchain applications. *
	2) Validate blockchain applicability by demonstrating successful use cases. *
	3) Facilitate a smooth transition through phased implementation.*
	4) Integrate blockchain into other digital delivery plans, such as BIM execution plans (BEP).**
	5) Learn from pilot projects and case studies to refine practices. **
Determine Project's Needs, Define Objectives and Scope	1) Clarify the purpose of blockchain implementation and begin with manageable pilot projects. **
	2) Determine the specific data to be secured via blockchain, avoiding overextension. ***
	3) Incorporate blockchain requirements into contractual documentation. ***
	4) Select appropriate blockchain types (public/private/hybrid) and operational models (e.g., proof of concept).***
	5) Establish realistic goals and secure stakeholder consensus on scope. ***
	6) Integrate blockchain with complementary technologies to maximize benefits.***
	7) Ensure robust mechanisms for data capture and recording to support blockchain functionality.***
Enhance Payment Management	1) Utilize BIM in your project and keep it synchronized with your BOQ ***
	2) Secure blockchain-enabled tracking of schedules, costs, and project progress. ***
	3) Develop automated progress tracking systems integrating robotics, IoT, and RFID technologies. ***
	4) Implement blockchain-based payment systems aligned with contractual payment terms. ***
	5) Utilize smart contracts to automate payments based on completed work percentages per BOQ item. ***
Streamline Supply Chain Management	1) Encourage and assist suppliers in adopting blockchain systems.**
	2) Leverage IoT and RFID technologies to collect and blockchain-enable material and transportation data. ***
	3) Automate supply chain management in accordance with contract terms. ***
	4) Utilize Smart Contracts to initiate the payments upon the defined completions. ***
	1) Employ an information management tool for your project ***
	2) Ensure all the project data is decentralized by blockchain***

Improve Information Management	3) Ensure data from other advanced technologies are blockchained ***
	4) Utilize blockchain for real-time digital twin data in facility management ***
Ensure System Integration	1) Integrate blockchain with legacy IT systems**
	2) Establish mechanisms for verifying the accuracy of blockchain data.**
	3) Ensure the system allows for a traceable, immutable, transparent and secure, data management ***
	4) Develop long-term strategies for sustaining blockchain networks across projects.***
	5) Expand blockchain applications across disciplines and foster collaboration among stakeholders. ***
	6) Assign blockchain champions within organizations to drive implementation. ***
	7) Employ risk management strategies to address potential challenges.***
	8) Ensure blockchain is integrated with relevant workflows. ***
Sustain Innovations	1) Support long-term innovation through sustained investments in training and technology. **
	2) Encourage collaboration among stakeholders throughout the project lifecycle. ***
Set Feedback Mechanisms	1) Regularly monitor progress toward previously set goals. ***
	2) Evaluate outcomes, identify issues, and take corrective actions as needed***
Leverage Results	1) Use successful outcomes to inform decision-making processes.**
	2) Promote blockchain successes to enhance organizational reputation.**
Share Knowledge and Experiences	1) Partner with institutions to share insights and experiences. *
	2) Create detailed case studies for benchmarking and improvement.*
	3) Learn from others to refine blockchain practices further.**
Level of Actions: *Industry, **Company, ***Project	

This strategic roadmap identifies a total of 58 recommended strategic actions for integrating blockchain technology into construction contract management, categorized under 13 key strategies. These actions are classified across three implementation levels: 13 actions are directed at the industry level, 16 at the company level, and 29 at the project level. This distribution highlights the emphasis on project-level initiatives, underlining the importance of operational experimentation and direct application in driving adoption.

The integration of blockchain technology into construction contract management begins with raising awareness across the industry. This involves engaging with blockchain communities, forming partnerships with academic institutions, and offering targeted training programs that enhance the knowledge base of professionals. Additionally, organizations are encouraged to invest in experiential learning through pilot projects, which serve as a practical entry point for understanding blockchain applications in real-world settings.

Developing clear guidelines and legal frameworks is fundamental to supporting secure and standardized blockchain implementation. This includes the publication of integration guides for legacy IT and accounting systems, as well as the development of legal instruments to ensure regulatory compliance. At the company level, actions such as the creation of industry-specific standards, the inclusion of blockchain-specific clauses in contracts, and the definition of organizational protocols tailored to blockchain use cases help build a robust legal and procedural foundation.

Organizational commitment is essential for the successful adoption of blockchain. Industry-level actions include providing financial incentives and mandating blockchain use in select applications. These are complemented by supportive project delivery models and sustained research and development efforts. At the company level, firms are advised to articulate clear objectives, facilitate internal study groups, and build incentive structures that reward successful blockchain integration at the project level.

To demonstrate the practical value of blockchain, it is crucial to identify and validate specific use cases. This involves assessing project needs, showcasing successful implementations, and adopting phased strategies to ease the transition. Further value is derived from aligning blockchain initiatives with broader digital strategies such as BIM execution plans. Learning from pilot applications and case studies enhances the refinement and scalability of practices over time.

A clear understanding of project needs, objectives, and scope enhances the targeted implementation of blockchain. Actions include clarifying the purpose of adoption, avoiding unnecessary data overextension, and embedding blockchain requirements within contractual documentation. Selecting the appropriate blockchain architecture and establishing realistic goals ensures alignment with stakeholder expectations. Integration with other technologies and robust mechanisms for data capture further support functional deployment.

Improving payment management is another critical area for blockchain adoption. By synchronizing blockchain with BIM and bill of quantities systems, construction teams can ensure accurate and real-time tracking of costs and progress. Automated systems that integrate robotics, IoT, and RFID technologies enhance data collection, while blockchain-based payment systems and smart contracts align disbursements with contractual performance, ensuring transparency and efficiency.

Blockchain also plays a significant role in streamlining supply chain management. Encouraging supplier adoption and integrating IoT and RFID for data collection enhances material tracking and logistical transparency. Automating these processes and employing smart contracts for payment execution helps reduce administrative burdens and ensures timely compliance with contractual terms.

Information management is strengthened through the deployment of blockchain-enabled tools that decentralize data storage and ensure immutability. Ensuring that data from advanced technologies is integrated and traceable supports comprehensive and real-time digital management systems, including the use of digital twins in facility operations. These practices are essential for informed decision-making and operational continuity.

