Anil, N.A. and Prabhu, P., 2026. Development of a blockchain-enabled smart contract framework for linear construction projects. In: Waidyasekara, K.G.A.S., Jayasena, H.S., Chandanie, H. and Tennakoon, G.A. (eds). *Proceedings of the 14th World Construction Symposium*, 10-11 July 2026, Sri Lanka. pp. 539-551. DOI: https://doi.org/10.31705/WCS.2026.40. Available from: https://ciobwcs.com/papers/

DEVELOPMENT OF A BLOCKCHAIN-ENABLED SMART CONTRACT FRAMEWORK FOR LINEAR CONSTRUCTION PROJECTS

Nair Aswaty Anil[1] and P. Prabhu[2]

ABSTRACT

Large-scale linear infrastructure projects such as high-speed rail corridors, metro systems, highways, and pipelines face major challenges in coordination, communication, material tracking, approval processes, and payment management due to their geographically distributed nature and involvement of multiple stakeholders. Conventional digital tools improve planning and monitoring but often fail to provide secure, transparent, and automated coordination across distributed project work fronts. Blockchain technology and smart contracts offer a decentralized and transparent solution for improving workflow synchronization, payment automation, material traceability, and progress verification in such projects. This paper introduces a blockchain-based smart contract implementation framework specifically designed for linear construction projects. The proposed framework deliberately avoids reliance on Building Information Modelling (BIM) and instead utilises chainage-based scheduling, integrated digital quantity and test records, and IoT/RFID-enabled logistics tracking. It adopts a seven-layer framework that segregates functions such as physical data capture, scheduling, quantity management, smart contract logic, blockchain infrastructure, user interfaces, and governance. The framework defines a segment-oriented workflow covering progress certification, material traceability, interface coordination across civil sub-zones and functional areas, and automated retention release. A schematic flowchart illustrates the end-to-end data and control sequence for a typical corridor segment. The paper further examines expected benefits—enhanced transparency, faster payment cycles, improved traceability, and better interface control—alongside key challenges in implementation, interoperability, scalability, and integration with existing construction management practises.

Keywords: *Blockchain; Linear Infrastructure; Productivity Improvement; Smart Contracts; Supply Chain.*

1. INTRODUCTION

Linear construction projects represent some of the most complex forms of infrastructure development due to their geographically distributed nature, repetitive construction processes, and involvement of numerous stakeholders operating simultaneously across extended corridors. Projects such as high-speed rail systems, highways, pipelines,

[1] Post Graduate Student, Department of Civil Engineering, National Institute of Technology (NIT), Tiruchirappalli, Tamil Nadu, India, aswathy.kure@gmail.com

[2] Assistant Professor, Department of Civil Engineering, National Institute of Technology (NIT), Tiruchirappalli, Tamil Nadu, India, prabu@nitt.edu

transmission corridors, and metro viaducts require continuous coordination between contractors, suppliers, consultants, subcontractors, and project authorities over long distances and multiple work fronts.

Despite advancements in project planning and construction technologies, contract administration in linear infrastructure projects continues to rely heavily on manual documentation, fragmented communication systems, and conventional approval mechanisms. Progress verification, quantity certification, material tracking, interface coordination, and payment approvals are often handled through disconnected workflows, resulting in delays, information inconsistencies, administrative inefficiencies, and contractual disputes (Ye et al., 2022; Gupta & Jha, 2024).

The complexity of these projects increases further due to repetitive segment-based construction activities that are distributed along the alignment. Activities such as pier construction, girder erection, segment installation, pavement works, utility integration, and station or depot construction frequently occur simultaneously across multiple chainages. Coordinating these activities while maintaining accurate progress records, ensuring supply chain visibility, and processing milestone-based payments presents considerable operational and contractual challenges.

Traditional contract administration systems are often inadequate for managing such large-scale distributed operations efficiently. Delays in progress certification and payment approvals can disrupt cash flow throughout the supply chain, while poor visibility over material movement and interface dependencies can lead to disputes, schedule overruns, and productivity losses. Furthermore, fragmented project documentation limits transparency and makes auditing and claims resolution more difficult (Elghaish et al., 2020).

In recent years, blockchain technology and smart contracts have emerged as promising tools for improving transparency, traceability, and automation in construction project management (Hu et al., 2020; Lima et al., 2023). Blockchain provides a decentralised and tamper-resistant ledger capable of securely recording project events, transactions, approvals, and contractual activities. Smart contracts extend this capability by enabling automated execution of predefined contractual conditions once specified criteria are satisfied (Bottoni et al., 2020; Alhanaee & Alhanaee, 2021).

