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DECENTRALIZED SYSTEM FOR CONSTRUCTION PROJECTS DATA MANAGEMENT USING BLOCKCHAIN AND IPFS

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Abstract. Construction projects' performance is not self-regulating. Therefore, a continuous progress tracking and monitoring process is highly demanded to avoid potential deviations or misalignments. The current practice for the progress tracking and monitoring process suffers from heavily intermediated workflows, human errors, transfer latencies, inaccuracies, and/or information holes. Such issues could gradually lead to severe delays or even complete project failure. This research introduces a novel Peer-to-Peer (P2P) system that relies on Blockchain Technology (BT) and Inter-Planetary File System (IPFS) for managing progress information and as-built digital assets or files. The system is developed based on a three-step approach. First, two chaincodes are formulated for mapping and governing the data operations. Second, a private blockchain network is configured based on Hyperledger Fabric as a hosting platform, including the relevant stakeholders. Third, a private IPFS network is configured and coupled with a cluster service to manage and distribute the off-chain visuals and as-built digital assets. A case study for a non-residential construction project is utilized to test and verify the system's practicability and assess its performance. The research significance is anticipated in diverse practical areas, including but not limited to; boosting coordination and trust among stakeholders, tracing progressive elaboration of As-built digital assets, accelerating incremental payments processing, assessing overall project performance and on-site productivity, supporting delay analysis and claim/dispute management, and streamlining data flow between the construction phase and the operation and maintenance phase. Further, the system's future is mapped by evolving it as a sub-unit in a more advanced data model.

Keywords: progress control, As-built assets, IPFS, blockchain, construction information systems.

Introduction

The effective on-site progress monitoring and control process is considered the success key for construction projects. Such process aims at avoiding potential discrepancies between the as-built state and the as-planned designs, baselines, and their related digital assets or files, including drawings, contracts, documents, and different n-dimensional building information models (3D models loaded with time, cost, safety, and productivity information) (Alaloul et al., 2021; Lin & Golparvar-Fard, 2020b; Sjekavica Klepo & Radujković, 2019; Tserng et al., 2014). It typically consists of four major tasks: coordination of work items under execution; tracking work items status and issues via traditional job walks and daily photos; documentation of work items status and issues; and review and adjustment of plans and digital assets (Omar & Nehdi, 2016). Moreover, it is a repetitive data-intensive process that exponentially generates vast amounts of on-site information. This information is categorized into textual data and visuals with a range of formats from texts, documents, voice notes, photos, and videos, to laser scans that are collected and exchanged based on disparate frequencies to sustain a smooth workflow (Garcia et al., 2014). The current practice of visuals and textual data collection and exchange is considered costly and time-consuming. Further, It often does not guarantee the quality and completeness of as-built state capture and the steady flow of on-site information, especially for construction firms with multiple simultaneous projects (Lin & Golparvar-Fard, 2020a). This practice tends to be questionable and less effective due to probable human errors, transfer latencies, and information inaccuracies or holes, which readily lead to project delays, uneconomical decisions, or even the complete fail-

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ure of a project. Accordingly, there is a persistent necessity to have a faultless fluent communication and information exchange system to be in place for real-time progress monitoring and sharing between on-site personnel and different stakeholders. The system should streamline and enhance the on-site information flow while reducing human involvement and several handoffs. Several research efforts have been conducted to improve the efficiency and quality of the progress monitoring and control process with the help of information and communication technologies such as multimedia tools, email services, voice-based tools, and handheld computing (Abdel-Monem & Hegazy, 2013; Akanmu et al., 2020; Garcia et al., 2014; Lin & Golparvar-Fard, 2020a; Mahami et al., 2019). Although these technologies support traditional tasks, ease communications, and speed up exchange processes, their utilization has some limitations that are summarized as follows:

- Textual and visual data collection and sharing are confined to a centralized framework leading to a high possibility of single-point failures or data losses without using a backup system.
- Textual data management, coordination, and transfer for managing future projects are not sustained or overlooked.
- Textual data integrity is not guaranteed due to possible tampering and manipulation.
- Management of accumulated visual data is overlooked and not taken into account.
- Effective textual and visual data sharing and reporting regarding replication, synchronization, frequency, amount of information is not guaranteed.

Inspired by the fourth industrial revolution (Industry 4.0), new technologies such as Blockchain Technology (BT) and Inter-Planetary File System (IPFS) can potentially offer a solution to tackle these limitations through using a peer-to-peer network system. This study addresses such limitations and potentials by proposing a clustered IPFS-Blockchain system for managing on-site progress information and related as-built digital assets. Through investigating the practical requirements of on-site progress monitoring and control process, including data types, uses, and related exchange methods, the proposed system tries to answer the following research question: How can an information exchange system based on BT and IPFS enhance the on-site data collection, sharing, and retrieval while increasing trust, coordination, and effectiveness for different stakeholders? Accordingly, the research objective is to digitalize and decentralize the progress monitoring and control process while maintaining consistency between the as-built state and the related as-planned designs, baselines, and digital assets. To achieve this objective, the following sub-objectives are performed: i) investigate the potentials of BT and IPFS in the construction field as new information exchange methods, ii) design and formulate a system based on BT and IPFS technologies for facilitating the exchange and management of on-site progress information and related as-built digital assets, iii) build a prototype of the proposed system and technically demonstrate its applicability via a case study, and iv) identify the potential adoption barriers and enablers of such a system in the construction industry. The system employs a permissioned Blockchain Network (BN) reinforced by a private IPFS network operated via a cluster service to act as an immutable single source of truth. The IPFS network is utilized for managing and storing on-site visual information and as-built digital assets. In contrast, the BN is utilized for exchanging and storing on-site textual information and IPFS hashes of related visuals and digital assets. As the construction field often adopts new technologies and developments slowly, BT and IPFS are still a novelty in this field. Compared to existing related research efforts, this study contributes to the knowledge by introducing a novel system that relies on the BT and IPFS for managing on-site progress information and related as-built digital assets. The system leverages the features of BT and IPFS to bypass the limitations associated with traditional information systems concerning information centralization, synchronization, integrity, transfer blockage, accumulated visuals management, and as-built digital assets tracking. The remainder of this paper is structured as follows. Section 1 provides a literature review for BT and IPFS. Section 2 clarifies the proposed system design. Section 3 focuses on the system development. Sections 4 and 5 are related to the system testing and performance evaluation using a case study. Sections 6 provides thorough discussion. Last section includes conclusions.

1. Literature review

1.1. Blockchain technology

Blockchain technology is an innovative technology that is defined as an immutable decentralized record medium. BT is able to record, maintain, and disseminate transactions, data exchange operations, or digital events among a network of members in a peer-to-peer manner without being dominated by a singular authority and/or verified by trusted intermediaries. It was introduced in 2008 as the core engine for the Bitcoin cryptocurrency network. Nevertheless, the term "blockchain" is no longer linked only with developing and circulating digital cryptocurrencies but extended to cover new use-cases in different domains with forecasted business value to exceed USD 3.1 trillion by 2030 (Chang et al., 2019; Onik & Miraz, 2019). The BT inner working is described as a sequential chain of data blocks that are linked together via cryptographic hashes. Each block records information about its data exchange operation while having a connection with its preceded block by recording its hash (see Figure 1). This connection allows BT data operations to be traceable while maximizing its invulnerability against tampering or manipulation (Chen et al., 2021). According to Chang et al. (2019), Perera et al. (2020), the essential features of BT can be summarized as follows:

- Decentralization: The data's blocks are duplicated and distributed among the entire network's nodes, which

diminishes the risks of single-point failures, attacks, or corruptions.
- Disintermediation: The data validation is carried out by the network's nodes without employing trusted third parties.
- Auditability: The data's blocks are chronologically ordered and time-stamped to be traced and audited with ease.
- Immutability: The data's blocks cannot be modified or tampered once being cryptographically hashed and included on-chain.

BT is currently under thorough research and development, which leads to a high fragmentation with more than 20 different platforms. These platforms have been released by universities, companies, and open-source communities. Ethereum and Hyperledger Fabric are referenced as the most exploited blockchain platforms (Perera et al., 2020; Yang et al., 2020). Ethereum is defined as a generic open-source platform that was released in 2015. It allows its users to execute programmable codes "smart contracts or chaincodes" and develop and circulate cryptocurrencies related to specific use-cases. In contrast, Hyperledger Fabric is a project of blockchain frameworks that was established and sponsored by a consortium of Linux Foundation, IBM, and other companies in 2016. It is defined as a permissioned blockchain platform that allows developing blockchain-based solutions and applications essentially for usage in a private enterprise environment. According to Nyaletey et al. (2019), Sonmez et al. (2021), Hyperledger Fabric is considered an ideal platform to support construction-related applications and model their complex transactions and business requirements especially in case of no involved cryptocurrencies due to the following characteristics:

- Its compatibility with several available commercial packages such as the IBM® Blockchain Cloud, the Oracle Blockchain platform, the AWS Blockchain Platform, the Microsoft Azure Blockchain Platform, and the SAP Cloud that facilitates its implementation.
- Its entire network's nodes are predefined. As a result, there is no mining process, which boosts the performance and reduces the consumed resources and time in the transaction processing.
- Its ability to dynamically manage multiple channels within a single blockchain network that allows restricting and controlling the transactions flow between the enrolled users in these channels only.
- Its extendable architecture that can be scaled over time.
- Its Plug & Play Interface support that facilitates the interaction with blockchain networks.

