Artificial Intelligence-Enabled Smart Contracts in Building Information Modelling (BIM) For Unified Project Execution: A Theoretical Framework.

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Abstract

Artificial intelligence (AI) for Computer-Aided Design has evolved significantly since its first suggestion in the 1970s, especially with the advent of CADGPT and computational design through generative algorithms. Similarly, several emergent technologies that characterize Industry 4.0 have been adopted to facilitate the efficient delivery of construction projects to offer maximum value to clients. In recent years, the dichotomy between the design and the construction phases has become more unified for optimal financial performance, but it is not without hindrance. In such models, every project team member has a stake in every stage of the project, irrespective of the extent of their roles, and the occurrence of errors and omissions is mitigated effectively with minimal contractual disruptions. This paper aims to address some of the well-documented barriers and challenges by proposing a conceptual framework that integrates novel concepts with Building Information Modeling (BIM), namely, AI and Smart Contracts (SC). In one direction, the study uses AI to optimize the BIM model by obtaining data from completed buildings to improve the shared BIM, which anchors the building contract. In the other direction, the AI triggers smart contracts to automate contractual actions at appropriate milestones such as signoffs, pay-outs, etc., based on construction progress monitored through the BIM model. Thus, the research seeks to leverage AI to mitigate contractual errors while ensuring seamless project execution in one single loop. The proposed framework is validated with qualitative analysis of information obtained based on AEC industry procurement workflows.

Keywords: Unified Project Delivery, Smart Contract, Blockchain, BIM, AEC, Artificial Intelligence.

1 Introduction

The AEC industry is dubbed the most significant industrial sector in the world (Lavikka, et al. 2018), and for so long, the industry has been plagued with challenges of information fragmentation and low productivity. The need for increased efficiency in construction has led to a more unified procurement process that fuses project design, construction, and operation into a seamless workflow. One way to promote construction efficiency is through digital innovation (Shibeika and Harty 2015). An excellent example of such procurement methods is Integrated Project Delivery. According to the American Institute of Architecture (AIA), Integrated Project Delivery (IPD) is an approach that integrates people, systems, business structures, and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction" (AIA California Council 2007).

Digital innovation in construction refers to the technologies and associated digital working practices used to manage and deliver projects in construction (Shibeika and Harty 2015). Building Information Modeling (BIM) has become the digital backbone of the AEC industry. (Pan and Zhang 2022). Integrated Project Delivery, as an example of Unified Project Delivery, is a type of relational project delivery arrangement (RPDA) developed to enhance trust and cooperation in project implementation where information is stored in a more decentralized system and communication channels are transparent (Lahdenpera 2012). In this construction procurement approach, stakeholders are appointed early in the project lifecycle. The early integration of different project participants is a critical success factor in optimizing the design and the construction as processes become more consistent with less rework (Heidemann and Gehbauer 2010).

This paper proposes the integration of Artificial Intelligence (AI) and Smart Contracts (SC) with BIM to enhance construction project delivery. This is achievable using Machine Learning (ML) algorithms and Large Language Models (LLM), which help in BIM-to-text workflow, beginning with a review of relevant literature under a few thematic headings. The research workflows are diagrammed to illustrate a conceptual framework where collaboration stakeholder is optimized, and AI is used to enhance the quality of information. Two use case scenarios are used to highlight different phases of the framework.

1.1 Research Methodology

Scholarly endeavors that are relevant to this topic were selected for review, and they were categorized under the following thematic areas: Challenges and limitations of a unified project delivery method, Artificial Intelligence with Building Information Modelling, Smart Contract-Enabled Automation for Contract Administration, and AI-assisted smart contract in BIM. Following a brief literature review, a framework is proposed for an AI-based optimization of BIM models as a comprehensive repository of construction documents that can form the basis of a contract and automate contractual obligations between parties. The framework development is in two parts. First, the study examines the mode of integration of BIM data with machine learning algorithms for optimization as a contract document. Secondly, the optimized BIM model is integrated with a smart contract feature of blockchain technology to allow process automation between the BIM model and the construction stakeholders. The research is validated using two applicable use cases, while further research findings will be validated through a survey of construction stakeholders. Figure 1 below outlines the research methodology workflow.