Several studies have explored the integration of blockchain and smart contracts within construction management systems, particularly for payment automation, supply chain traceability, and project governance (Hamledari & Fischer, 2021; Elsharkawi et al., 2025; Song et al., 2023). Research has demonstrated the potential of blockchain-enabled systems in integrated project delivery and governance models through automated financial workflows and decentralised coordination mechanisms (Elghaish et al., 2020; Hunhevicz et al., 2022). However, many existing frameworks depend extensively on Building Information Modelling (BIM) environments and are primarily focused on building projects rather than geographically distributed linear infrastructure systems (Kamel et al., 2023). Limited research has addressed how smart contracts can be implemented effectively in long linear projects characterised by chainage-based workflows, repetitive production cycles, distributed logistics operations, and multiple functional interfaces (Ye et al., 2022, Luo et al. 2019,).

This paper addresses this gap by proposing a blockchain-enabled smart contract implementation framework specifically tailored for linear construction projects. The framework adopts a BIM-independent approach and instead utilises chainage-based scheduling systems, digital quantity records, logistics tracking technologies, and structured workflow automation to facilitate contract administration and project coordination. The proposed model aims to improve transparency, reduce administrative delays, automate milestone-based payments, strengthen supply chain visibility, and provide a reliable digital audit trail across distributed project environments (Hamledari & Fischer, 2021; Gupta & Jha, 2024).

Accordingly, the primary aim of this study is to develop a blockchain-enabled smart contract implementation framework for improving contract administration, workflow coordination, and information management in linear construction projects. To achieve this aim, the study first investigates the major contract administration, communication, and coordination challenges commonly encountered in large-scale linear infrastructure projects. A comprehensive review of existing literature on blockchain technology and smart contract applications in construction management is then undertaken to identify current developments, implementation approaches, and research gaps. Based on these findings, a BIM-independent smart contract framework is developed by integrating chainage-based scheduling, digital quantity records, logistics tracking mechanisms, and oracle-based verification systems capable of validating field events and project progress. Building upon these components, the study proposes a seven-layer implementation framework designed to automate progress verification, payment processing, supply chain traceability, and interface management within linear construction environments. Through this framework, the research seeks to establish a structured and scalable approach for enhancing transparency, accountability, and operational efficiency in the administration of complex linear infrastructure projects.

2. LITERATURE REVIEW

Research increasingly explores blockchain and smart contracts in construction to address payment delays, supply chain fragmentation, and contract inefficiencies through automated milestone payments and immutable records. While early work focused on payment automation and BIM integration, recent studies examine supply chain traceability and linear infrastructure applications.

2.1 BLOCKCHAIN AND SMART CONTRACTS FOR CONSTRUCTION PAYMENTS

A group of papers investigates blockchain as an enabler of transparent, traceable, and tamper-resistant construction supply chains. These studies argue that fragmented information and low visibility over material flows create opportunities for fraud, quality problems, and coordination failures in complex projects, and they propose blockchain ledgers to record procurement, shipment, delivery, and payment events end-to-end (Bottoni et al., 2020; Hu et al., 2020; Gupta & Jha, 2024). Proposed frameworks typically combine smart contracts with digital documentation and tracking to ensure that only compliant, properly documented deliveries are accepted and paid, improving auditability and trust among stakeholders (Kamel et al., 2023; Hamledari & Fischer, 2021). Case applications in public works suggest benefits in terms of traceability and stakeholder confidence yet remain at a relatively high level in terms of process detail (Elghaish et al., 2020; Ye et al., 2022; Hunhevicz et al., 2022). Importantly, they seldom consider the specific logistics patterns and chainage-based material flows characteristic of large high-speed rail viaduct and segmental construction (Song et al., 2023; Lima et al., 2023).

