A Blockchain 3.0 paradigm for digital twins in construction project management

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Abstract

Construction project management (CPM) is inherently complex and distributed, while digital twin and blockchain are recognized as promising solutions for information-reliant CPM. By learning from the lessons of Blockchain 1.0 and 2.0 paradigms in the literature, such as slow synchronization and failed offline functions, this paper proposes ChainPM as a Blockchain 3.0 paradigm. ChainPM extends Blockchain 2.0 with innovative indexing, query, and analysis function sets for key CPM data. Experimental results from a pilot study of a modular construction project showed that the information synchronization latency was reduced by 99.2% to 99.8%, and query and analytical functions worked equally well without network connections. ChainPM contributes to a novel trend of Blockchain 3.0 paradigms for CPM digital twins, emphasizing indexing key CPM data, combinatorial query, digital authorship, and fast response without downgrading the 'single source of truth.' For practitioners, ChainPM addresses key barriers of Internet reliance and information delay to CPM digital twins.

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Keywords

Blockchain 3.0; Construction project management; Digital twins; Smart contracts; Modular construction

Highlights

- Blockchains 1.0 and 2.0 fail to meet the demands of CPM due to high latency and Internet reliance.
- A Blockchain 3.0 paradigm ChainPM is proposed for CPM digital twins.
- ChainPM has unique two-step workflow: a fast response by local Cached Twin before Blockchain.
- Three decentralized CPM applications are designed for contractors, manufacturers, and regulators.
- Experiments showed ChainPM saved 99.2– 99.8% time and worked offline as a Blockchain 3.0.

1 Introduction

Construction project management (CPM) is inherently complex (Bryde et al. 2013; Oraee et al. 2017). Large quantities of construction information are often susceptible to a variety of interrelated factors, such as multiple stakeholders with conflicts of interest (Taylan et al. 2014), complex roles of participants (Vrchota et al. 2021), uncertainties in a changeable environment (Stanitsas et al. 2021), and out-of-date models and schedules (Xue et al. 2018). Ballard and Howell (1994) claimed that 50% to 80% of construction site problems occur due to a delayed receipt or lack of available information. Therefore, CPM has been questioned for construction projects' unsatisfactory efficiency and productivity. In comparison with the projects in other industries, construction projects have been deemed to achieve inadequate efficiency gains in the past 50 years (Daboun et al. 2022).

Several reasons lie behind the phenomenon of low efficiency. The first and foremost reason is that construction is becoming increasingly complicated as technology advances, with significant structural and building projects of unprecedented complexity (Wang et al. 2020). Meanwhile, the intricacy of the designs has necessitated a higher level of project management that had not been required earlier. Furthermore, project partners often have highly specialized expertise and collaborations in modern construction projects (Liu et al. 2019). Finally, the execution of such a project challenges prevalent practices in teamwork, trust, transparency, and regulation (Owusu et al. 2019). Thus, the innovative CPM must learn to adapt to the changing environment.

The recent key trend is the digital twin (DT) (PwC 2020) for information sharing, simulations (Xue et al. 2020b), and collaborative decision-making (Wollschlaeger et al. 2017) to meet the new management demands of the sector. Construction is an increasingly information-reliant industry, where modern CPM depends heavily on the data shared between contracting organizations during the life cycle of a project (Bryde et al. 2013). Secured, authentic, up-to-date, and complete information in DTs enables computational simulations of the components and systems and, thus, enhances managers' decision-making and management with the latest information for evidence-based decisions at any location (Kochovski & Stankovski 2018). Successful examples include a random forest–based predictive model for the projects' carbon emissions at the early design stage (Fang et al. 2021), a DT of construction sites at the disaster preparedness stage (Kamari & Ham 2022), and a fire risk assessment for the building at the operation and maintenance stage (Wang et al. 2021). However, there exists a dilemma between the centralized CPM DT and the distributed and dynamic nature of CPM. Consequently, the industry requires systematic and fundamental changes to respond to the dilemma.

Blockchain is an influential emerging distributed ledger technology that provides many benefits of data security, autonomy, transparency, audit ability, privacy, immutability, and efficiency (Scott et al. 2021). Blockchain can thus lay a foundation for distributed administration and the creation of an irreversible ledger to facilitate collaborations. Moreover, an identical ledger exists for all nodes participating in the blockchain network (Lu 2018). The distributed data storage mechanism can effectively reduce the risk of data corruption, loss, and tampering (Elli et al. 2018). The evolution of blockchains leads to four maturity levels (i.e., Blockchain 1.0, 2.0, 3.0, and 4.0), whereas the existing blockchain applications in CPM are confined to levels 1.0 and 2.0, as far as we are concerned (Elghaish et al. 2021). Briefly, the focal point of Blockchain 1.0 is finance, which is often referred to as cryptocurrency (Figueiredo et al. 2022). In Blockchain 2.0, smart contracts execute many agreement terms automatically (Li et al. 2021b). Blockchain 3.0 emphasizes the decentralized nature of blockchain for functions such as web user interfaces of Decentralized Applications (DApps) (Hunhevicz & Hall 2020). Finally, in Blockchain 4.0, blockchain becomes intelligent and is applied together with artificial intelligence, other data analytics, and Industry 4.0's technologies.