The structure of the Hyperledger Fabric consists of ten major components (Elghaish et al., 2020; Yang et al., 2020):

1. Ledger: a non-modifiable list of blocks that includes all transactions within a specific channel.
2. Peer: a node that manages ledgers and smart contracts.
3. Transaction: a requested action to be executed in the form of a read or write process.
4. Chaincode: a software component that is installed on a particular channel and performs transactions according to a specific endorsement policy.

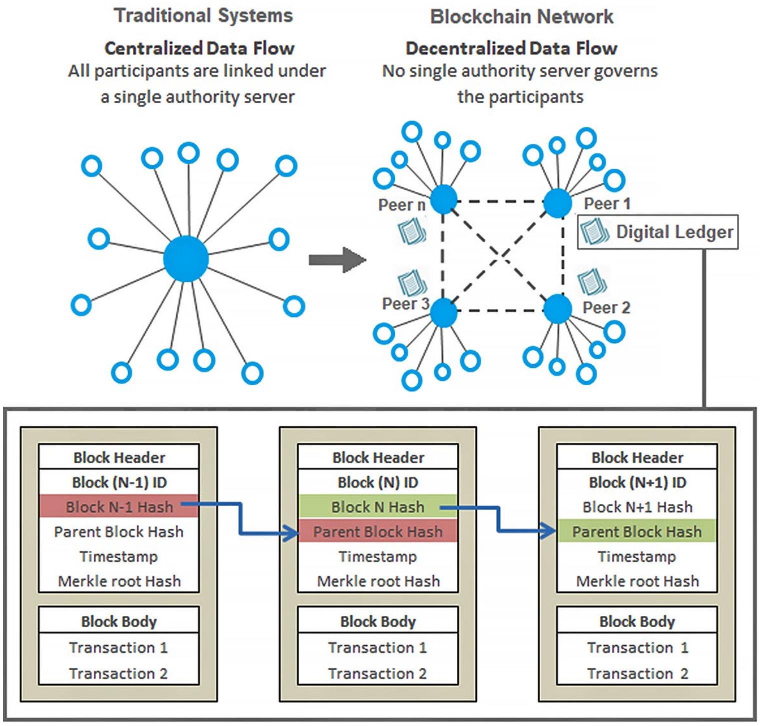


Figure 1. Traditional systems and blockchain network

5. Channels: a particular communication layer for a subgroup of nodes to allocate the transactions and maintain their privacy.
6. Endorsement policy: a set of specific metrics to peers for assessing the received transactions' validity.
7. Ordering service node: a node utilized to order transactions based on the agreed consensus algorithm while including information about block size, block time, and transactions' number per block.
8. Certificate Authority (CA): a node that produces certificates for registered network members.
9. Membership Service Provider (MSP): a provider that uses a certificate authority to validate and authorize network members and manage connection profiles for peers.
10. Consensus algorithm: a set of protocols coded to ensure that the entire network's nodes interact adequately based on the predefined conditions and the endorsement policy.

Recent construction research efforts have investigated the potential utilization of BT as a transaction-oriented technology only for exchanging and maintaining information. These efforts are scattered around eight major areas with different levels of adoption. Areas of asset management, intelligent contract management, and decentralized autonomous organizations are still in the conceptualization phases and going under extensive research (McNamara & Sepasgozar, 2020; Raslan et al., 2020; Sreckovic & Windsperger, 2019). In contrast, areas of payment management, supply chain management, quality information management, Building Information Modeling (BIM), supervision information management are the most matured or explored areas for BT utilization with pioneer achievements.

1.1.1. Payment management

Elghaish et al. (2020) introduced a framework for integrated project delivery projects (IPD) based on blockchain technology. The framework was built using Hyperledger Fabric and tested to demonstrate its capabilities to automatically execute and settle all financial transactions and enhance risk/reward sharing practices in IPD. Ahmadisheykhsarmast and Sonmez (2020) proposed an approach for handling payment issues in the construction sector using an automated computerized protocol that runs on a decentralized blockchain network. The approach guarantees the security of payments for works under construction while reducing administrative costs and burdens of trusted intermediaries such as lawyers or banks. Das et al. (2020) presented a distributed blockchain-based framework to automatically execute terms and conditions related to interim payments and share payment records between relevant key actors. The framework was technically evaluated using a case study in terms of immutability, data confidentiality, user integrity, performance, and cost of deployment. A study by Sigalov et al. (2021) provided a novel approach for automated, transparent, and traceable payment processing in construction projects that combines BIM approaches with blockchain-based smart contracts. A case study was used to demonstrate the approach's implementation and its intended outcomes. Ahmadisheykhsarmast and Sonmez (2020) introduced a novel payment system relying on BIM and blockchain technology to enhance and accelerate the traditional progress payment procedure in construction projects. The system was applied to a real construction project to validate its applicability and explore the construction professionals' related opinions through a questionnaire survey. Elghaish et al. (2022) introduced a blockchain-based financial system to address the issues related to financial management practices adopted in construction projects. The system was tested on a real-life case study, where results showed its workability to provide a secure scalable financial transacting platform for all project stakeholders with no third-party involvement.

1.1.2. BIM

A study by Le (2021) introduced a blockchain-based application to solve BIM models' ownership issues and increase their quality and usefulness. The study clearly illustrated the application's development sequence and its inner data flow mapping using the Ethereum platform. Suliyanti and Sari (2021) explored the exchange of BIM information among different parties in a peer-to-peer manner using a permissioned blockchain network throughout the building lifecycle. A prototype was developed using Hyperledger Composer and evaluated using a case study in terms of security, and average response time. Shojaei et al. (2020) integrated BIM and blockchain networks for governing construction project contracts while using a smart contract for network operation logic. The study aimed to maintain a tamper-proof record of project progress and automate the consequent actions.

1.1.3. Supply chain management

In a study by Wang et al. (2020), the authors introduced a blockchain-based information management framework for precast supply chain management. The framework was built using the Hyperledger Fabric platform and aimed at achieving 1) decentralized information management, 2) real-time control of schedule works, and 3) information traceability. A study by Lu et al. (2021a) proposed a blockchain-based framework for regulating and managing off-site logistics and on-site assembly services. The study illustrated the development steps for the framework architecture and used a case study to validate the framework's applicability in real-life projects. Li et al. (2022) proposed a novel architecture based on blockchain and IoT for automating and decentralizing supply chain management in modular construction. A prototype was developed and applied to a demonstrative case study to evaluate the architecture performance in terms of storage size, latency, throughput, privacy, and stakeholders' feedback.

1.1.4. Quality information management

Wu et al. (2021) introduced an on-site construction quality inspection system that relies on BT to tackle the issues of traditional paper-based practices, overcome information fraud and enhance the automation level for quality inspection processes. A system prototype was built using the Hyperledger Fabric platform and implemented in a case study to validate its practical feasibility. In a study by Sheng et al. (2020), the authors introduced a novel system for managing construction quality information using the Hyperledger Fabric platform. A system prototype was built to verify its workability and assess its performance.

1.1.5. Supervision information management

Lu et al. (2021b) proposed a novel framework for governmental supervision of construction work based on BT. A prototype was developed using the Hyperledger Fabric platform, and its strengths and weaknesses were evaluated for further development and future enhancement. Li et al. (2021) developed a blockchain-based supervision model for off-site modular housing production operations. The model allows real-time information sharing, affords enhanced communications between trading participants, and avoids tampering with the operations' records. Lu et al. (2022) introduced a novel solution to support e-inspection 2.0 in construction processes using blockchain technology. The solution was designed and developed using the design science research approach. Further, it was tested on a real-life case study to demonstrate its capability to tackle e-inspection-related concerns (e.g., authenticity and traceability) in the COVID-19 pandemic era.