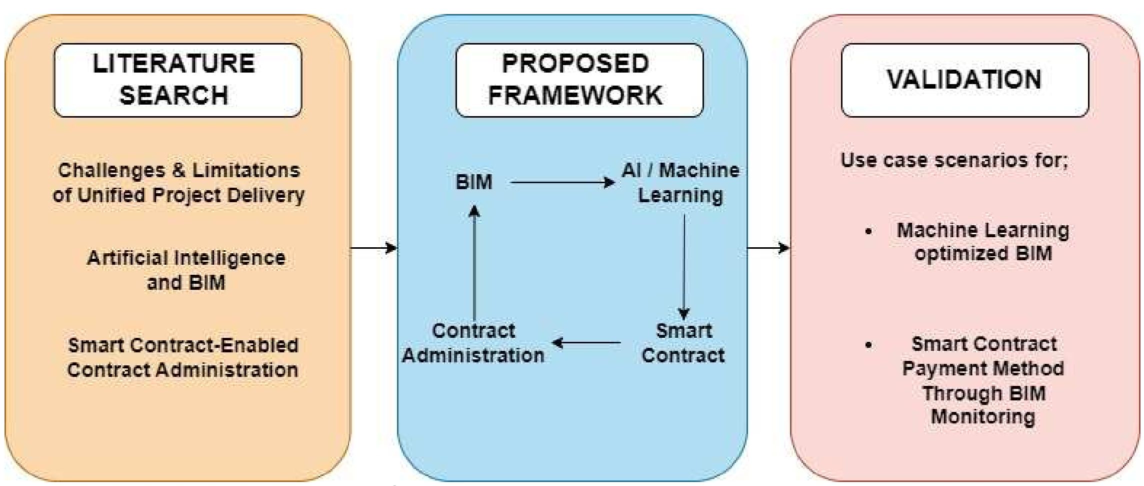

Figure 1. Research Methodology Workflow

2 Literature Review

Advanced digital technologies have disrupted conventional business models, expanded disciplines, and opened up opportunities for new stakeholders from other industries to joint the AEC industry (Lavikka, et al. 2018). Procurement processes and methods, as well as the construction industry at large, is constantly evolving depending on the prevalent needs and concerns of the times. Each method has its unique effect on cost, time, and schedule. (Sullivan, et al. 2017). A high level of shared understanding for cooperation, control, and coordination among stakeholders is critical to achieving mutually desired outcomes. (Ali and Haapasalo 2023). However, disputes and conflicts are bound to arise given the complexity of construction and the multiplicity of stakeholders and their interests, as Alaloul et al. (2019) described construction as a fertile seedbed for disputes. (Alaloul, Hasaniyah and Tayeh 2019). Kumar et al. (2020) posited that among the factors that may lead to a disagreement in construction, the ambiguous language of the contract was the most influential factor, which may also bring about opportunistic behavior, delayed response to decisions, and unrealistic expectations, poor communication between project partners, culminating together with other factors to result in project cost overrun (Kumar Viswanathan, et al. 2020). However, The use of artificial intelligence and machine learning in BIM addresses many of these challenges. (Bassir, et al. 2023).

2.1 Challenges and Limitations of a Unified Project Delivery

The construction industry's high inefficiencies, low productivity, and slow technology adoption have been well documented. Due to the conflicting nature of demand and supply, coupled with the above-listed challenges in construction, the construction supply chain is often fragmented and highly disputed (Cox and Ireland 2002). Kahvandi et al. (2019) highlighted the following limitations for the adoption of a more unified project delivery, namely, contractual, environmental, managerial, and technical limitations. (Kahvandi, et al. 2019). Some practitioners in developing economies know the benefits of a Unified Project Delivery but are not as proactive towards its application. This phenomenon limits general widespread technology adoption in the construction industry (Ebekozien, et al. 2023). Some stakeholders within the construction supply chain lack interest, while some harbor negative perceptions about the efforts, risk, and expenses required in implementing IPD, which are observed as limitations to its use (Durdyev, et al. 2020).