However, the currently adopted blockchain levels (i.e., 1.0, 2.0, and web DApps) in the literature cannot meet the requirements for CPM DTs. The most notable drawbacks are high latency and performance loss (Sanka & Cheung 2021). In the same blockchain network, the nodes participating in the network have a complete ledger that records every record completely for traceability. Therefore, as time advances, the large amount of transaction data will make the blockchain lengthy, leading to performance loss. Furthermore, in Blockchain 2.0, the network transactions are run in a smart contract, automatically processed and executed by the blockchain (Lu 2018). The common web DApps, though they are Blockchain 3.0, rely heavily on the Internet as well. Thus, a stable network environment is required for every data transaction and query in Blockchain 2.0 and web DApps. However, the complex physical environment on construction sites challenges Internet connection stability (Jin et al. 2020) and hinders the adoption of any blockchains at the levels of 1.0, 2.0, and web DApps

(Zhong et al. 2022).

This paper aims to present ChainPM, a Blockchain 3.0 paradigm with fast synchronization and offline functions for CPM DTs. The key innovative mechanism in ChainPM is CPM data transaction schema-based functions, including indexing, query, and analytics, specified for CPM. The major contribution of this paper is twofold. First, ChainPM extends existing Blockchain 2.0 technology to 3.0 by introducing indexing for CPM data transactions, digital authorship, combinatorial query, and expeditious response. Second, ChainPM is an effective management method enabling offline decision-making functions to streamline distributed CPM collaboration rather than a ‘single source of truth’ on the Internet, addressing the barriers of Internet reliance and information delay. The proposed ChainPM framework was demonstrated via a case of modular construction.

The rest of the paper is organized as follows: The systematic review of CPM and blockchain is given in Section 2, and Section 3 proposes the ChainPM framework for distributed CPM. Section 4 presents a case study of a modular construction project, followed by experimental results and analyses in Section 5. Discussions appear in Section 6, and the conclusion is drawn in Section 7.

2 Literature review

2.1 Construction project management as distributed activities

A construction project, a series of long-term but closely linked organized processes, is regarded as complex traditional activity (Walker 2015). The basic procedure of a construction project starts with investment and bidding, then goes through the life cycle stages of design, survey, construction, transportation, and transfer to use (Li et al. 2021a). As a result, it inherently leads to heavy reliance on extensive data exchange (Bryde et al. 2013).

CPM is the systematic management of physically and temporally distributed activities (Martínez-Rojas et al. 2016). In particular, many construction projects involve multiple—sometimes global—stakeholders (e.g., architects, engineers, surveyors, and clients) with diverse professions, in full-time or momentary employment, who are engaged in the processes (Walker 2015). Meanwhile, stakeholders are responsible for different stages during off-site or on-site work. As a result, various barriers impeded the recording and sharing of an abundance of data, such as inaccurate and belated recording, inadequate information sharing, ineffective communication, and inconvenient query (Daboun et al. 2022). Notably, the pains in information sharing were magnified by the reduced face-to-face collaboration due to the 2019 coronavirus disease (Covid-19) outbreak.

The recent development of DT (Opoku et al. 2021; Lee et al. 2021; Xue et al. 2020b), sometimes synchronized by the Internet of Things (IoT), has brought new opportunities for real-time information gathering, timely data accessing, and efficient collaboration and coordination among shareholders. IoT can provide accurate and timely information collection, such as using radio frequency identification (RFID) tags in prefabricated construction logistics (Li et al. 2022b) and real-time kinematic positioning for bridge maintenance (Elnabwy et al. 2013). However, project data used to be stored in a centralized database in traditional ways, where the data accessibility and security do not meet the requirements of DT (Xue & Lu 2020a). For instance, one user may find it exhausting to synchronize a 0.5 GB Building Information Modeling (BIM) file daily. Popular cloud services can partly resolve the security issue but endangers the accessibility issue simultaneously—assuming that Internet speed is slower than a project's intranet (Kochovski & Stankovski 2018). However, construction projects have a dynamic nature that is affected by unstable environments and changing situations (Xue & Lu 2020a). Therefore, there exists a dilemma between the centralized CPM DT and the distributed and dynamic nature of CPM.