System integration is essential for ensuring that blockchain is embedded within existing digital infrastructures. This includes integrating with legacy IT systems, verifying data accuracy, and developing traceable and secure data management systems. Long-term strategies for sustaining blockchain networks, cross-disciplinary collaboration, and risk mitigation practices are emphasized to ensure resilience and adaptability in complex project environments.

Sustaining innovation requires consistent investment in human capital and technology, encouraging long-term adoption. Ongoing training and the establishment of collaborative practices across stakeholders are recommended to facilitate the continuous evolution of blockchain applications throughout the project lifecycle.

Implementing structured feedback mechanisms is vital to measure progress and improve performance. Regular monitoring of project milestones and systematic evaluation of outcomes enable organizations to identify challenges early and take corrective actions, thereby ensuring adaptive and evidence-based management of blockchain initiatives.

To build momentum, organizations are encouraged to leverage successful blockchain implementations. These outcomes can inform strategic planning, strengthen organizational reputation, and serve as reference points for scaling efforts. Communicating results effectively contributes to increased confidence and broader acceptance across the industry.

Finally, sharing knowledge and experiences is critical for collective industry advancement. Partnering with academic institutions, producing case studies, and engaging in mutual learning allow organizations to benchmark practices, refine strategies, and accelerate the institutionalization of blockchain technologies in construction contract management.

6.4. Limitations

Despite the comprehensive nature of this study, certain limitations should be acknowledged. One notable limitation is that only 10% of the survey respondents possess direct, hands-on experience with blockchain applications within the construction industry. As a result, many of the responses may be more perception-based rather than grounded in practical experience. This limitation can be attributed to the fact that blockchain adoption in the construction industry is still in its early stages, with relatively few projects fully implementing blockchain-based systems at this time. Consequently, the data collected may reflect a broader, less detailed understanding of blockchain technology in actual construction practices. However, it is important to note that the respondents' significant industry experience likely compensated for this limitation by providing well-informed and knowledgeable perspectives on the subject matter.

In addition, the findings of this study were validated through expert feedback, particularly through a focus group study, which strengthens the credibility of the conclusions drawn. Expert opinions from professionals with in-depth experience in construction contract management and blockchain technology offer additional reliability and ensure that the insights are well-grounded in the current realities of the industry.

Another limitation pertains to the formulation of hypotheses and the identification of the underlying factors within the proposed model. These components were derived through an integration of existing literature and expert input, a process that inevitably involves a degree of subjective interpretation. As such, while the approach is based on established knowledge and expert insights, there is the potential for personal bias or subjective judgments to influence the way in which these factors were conceptualized. Future research may seek to refine these hypotheses by incorporating more diverse data sources or longitudinal studies that provide a deeper empirical foundation for the model.

6.5. Further Studies

Considering the dynamic and rapidly evolving landscape of blockchain technology within the construction industry, coupled with its relatively limited representation in existing scholarly literature, it is essential for future research to build upon the insights derived from this study. One promising avenue for advancing knowledge is through the use of case studies and empirical research that focuses on real-world blockchain applications within the industry. Such research would provide valuable context and evidence for how blockchain is being adopted and integrated into actual construction projects, offering a clearer understanding of its practical implications.

As blockchain technology continues to mature, it will become increasingly crucial for subsequent studies to incorporate longitudinal research methodologies. These studies could follow the progress of blockchain integration over extended periods, allowing for a more thorough examination of its long term impacts on contract management practices and overall project outcomes. To enhance the richness of data, future research efforts should specifically target participants with direct, hands-on experience in implementing blockchain solutions within their organizations. This would provide deeper empirical insights into the challenges and opportunities that arise from real-world applications, enabling a more comprehensive understanding of blockchain's effectiveness and limitations in a practical context.

Additionally, the same research structure could be utilized for other novel concepts that are at the infant stage within the construction industry such as AI. By engaging the same methodology for different industries, future investigations can significantly enrich the theoretical frameworks established in this study and offer actionable insights for practitioners in other industries. Ultimately, future research will be vital for unlocking the full potential of blockchain technology and guiding its successful adoption in other industries.

REFERENCES

Abuhamda, E., I. Ismail, and T. Bsharat, 2021, Understanding quantitative and qualitative research methods: A theoretical perspective for young researchers, International Journal of Research. Vol. 8, pp. 71-87.

Adel, K., A. Elhakeem, and M. Marzouk, 2022, Decentralizing construction AI applications using blockchain technology, Expert Systems Applications, Vol. 194.

Ahmad, S., N. N. A. Zulkurnain, and F. I. Khairushalimi, 2016, Assessing the validity and reliability of a measurement model in structural equation modeling (SEM), Journal of Advanced Mathematical Computation Science, Vol. 15, No. 3, pp. 1-8.

Ahmadisheykhsarmast, S., and R. Sonmez, 2020, A smart contract system for security of payment of construction contracts, Automation in Construction, Vol. 120.

Alharby, M., and A. van Moorsel, 2017, Blockchain-based smart contracts: A systematic mapping study, International Journal of Computer Science and Information Technology, pp. 125-140.

Ameyaw, E. E., D. Edwards, B. Kumar, N. Thurairajah, D. Owusu-Manu, and G. Oppong, 2023, Critical Factors Influencing Adoption of Blockchain-Enabled Smart Contracts in Construction Projects, Journal of Construction Engineering and Management, Vol. 149, pp. 1-16.

Andoni, M., V. Robu, D. Flynn, S. Abram, D. Geach, D. Jenkins, P. Mccallum, and A. Peacock, 2019, Blockchain technology in the energy sector: A systematic review of challenges and opportunities, Renewable and Sustainable Energy Reviews, Vol. 100, pp. 143–174.

Arceri, V., M. Bartoletti, M. Murgia, and L. Pompianu, 2023, Information flow analysis for detecting non-determinism in blockchain, ECOOP, Seattle, WA, United States.

ARUP, 2019, Blockchain and The Built Environment, Company Report.

Azaria, A., A. Ekblaw, T. Vieira, and A. Lippman, 2016, Using blockchain for medical data access and permission management, 2nd International Conference on Open and Big Data (OBD), Vienna, Austria.

Bagozzi, R. P. and Y. Yi, 2012, Specification, evaluation, and interpretation of structural equation models, Journal of the Academy of Marketing Science, Vol. 40, pp. 8-34.