Table 1 provides a brief comparison of the recent BT research efforts in terms of domain area, platform, adoption level, and limitations. As per the table, there are two

Table 1. Recent BT research efforts in the construction field

Study	Domain	Platform	Adoption Level	Major Limitations	
				Adoption Barriers & Enablers Identification	Large-size & Visual Data Support
Raslan et al. (2020)	Asset Information Management	Ethereum	Conceptualization	•	•
Gunasekara et al. (2021)		–	Conceptualization	•	•
Li et al. (2020)		–	Conceptualization	•	•
McNamara and Sepasgozar (2020)	Intelligent Contract Management	–	Conceptualization	•	•
McNamara and Sepasgozar (2021)		–	Conceptualization	•	•
Sreckovic and Windsperger (2019)	Decentralized Autonomous Organizations	–	Conceptualization	•	•
Shi et al. (2019)		–	Conceptualization	•	•
Elghaish et al. (2020)	Payment Management, Automation & Security	Hyperledger Fabric	Proof of Concept	•	•
Ahmadisheykhsarmast and Sonmez (2020)		Ethereum	Proof of Concept	•	•
Das et al. (2020)		Ethereum	Proof of Concept	•	•
Sigalov et al. (2021)		Ethereum	Proof of Concept	•	•
Sonmez et al. (2022)		Ethereum	Proof of Concept	•	•
Elghaish et al. (2022)		Hyperledger Fabric	Proof of Concept	•	•
Le (2021)	Building Information Modeling	Ethereum	Proof of Concept	•	•
Suliyanti and Sari (2021)		Hyperledger Fabric	Proof of Concept	•	•
Shojaei et al. (2020)		Hyperledger Fabric	Proof of Concept	•	•
Wang et al. (2020)	Supply Chain Management	Hyperledger Fabric	Proof of Concept	•	•
Lu et al. (2021a)		Hyperledger Fabric	Proof of Concept	•	•
Li et al. (2022)		Hyperledger Fabric	Proof of Concept	•	•
Wu et al. (2021)	Quality Information Management	Hyperledger Fabric	Proof of Concept	✓	•
Sheng et al. (2020)		Hyperledger Fabric	Proof of Concept	•	•
Lu et al. (2021b)	Supervision/ Inspection Information Management	Hyperledger Fabric	Proof of Concept	•	•
Li et al. (2021)		Hyperledger Fabric	Proof of Concept	•	•
Lu et al. (2022)		Hyperledger Fabric	Proof of Concept	•	•
This Study	Progress Monitoring & Control As-built Digital Assets Evolution	Hyperledger Fabric	Proof of Concept	✓	✓

Notes: ✓ – Addressed; • – Not Addressed.

major limitations. First, these efforts did not intelligibly identify or state the potential BT adoption barriers and enablers in the construction industry context with respect to technological factors, organizational characteristics, and environmental aspects. Second, these efforts utilized BT as a transaction-oriented technology for exchanging raw textual and numeric data without supporting visual or large-size data due to the BT storage-bloating problem. This problem refers to the continuously growing nature of blockchain transactions in number and size due to the immutability and append-only features since the new blocks are added on-chain, and the old blocks cannot be deleted. Consequently, the on-chain data must be stored by all nodes, which creates significant memory and bandwidth constraints, wastes computational resources for storage and access, and inversely affect the network performance. Such a problem can be tackled by recording only the sensitive textual data on-chain and including the hashes of off-chain visuals that are maintained in a separate storage system. This approach can bypass the storage-bloating problem while ensuring the integrity and linkage between on-chain and off-chain data. The storage system is traditionally categorized into a cloud system or a server-client system. The server-client system is a distributed system concerning hardware specifications only, but the stored data is still controlled or dominated by a single party. The cloud system provides distributed access while operating in a centralized manner due to service provider control and restrictions. Therefore, the need for a subsidiary decentralized storage system that maintains large-size data or files and distributes the risks of attacks or failures among all the involved parties is more apparent while not compromising on security, access control, or data availability. The IPFS can be that system while relaxing the barrier to BT adoption and deployment in the construction industry.

1.2. IPFS

IPFS is a decentralized data storage and version-control system that was introduced by Benet (2014) to provide high throughput, stable and secure content-addressed block storage model. It is designed to distribute and store data or files throughout scattered connected nodes in a peer-to-peer manner with no centralized server while allowing high-capacity storage, supporting high access concurrency, and ensuring consistency among the nodes. The exchanged file via the IPFS is marked with a unique content identifier (CID) that is computed via a cryptographic hash function based on its content and the exchanging node (see Figure 2). This CID makes the data/file to be content-addressable rather than location-addressable while ensuring the content's uniqueness but not guaranteeing its ownership or authenticity (Andrian et al., 2019; Huang et al., 2020; Ren et al., 2021). Furthermore, whenever modifications are made to the content of this file by even one bit, a new different identifier gets generated. This avoids content reduplication by maintaining the file with the same content only once through using a version-control history. As a result, routing and searching in IPFS depend mainly on a Distributed Hash Table (DHT). This DHT stores the different CIDs to effectively find and access data among the network nodes instead of

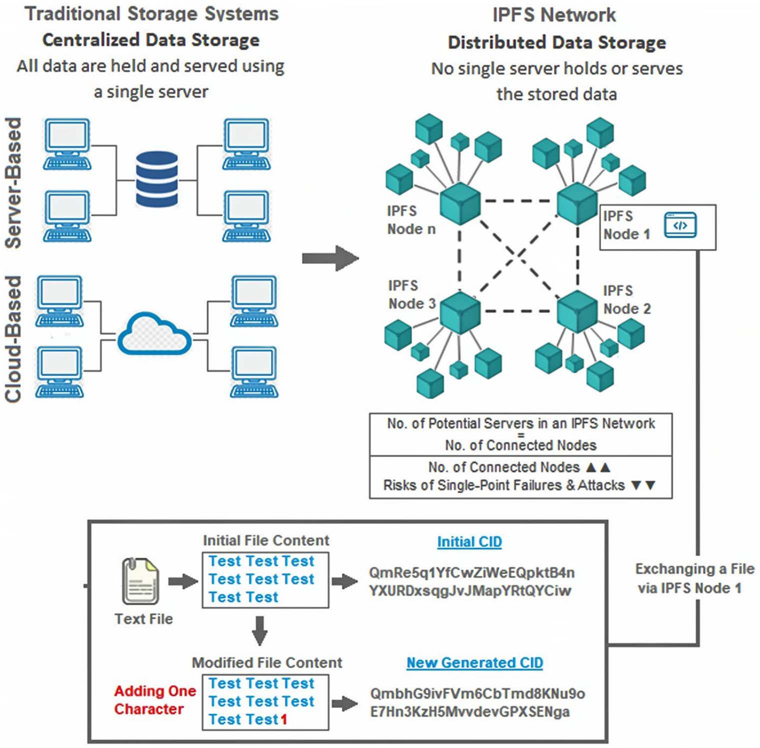


Figure 2. Traditional storage systems and IPFS network

using its location (Zheng et al., 2018). According to IPFS-Docs (2020), Nyaletey et al. (2019), the main features of IPFS can be summarized as follows:

- The IPFS network is decentralized and secured against single-point failures or attacks since all nodes act as individual servers that can serve the content to others.
- The IPFS network's caching approach ensures the off-line availability of static content that is regularly viewed and independent of latency or backbone connectivity.
- The IPFS network's garbage collection mechanism allows automatic resource management by freeing the nodes' disk space through deleting data or objects that are no longer used or needed.
- IPFS allows the formation of scalable private networks that are independent of the public IPFS network for exchanging sensitive or confidential data.

In the construction field, limited research efforts addressed the usage of IPFS. For instance, Darabseh and Martins (2021) explored the main functions of IPFS and its potential applications in managing and governing design documents flow. Das et al. (2022) developed a document management framework for construction applications based on BT and IPFS. The framework inherits the BT and IPFS merits to securely track document versioning history and lifecycle. A prototype was developed using Hyperledger Fabric and applied to a demonstrative case study to evaluate its workability and technical performance. Tao et al. (2021) introduced a common data environment framework relying on BT and IPFS. The framework was designed for managing BIM-based collaborative design changes, workflows, and products considering ISO 19650 standards. A prototype was built using Hyperledger Fabric and tested using an illustrative design example to assess its applicability and performance. Xiong et al. (2022) introduced a scheme that relies on IoT, BT, and IPFS for object detection applications in construction sites. The scheme utilized BT and IPFS in specific for securely, traceable, and undeniably maintaining all construction operations records. Moreover, it was applied in a case study for detecting safety helmets at construction sites to demonstrate its applicability and quantify its performance. Despite the contributions of these efforts, the automated availability or redundancy of large-size or visual data is still a major issue even in private IPFS networks since each network's node acts as an autonomous server that serves content based on other nodes' demand via a pull mechanism (Andrian et al., 2019; Nyaletey et al., 2019). This could reduce the network performance, increase the transfer latency, delay the data updating across the multiple nodes, and cause intense traffic volumes and link bottlenecks. Coupling the IPFS network with IPFS-Cluster can solve this issue as proposed by Christodoulou et al. (2020), Huang et al. (2020), IPFS-Docs (2020), Naz et al. (2019). The IPFS-cluster is a distributed tool that runs independently as a sidecar to the IPFS nodes. It allows data unification and synchronization by automatically allocating, propagating, pinning, or unpinning files or objects over a consortium of IPFS nodes.

2. System design

2.1. Overview

This study introduces a P2P information system for digitalizing and decentralizing the progress monitoring and control process. The system aims at facilitating on-site progress information collection, exchange, and documentation while managing as-built digital assets evolution and versioning during the construction phase. The on-site progress information is directed to schedule-related work items' details, while the digital assets denote up-to-date project schedules and as-built 4D/5D BIM models. In this regard, the system design relies on a permissioned blockchain network (BN) hosted by Hyperledger Fabric. This BN includes a set of chaincodes and data-flow channels to continuously manage the on-chain data transactions and fluctuations while being front-ended with a serverless action for textual data feeding. In tandem with BN, a private IPFS network is utilized to store and exchange the off-chain progress visuals and as-built digital assets. This private IPFS network is coupled with a cluster service to ensure the automated replication and redundancy of visuals and digital assets among a P2P swarm of the system's actors while being front-ended with a command line-based interface for visuals and assets feeding (see Figure 3).