2.2 SMART-CONTRACT FRAMEWORKS WITH BIM AND INDUSTRY 4.0 TECHNOLOGIES

A category of research develops integrated frameworks that embed smart contracts within broader digital ecosystems built around BIM, IoT, and other Industry 4.0 tools. In these models, BIM is usually treated as the central data environment, with 3D/4D models generating verified quantities and progress states that feed directly into blockchain-based smart contracts for payment or performance management (Kamel et al., 2023; Hamledari & Fischer, 2021). Additional work explores linking smart contracts to sensor networks, computer vision, and automated data capture to enable near real-time verification of work completion and quality before contractual actions are triggered (Hamledari & Fischer, 2021; Elsharkawi et al., 2025). Systematic reviews in this area highlight the potential of such integrated frameworks to improve coordination, reduce disputes, and provide a single source of truth for project information across the asset lifecycle (Ye et al., 2022; Gupta & Jha, 2024; Hu et al., 2020). However, their dependence on mature BIM implementations and tightly integrated digital platforms limits direct applicability in contexts where administration is primarily schedule- and quantity-driven and BIM is not fully deployed.

2.3 BLOCKCHAIN IN LINEAR AND INFRASTRUCTURE PROJECTS

A smaller yet increasingly relevant body of literature targets blockchain applications in infrastructure and linear projects such as highways, railways, and pipelines. These studies situate blockchain within the broader "Construction 4.0" agenda for linear assets, emphasising its potential to support distributed work fronts, long supply chains, and multi-stakeholder governance over extended corridors (Lima et al., 2023; Bottoni et al., 2020). Conceptual frameworks and pilots in transport infrastructure show how smart contracts can formalise milestone-based payments, concession obligations, and interface management between public and private actors, with all key events recorded on a shared ledger (Elghaish et al., 2020; Gupta & Jha, 2024). Some authors also note that repetitive, segment-based production processes in linear works are particularly suitable for codified smart-contract rules and standardised data flows (Hamledari & Fischer, 2021; Kamel et al., 2023). Nevertheless, existing studies rarely drill down to the level of a single, very long EPC package with detailed chainage-based segmentation, precast logistics, and segment-wise retention and defects management.

2.4 BLOCKCHAIN FOR CONTRACT GOVERNANCE AND DISPUTE REDUCTION IN CONSTRUCTION

Another stream of research examines blockchain as a mechanism for improving contractual governance, transparency, and dispute reduction in construction projects. Traditional contract administration in construction is often document-intensive and affected by information asymmetry, delayed certifications, and disagreements over progress verification, which frequently lead to disputes and payment conflicts. Blockchain-based systems have therefore been proposed as shared digital environments where contractual events, approvals, and performance records are stored in immutable ledgers, creating verifiable audit trails and improving trust among project stakeholders (Hunhevicz et al., 2022; Ye et al., 2022). Within such frameworks, smart contracts can encode contractual rules, verification procedures, and payment triggers hence actions such as work certification, documentation validation, and milestone-based payments are executed automatically once predefined conditions are satisfied (Hamledari & Fischer, 2021; Kamel et al., 2023). These approaches are expected to reduce administrative delays, enhance transparency, and minimise disputes arising from unclear documentation or delayed approvals in complex projects involving multiple stakeholders and subcontractors (Gupta & Jha, 2024).

2.5 Blockchain for Construction Supply Chain and Material Traceability Management

Construction projects involve extensive supply chains comprising material suppliers, manufacturers, transporters, subcontractors, and project owners. The fragmented nature of these supply chains often results in limited visibility, inefficient information sharing, material delays, and difficulties in verifying the provenance and quality of construction materials. To address these challenges, several studies have proposed blockchain-based supply chain management systems that provide secure, transparent, and immutable records of material transactions throughout the project lifecycle (Bottoni et al., 2020; Hu et al., 2020). Within these systems, blockchain ledgers are used to record procurement orders, manufacturing data, shipment events, delivery confirmations, and quality certifications, creating an auditable chain of custody for construction materials (Song et al., 2023).

Researchers have further explored the integration of smart contracts with supply chain operations to automate material acceptance procedures, inventory management, and supplier payments based on predefined delivery and quality conditions (Hamledari & Fischer, 2021; Kamel et al., 2023). Emerging studies combining blockchain with IoT technologies demonstrate how sensors, RFID tags, and GPS-enabled tracking devices can provide real-time information on material location, condition, and transportation status, thereby improving supply chain visibility and reducing risks associated with delays, losses, and counterfeit materials (Elsharkawi et al., 2025; Gupta & Jha, 2024). While these studies establish the potential of blockchain-enabled material traceability, most focus on general building construction or conceptual supply chain frameworks. Limited attention has been given to highly repetitive and geographically distributed linear infrastructure projects, where thousands of precast components must be tracked across production yards, transportation networks, and chainage-based installation locations. This gap highlights the need for dedicated blockchain frameworks tailored to segment-wise logistics and material traceability requirements in large-scale high-speed rail construction projects (Lima et al., 2023; Ye et al., 2022).