2.2 Structuring the document

The AECO industry has been actively deploying BIM on projects since the early and mid-2000s (Jung and Lee 2016). The quantum of information and data reposited in BIM-based projects presents an opportunity for analysis and extraction of knowledge throughout the project lifecycle, and Machine Learning has proven to be an effective approach for such extraction. (Zabin, et al. 2022). Ghimire et al. (2023) recommended a conceptual Generative AI implementation framework capable of finetuning generative Large Language Models through collecting BIM data and other cloud-based data repositories (Ghimire, Kim and Acharya 2023). Nabavi et al. (2023) proposed a framework to facilitate the retrieval of information from BIM models using a support vector machine (SVM) algorithm to determine user's likely questions while also relying on Natural Language Processing (NLP) for syntactic analysis (Nabavi, et al. 2023).

2.3 Smart Contract-Enabled Automation for Contract Administration

Smart contracts (SC) are codified clauses written as computer programs that can self-execute once certain conditions are met. They are executable codes that run on top of a blockchain to execute and enforce an agreement between untrusted parties without the involvement of a trusted intermediary(Nawari et al. 2019, 2023) (Alharby and Van Moorsel 2017). They consist of transactions that are stored, replicated, and updated in distributed blockchains (Zheng, et al. 2020). The construction industry worldwide is known for its adversarial working relationships which exist between the stakeholders (Phua and Rowlinson 2003) and scholars such as Young-Ybarra & Weirsema (1999) found trust to be the only component of social exchange theory that had a positive effect on flexibility of strategies (Young-Ybarra and Wiersema 1999). Therefore, smart contracts provide a platform for peer-to-peer collaboration without the need for a trusted intermediary, which addresses the inter-party conflicts prevalent in the construction industry. Smart Contracts capture the entire lifecycle of a contract from negotiation to control and verification of the fulfillment of contract obligation, and recent advancements have made it possible to run smart contracts outside of blockchain technology, negating the challenges of immutability and irreversibility(Lawal and Nawari, 2023) (Khan, et al. 2021). Blockchain-BIM and AI-BIM integration have been deployed in pre-construction stages for secure and traceable control and optimization of design documentation; however, further research is required to increase the maturity level of such integrations. For projects that are BIM-enabled, knowledge towards implementing legally sound smart contracts has also been developed (Lawal and Nawari, 2023) (Chong & Cheng, 2023) for automated, transparent, and traceable payment processing for construction projects achieved by combining BIM approaches with blockchain-based smart contracts (Sigalov et al., 2021). Integrating smart contracts in BIM can impact the construction progress when used in payment administration, where BIM links real-world data to a blockchain (Lawal and Nawari, 2023) (Sonmez et.al, 2022).

2.4 AI-assisted Smart Contract in BIM

Traditional payment processes are characterized by low transparency and, eventually, reduced trust (Sigalov et al., 2021). The deployment of smart contracts to mitigate this has been enumerated in section 2.3 above. In the automobile industry, AI has been used in decentralized blockchain with smart contracts to effectively handle market risk assessments during socio-economic crises, incorporating cost functions, delivery time, and energy evaluations (Manimuthu, 2022). AI and blockchain are two emergent technologies with bi-directional impact. AI can be used to improve blockchain technology through its strengthening of security of smart contracts (Krichen, 2023), while blockchain can also improve AI by providing a data repository or a distributed ledger that is reliable, secure, trusted, and credible (Salah, Rehman, Nizamuddin, & Al-Fuqaha, 2019; Asif, Hassan & Parr, 2023). Therefore, despite the significant improvements that smart contracts offer in BIM and contract administration, AI can further eliminate challenges of low trust amongst various stakeholders while offering predictive capabilities for the automation of the integrated project delivery process.