2.2. Key actors

The typical construction project's stakeholders are referenced as the system's key actors and divided into three organizations as follows:

- Organization I includes Portfolio Manager, Project Manager, Project Team, and System Developer.
- Organization II includes Client and Consultant.
- Organization III includes Suppliers, Financial Institutions, Claim-dispute Adjudicators, and Sub-Contractors.

Organizations I and II have full operator privileges regarding write/read operations, while organization III has only reader privileges. The system developer initially holds the overall governance to build the BN, configure the IPFS network and the IPFS-Cluster service, register the other actors within the system and technically train them for exchanging data through the system. The number of key actors can evolve at any point of time to suit new requirements or satisfy any contractual aspects. Each organization is represented by one system node or more, which is identified using a unique account address while having its own key and certificate for interaction and information exchange. Each system node is equipped with a blockchain node, an IPFS node, and an IPFS-Cluster node to establish the IPFS-Blockchain consortium. The block-

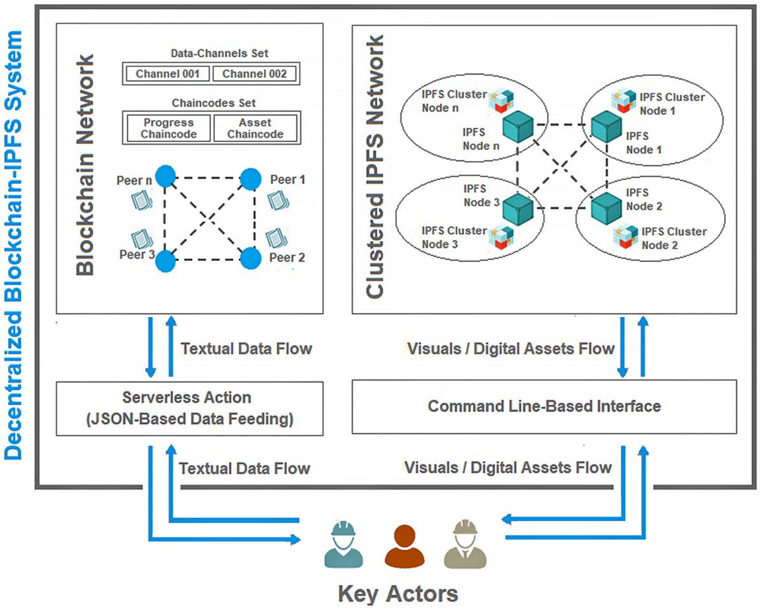


Figure 3. P2P information system for digitalizing and decentralizing the progress monitoring and control process

chain node holds and manages the blockchain ledger that includes a complete historical and immutable record of all textual data transactions. The IPFS node and the IPFS-Cluster node are referenced as the storage nodes that are responsible for keeping the off-chain visual data and digital assets in persistent traceable storage. The actors' data exchange relationships are initially mapped based on the typical communications and information flows for the construction progress and monitoring process proposed by Abdelrehim (2013), McNamara and Sepasgozar (2021), Omar and Nehdi (2016). These relationships are logged on the Blockchain-IPFS system in the form of multiple BN chaincodes and data-flow channels to provide access control and ensure data privacy and integrity (see Table 2).

2.3. Chaincodes

The chaincode is the smart contract that originates data transactions and governs all interactions between the system's actors based on algorithmic logic. For the proposed system, the chaincode typically consists of methods and variables. The methods represent the embedded functions in the chaincode. These functions are commonly used to create/submit a record that is added to the distributed blockchain ledger or query/evaluate specific or multiple records. The variables refer to the input parameters used for functions' calls or executions. As per Table 2, the BN depends on two chaincodes (Progress chaincode and As-built Asset chaincode). The progress chaincode is used to exchange and manage the on-site textual information, including the CID of off-chain data via a public channel that includes all organizations. The as-built asset chaincode is used to track and monitor the evolution of the project's digital assets over time via a private channel that includes only organizations I and II to ensure the confidentiality of these assets.

2.4. Data processing

The system processes the progress information and the as-built digital assets in ten main steps, as shown in Figure 4. These steps are illustrated as follows:

1. The on-site information is captured by the project team using text-based formats, portal cameras, and smartphones via traditional walkthroughs and classified into visual data and related or supporting textual data.
2. The visual data is shared and pinned among the predefined actors via the private IPFS network and the IPFS-Cluster with no size or type limitations [e.g., image, audio, video, or laser scan], and the relevant CID is obtained.
3. The on-site textual data and the obtained CID are indexed with a unique progress code and proposed to the BN via channel 1 to initiate the progress chaincode.
4. As is predefined in Table 1, the proposed progress data is sent to certain peer nodes for authentication and validation.
5. Once the data is validated, it is time-stamped, stored in a block, and broadcasted to the peer nodes of channel 1 to be included in their ledgers.
6. Guided by the 2^{nd}-Level of BIM-to-Blockchain integration (Dounas et al., 2021), the on-chain progress records are extracted in a JSON-based format and utilized to update the relevant digital assets, including project schedule XER files and as-built 4D/5D BIM models.
7. The up-to-date version of digital assets is shared and pinned among the predefined actors via the private IPFS network and the IPFS-Cluster, and the relevant CID is obtained.

Table 2. Data exchange mapping

Channel	Chaincode	Proposed by	Transaction	Operation	Validated by	Ordered to
Channel - C01	Progress Chaincode	Org. (I) Node	- Add Progress Record - Modify Existing Record - Delete Existing Record	Write	- Org. (I) Node; and/or - Org. (II) Node	Org. (I) Ledgers Org. (II) Ledgers Org. (III) Ledgers
			- Read Specific Record - Query all Records	Read	- None	
		Org. (II) Node	- Add Progress Record - Modify Existing Record - Delete Existing Record	Write	- Org. (I) Node; and/or - Org. (II) Node	
			- Read Specific Record - Query all Records	Read	- None	
		Org. (III) Node	- Read Specific Record - Query all Records	Read	- None	
Channel - C02	Asset Chaincode	Org. (I) Node	- Add Asset Record - Modify Existing Record - Delete Existing Record	Write	- Org. (I) Node; and/or - Org. (II) Node	Org. (I) Ledgers Org. (II) Ledgers
			- Read Specific Record - Query all Records	Read	- None	
		Org. (II) Node	- Add Asset Record - Modify Existing Record - Delete Existing Record	Write	- Org. (I) Node; and/or - Org. (II) Node	
			- Read Specific Record - Query all Records	Read	- None	

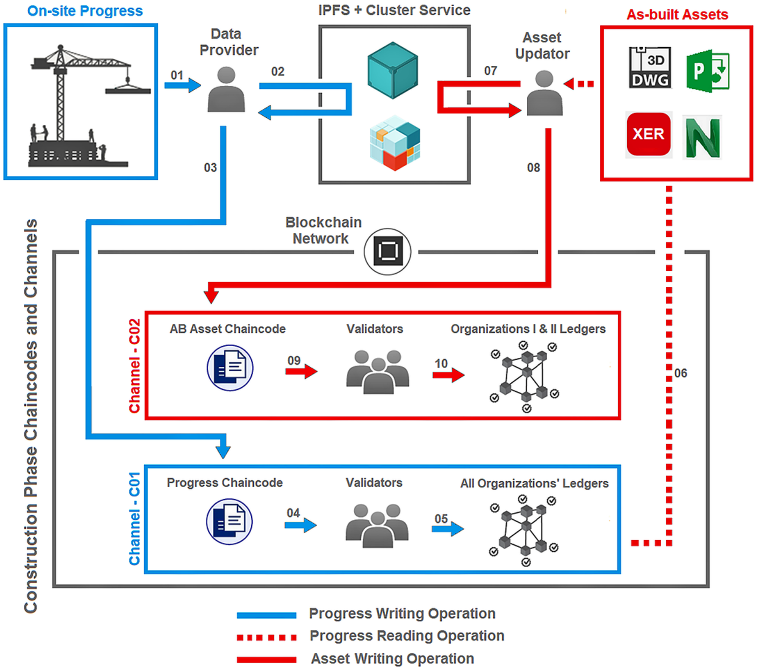


Figure 4. Processing of the progress information

8. The obtained CID and the textual data related to the digital asset updating are indexed with a unique updating code and submitted to the BN via channel 2 to initiate the as-built asset chaincode.
9. The submitted data is sent to the validators of channel 2 for authentication and validation.
10. Once the validation is performed, it is time-stamped, stored in a block, and broadcasted to the peer nodes of channel 2 to be included in their ledgers.

In case of the proposed data via the BN is not validated, the shared visuals and digital assets over the IPFS network are unpinned and removed simultaneously from the actors' local directories using the IPFS-Cluster and the IPFS garbage collection feature.