3. RESEARCH METHODOLOGY

This study adopts a conceptual framework development methodology to design a blockchain-enabled smart contract implementation framework for linear construction projects. The methodology was structured in four stages: literature review, problem identification, process analysis, and framework development.

3.1 Literature Review

A comprehensive review of existing literature related to blockchain technology, smart contracts, Construction 4.0, contract administration, payment automation, supply chain management, and infrastructure project governance was conducted. Research papers, journal articles, conference proceedings, and technical studies focusing on construction blockchain applications were analysed to identify current developments, benefits, limitations, and implementation approaches. Particular attention was given to studies related to smart contract-based payment systems, BIM-integrated blockchain frameworks, logistics traceability systems, and governance mechanisms in construction projects.

The literature review helped identify key research gaps, particularly the limited focus on geographically distributed linear infrastructure projects and the overdependence of many existing frameworks on BIM environments. Existing studies were further analysed to understand the use of oracle systems, IoT technologies, RFID/GPS tracking, digital quantity verification, and automated milestone certification mechanisms.

3.2 ANALYSIS OF LINEAR CONSTRUCTION PROJECT CHARACTERISTICS AND CHALLENGES

The operational characteristics of large-scale linear infrastructure projects were analysed to identify challenges that distinguish them from conventional building projects. This analysis focused on geographically distributed work fronts, chainage-based project segmentation, repetitive construction activities, complex stakeholder interactions, precast component logistics, interface management, milestone-based payment structures, and fragmented information flows. The identified challenges were mapped against limitations observed in traditional contract administration practices and existing digital project management approaches. This stage established the practical problem context that the proposed framework seeks to address.

3.3 PROCESS MAPPING AND FUNCTIONAL REQUIREMENT IDENTIFICATION

A detailed examination of typical project workflows was undertaken to understand the flow of information and contractual actions across various project stakeholders. Key processes analysed included progress reporting, quantity verification, inspection and approval procedures, material delivery tracking, payment certification, retention management, and dispute-related documentation.

Based on this workflow analysis, the study identified critical system requirements necessary for a blockchain-enabled environment. These requirements included secure and immutable data recording, automated milestone verification, transparent audit trails, role-based access control, logistics traceability, interoperability with external data sources, and automated execution of contractual obligations through smart contracts.

3.4 FRAMEWORK DESIGN AND DEVELOPMENT

The proposed seven-layer smart contract framework was developed through the synthesis of findings obtained from the literature review and process analysis stages. A layered architectural approach was adopted to organise the system into distinct functional components while maintaining interoperability and scalability. Each layer was assigned specific responsibilities relating to data generation, verification, integration, contract execution, blockchain recording, stakeholder interaction, and governance oversight.

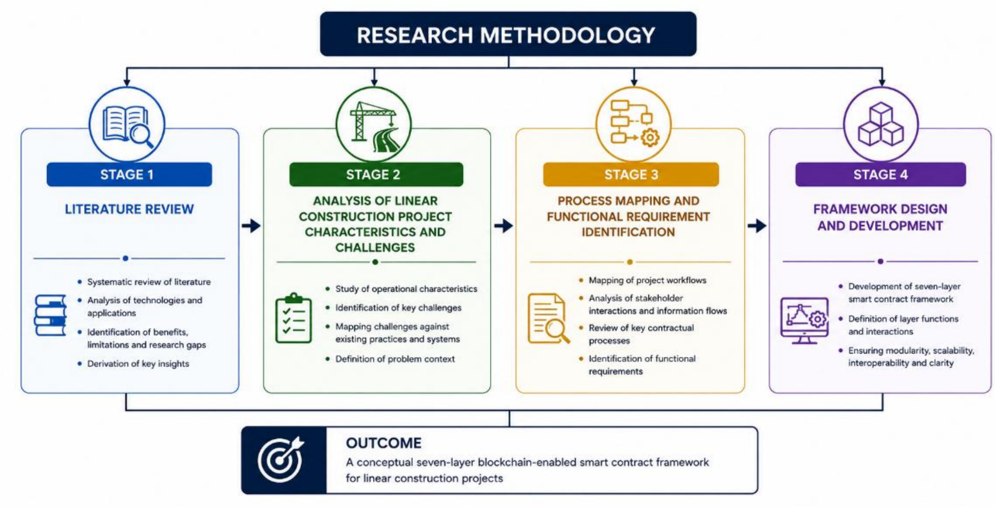

Figure 1: Methodology flowchart

The layered framework facilitates modular implementation while ensuring transparency, traceability, and automation across project workflows.