3 Theoretical Framework

Building Information Models (BIM) is the foremost method for object-based information modeling in the AEC industry. This framework is a double-pivot approach that uses machine learning to optimize the BIM model for construction and contract administration to avoid errors due to omissions, which can lead to disputes during project execution. Secondly, the use of smart contracts, which is a feature of blockchain technology, automates the contract administration with minimal human interference.

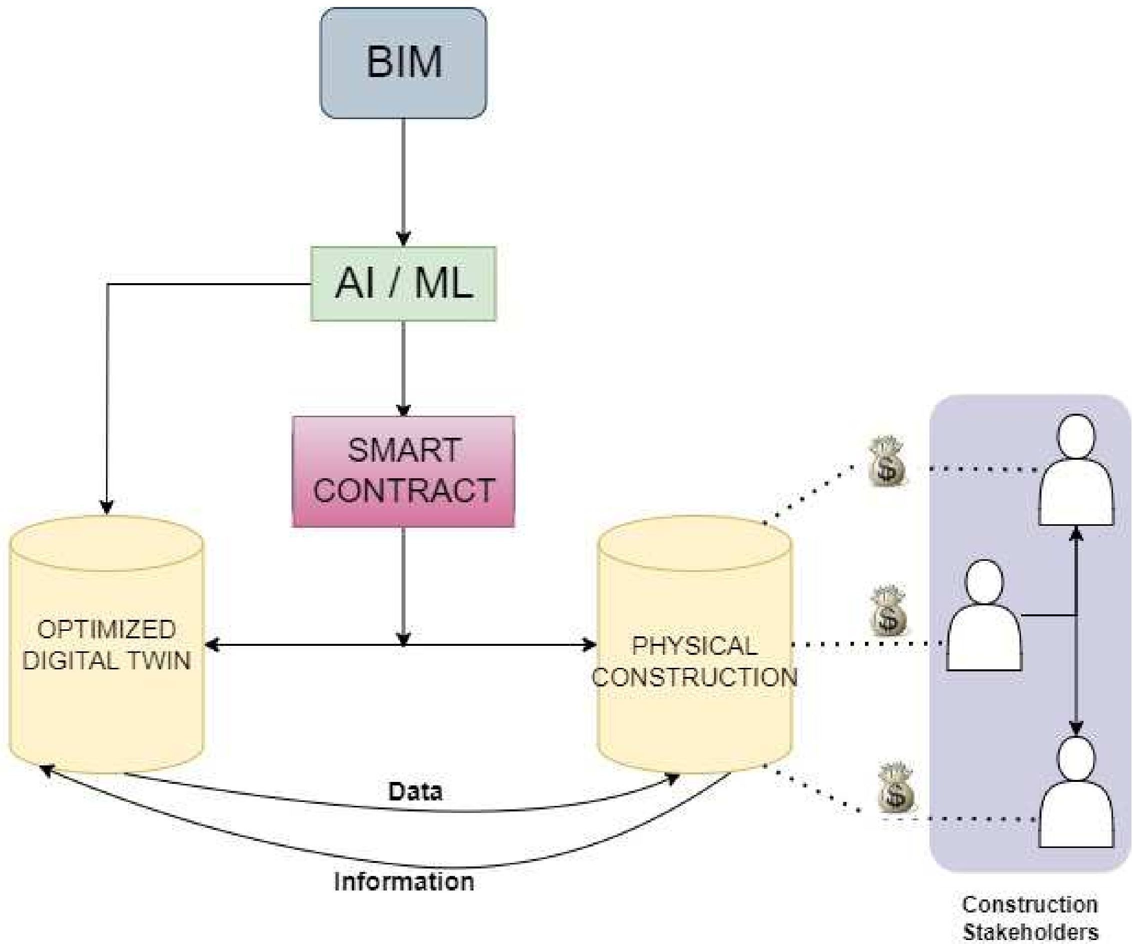

Figure 2. Overview of the proposed framework.