3. System development

The proposed system is developed via three steps. The first step is coding the chaincodes to manage the on-site information and track the as-built digital assets changes. The second step is building the BN. The third step is configuring the private IPFS network and IPFS-Cluster on each system node.

3.1. Chaincodes development

The progress and as-built asset chaincodes are developed using the IBM® VSCode extension. The progress chaincode is designed to enclose six functions (Exist, Add, Read, Update, Delete, and Query). The "Exist" function is a side function that is used to check the existence of previous progress records to avoid the unnecessary duplication of progress data. The "Add" and "Update" functions are used to submit or modify the parameter's value of a specific progress record. The "Delete" function is used to set the parameters of a progress record to a null value. The "Read" and "Query" functions are used to recall the stored data in the blocks. These functions can be modified to match the organizations' requirements or accommodate the project's needs. Since the progress chaincode is directed to tracking and monitoring the work progress in construction projects, its variables are deduced from the Daily Work Report (DWR) data attributes. The DWR data attributes are typically related to pay items and work items, which are used to establish the project schedule and cost baselines (Shrestha & Jeong, 2017). These attributes are classified into six categories; general information, work activities, weather information, equipment, labor, and remarks. According to Mubarak (2015) and most commercial planning and scheduling tools like Primavera P6, Synchro Pro, or Microsoft Project, work activities, equipment, labor, and remarks categories contain the relevant parameters for progress tracking. These parameters are [RC] Progress Record Code, [P1] Cut-off Date, [P2] Activity Code, [P3] Activity Name, [P4] Activity Status, [P5] Responsible Engineer, [P6] Activity Remaining Duration, [P7] Activity Actual Cost, [P8] Activity Percent Complete, [P9] On-site Data Provider, [P10] Labor Resources' Usage, [P11] Non-labor Resources' Usage, [P12] Material Resources' Usage, [P13] Remarks, and [PCID] CID of Progress Visuals. The as-built asset chaincode is designed to include the same functions as detailed in Algorithm 2. These functions are utilized to monitor and update the as-built digital assets based on the on-chain progress records with the following parameters: [AC] Asset Updating Code, [A1] Asset Title, [A2] Asset Version Number, [A3] Asset Category, [A4] Asset Status, [A5] Asset Updating Date, [A6] Asset Updator, [A7] Range of On-chain Progress Records, and [ACID] CID of Asset.

3.2. BN configuration

The blockchain network is configured using the IBM Blockchain Platform that depends on Hyperledger Fabric as a hosting platform. The IBM Blockchain platform permits building and operating a permissioned or private network through nine main steps, as depicted in Figure 5.

Step 1: A kubernetes cluster is created to operate the IBM Blockchain platform while allowing computational resources scheduling, re-allocation, and balancing.

Step 2: Three certificate authorities are created to provide the different organizations with the required certificates for registered users to interact with the BN.

Step 3: MSP for each organization is configured to hold the organization's definition and provide the connection profiles.

Step 4: The peer nodes are created to represent the organization's nodes and manage their ledgers.

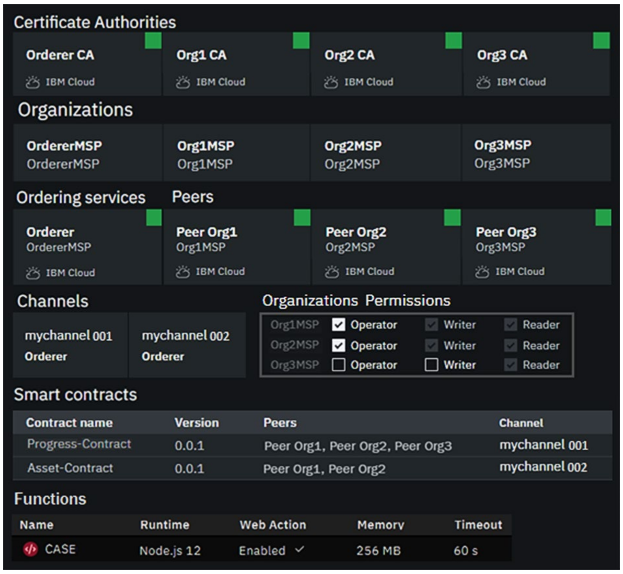
Step 5: The ordering service is established for registering the defined peer nodes within its consortium to build and run validation and recording channels.

Step 6: The channels are configured to allow peer nodes to submit, validate and record transactions within particular data-flows without exposing these transactions to unauthorized nodes. As per the above system design, two channels among the stakeholders are established to secure and allow public and private communications within the network.

Step 7: The developed chaincodes are installed and instantiated in their related channels.

Step 8: Each MSP's connection profiles and user identities are downloaded to provide the required credentials to transact effectively with the BN.

Step 9: A serverless action is configured using IBM Cloud Function as a user interface to interact with the BN and execute the instantiated chaincodes. The action is initiated via the chaincodes' parameters besides three additional parameters representing user identity [id], chaincode name [cc], and chaincode function [fn].



Certificate Authorities

Orderer CA	Org1 CA	Org2 CA	Org3 CA
IBM Cloud	IBM Cloud	IBM Cloud	IBM Cloud

Organizations

OrdererMSP	Org1MSP	Org2MSP	Org3MSP
OrdererMSP	Org1MSP	Org2MSP	Org3MSP

Ordering services	Peers		
Orderer OrdererMSP IBM Cloud	Peer Org1 Org1MSP IBM Cloud	Peer Org2 Org2MSP IBM Cloud	Peer Org3 Org3MSP IBM Cloud

Channels

mychannel 001	mychannel 002
Orderer	Orderer

Organizations Permissions

Org1MSP	☑ Operator	☑ Writer	☑ Reader
Org2MSP	☑ Operator	☑ Writer	☑ Reader
Org3MSP	☐ Operator	☐ Writer	☑ Reader

Smart contracts

Contract name	Version	Peers	Channel
Progress-Contract	0.0.1	Peer Org1, Peer Org2, Peer Org3	mychannel 001
Asset-Contract	0.0.1	Peer Org1, Peer Org2	mychannel 002

Functions

Name	Runtime	Web Action	Memory	Timeout
CASE	Node.js 12	Enabled ✓	256 MB	60 s

Figure 5. Blockchain network is configuration

3.3. IPFS configuration

IPFS gives the system the power of content-addressed storage while not compromising its decentralization or efficiency. The IPFS configuration is conducted through a command-line interface since it allows prompt iteration and development at a more granular level before building applications or services on top of the IPFS nodes. Specific prerequisites are obtained and installed on each node's machine, including go-package for the node's operating system and go-ipfs, ipfs-cluster-service, and ipfs-cluster-ctl binaries. These prerequisites are essential for running and operating the IPFS nodes consortium and performing synchronized actions via the IPFS-Cluster. Moreover, the IP addresses of all nodes should be known before any configuration or linkage process.

3.3.1. Private network formation

For network formation, four configuration steps are performed on each node's machine. The first step is initializing the node using the command [`$ ipfs init`]. As a result, an IPFS directory is generated on the node with a specific IPFS-Peer identity. The second step is creating a swarm key that is referenced by the system nodes to form the private network. The third step is removing the default bootstrap entries that are resulted from the first step to avoid the connection with the public IPFS network using the command [`$ ipfs bootstrap rm --all`]. The fourth step is adding the IP Address and IPFS-Peer Identity of the system developer's node as a new bootstrap entry using the command [`$ ipfs bootstrap add /ip4/<System Developer IP Address>/tcp/4001/ipfs/<System Developer IPFS-Peer Identity >`]. At this point, the IPFS node is configured and activated using the command [`$ ipfs daemon`].