4. CHARACTERISTICS AND CHALLENGES OF LINEAR CONSTRUCTION PROJECTS

4.1 CHARACTERISTICS OF LINEAR INFRASTRUCTURE PROJECTS

Linear construction projects are distinguished by their elongated geographical alignment and repetitive construction processes. Unlike conventional building projects that are concentrated within a single site boundary, linear projects extend across large distances and involve multiple simultaneous work fronts (Ye et al., 2022).

Typical linear infrastructure projects include high-speed rail corridors, highways, metro viaducts, pipelines, canals, and transmission networks. These projects commonly involve repetitive structural components such as spans, piers, pavement sections, utility segments, or track systems distributed continuously along the alignment.

Construction activities are usually segmented based on chainage or location references, enabling planners to divide the project into manageable sections for scheduling, execution, monitoring, and payment administration. Due to their scale and distributed nature, these projects depend heavily on coordinated logistics systems for transporting materials, equipment, and prefabricated components across different work zones (Song et al., 2023; Bottoni et al., 2020).

4.2 CONTRACT ADMINISTRATION COMPLEXITY

The distributed nature of linear projects creates significant challenges in contract administration and project coordination. Progress measurement and verification must be performed across numerous locations simultaneously while ensuring consistency in quantity records and milestone certification (Ye et al., 2022; Gupta & Jha, 2024).

Material logistics management is another major challenge, particularly in projects involving precast or modular construction methods. Tracking the production, transportation, storage, and installation of structural components across long corridors requires accurate and reliable information systems (Song et al., 2023; Bottoni et al., 2020). Interface management also becomes increasingly complex due to dependencies between multiple contractors, subcontractors, utility agencies, and functional zones. Delays in one segment or interface location can affect downstream activities and disrupt overall project schedules. Traditional manual workflows for approvals, inspections, documentation, and payment certification often result in administrative bottlenecks, reduced transparency, and delayed decision-making. These inefficiencies increase the likelihood of disputes related to progress verification, quantity measurement, payment claims, and responsibility allocation (Elghaish et al., 2020; Hunhevicz et al., 2022).

The limitations of existing contract administration systems highlight the need for digital frameworks capable of supporting distributed project environments while improving transparency, automation, and information reliability (Hamledari & Fischer, 2021; Lima et al., 2023).

5. SMART CONTRACT FRAMEOWRK FOR LINEAR CONSTRUCTION PROJECTS

The proposed framework introduces a blockchain-enabled smart contract system specifically designed for the operational and contractual requirements of linear construction projects. The framework focuses on automating chainage-based workflows, improving supply chain visibility, and enabling secure digital contract administration through blockchain technology.

Unlike BIM-dependent frameworks, the proposed model relies on schedule-based and quantity-based workflows supported by digital records, IoT devices, RFID systems, GPS tracking, and blockchain-enabled smart contracts. The framework transforms validated field data into automated contractual events, enabling milestone certification, payment processing, and interface coordination within a secure and transparent digital environment.

5.1 DESIGN PRINCIPLES

Chainage-Based Segmentation

The framework organizes project activities based on chainage-oriented segments or location-based work packages. Each segment functions as an independent unit for tracking progress, quantities, milestones, approvals, and payments.

BIM-Independent Data Integration

The proposed framework avoids dependence on BIM systems and instead utilizes digital schedules, measurement records, logistics data, inspection reports, and testing documentation as the primary sources for smart contract execution.

Role-Based Access and Responsibilities

Different project stakeholders are assigned defined digital roles and permissions. Contractors, consultants, suppliers, subcontractors, and project authorities interact with the system according to predefined responsibilities for data submission, approvals, and contract execution.

Layered System Architecture

The framework adopts a layered architecture that separates physical data collection, validation processes, smart contract execution, blockchain infrastructure, and governance functions. This modular approach improves scalability, interoperability, and system adaptability.

5.2 SEVEN-LAYER FRAMEWORK

Layer 1 – Physical Works and Data Acquisition

This layer includes physical construction activities and all associated field-level data collection systems. Data sources may include IoT sensors, GPS-enabled equipment tracking, RFID tagged materials, digital inspection records, testing reports, mobile applications, and site measurement systems.