Figure 2 above shows a diagrammatic overview of the proposed framework. The study illustrates the integration of machine learning algorithms within the BIM interface to optimize the model from data collection across a wide range of successful existing projects. Details of the ML optimization is explained in Figure 3. The optimized BIM and its physical twin remain in constant communication, and the state of the physical twin is reflected in its digital twin (the BIM model). Smart Contracts are therefore integrated into this Digital Twin.

In the health sector, a patient digital twin can rely on smart contracts to automate its updating and communicating process (Amofa et al., 2024). Digital twins are also valuable for the execution of performance-based digital payments due to their data storage and evaluation capacity in real-time (Hunhevics, Motie & Hall, 2021). Therefore, in this framework, a digital twin consisting of a BIM model of the proposed construction, in communication with the construction, is required for performance-based automated instructions to stakeholders.

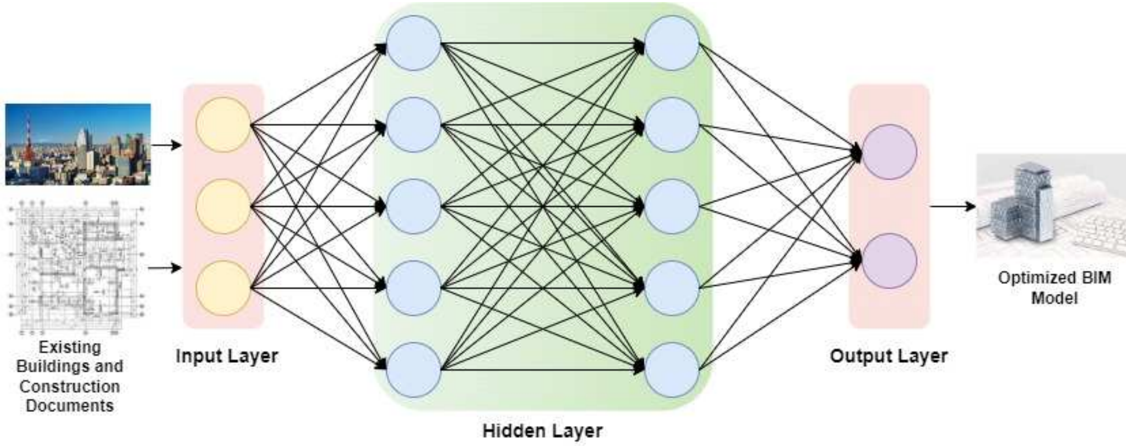

Figure 3. Machine Learning Optimization Framework

Machine Learning optimization uses several techniques such as Deep Learning, Convolutional Neural Networks (CNN) and Large Language Models (LLM), to train the AI engine. 2D and 3D contract documents of successful projects are fed in as input, and the AI engine uses LLM to extract textual information from the input and check for errors in text data within the BIM model. It also refines critical construction details to reduce or eliminate the possibility of transferring errors into the contract document.

A key component of this framework is the Large Language Model (LLM) engine. Large Language Models (LLMs) can provide a high level of language comprehension and syntax accuracy for optimizing building specifications and contract documentation through robust pre-training models.

In the BIM interface, annotations with regards to the work schedule are codified into the smart contract, such that a payment instruction is triggered once the project is at the stage associated with the text on the work schedule and according to the payment amount associated with the milestone reached.

The BIM interface also contains annotated drawings and details that feed the specification writeup. LLMs are trained with a dataset comprising a vast array of specifications. The LLM engine prompts the smart contract if specifications reported during construction are not in accordance with the dataset for which it has been trained based on the BIM model. Therefore, the AI integration with smart contract can also function as a quality checker during construction.