3.3.2. IPFS-Cluster configuration

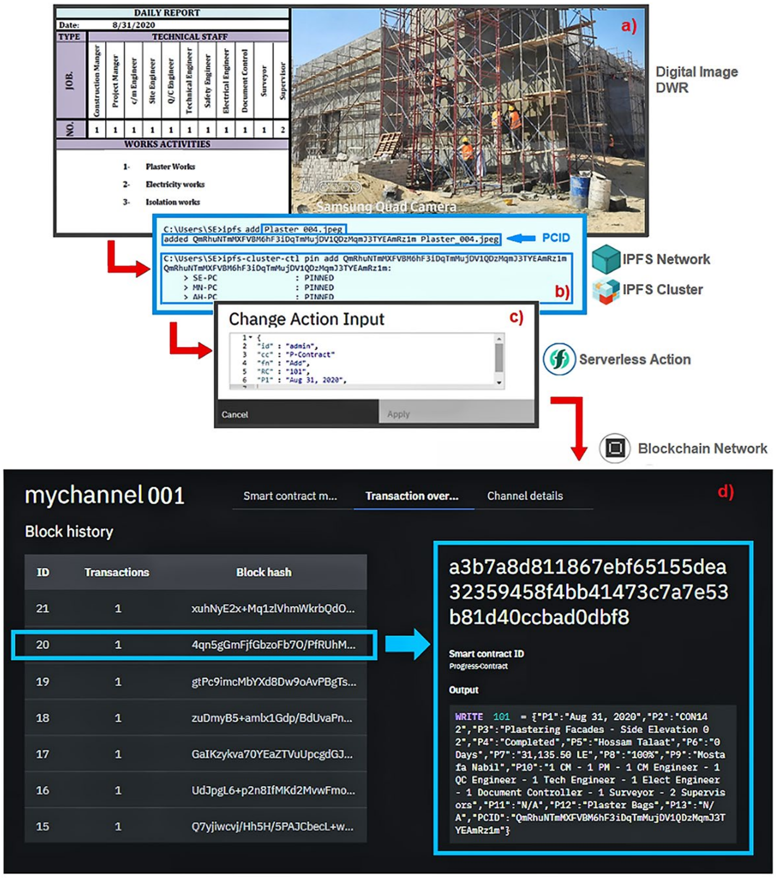
After the network formation, the IPFS-Cluster can be configured on top of the IPFS nodes. The IPFS-Cluster is introduced to maintain synchronization across the system by flexibly pin/replicate or unpin/delete the large-size files among the system nodes. Therefore, the system nodes are managed uniformly via the obtained ipfs-cluster-service and the ipfs-cluster-ctl binaries to unify the files' addition or deletion. The ipfs-cluster-service is referenced as an easy-to-run application that operates as an independent daemon while interacting with the IPFS node. The ipfs-cluster-ctl is referenced as a command-line client that is used to administer the files and control the replicate/delete operations among the system nodes. The configuration is performed via a two-step approach. The first step is initializing cluster service using the command [`$ ipfs-cluster-service init`]. As a result, an IPFS-Cluster directory is generated on the node with a specific Cluster-Peer identity. The second step is starting cluster service using the command [`$ ipfs-cluster-service daemon --bootstrap /ip4/<System Developer IP Address>/tcp/9096/ipfs/<System Developer Cluster-Peer Identity>`]. At this point, the IPFS-Cluster node is configured.

4. System testing

For demonstration purposes, a prototype of the proposed system was built and applied to a case study of tracking façade works in a mosque project in Egypt. The project is a two-story building that encloses two main halls, two wet areas, and a minaret tower with a total footprint area of 1041 m^2. Four activities of façade works were involved in the case study with an estimated duration of 39 working days. The progress data and relevant as-built schedule of these activities were exchanged and processed as presented in Figure 4. The detailed step-by-step workflow is provided in Figures 6–7 and illustrated as follows. Regarding progress data, the construction state of the façade was captured by the contractor's on-site personnel using smartphone images and daily work reports as shown in Figure 6a. The smartphone's images were passed to the project participants over the clustered IPFS network, and their CID was generated as shown in Figure 6b. The CID and the textual progress data were submitted to the BN via channel 1 that includes the progress chaincode using the serverless action as shown in Figure 6c. The submitted progress data was then checked and validated by the client representative. Once the progress data was validated, it was time-stamped, stored in a block, and broadcasted to the ledgers included in the consortium of channel 1 as shown in Figure 6d. Regarding as-built assets, the contractor's planning engineer retrieved and utilized the on-chain progress records as per Figure 6d to update the XER file of project schedule via Primavera P6 to obtain its latest as-built version as shown in Figure 7a. The up-to-date XER version was shared over the IPFS network with the assistance of the cluster service, and its CID was generated as shown in Figure 7b. The obtained CID and the relevant updating parameters were submitted to the BN via channel 2 that includes the as-built asset chaincode using the serverless action as shown in Figure 7c. The submitted XER data was then checked and validated by the client representative. The validated data was time-stamped, stored in a block, and broadcasted to the ledgers listed in the consortium of channel 2 as per Figure 7d.

5. System evaluation

Based on the case study, the system has been evaluated in terms of (1) BN's writing and reading latencies, (2) block compression ratio, (3) generalization and scalability, and (4) privacy and security, as provided in the following subsections.



DAILY REPORT											
Date:	8/31/2020										
TYPE	TECHNICAL STAFF										
JOB.	Construction Manger	Project Manger	c/m Engineer	Site Engineer	Q/C Engineer	Technical Engineer	Safety Engineer	Electrical Engineer	Document Control	Surveyor	Supervisor
NO.	1	1	1	1	1	1	1	1	1	1	2

WORKS ACTIVITIES

1- Plaster Works
2- Electricity works
3- Isolation works

```
C:\Users\SE>ipfs add Plaster 004.jpeg
added QmRhuNTmMXFVBM6hF3iDqTmMujDV1QDzMqmJ3TYEAmRz1m Plaster_004.jpeg

C:\Users\SE>ipfs-cluster-ctl pin add QmRhuNTmMXFVBM6hF3iDqTmMujDV1QDzMqmJ3TYEAmRz1m
QmRhuNTmMXFVBM6hF3iDqTmMujDV1QDzMqmJ3TYEAmRz1m:
    > SE-PC                  : PINNED
    > MN-PC                  : PINNED
    > AH-PC                  : PINNED
```

Change Action Input

```
{
"id" : "admin",
"cc" : "P-Contract"
"fn" : "Add",
"RC" : "101",
"P1" : "Aug 31, 2020",
```

mychannel 001

Block history

ID	Transactions	Block hash
21	1	xuhNyE2x+Mq1zlVhmWkrbQdO...
20	1	4qn5gGmFjfGbzoFb7O/PfRUhM...
19	1	gtPc9imcMbYXd8Dw9oAvPBgTs...
18	1	zuDmyB5+amlx1Gdp/BdUvaPn...
17	1	GaIKzykva70YEaZTVuUpcgdGJ...
16	1	UdJpgL6+p2n8IfMKd2MvwFmo...
15	1	Q7yjiwcvj/Hh5H/5PAJCbecL+w...

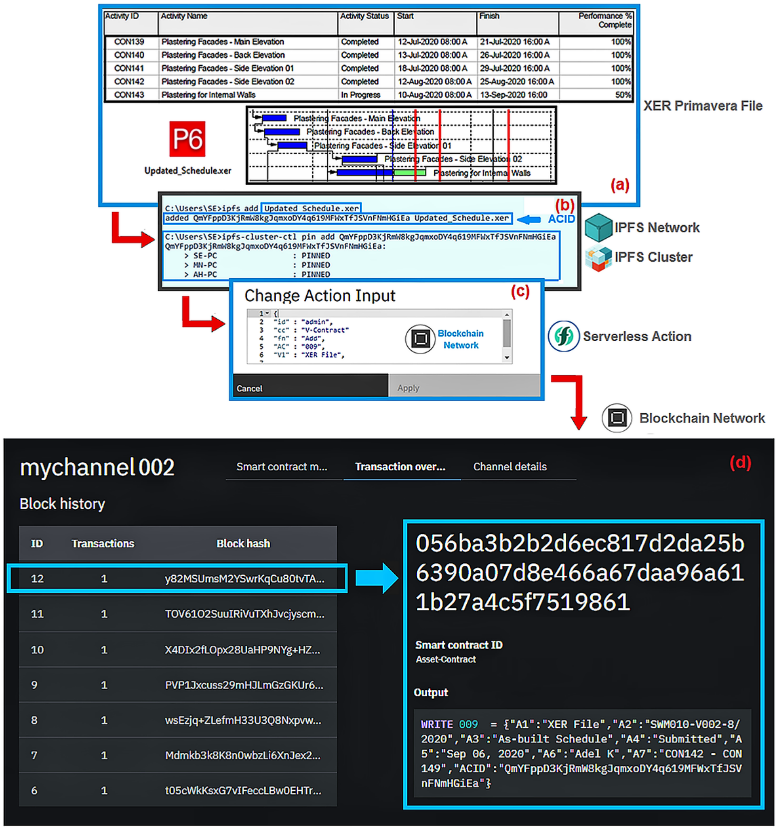
a3b7a8d811867ebf65155dea
32359458f4bb41473c7a7e53
b81d40ccbad0dbf8

Smart contract ID
Progress-Contract

Output

```
WRITE  101  = {"P1":"Aug 31, 2020","P2":"CON14
2","P3":"Plastering Facades - Side Elevation 0
2","P4":"Completed","P5":"Hossam Talaat","P6":"0
Days","P7":"31,135.50 LE","P8":"100%","P9":"Mosta
fa Nabil","P10":"1 CN - 1 PM - 1 CM Engineer - 1
QC Engineer - 1 Tech Engineer - 1 Elect Engineer
- 1 Document Controller - 1 Surveyor - 2 Supervis
ors","P11":"N/A","P12":"Plaster Bags","P13":"N/
A","PCID":"QmRhuNTmMXFVBM6hF3iDqTmMujDV1QDzMqmJ3T
YEAmRz1m"}
```

Figure 6. System testing (1)