The objective of this layer is to continuously capture time-stamped and location-referenced information regarding construction progress, material movement, equipment usage, inspections, and quality verification.

Layer 2 – Schedule, Quantity, and Chainage Management

This layer manages project schedules, quantity records, milestone definitions, and chainage-oriented activity mapping. Planning systems such as Primavera or MS Project can be integrated with digital quantity measurement systems and bill-of-quantities databases.

Each project segment is linked to planned activities, target quantities, completion criteria, and payment milestones.

Layer 3 – Integration and Oracle Layer

The oracle layer acts as an intermediary between external project management systems and the blockchain network. It validates schedule data, inspection results, quantity records, and logistics information against predefined rules.

Once all contractual conditions are satisfied, the oracle generates verified milestone events and submits them to the blockchain network for smart contract execution.

Layer 4 – Smart Contract Layer

This layer contains the programmable smart contracts responsible for automating contractual workflows.

The framework includes multiple categories of smart contracts:

Progress verification smart contracts for milestone certification and payment calculation.

Supply chain smart contracts for tracking material movement and automating supplier payments.

Interface management smart contracts for documenting interdependent work handovers.

Retention and defects liability smart contracts for managing post-completion obligations.

These smart contracts execute automatically once predefined verification conditions are met.

Layer 5 – Blockchain and Network Layer

This layer consists of a permissioned blockchain network operated by project stakeholders. The blockchain stores smart contract logic, milestone events, approvals, and payment records within a tamper-resistant distributed ledger.

Detailed project documents may remain off-chain while their digital hashes are stored on-chain to ensure integrity verification.

Layer 6 – Application and User Interface Layer

This layer provides dashboards and digital interfaces for stakeholders to monitor project status, approvals, payment events, supply chain activities, and interface coordination.

The interfaces enable users to access project information according to their roles and permissions while maintaining integration with existing project management systems.

Layer 7 – Governance, Legal, and Policy Layer

The governance layer establishes legal, operational, and cybersecurity frameworks for smart contract deployment.

This layer defines procedures for dispute resolution, data correction, stakeholder responsibilities, blockchain governance policies, and integration of smart contract outputs within contractual agreements.