Blycha, M., 2018, Smart contracts in the construction industry, https://www.lexology.com/library/detail.aspx?g=78d1740e-bb52-4c67-9135-3d0193a2b2b7, Last Access: 01.05.2025.

Bollen, K. A., and J. S. Long, 1993, Testing structural equation models, Sage Publications, Vol. 154.

Bowen, N. K., and S. Guo, 2011, Structural equation modeling, Oxford University Press, pp. 1-240.

Brandin, R. and S. Abrishami, 2024, IoT-BIM and blockchain integration for enhanced data traceability in offsite manufacturing, Automation in Construction, Vol. 159.

Byrne, B. M., 2012, Structural Equation Modeling With Mplus: Basic Concepts, Applications, and Programming, Taylor and Francis Group, New York, NY, United States.

Byrne B. M., 2016, Structural Equation Modeling with AMOS: Basic Concepts, Applications, and Programming, Routledge, United States.

Caglayan, S., and B. Ozorhon, 2023, Determining building information modeling effectiveness, Automation in Construction, Vol 151.

Cecconi, F. R., M. C. Dejaco, N. Moretti, A. Mannino, and J. D. B. Cadena, 2020, Digital asset management, Digital transformation of the design, construction and management processes of the built environment, pp. 243–253.

Celik, Y., I. Petri, and Y. Rezgui, 2023, Integrating BIM and Blockchain across construction lifecycle and supply chains, Computers in Industry, Vol. 148.

Chaphalkar, N. and S. Sandbhor, 2015, Application of neural networks in resolution of disputes for escalation clause using neuro-solutions, KSCE Journal of Civil Engineering, Vol. 19, No. 1, pp. 10-16.

Chen, Y., S. Ding, Z. Xu, H. Zheng, and S. Yang, 2020, Blockchain-based medical records secure storage and medical service framework, Journal of Medical Systems, Vol. 44, No: 2, pp. 1-11.

Cheng, M., G. Liu, Y. Xu, and M. Chi, 2021, When Blockchain Meets the AEC Industry: Present Status, Benefits, Challenges, and Future Research Opportunities, Buildings, Vol. 11, No. 8, pp. 340.

Ciotta, V., G. Mariniello, D. Asprone, G. Manfredi, and A. Botta, 2021, Integration of blockchains and smart contracts into construction information flows: Proof-of-concept, Automation in Construction, Vol. 132.

Clohessy, T., 2023, Blockchain in Supply Chain Digital Transformation, CRC Press, Routledge, FL, United States.

Crosby, M., P. N. Pattanayak, S. Verma, and V. Kalyanamaran, 2016, Blockchain technology: beyond bitcoin, Applied Innovation Reviews, Applied Innovation, Vol. 2, No. 71.

Daim, T. U., and T. Oliver, 2008, Implementing technology roadmap process in the energy services sector: A case study of a government agency, Technological Forecasting and Social Change, Vol. 75, pp. 687-720.

Das, M., H. Luo, and J. C. P. Cheng, 2020, Securing interim payments in construction projects through a blockchain-based framework, Automation in Construction, Vol. 118.

Das, M., X. Tao, and J. C. Cheng, 2021, BIM security: A critical review and recommendations using encryption strategy and blockchain, Automation in Construction, Vol. 126.

Das, M., X. Tao, Y. Liu, and J. C. P. Cheng, 2022, A blockchain-based integrated document management framework for construction applications, Automation in Construction, Vol. 133.

De Vaus, D. A., 2014, Surveys in Social Research, UCL Press, Australia.

Di Giuda, G., G. Pattini, E. Seghezzi, M. Schievano, and F. Paleari, 2020, The Construction Contract Execution Through the Integration of Blockchain Technology, Digital Transformation of the Design, Construction and Management Processes of the Built Environment, Springer, Cham.

Dib, O., K. Brousmiche, A. Durand, E. Thea, and E. Hamida, 2018, Consortium Blockchains: Overview, Applications and Challenges, International Journal On Advances in Telecommunications, Vol. 11 pp. 51-64.

Diekmann J. E. and M. C. Nelson, 1985, Construction Claims: Frequency and Severity, Journal of Construction Engineering and Management. Vol. 111, pp. 74-81.

Do, S., V. Nguyen, C. Tran, and Z. Aung, 2022, Identifying and evaluating the key claim causes leading to construction delays. International Journal of Construction Management, pp 1-13.

Dounas, T., D. Lombardi, and W. Jabi, 2021, Framework for decentralised architectural design, BIM and Blockchain integration, International Journal of Architectural Computing Vol. 19, No. 2, pp. 157-173.

Elghaish, F., S. Abrishami, and M. R. Hosseini, 2020, Integrated project delivery with blockchain: An automated financial system, Automation in Construction, Vol. 114.

Elghaish, F., M. R. Hosseini, S. Matarneh, S. Talebi, S. Wu, I. Martek, M. Poshdar, and N. Ghodrati, 2021, Blockchain and the Internet of Things for the construction industry: Research trends and opportunities, Automation in Construction, Vol. 132.

Elkington, J., 1998, Accounting For The Triple Bottom Line, Measuring Business Excellence, Vol. 2, No. 3.

Ernst & Young, 2018, Smart contracts using blockchain technology: A better way to deliver construction technology, Company Report.

Fernando, Y., N. H. M. Rozuar, and F. Mergeresa, 2021, The blockchain-enabled technology and carbon performance: Insights from early adopters, Technology in Society, Vol. 64.

Forcael, E., I. Ferrari, A. Opazo-Vega, and J. A. Pulido-Arcas, 2020, Construction 4.0: A Literature Review, Sustainability, Vol. 12, No. 22.

Fornell, C., and D. F. Larcker, 1981, Evaluating structural equation models with unobservable variables and measurement error, Journal of Marketing Research, Vol. 18, No. 1, pp. 39-50.

Gao, M., J. Han, Y. Yang, T. Tiong, C. Zhao, and C. Han, 2024, BIM-Based and IoT-Driven Smart Tracking for Precast Construction Dynamic Scheduling, Journal of Construction Engineering and Management, Vol. 150, No. 9.

Garver, M. S., and J. T. Mentzer, 1999, Logistics research methods: employing structural equation modeling to test for construct validity. Journal of business logistics, Vol. 20, No. 1, pp. 33.