Activity ID	Activity Name	Activity Status	Start	Finish	Performance % Complete
CON139	Plastering Facades - Main Elevation	Completed	12-Jul-2020 08:00 A	21-Jul-2020 16:00 A	100%
CON140	Plastering Facades - Back Elevation	Completed	13-Jul-2020 08:00 A	26-Jul-2020 16:00 A	100%
CON141	Plastering Facades - Side Elevation 01	Completed	18-Jul-2020 08:00 A	29-Jul-2020 16:00 A	100%
CON142	Plastering Facades - Side Elevation 02	Completed	12-Aug-2020 08:00 A	25-Aug-2020 16:00 A	100%
CON143	Plastering for Internal Walls	In Progress	10-Aug-2020 08:00 A	13-Sep-2020 16:00	50%

```
C:\Users\SE>ipfs add Updated Schedule.xer
added QmYFppD3KjRmW8kgJqmxoDY4q619MFWxTfJSVnFNmHGiEa Updated_Schedule.xer

C:\Users\SE>ipfs-cluster-ctl pin add QmYFppD3KjRmW8kgJqmxoDY4q619MFWxTfJSVnFNmHGiEa
QmYFppD3KjRmW8kgJqmxoDY4q619MFWxTfJSVnFNmHGiEa:
    > SE-PC                  : PINNED
    > MN-PC                  : PINNED
    > AH-PC                  : PINNED
```

Change Action Input

```
{
"id" : "admin",
"cc" : "V-Contract"
"fn" : "Add",
"AC" : "009",
"V1" : "XER File",
```

mychannel 002

Block history

ID	Transactions	Block hash
12	1	y82MSUmsM2YSwrKqCu80tvTA...
11	1	TOV61O2SuuIRiVuTXhJvcjyscm...
10	1	X4DIx2fLOpx28UaHP9NYg+HZ...
9	1	PVP1Jxcuss29mHJLmGzGKUr6...
8	1	wsEzjq+ZLefmH33U3Q8Nxpvw...
7	1	Mdmkb3k8K8n0wbzLi6XnJex2...
6	1	t05cWkKsxG7vIFeccLBw0EHTr...

056ba3b2b2d6ec817d2da25b
6390a07d8e466a67daa96a61
1b27a4c5f7519861

Smart contract ID
Asset-Contract

Output

```
WRITE 009  = {"A1":"XER File","A2":"SWM010-V002-8/
2020","A3":"As-built Schedule","A4":"Submitted","A
5":"Sep 06, 2020","A6":"Adel K","A7":"CON142 - CON
149","ACID":"QmYFppD3KjRmW8kgJqmxoDY4q619MFWxTfJSV
nFNmHGiEa"}
```

Figure 7. System testing (2)

5.1. Writing and read latencies

The BN's writing latency is defined as the inclusion time taken by a transaction to be validated, packaged into a block, and stored on-chain. On the contrary, the BN's reading latency reflects the time taken to recall a specific block's data. Both times have been measured using the IBM Cloud Function monitoring tool based on 10 write/read operations, as shown in Table 3. The writing latency has not exceeded 5000 milliseconds, while the reading latency has been less than 2000 milliseconds. These measurements show acceptable performance for both write/read operations as guided by Adel et al. (2022) and Xu et al. (2019).

Table 3. Latency measurements

Chaincode	Measure	Function				
		Writing			Reading	
		Add	Update	Delete	Read	Query
Progress	Minimum	4313	4317	4266	1625	1660
	Average	4389	4382	4340	1666	1683
	Median	4340	4366	4325	1666	1678
	Maximum	4882	4589	4470	1696	1718
Asset	Minimum	4378	4304	4335	1679	1686
	Average	4464	4367	4395	1702	1737
	Median	4416	4358	4402	1704	1734
	Maximum	4711	4464	4478	1715	1793

5.2. Block compression ratio

The block compression ratio (BCR) is employed to quantify the effect of using the IPFS to store the large-size files on controlling and lowering the BN's size. Such ratio is calculated using Chained Block Size CBS and Original Block Size OBS as per Eqn (1). CBS is calculated based on Fixed Size Components (FSC) and Transacted Record Size (TRS) as per Eqn (2). FSC refers to parent block hash, block hash, Merkle root, timestamp, and Merkle tree hash number with a total size of 719 Bytes. In contrast, TRS refers to the text size for a typical record exchanged through a specific channel. For channel 1, a typical progress record encloses 15 input parameters, including the IPFS's CID and ranges from 500 Bytes to 1000 Bytes in size. Regarding OBS, it is calculated using FCS and Average Size of Visuals (ASV) as per Eqn (3). ASV refers to the size of smartphone images and ranges from 2 MB to 3 MB for the project under study. Accordingly, the compression ratio has been measured and equals 99.91% for each data transaction submitted through channel 1. The same calculations have been conducted for channel 2, and the ratio equals 97.58%. Both ratios reflect the prototype's ability to tackle the storage-bloating problem by reducing each block size by more than 97% while ensuring the integrity and linkage between on-chain and off-chain data as guided by Zheng et al. (2018). Furthermore, these ratios have a salient impact on boosting the prototype's latencies and performance:

$$BCR = \frac{OBS - CBS}{OBS} * 100; \quad (1)$$

$$CBS = (FCS + TRS); \quad (2)$$

$$OBS = (FCS + ASV). \quad (3)$$

5.3. Generalization and scalability

The proposed system is designed to be generic and extendable. As such, the system can be developed and implemented for tracking and managing work progress and related digital assets in any work phase, including design, tendering, construction, and operation phase (see Figure 8).

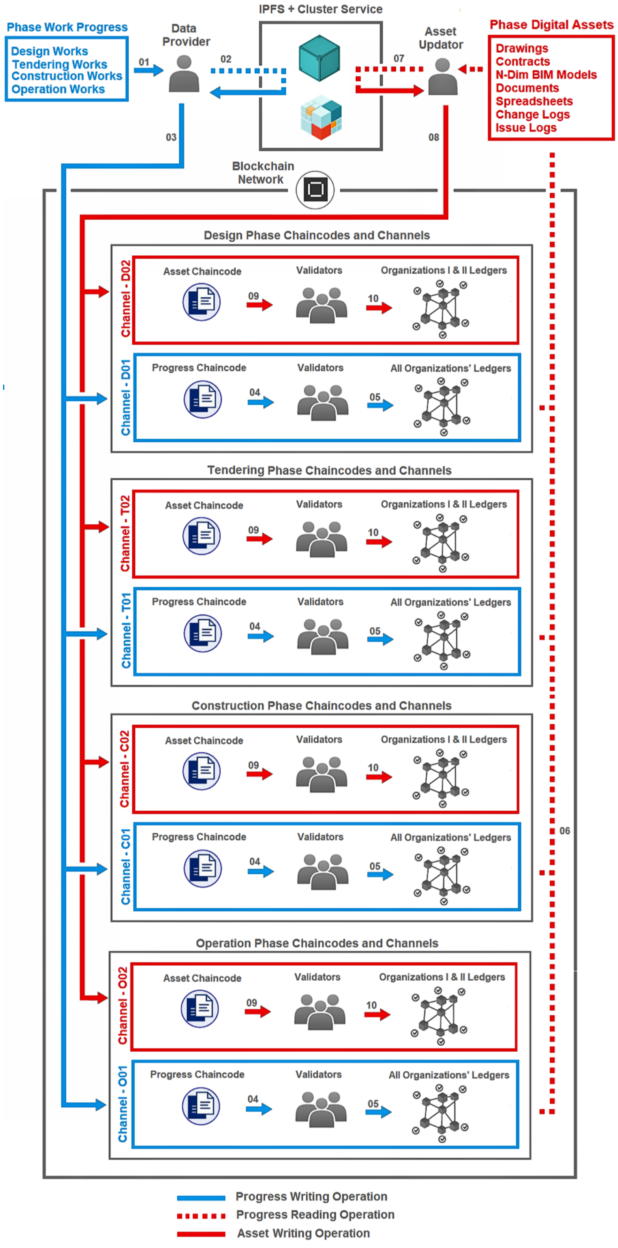


Figure 8. Application of the system in various work phases

Moreover, the BN's organizations, chaincodes, and data-flow channels can be smoothly altered without reformulating the whole system. The number of organizations can be scaled to include the relevant stakeholders of each work phase in a five-step approach: (1) creating a CA for the new organization, (2) configuring its MSP, (3) creating peer nodes for the organization's actors, (4) updating the data-flow channels to include new peer nodes in their consortiums, and (5) re-instantiating the chaincodes to take into account new peer nodes. It is worth noting that the source codes of chaincodes can be customized by adding or removing new functions and input parameters to fulfill the transactions' requirements of each work phase. On the other hand, the number of data-flow channels can be scaled by adding new channels to fit the communication and information flow requirements of each work phase.

5.4. Privacy and security

According to Li et al. (2022), Omar et al. (2022), the system's privacy and security are explored with respect to confidentiality, integrity, non-repudiation, authentication, and authorization:

- Confidentiality: Due to multiple data-flow channels, the system can maintain data confidentiality by allowing exclusive authorized peer nodes to access and engage in each channel with predefined permission levels.
- Integrity: the content of data transactions exchanged within different channels is tamper-proof and cryptographically secured using hashing mechanisms once included on-chain.
- Non-repudiation: The actors registered in the BN channels are not able to disclaim regarding submitting, approving, or receiving data transactions.
- Authentication: In the BN, each peer node holds its own private key and certificate that are necessary to digitally sign or validate data transactions.
- Authorization: In the BN, MSP is used to authorize the identity of peer nodes for joining the network and generate their connection profiles.