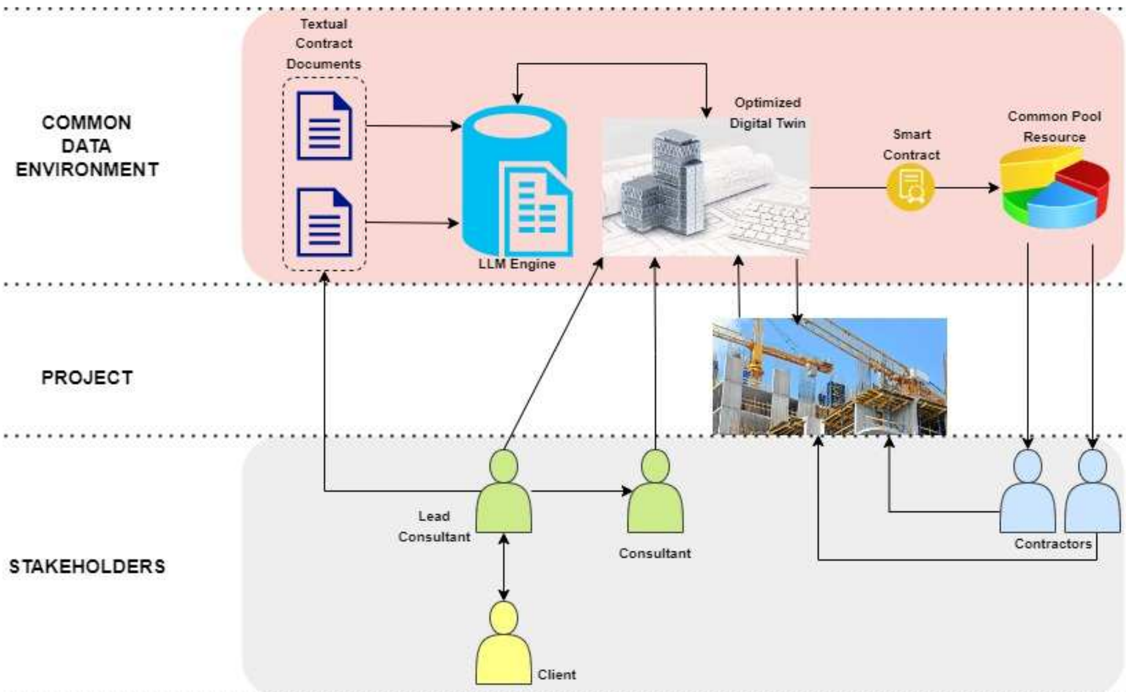

Figure 4. Common Data Environment Framework

Three primary communication layers in the proposed framework are The Common Data Environment (CDE), the project, and the stakeholder groups. The CDE is a cloud-based platform that allows stakeholders to share project information. The CDE is a repository of paper-based and model-based project information and an LLM engine that bridges the textual data and the BIM model. Figure 2 shows smart contracts are integrated with BIM to trigger actions towards the Common Pool Resource (CPR). CPR is another CDE that is solely for financial resources.

Figure 4 depicts an interconnected loop between all project stakeholders and stakeholders and the BIM model, housed in a cloud-based Common Data Environment. Earlier studies have proposed a Common Data Environment (CDE) for secure data storage of digital assets, interdisciplinary coordination, management, and versioning of information containers (Sreckovic, et al. 2021) (Wang, et al. 2017) (Pishdad-Bozorgi, Yoon and Dass 2020). Also, Figure 4 above displays the interrelationship between all project stakeholders. A cloud-hosted blockchain CDE, which is the agreed information repository that records all additions and alterations to the information contained, is used to house a shared BIM model. Blockchain provides a decentralized, automated, and secured financial platform that enables multiple parties to control and track financial transactions (Elghaish, Abrishami and Hosseini 2020).

4 Use Cases

The use case scenario will be discussed under two main headings; 1) A machine learning-optimized BIM model for effective contract formulation and 2) Smart Contract-Automated Contract Obligations through BIM Monitoring.