Greenhalgh, B., 2016, Introduction to construction contract management, Oxfordshire, Routledge, United Kingdom.

Guest, G., A. Bunce, and L. Johnson, 2006, How many interviews are enough? An experiment with data saturation and variability, Field Methods, Vol. 18, No. 1, pp. 59-82.

Gupta, P., and K. N. Jha, 2023, A Decentralized Contracting System in Digital Construction, Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, Vol. 15.

Gurgun, A. P., M. I. Genc, K. Koc, and D. Arditi, 2022, Exploring the Barriers against Using Cryptocurrencies in Managing Construction Supply Chain Processes, Buildings, Vol. 12, pp. 357.

Haber, S., and W. S. Stornetta, 1991, How to time-stamp a digital document, Journal of Cryptology, Vol. 3, pp. 99-111.

Hall, D., J. Hunhevicz, and M. Bonanomi, 2022, Blockchain Governance for Integrated Project Delivery 4.0, Routledge, United Kingdom.

Hair J. F., W. C. Black, B. J. Babin and R. E. Anderson, 2010, Multivariate Data Analysis, Pearson Prentice Hall, New York, NY, United States.

Hamledari, H., and M. Fischer, 2020, Role of Blockchain-Enabled Smart Contracts in Automating Construction Progress Payments, Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, Vol. 13.

Hamledari, H., and M. Fischer, 2021, Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies, Automation in Construction, Vol. 132.

Hargaden, V., N. Papakostas, A. Newell, A. Khavia, and A. Scanlon, 2019, The role of blockchain technologies in construction engineering project management, International Conference on Engineering, Technology and Innovation (ICE/ITMC), New York, NY, United States.

Heiskanen, A., 2017, The technology of trust: How the Internet of Things and blockchain could usher in a new era of construction productivity, Construction Research and Innovation. Vol. 8, No. 2, pp. 66-70.

Hijazi, A., S. Perera, R. Calheiros, and A. Alashwal, 2021, Rationale for the Integration of BIM and Blockchain for the Construction Supply Chain Data Delivery: A Systematic Literature Review and Validation through Focus Group, Journal of Construction Engineering and Management, Vol. 147.

Hooper D., J. Coughlan and M. R. Mullen, 2008, Structural Equation Modelling: Guidelines for Determining Model Fit, The Electronic Journal of Business Research Methods, Vol. 6, No. 1, pp. 53-60.

Hoyle R. H., 2012, Handbook of Structural Equation Modeling, Guilford Press, New York, NY, United States.

Institution of Civil Engineers (ICE), 2018, Blockchain Technology In The Construction Industry. Digital Transformation for High Productivity.

Javaid, M., A. Haleem, T. P. Singh, R. Suman, and S. Khan, 2022, A review of Blockchain Technology applications for financial services, BenchCouncil Transactions on Benchmarks, Standards and Evaluations, Vol. 2, No. 3.

Jayarathna, H. S. N. M., B. A. K. S. Perera, D. Atapattu, and N. Rodrigo, 2025, Circular economy and blockchain-integrated road map to improve construction waste management, Construction Innovation, Vol. 25, No. 7, pp. 23-49.

Kang, K., X. Liu, Y. Jiang, K. K. H. Lee, S. K. W. Wan, G. Q. Huang, and R. Y. Zhong, 2023, Blockchain opportunities for construction industry in Hong Kong: a case study of RISC and site diary, Construction Innovation, Vol. 23, No. 2, pp. 443-466.

Kaplan D., 2009, Statistical Assumptions Underlying Structural Equation Modeling, Structural Equation Modeling: Foundations and Extensions, Vol. 10, pp. 85-108.

Karacigan, A. and B. Ozorhon, 2023, A Systematic Literature Review on Blockchain Technology for Construction Contract Management, International Congress on Advances in Civil Engineering, pp. 181-191.

Karacigan, A., B. Ozorhon, and S. Caglayan, 2023, A Systematic Approach To Investigate BIM Implementation in Turkish Construction Industry, Journal of Information Technology in Construction (ITcon), Vol. 28, pp. 306-321.

Kifokeris, D., and A. Tezel, 2023, Blockchain and lean construction: an exploration of bidirectional synergies and interactions, Architectural Engineering and Design Management Vol. 21, pp. 1-20.

Kline, R. B., 1998, Principles and Practices of Structural Equation Modeling, Guilford, New York.

Kline R. B., 2015, Principles and Practice of Structural Equation Modeling, Guilford, New York.

Koc, K., and A. P. Gurgun, 2020, Drivers for construction stakeholders to adopt smart contracts, Journal of Construction Engineering, Management and Innovation, Vol. 3, pp. 101-112.

Lanko, A., N. Vatin, and A. Kaklauskas, 2018, Application of RFID combined with blockchain technology in logistics of construction materials, MATEC Web of Conferences, Online.

Lavikka, R., J. Kallio, T. Casey, and M. Airaksinen, 2018, Digital disruption of the AEC industry: Technology-oriented scenarios for possible future development paths, Construction Management and Economics, Vol. 36, No. 11, pp. 635-650.

Lee, D., S. H. Lee, N. Masoud, M. S. Krishnan, and V. C. Li, 2021, Integrated digital twin and blockchain framework to support accountable information sharing in construction projects, Automation in Construction, Vol. 127.

Li, C., Y. Zhang, and Y. Xu, 2022, Factors Influencing the Adoption of Blockchain in the Construction Industry: A Hybrid Approach Using PLS-SEM and fsQCA, Buildings, Vol. 12, No. 9.

Li, J., D. Greenwood, and M. Kassem, 2018, Blockchain in the built environment: analysing current applications and developing an emergent framework, Creative Construction Conference, Ljubljana, Slovenia.

Li, J., D. Greenwood, and M. Kassem, 2019, Blockchain in the built environment and construction industry: a systematic review, conceptual models and practical use cases, Automation in Construction. Vol. 102, pp. 288-307.

Li, J., and M. Kassem, 2019, A Proposed Approach Integrating DLT, BIM, IoT and Smart Contracts: Demonstration Using a Simulated Installation Task, International Conference on Smart Infrastructure and Construction, Cambridge, United Kingdom.

Li J., M. Kassem and R. Watson, 2020, A blockchain and smart contract-based framework to increase traceability of built assets, 37th CIB W78 Information Technology for Construction Conference (CIB W78), Sao Paulo, Brazil, pp. 347-362.