6. Discussion

6.1. Theoretical values

The adoption of BT and IPFS is foreseen to significantly promote and digitalize the construction industry in diverse directions. This study introduces a novel data exchange and management system for the construction progress monitoring and control process. The study holds five significant theoretical values that are relevant to the academic area. The first value is moving forward from the primary exploration stage of BT and IPFS as per Gunasekara et al. (2021), Li et al. (2020), McNamara and Sepasgozar (2020, 2021), Raslan et al. (2020), Shi et al. (2019), Sreckovic and Windsperger (2019) to the design, development, and deployment stages in the construction field. The second value is evolving the progress monitoring and control process from a being centralized process as per Abdel-Monem and Hegazy (2013), Akanmu et al. (2020), Garcia et al. (2014), Lin and Golparvar-Fard (2020a), Mahami et al. (2019) to a distributed peer-to-peer one while eliminating the potential for progress data leakage and losses over time and enhancing information documentation and transfer. The third value is integrating the BT with a private IPFS that acts as a subsidiary decentralized storage structure to overcome the BT storage-bloating problem as per Elghaish et al. (2022), Lu et al. (2021b), Sheng et al. (2020), Suliyanti and Sari (2021), Wang et al. (2020) and address large amounts of visuals and digital assets that accumulate over time. The fourth value is coupling the IPFS network with IPFS-Cluster service to overstep the IPFS automated data availability or redundancy issue as per Das et al. (2022), Tao et al. (2021), Xiong et al. (2022) by synchronically allocating, propagating, pinning, or unpinning visuals and digital assets over the IPFS nodes swarm. The fifth value is systematically stating the potential barriers and enablers related to the BT-IPFS adoption as per the following Subsection 6.3 that can be reused in further empirical investigations to deeply explore the stakeholders' visions and values in developing and deploying BT-IPFS applications.

6.2. Practical implications

The system's practical implications are anticipated in diverse areas. Concerning stakeholder management, the system can boost the coordination and trust among different stakeholders by maintaining the information in a synchronized distributed manner with no central authority. Moreover, it allows validating the on-chain and off-chain data while minimizing face-to-face consultations, recurring meetings, and administrative workloads. For as-built information, the system can guarantee the progressive elaboration of As-built files, drawings, or models along the project duration while identifying deficiencies as early as possible to avoid reworks. Moreover, it enables recording the existing construction conditions to be used for the purpose of renovation and restoration of similar historical projects. For payment management, the system can be utilized to automate the incremental payments processing with respect to the progress state and the agreed contractual parameters as soon as the on-site data is captured, exchanged, and validated by the key stakeholders. Concerning performance analysis, the system's progress on-chain progress records can be queried to compute Actual Costs (AC) and Earned Values (EV). Further, these values are compared to Planned Values (PV) to obtain cost/schedule indices and variances. These indices and variances are utilized for assessing contractor performance, making relevant corrective or preventive actions, increasing awareness about the project state, and communicating captured deviations in a timely manner. Concerning productivity analysis, the system's progress on-chain progress records can be queried and analyzed to compute the actual productivity rate for a certain trade. Later on, this rate is utilized as a practical guiding measure for re-quantifying remaining or future works. Regarding delay analysis and claim/dispute management, the system's on-chain progress and digital asset records can be utilized as a tamper-proof log for as-planned and as-built states compliance checking, delay events documentation, extension of time and financial compensation claims quantification, and future disputes resolution. Regarding operation and maintenance, the system is able to overcome the data transfer blockage between the construction phase and the operation and maintenance phase by automating and streamlining the flow of construction records and as-built models into asset management information systems while eliminating individual data gathering efforts or information losses.

6.3. Adoption barriers and enablers

The gap between the growing BT-IPFS research attention and their real-life implementation requires an intelligible comprehension of the adoption barriers and enablers. Several studies have investigated the strategic adoption of BT-IPFS in their relevant industries. These studies have utilized the TOE framework to evaluate the BT-IPFS adoption's barriers and enablers in terms of technological, organizational, and environmental contexts (Fernando et al., 2021; Gökalp et al., 2022; Kamble et al., 2021; Kumar Bhardwaj et al., 2021; Lustenberger et al., 2021; Malik et al., 2021; Orji et al., 2020; Wong et al., 2020). Similarly, the TOE framework is employed to clarify the potential enablers and challenges associated with the BT-IPFS adoption in the construction industry. Technological context involves perceived relative advantage, perceived compatibility, and perceived complexity. Perceived relative advantage denotes the BT-IPFS advantages related to cost-saving and time-saving effects, data-error reduction rate, and overall productivity enhancement in projects/organizations' operations. Perceived compatibility denotes the BT-IPFS compatibility with the organization's existing practices and hardware/software infrastructure. Perceived complexity denotes the BT-IPFS complexity in terms of technical operation and integration skills required by the organization's members. Organizational context involves top management support and organizational readiness. Top management support refers to top management's willingness to tolerate risks (financial and organizational) involved in the BT-IPFS adoption and participate in establishing visions and strategies for implementing the BT-IPFS. Organizational readiness refers to the flexible allocation of necessary financial, human, and IT infrastructure resources for BT-IPFS adoption. Environmental context involves competitive pressure, government policy and support, and partner readiness and support. Competitive pressure denotes the potential experience of competitive disadvantages if BT-IPFS is not adopted. Government policy and support denote governmental economic incentives for BT-IPFS adoption and governmental regulations for protecting the BT-IPFS usage. Partner support and readiness denote the business partners' willingness to change the related processes and practices in addition to their technological and financial readiness for BT-IPFS adoption.

Conclusions

The importance of construction progress monitoring and control process is rapidly demanding continuous research and development to accommodate the exponential growth of on-site data and reduce the heavily intermediated workflows. Accordingly, this study has introduced a novel system to digitalize and semi-automate the progress monitoring and control process through leveraging the features of BT and IPFS. The introduced system has been designed to be completely secure and decentralized while eliminating the need for trusted third parties. The system has aimed to enhance the on-site data collection and sharing and the related as-built digital assets' evolution while maintaining trust and synchronization between the project stakeholders. The system has been developed based on a three-step approach. The first step is formulating two chaincodes to exchange the on-site information and the as-built digital assets separately. The second step is configuring a private BN that depends on Hyperledger Fabric as a hosting platform. The third step is creating a clustered private IPFS network. A case study was used to verify the system workability and assess its performance. The system has shown acceptable and reliable performance in terms of writing/reading latency, block compression ratio, generalization & scalability, and privacy & security.

This research can be extended in the future to overcome its current limitations. First, the proposed BN relies on Crash Fault Tolerance (CFT) algorithm to verify/validate the data blocks' order and correctness. Although CFT guarantees higher performance, scalability, and resiliency against system node failures (e.g., crashed processes, software bugs, failed hardware, or broken network), it cannot address or detect malicious-activity threats, especially when a system node tries to violate the consensus operations. Further, unlike other consensus algorithms (e.g., Proof-of-Work and Proof-of-Stake), its utilization is confined to controlled environments similar to enterprise permissioned blockchain solutions where the key actors are not anonymous, as provided in the current study. This limitation can be addressed by employing different consensus algorithms and performing a comparative analysis on the algorithms' impact on the system performance indicators, including: 1) writing/reading latencies, 2) generalization & scalability, and 3) privacy & security. Second, regarding the progress data acquisition and off-chain updating of digital assets, both processes rely on manual handling by the involved actors, which may impact the smoothness of information flow and the evolution of digital assets. This limitation can be addressed by evolving the current system to act as a sub-unit in a more sophisticated model. This model can be referenced as a Decentralized Cyber-Physical System (DCPS) that aims at enabling a more dynamic project control process. Its scope relies on forming a fully automated bi-directional workflow cycle, from progress data collection, storage, and analysis to decision-making and reporting, as follows: i) DCPS employs three-dimensional laser scanning

(LADAR), Radio Frequency Identification (RFID), virtual assistants, IoT, and capture reality technologies for accelerated data acquisition, ii) DCPS utilizes a digital twin tool for automated updating and versioning of as-built digital assets, especially for 4D and 5D BIM models, iii) DCPS utilizes an AI text mining algorithm for inspecting and analyzing progress data to provide helpful analytics and insights regarding the overall project status, and iv) DCPS employs a dynamic decentralized web-based tool for data representation and dashboarding, including project status' analytics, time-interval/cumulative resource usage, and delay/risk events.

Author contributions

Kareem Adel: Conceptualization, Methodology, Modelling, Writing- Original draft preparation. Ahmed Elhakeem: Supervision, Validation, Writing- Reviewing and Editing. Mohamed Marzouk: Conceptualization, Supervision, Validation, Writing-Reviewing and Editing.

Disclosure statement

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

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