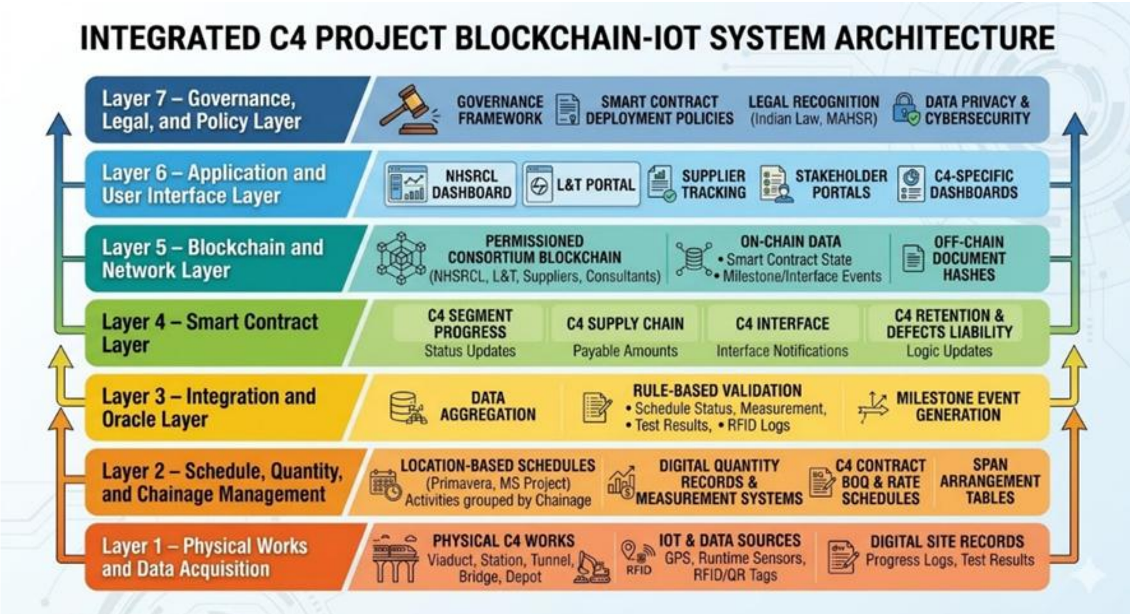

Figure 2: Diagrammatic representation of the 7-layer framework

6. DISCUSSION

The proposed blockchain-based smart contract framework effectively addresses several operational and contractual challenges associated with large linear EPC construction projects, particularly fragmented information management, manual progress verification, distributed logistics coordination, and interface management across geographically dispersed work fronts. The chainage-based segmentation approach supports location-oriented monitoring and milestone verification, which aligns with findings by Ye et al. (2022) that repetitive and standardised workflows in construction are well suited for smart contract implementation. Similarly, the use of IoT, RFID, GPS technologies, and oracle-based validation mechanisms support automated and reliable verification of construction progress, extending the work of Hamledari and Fischer (2021), who highlighted the role of digital data capture and reality-based verification in blockchain-enabled payment automation systems.

The framework contributes to existing literature by integrating multiple contractual functions including progress certification, supply chain management, interface coordination, and retention management within a unified smart contract environment. Previous studies have largely focused on isolated applications such as payment automation or BIM-based contract execution (Kamel et al., 2023). In contrast, the present framework broadens the application scope to address the distributed and interdependent nature of linear infrastructure projects. The inclusion of interface smart contracts is particularly relevant for linear projects where delays or disruptions in one work zone frequently affect downstream activities and multiple contractors simultaneously.

Unlike many existing blockchain frameworks that rely heavily on BIM environments and centralised digital models, the proposed system adopts a BIM-independent framework using scheduling systems, digital quantity records, logistics data, and chainage-based workflows. This improves practical applicability in large infrastructure projects where BIM implementation may be incomplete or inconsistent, thereby addressing limitations identified in earlier studies (Gupta & Jha, 2024; Lima et al., 2023). The seven-layer framework provides clearer functional separation between data acquisition, validation, contract execution, blockchain infrastructure, stakeholder interaction, and governance compared to several conceptual blockchain models proposed in existing construction literature.

However, despite its advantages, the framework remains conceptual and faces several implementation challenges similar to those identified in prior blockchain studies. Integration with legacy project management systems, cybersecurity vulnerabilities, legal enforceability of smart contracts, interoperability among stakeholders, and organisational resistance may limit practical adoption (Hunhevicz et al., 2022; Hu et al., 2020). Furthermore, the scalability of blockchain networks and the reliability of oracle-generated data remain important technical concerns in large-scale distributed infrastructure environments. Nevertheless, the framework demonstrates significant potential for advancing Construction 4.0 principles in linear infrastructure projects by improving transparency, automation, traceability, and trust without requiring full BIM dependency.

7. CONCLUSIONS

This study proposed a blockchain-enabled smart contract framework for improving contract administration, workflow coordination, and information management in linear construction projects characterised by geographically distributed work fronts, repetitive construction activities, extensive logistics operations, and multi-stakeholder interactions. The framework integrates chainage-based scheduling systems, digital quantity records, RFID/GPS-enabled logistics tracking, oracle-based validation mechanisms, and blockchain-supported smart contracts within a seven-layer framework designed to automate milestone verification, payment processing, supply chain traceability, interface coordination, and retention management. By eliminating fragmented workflows and reducing dependency on manual verification processes, the framework aims to improve transparency, traceability, accountability, and operational efficiency across distributed project environments.

The study contributes to theoretical knowledge by extending existing blockchain and smart contract research beyond BIM-centric and building-oriented applications toward the specific operational characteristics of linear infrastructure projects. Unlike many previous studies that focus primarily on payment automation, the proposed framework integrates multiple contractual and administrative functions into a unified blockchain-enabled ecosystem tailored for chainage-based project execution. From a practical perspective, the framework provides a scalable and adaptable implementation model for large infrastructure projects such as highways, rail corridors, metro systems, pipelines, and transmission networks where distributed logistics, repetitive workflows, and interface management create major coordination challenges.

However, the study has several methodological limitations. The framework is conceptual in nature and has not been validated through real-world implementation, pilot deployment, or quantitative performance analysis. The study is primarily based on literature synthesis and process-level analysis rather than empirical data collection from active projects or stakeholder interviews. In addition, issues related to blockchain scalability, cybersecurity risks, interoperability with legacy systems, organizational readiness, legal enforceability of smart contracts, and regulatory compliance require further investigation before large-scale implementation can be achieved.