Li, J., and M. Kassem, 2021, Applications of distributed ledger technology (DLT) and blockchain enabled smart contracts in construction, Automation in Construction, Vol. 132.

Linderoth, H. C. J., 2017, From visions to practice-The role of sensemaking, institutional logic and pragmatic practice, Construction Management and Economics, Vol. 35, No. 6, pp. 324–337.

Liu, H., S. Han, and Z. Zhu, 2023, Blockchain Technology toward Smart Construction: Review and Future Directions, Journal of Construction Engineering and Management, Vol. 149.

Liu, Y., X. Tao, M. Das, X. Gong, H. Liu, Y. Xu, A. Xie, and J. C. P. Cheng, 2024, Blockchain-enabled platform-as-a-service for production management in off-site construction design using openBIM standards, Automation in Construction, Vol. 164.

Liu, Z., L. Jiang, M. Osmani, and P. Demian, 2019, Building information management (BIM) and blockchain (BC) for sustainable building design information management framework, Electronics, Vol. 8, No. 7, pp. 724.

Luo, H., M. Das, J. Wang, and J. C. P. Cheng, 2019, Construction payment automation through smart contract-based blockchain framework, International Symposium on Automation and Robotics in Construction, Hong Kong, pp. 254-260.

Makhdoom, I., M. Abolhasan, H. Abbas, and W. Ni, 2019, Blockchain's adoption in IoT: the challenges, and a way forward, Journal of Network and Computer Applications, Vol. 125, pp. 251-279.

Martinovic, I., L. Kello, and I. Sluganovic, 2017, Blockchains for Governmental Services: Design Principles, Applications, and Case Studies, Centre for Technology and Global Affairs: Oxford, UK.

Mason, J., 2017, Intelligent contract and the construction industry, Journal of Legal Affairs and Dispute Resolution in Engineering and Construction, Vol. 9.

Matt, V., 2020, Late payments in the construction industry: Who’s to blame?, https://www.levelset.com/blog/late-payments-in-the-construction-industry-whos-to-blame/, Last Access: 01.05.2025.

McKinsey & Company, 2017, Reinventing Construction: A Route to Higher Productivity, Company Report.

McKinsey & Company, 2020, The next normal in construction, Company Report.

McNamara, A. J., and S. M. E. Sepasgozar, 2021, Intelligent contract adoption in the construction industry: Concept development, Automation in Construction, Vol. 122.

Morabito, V., 2017, Blockchain value system, Business Innovation through Blockchain, Springer, pp. 21-39.

Msawil, M., D. Greenwood, and M. Kassem, 2022, A Systematic evaluation of blockchain-enabled contract administration in construction projects, Automation in Construction, Vol. 143.

Murari, K., 2015, Impact of leadership styles on employee empowerment, Partridge Publishing, India.

Nakamoto, S., 2008, Bitcoin: A Peer-to-Peer Electronic Cash System, https://bitcoin.org/bitcoin.pdf, Last Access: 01.05.2025.

Nanayakkara, S., S. Perera, S. Senaratne, T. Weerasuriya, and D. Bandara, 2021, Blockchain and Smart Contracts: A Solution for Payment Issues in Construction Supply Chains, Informatics, Vol. 8, No. 2, pp. 36.

Nawari, N. O., and S. Ravindran., 2019, Blockchain technology and BIM process: Review and potential applications, Journal of Information Technology in Construction, Vol. 24, No. 12, pp. 209-238.

Nunnally, J. C., 1978, Psychometric Theory, McGraw-Hill, New York, NY, United States.

Obidallah, W. J., W. Rashideh, A. M. Kamaruddeen, T. Alzahrani, Y. Alduraywish, A. Alsahli, and N. Alshuqayran, 2024, Beyond the hype: A TAM-based analysis of blockchain adoption drivers in construction industry, Heliyon, Vol. 10, No. 19.

Ozorhon, B., 2013, Analysis of Construction Innovation Process at Project Level, Journal of Management in Engineering, Vol. 29, No. 4.

Ozorhon, B., F. Cardak, and S. Caglayan, 2022, Investigating the Agile Hybrid Approach in Construction, Journal of Management in Engineering, Vol. 38.

Ozorhon, B., O. Kutluhan, and S. Demirkesen Cakir, 2015, Investigating the Components of Innovation in Construction Projects, Journal of Management in Engineering, Vol. 32.

Parn, E. A., and D. Edwards, 2019, Cyber threats confronting the digital built environment: Common data environment vulnerabilities and block chain deterrence, Engineering, Construction and Architectural Management, Vol. 26, No. 2, pp. 245-266.

Paul, P. K., P. S. Aithal, R. Saavedra, and S. Ghosh, 2021, Blockchain Technology and its Types-A Short Review, International Journal of Applied Science and Engineering, Vol. 9, No. 2, pp. 189-200.

Penzes B., 2018, Blockchain Technology in the Construction Industry, ICE.

Perera, S., S. Nanayakkara, M. N. N. Rodrigo, S. Senaratne, and R. Weinand, 2020, Blockchain technology: Is it hype or real in the construction industry?, Journal of Industrial Information Integration, Vol. 17.

Pinna, A., G. Baralla, G. Lallai, M. Marchesi, and R. Tonelli, 2020, Design of a Sustainable Blockchain-Oriented Software for Building Workers Management, Frontiers in Blockchain, Vol. 3, No. 38.

Prabhakar, V. V., C. S. Belarmin Xavier and K. M. Abubeker, 2023, A Review on Challenges and Solutions in the Implementation of Ai, IoT and Blockchain in Construction Industry, Materials Today: Proceedings.

Qian, X. A., and E. Papadonikolaki, 2020, Shifting trust in construction supply chains through blockchain technology, Engineering Construction and Architectural Management, Vol. 28, No. 2, pp. 584–602.

Randa, D., 2024, Types of Blockchain Technology: A Complete Overview, https://crustlab.com/blog/types-of-blockchain-technology-a-complete-overview/#:~:text=Blockchain\%20technology\%20can\%20include\%20public,specific\%20use\%20cases\%20or\%20applications, Last Access: 01.05.2025.

Randall, W. S., M. Gravier, and V. R. Prybutok, 2011, Connection, trust, and commitment: Dimensions of co-creation?, Journal of Strategic Marketing, Vol. 19, No. 1, pp. 3-24.