4.1 A Machine Learning-Optimized BIM Model for Effective Contract Formulation

AI and ML have proven efficient in extracting useful data sources and predicting when and where to provide quality control (Bassir, et al. 2023). However, BIM has a unique ability to replicate physical scenarios and embed information with real physical and non-physical properties, making it an effective tool for collaboration. BIM and Unified Project Delivery methods are technology-intensive process innovations capable of reconfiguring social relationships (Rowlinson 2017). Existing literature suggests that BIM and/or IPD can dramatically enhance project performance through conceptualization through building management and ongoing operations. (Ilozor and Kelly 2012). This scenario adopts ML/AI approaches to train a BIM-model using a dataset of existing construction documents. Training data will consist of paper-based and BIM-based data of successful existing projects. LLM engines will be used to enhance text information in contract documents to reduce contractual ambiguities while Deep Learning algorithms will help to enhance BIM construction details. This approach improves the integrity of contract documents.

4.2 Smart Contract – Automated Contract Obligations Through BIM Monitoring

Upon optimization of contract information to eliminate ambiguity and dispute, Smart Contracts (SC) can be used to automate administrative procedures by activating various contractual obligations via the Common Pool Resource (CPR) as the project traverses its set timelines. The CPR as shown in Figure 4 are systems that generate finite quantities of resource units so that one person's use subtracts from the quantity of resource units available to others (Ostrom, Gardner and Walker 1994). Hunhevics et al (2020) suggested that the governance of a Common Pool Resource (CPR) scenario was a useful guide to future research and blockchain applications in construction. (Hunhevicz, et al. 2020). This phase relies on sensory technology, which ensures information flow from the construction site to the Digital Twins and interconnectivity with the CPR using Smart Contracts. This approach reduces human intermediaries and adversarial tendencies prevalent in the AEC industry.

Contract administration, contract ambiguities, and delays in fulfilling obligations by certain parties make traditional project delivery methods cumbersome, thereby bringing about low productivity and high inefficiencies. This research demonstrates a de-emphasized human component of contract formulation and administration. Machine learning is used to improve and filter erroneous aspects of contracts by learning from large quantum of datasets that are nearly impossible to process manually. The CPR then acts as a contract intermediary governed by encoded rules that trigger irreversible actions once any project stakeholders reach a contract milestone.

5 Conclusion

This research aims to enhance project delivery by proposing and integrative framework of BIM, Artificial Intelligence and Blockchain Technology. With BIM becoming the backbone of the industry's digital transformation, it is integrated with many of the most cutting-edge innovations in construction. This paper covers brief literature review capturing scholarly efforts under thematic headings such as challenges and limitations of IPD, Artificial Intelligence in Building Information Modelling, and Smart Contract-Enabled Automation for Contract Administration. The proposed conceptual framework uses AI/ML to optimize the quality of BIM data, thereby enhancing the model as a contract document. This is achieved by using LLM to synchronize text data with BIM data. Digital Twin technology connects the BIM to the ongoing construction, and smart contracts ensure an automated Unified Project Delivery by ensuring that the contents of the CPR are released according to contractual obligations. Two use case scenarios helped to validate the framework. The first uses a Machine Learning-Optimized BIM model for effective Contract Formulation. Large datasets in the form of working drawings are used to train the AI model, which, in turn, finetunes with the specifications of the BIM model. The second use case deploys SC to automate contract obligations through BIM monitoring. The SC is interlinked with the BIM model, which receives data from the physical project as well as the Common Pool Resource (CPR). The SC triggers payment instructions and other contract obligations at the appropriate schedules. This concept offers an error-free contract formulation and simultaneously automated contract execution. Future research is required to develop the BIM interface so that AI and smart contract features are embedded, thereby lowering the technical entry requirements for this innovation, as current BIM users will be able to adopt this technology more readily. This study also provided the unique opportunity of bringing all stakeholders into construction under one digital interface, thereby unifying the project execution across its lifecycle.

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