Future research may focus on developing prototype systems and conducting pilot implementations in live linear infrastructure projects to evaluate technical feasibility and operational performance. Further studies may examine integration with digital twins, IoT ecosystems, AI-based analytics, and automated inspection systems for real-time project monitoring and decision-making. Quantitative assessment of impacts on project cost, schedule performance, dispute reduction, payment efficiency, and supply chain visibility would provide stronger validation of the framework's effectiveness. Additionally, future work should investigate governance models, cybersecurity protocols, legal frameworks, and stakeholder adoption strategies necessary for large-scale deployment of blockchain-enabled smart contract systems in the construction industry.

8. REFERENCES

Alhanaee, N., & Alhanaee, T. (2021). Smart contract using blockchain in construction and infrastructure sector in the COVID-19 pandemic. In *Proceedings of the 38th International Symposium on Automation and Robotics in Construction* (pp. 1018–1024). International Association for Automation and Robotics in Construction. https://doi.org/10.22260/ISARC2021/0137

Bottoni, P., Gessa, N., Massa, G., Pareschi, R., Selim, H., & Arcuri, E. (2020). Intelligent smart contracts for innovative supply chain management. *Frontiers in Blockchain*, 3, Article 535787. https://doi.org/10.3389/fbloc.2020.535787

Elghaish, F., Abrishami, S., & Hosseini, M. R. (2020). Integrated project delivery with blockchain: An automated financial system. *Automation in Construction*, 114, Article 103182. https://doi.org/10.1016/j.autcon.2020.103182

Elsharkawi, H., Elbeltagi, E., Eid, M. S., Alattyih, W., & Wefki, H. (2025). Construction payment automation through scan-to-BIM and blockchain-enabled smart contract. *Buildings*, 15(2), Article 213. https://doi.org/10.3390/buildings15020213

Gupta, P., & Jha, K. N. (2024). Integration of blockchain in contract management for prevention of construction disputes: A systematic literature review and conceptual framework. *International Journal of Construction Management*, 24(10), 1054–1065. https://doi.org/10.1080/15623599.2023.2274720

Hamledari, H., & Fischer, M. (2021). Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. *Automation in Construction*, 132, Article 103926. https://doi.org/10.1016/j.autcon.2021.103926

Hu, B., Zhang, Z., Liu, J., Liu, Y., Yin, J., Lu, R., & Lin, X. (2020). A comprehensive survey on smart contract construction and execution: paradigms, tools, and systems. *Patterns*, 2, 1–51. https://doi.org/10.48550/arxiv.2008.13413

Hunhevicz, J. J., Brasey, P., Bonanomi, M. M. M., Hall, D. M., & Fischer, M. (2022). Applications of Blockchain for the governance of Integrated Project Delivery: a Crypto Commons approach. Project Leadership and Society, 5, 1–19. https://doi.org/10.48550/arxiv.2207.07002

Kamel, M. A., Bakhoum, E. S., & Marzouk, M. M. (2023). A framework for smart construction contracts using BIM and blockchain. Scientific Reports, 13(1), 10217. https://doi.org/10.1038/s41598-023-37353-0

Lima, T. a. R. M., Da Mota, I. T. S., & Melo, C. M., Junior. (2023). Blockchain e contratos inteligentes na construção civil 4.0. Revista Multidisciplinar Do Nordeste Mineiro, 11(1). https://doi.org/10.61164/rmnm.v11i1.1598

Luo, H., Das, M., & Wang, J. (2019). Construction payment automation through smart contract-based blockchain framework. In *Proceedings of the 36th International Symposium on Automation and Robotics in Construction* (pp. 280–287). International Association for Automation and Robotics in Construction. https://doi.org/10.22260/ISARC2019/0168

Song, W., Wu, H., Meng, H., Bian, E., Tang, C., Xi, J., & Zhu, H. (2023). A Blockchain based Fund Management System for Construction Projects -- A Comprehensive Case Study in Xiong'an New Area China. In *8th International Conference on Smart Finance*. https://doi.org/10.48550/arxiv.2308.12834

Ye, X., Zeng, N., & König, M. (2022). Systematic literature review on smart contracts in the construction industry: Potentials, benefits, and challenges. *Frontiers of Engineering Management*, 9(2), 196–213. https://doi.org/10.1007/s42524-022-0188-2