Rathnayake, I., G. Wedawatta, and A. Tezel, 2022, Smart Contracts in the Construction Industry: A Systematic Review, Buildings, Vol. 12.

Ren, Z., C. Anumba, and O. Ugwu, 2003, Multiagent system for construction claims negotiation, Journal of Computing in Civil Engineering, Vol. 17, No. 3, pp. 180-188.

Risso, L.A., G. Miller, D. Ganga, M. G. Filho, L. A. De Santa-eulalia, T. Chikhi, E. Mosconi, L. Antonio, G. Miller, D. Ganga, M. Godinho, 2023, Present and future perspectives of blockchain in supply chain management: a review of reviews and research agenda, Computers and Industrial Engineering, Vol. 179.

Rugina, C. R., 2021, Smart Contracts Technology and Avoidance of Disputes in Construction Contracts. Lex ET Scientia International Journal, Vol. 2, pp. 30-46.

Safa, M., S. Baeza, and K. Weeks, 2019, Incorporating blockchain technology in construction management, Strategic Direction, Vol. 35.

Salimitari, M., M. Chatterjee, and Y. P. Fallah, 2020, A survey on consensus methods in blockchain for resource-constrained IoT networks, Internet of Things, Vol. 11.

Schumacker R. E. and R. G. Lomax, 2016, A Beginner's Guide to Structural Equation Modeling, Routledge, United Kingdom.

Shaikh, H., N. Zainun, and S. H. Khahro, 2020, Claims in Construction Projects: A Comprehensive Literature Review, IOP Conference Series: Earth and Environmental Science, Vol. 498, Johor, Malaysia.

Shank, G., and L. Brown, 2007, Exploring Educational Research Literacy, Routledge, New York, NY, United States.

Sharma, M. G., and S. Kumar, 2020, The Implication of Blockchain as a Disruptive Technology for Construction Industry, IIM Kozhikode Society & Management Review, Vol. 9, pp. 177-188.

Shojaei, A., 2019, Exploring Applications of Blockchain Technology in The Construction Industry, Proceedings of International Structural Engineering and Construction, Vol. 6, Chicago, IL, United States.

Silva, B., J. Vidal-Vieira, and H. Yoshizaki, 2024, Motivating factors for blockchain technology adoption: a theoretical analysis from the perspective of supply chain collaboration, Journal of Global Operations and Strategic Sourcing Vol. 18, No. 1.

Simister, N., and D. James, 2020, Qualitative and Quantitative Methods, INTRAC for civil society, United Kingdom.

Singh, A. K., V. R. Prasath Kumar, M. Shoaib, T. S. Adebayo, and M. Irfan, 2023, A strategic roadmap to overcome blockchain technology barriers for sustainable construction: A deep learning-based dual-stage SEM-ANN approach, Technological Forecasting and Social Change, Vol. 194.

Smith, S. Z. and A. Garcia, 2022, Blockchain Smart Contracts Part 1: Introduction for Accounting and Auditing Professionals, ISACA Journal, Vol. 4, pp. 1-6.

Sun, W., M. Antwi-Afari, L. Mehmood, S. Anwer, and W. Umer, 2023, Critical success factors for implementing blockchain technology in construction, Automation in Construction, Vol. 156.

Szabo, N., 1996, Smart contracts: building blocks for digital markets, EXTROPY Journal of Transhumanist Thought, Vol. 16, pp. 1-11.

Szabo, N., 1998, Bitgold. http://unenumerated.blogspot.com/2005/12/bit-gold.html, Last Access: 30.04.2025.

Tabachnick B. G. and L. S. Fidell., 2012, Using Multivariate Statistics, Pearson, Boston, MA, United States.

Tavakol, M., and J. Sandars, 2014, Quantitative and quantitative methods in medical education research: AMEE, Med Teach, Vol. 36, No. 9, pp. 746-756.

Teisserenc, B. and S. Sepasgozar, 2021, Adoption of blockchain technology through digital twins in the construction industry 4.0: a PESTELS approach, Buildings, Vol. 11, No. 12, pp. 670.

Tezel, A., P. Febrero, E. Papadonikolaki, and I. Yitmen, 2021, Insights into Blockchain Implementation in Construction: Models for Supply Chain Management, Journal of Management in Engineering, Vol. 37.

Tezel, A., D. Kifokeris, C. Formoso, L. Koskela, and C. Koch, 2022, A Conceptual Framework for Lean Construction and Blockchain Synergy, Proceedings of the 30th Annual Conference of the International Group for Lean Construction (IGLC30), Edmonton, Canada, pp. 576-587.

Tezel, A., E. Papadonikolaki, I. Yitmen, and P. Hilletofth, 2020, Preparing construction supply chains for blockchain technology: An investigation of its potential and future directions, Frontiers of Engineering Management, Vol. 7.

Tucker L. R. and C. Lewis, 1973, A Reliability Coefficient for Maximum Likelihood Factor Analysis, Psychometrika, Vol. 38, No. 1, pp. 1-10.

Turk, Z., and R. Klinc, 2017, Potentials of blockchain technology for construction management, Procedia Engineering, Vol. 196, pp. 638-645.

Wan, P. K., L. Huang, and H. Holtskog, 2020, Blockchain-enabled information sharing within a supply chain: A systematic literature review, IEEE Access, Vol. 8.

Wang, J., P. Wu, X. Wang, and W. Shou, 2017, The outlook of blockchain technology for construction engineering management, Frontiers in Engineering Management, Vol. 4, No. 1, pp. 67-75.

Wang, Z., T. Wang, H. Hu, J. Gong, X. Ren, and Q. Xiao, 2020, Blockchain based framework for improving supply chain traceability and information sharing in precast construction, Automation in Construction, Vol. 111.

Wen, H., S. Abourizk, and Y. Mohamed, 2025, Gap Analysis of Digitalization Levels in Construction and Manufacturing: A Comparative Study of Construction 4.0 and Industry 4.0, Journal of Construction Engineering and Management, Vol. 151, No. 3.

Werner, C., and K. Schermelleh-Engel, 2009, Structural equation modeling: Advantages, challenges, and problems, Introduction to structural equation modeling with LISREL, Goethe University, Frankfurt, Germany.

White, H., 2009, Theory-Based Impact Evaluation: Principles and practice, Journal of Development Effectiveness, Vol. 1, No. 3, pp. 271-284.

Wu, M., K. Wang, X. Cai, S. Guo, M. Guo, and C. Rong, 2019, A comprehensive survey of blockchain: from theory to IoT applications and beyond, Internet of Things Journal, Vol. 6.

Wu, H., P. Zhang, H. Li, B. Zhong, I. Fung, and Y. Lee, 2022, Blockchain Technology in the Construction Industry: Current Status, Challenges, and Future Directions, Journal of Construction Engineering and Management, Vol. 148.

Xiong, B., M. Skitmore, and B. Xia, 2015, A critical review of structural equation modeling applications in construction research, Automation in Construction, Vol. 49.

Xu, Y., X. Tao, M. Das, H. H. L. Kwok, H. Liu, G. Wang, and J. C. P. Cheng, 2023, Suitability analysis of consensus protocols for blockchain-based applications in the construction industry, Automation in Construction, 145.

Yang, R., R. Wakefield, S. Lyu, S. Jayasuriya, and S. Chen, 2020, Public and private blockchain in construction business process and information integration, Automation in Construction, Vol. 118.

Ye, X., N. Zeng, and M. König, 2022, Systematic literature review on smart contracts in the construction industry: Potentials, benefits, and challenges, Frontiers of Engineering Management, Vol. 9.

Yli-Huumo, J., D. Ko, S. Choi, S. Park, and K. Smolander, 2016, Where is current research on blockchain technology? A systematic review, PLoS One, Vol. 11, No. 10.

Yoon, J. H., and P. Pishdad-Bozorgi, 2022, State-of-the-Art Review of Blockchain-Enabled Construction Supply Chain, Journal of Construction Engineering and Management, Vol. 148.

Younis, G., G. Wood, and M. A. A. Malak, 2008, Minimizing construction disputes: the relationship between risk allocation and behavioural attitudes, Construction Management and Economics, Vol. 20, No. 1, Taylor & Francis, Routledge, United Kingdom.

Zaneldin, E. K., 2006, Construction claims in United Arab Emirates: Types, causes, and frequency, International Journal of Project Management, Vol. 24, No. 5, pp. 453-459.

Zaneldin, E. K., 2020, Investigating the types, causes and severity of claims in construction projects in the UAE, International Journal of Construction Management, Vol. 20, No. 5, pp. 385-401.

Zeba, S., P. Suman, and K. Tyagi, 2023, Types of blockchain, Distributed Computing to Blockchain, Academic Press, pp. 55-68.

Zhang, Y., R. Xue, and L. Liu, 2021, Security and privacy on blockchain, ACM Computing Surveys, Vol. 54, No. 6, pp. 1-36.

Zhang, X., T. Liu, A. Rahman, and L. Zhou, 2023, Blockchain Applications for Construction Contract Management: A Systematic Literature Review, Journal of Construction Engineering and Management, Vol. 149, No. 1.

Zhou, C., H. Ren, and L. Zhang, 2020, Construction and empirical analysis of information management system of engineering investigation quality, Journal of Physics: Conference Series, Vol. 1544, No. 1, Suzhou, China.

APPENDIX A:

Blockchain Technology in The Construction Industry: Implications on Contract Management

Dear Respondent,

This research aims to collect information and opinions about the implementation of blockchain technology within the construction industry.

This research is a part of PhD dissertation which conducted through University of Nottingham & Boğaziçi University.

Filling out the questionnaire will take 5 to 10 minutes at most.

The data collected in this survey will be kept confidential and will only be considered as collective findings in the doctoral thesis.

Thank you in advance for your participation and support.

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1) I have ..... years of experience in the construction industry. *

2) I have been familiar with the construction contracts for ..... years. *

3) I have been familiar with the blockchain technology for ..... years. *

4) I am currently working in ..... . *

- Arab Countries
- China
- European Union Countries
- India
- Japan
- Russia
- Turkey
- United Kingdom
- United States
- Diğer:

5) My role as a professional is ..... . *

Yalnızca bir şıkkı işaretleyin.

- Academician
- Engineer/Architect
- Manager
- Director
- Senior Management
- Owner/Board
- Member/Investor Diğer:

6) The organisation I am working for is a ..... . *

- University
- Contractor
- Designer
- Consultant
- Developer/Investor
- Diğer:

7) The organisation I am working for have ..... years of experience. *

- 1-10
- 11-50
- 51-100
- 101+

8) The organisation I am working for have a total of ..... employees. *

- 1-25
- 26-100
- 101-500
- 501-1000
- 1001+

9) The organisation I am working for have an approximately ..... annual turnover . *

- Less than 1 Million USD
- 1 to 10 Million USD
- 10 to 50 Million USD
- 50 to 100 Million USD
- More than 100 Million USD
- I don't know

10) The organisation I am working for is specialized in following types of projects *

- ☐ Airport
- ☐ Subway
- ☐ Highway
- ☐ Industrial
- ☐ Infrastructure
- ☐ Residential Building
- ☐ Commercial Building
- ☐ Diğer:

11) Have you ever been involved in a construction project utilizing blockchain technology? *

- Yes
- No

Project Information

Please fill the below questions based on your particular experience in the construction project that utilized blockchain technology.

11.1) The project type was ..... . *

- [ ] Airport
- [ ] Subway
- [ ] Highway
- [ ] Industrial
- [ ] Infrastructure
- [ ] Residential Building
- [ ] Commercial Building
- [ ] Diğer:

11.2) The company's role was ..... . *

- Contractor
- Designer
- Consultant
- Client
- Diğer:

11.3) The duration of the project was ..... . (in months) *

11.4) The total budget of the project was ..... . (in USD) *

11.5) Blockchain technology was utilized for ..... . *

- ☐ Payment Management
- ☐ Supply Chain Management
- ☐ Information Management
- ☐ Diğer:

11.6) Please explain shortly how you utilized the blockchain technology?

PROPOSED MODEL

Please read the brief information below.

Blockchain technology offers an infrastructure to create a transparent and traceable way of sharing and storing information among the project stakeholders. Within the literature, construction industry and blockchain technology mostly mentioned to be utilized on contract management processes mainly payment management, supply chain management, and information management.

A model framework has been developed in order to represent the implementation of blockchain technology in the construction industry. There are total of 8 clusters identified within the implementation process and modeled to represent a timeline from pre implementaton to post implementation. The arrows among clusters represent that a cluster assumed to be positivelty affecting the other.

Please evaluate the following factors based on your perception.

Your evaluations regarding the factors determined within this model framework will contribute to the development of this research.

Model Framework

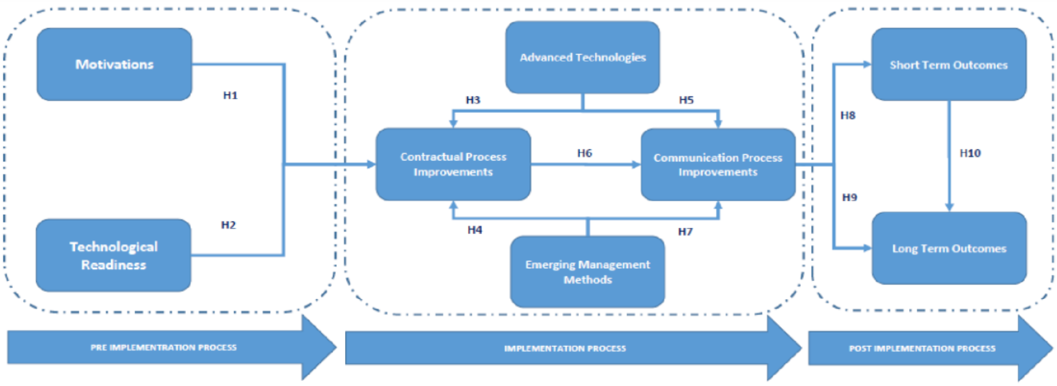

Figure A.1. Initial framework for questionnaire survey

Motivations

To what extent do you think the motivational factors listed below have an influence on the implementation of the blockchain technology for contract management purposes in the construction industry? (1: Very Low, 5: Very High)

	1	2	3	4	5
Competence of Project Staff					
Willingness of Project Parties					
Company Experience					
Top Management Support					
Budget and Investments					
Competitive Pressure					

Technological Readiness

To what extent do you think the technological readiness factors listed below have an influence on the implementation of the blockchain technology for contract management purposes in the construction industry? (1: Very Low, 5: Very High)

	1	2	3	4	5
Level of Industry Awareness	◯	◯	◯	◯	◯
Availability of Guidelines and Standards	◯	◯	◯	◯	◯
Applicability of Technology	◯	◯	◯	◯	◯
Availability of Benchmarks	◯	◯	◯	◯	◯
Feasibility of Pilot Trials	◯	◯	◯	◯	◯
Convenience of Legal Infrastructure	◯	◯	◯	◯	◯

Advanced Technologies

To what extent do you think the utilization of advanced technologies listed below have an influence on the implementation of the blockchain technology for contract management purposes in the construction industry? (1: Very Low, 5: Very High)

	1	2	3	4	5
Building Information Modeling (BIM)	◯	◯	◯	◯	◯
Geographic Information System (GIS)	◯	◯	◯	◯	◯
Internet of Things (IoT)	◯	◯	◯	◯	◯
Radio Frequency Identification (RFID)	◯	◯	◯	◯	◯
Artificial Intelligence (AI)	◯	◯	◯	◯	◯
Big Data	◯	◯	◯	◯	◯
Robotics	◯	◯	◯	◯	◯

Emerging Management Methods

To what extent do you think the utilization of emerging management methods listed below have an influence on the implementation of the blockchain technology for contract management purposes in the construction industry? (1: Very Low, 5: Very High)

	1	2	3	4	5
Lean Construction					
Integrated Project Delivery System					
Agile Management Techniques					

Contractual Process Improvements

To what extent do you think the contractual process improvements listed below may be influenced by the implementation of the blockchain technology for contract management purposes in the construction industry? (1: Very Low, 5: Very High)

	1	2	3	4	5
Automated Progress Tracking	○	○	○	○	○
Automated Payment	○	○	○	○	○
Automated Material Tracking	○	○	○	○	○
Improved Vendor Management	○	○	○	○	○
Improved Data Management	○	○	○	○	○
Improved Change Management	○	○	○	○	○

Communication Process Improvements

To what extent do you think the communication process improvements listed below may be influenced by the implementation of the blockchain technology for contract management purposes in the construction industry? (1: Very Low, 5: Very High)

	1	2	3	4	5
Improved Data Traceability	⬭	⬭	⬭	⬭	⬭
Improved Data Reliability	⬭	⬭	⬭	⬭	⬭
Improved Data Consistency	⬭	⬭	⬭	⬭	⬭
Enhanced Information Transparency	⬭	⬭	⬭	⬭	⬭
Enhanced Information Security	⬭	⬭	⬭	⬭	⬭
Improved Trust Among Stakeholders	⬭	⬭	⬭	⬭	⬭
Improved Collaboration Among Stakeholders	⬭	⬭	⬭	⬭	⬭

Short Term Outcomes

To what extent do you think the short-term outcomes listed below may be influenced by the implementation of the blockchain technology for contract management purposes in the construction industry? (1: Very Low, 5: Very High)

	1	2	3	4	5
Reduced Number of Claims and Disputes	◯	◯	◯	◯	◯
Eliminated Payment Issues	◯	◯	◯	◯	◯
Reduced Risks	◯	◯	◯	◯	◯
Accelerated Schedule	◯	◯	◯	◯	◯
Reduced Costs	◯	◯	◯	◯	◯
Improved Client Satisfaction	◯	◯	◯	◯	◯

Long Term Outcomes

To what extent do you think the long-term outcomes listed below may be influenced by the implementation of the blockchain technology for contract management purposes in the construction industry? (1: Very Low, 5: Very High)

	1	2	3	4	5
Fostered Innovation and Digitalization	◯	◯	◯	◯	◯
Automated Processes	◯	◯	◯	◯	◯
Improved Decision Making	◯	◯	◯	◯	◯
Improved Brand Value	◯	◯	◯	◯	◯
Improved Sustainability	◯	◯	◯	◯	◯
Enhanced Knowledge Management	◯	◯	◯	◯	◯

26. Do you believe that implementation of blockchain technology become widespread among the construction industry in the future? *

- ◯ Yes
- ◯ No
- ◯ Not Sure