2.2 Blockchain as a new distributed technology

Blockchain is an emerging technology for distributed applications (Elli et al. 2018). Three key elements contribute to its innovative practice. First, distributed ledgers represent a shared approach to recording transactions launched by peer nodes, through the shared approach datasets with interacting data blocks could be recognized (Scott et al. 2021). Second, consensus mechanisms ensure that added transaction data can join the blockchain only after meeting a series of previously defined protocols and formulating a consensus (Anjum et al. 2020). Therefore, every new block is verified by preset conditions and its ability to meet specific rules, such as Proof of Work (PoW) (Sanka & Cheung 2021). The third element is cryptography, where the hash algorithm is a typical representative (Xue & Lu 2020a). Therefore, it serves as an eligible gatekeeper for assuring data in the blockchain are information-encrypted, modification-detected, and content-authorized, thus making the data unable to be tampered with or hacked maliciously at the slightest chance.

Table 1 The evolution of blockchain (Figueiredo et al. 2022; Zhao et al. 2019)

Time	Maturity (gen.)	Example	Enabler	Value driver
2008	Blockchain 1.0	Bitcoin	Distributed consensus	Transaction cost
2013	Blockchain 2.0	Ethereum	Smart contracts	Added services
2015	Blockchain 3.0	Blockchain database	Decentralized application (DApp)	Organizational boundaries
2018	Blockchain 4.0	Blockchain for Industry 4.0	Decentralized AI	Automatic AI decision-making

As shown in Table 1, the past few years witnessed blockchain development at an increasing pace. Blockchain 1.0, a prominent example, is used for cryptocurrencies (e.g., Bitcoin). It is the first symbolic component in blockchain through which financial applications realize secure, anonymized, peer-to-peer transactions (Scott et al. 2021). Heralded by the rise of Ethereum, blockchain embraced its 2.0 stage wherein smart contracts 'live' in the blockchain in the manner of smart computer programs (Wang et al. 2020). Its decentralized structure reduced dependency on third parties in executing and monitoring contract terms. Meanwhile, the smart contract, such as automated protocol in construction payment (Ahmadisheykhsarmast & Sonmez 2020), reaches the lower cost of verification, execution, and arbitration, allowing transparent contract definition that prevents moral hazard problems. In the Blockchain 3.0 age, decentralized storage and communication are integrated as a self-enforced blockchain platform (Maesa & Mori 2020), referred to as DApp (usually web-based). For example, secure personal health record sharing (Wang et al. 2021b), food supply chain management (Zhao et al. 2019), and regulation compliance (Zhong et al. 2022). DApps can digitize and customize blockchain-based solutions for business processes; the development of Blockchain 4.0 is expected to involve automatic AI decision-making.

The conventional CPM includes paper-based or electronic management methods, which constantly suffer from the lack of approaches supporting sufficient information integration and security (Das et al. 2022). For instance, Sun (2020) proposed a file management system to eliminate CPM's ambiguity and loss of information; however, traditional file-based CPM is neither efficient (e.g., less cost in time and space) nor effective (e.g., better accuracy) in exchanging and validating projects' real-time changes. Cloud-based CPM was then developed with Autodesk BIM 360, Google Drive, and Oracle Aconex for construction data storage and distribution. However, it is also unsatisfactory for data handling due to construction projects' temporary and fragmented nature. Meanwhile, timely accessing and accurate data queries are still not full-blown applications in existing CPM practice, let alone automatically grouping and searching construction information in such datasets.

Blockchain is a promising solution for the next upgrade across the CPM (Stanitsas et al. 2021). As a trending technology, blockchain has been explored and applied to several pioneering industrial and academic studies, though the implementation in CPM practice is still in the initial stages. For instance, Xue and Lu (2020a) proposed a semantic differential transaction (SDT) approach to minimizing information redundancy in BIM development. Li (2021b) developed a blockchain-enabled model for supervising spatial-temporal operations in construction while the latency level is currently problematic. Smart contracts also have significant value in automating construction processes, such as updating variations (Hamledari & Fischer 2021), automatic payments (Wu et al. 2021), and documentation approval (Das et al. 2022). It intrinsically relied on various interactions and the participation of project shareholders in decision-making.

2.3 A dilemma identified

There exists a dilemma between the centralized CPM DT in the literature and the distributed and dynamic nature of CPM. The recent advancement in DT has brought potential opportunities for the digital transformation of CPM. However, three application gaps noted can be summarized as follows: 1) The DT can be used to serve as 'a single source of truth' in a centralized manner, which fails to meet the distributed applications in CPM; 2) access to centralized DTs relies heavily on stable Internet, which cannot be guaranteed on construction sites with complex physical environments and various certainty (Jin et al. 2020); 3) centralized DTs are sometimes prone to security issues such as data tampering and hacking, which undermines the information trustworthiness and accuracy.

Blockchain, as a distributed technology, has the potential to resolve the dilemma. However, most research reported in the literature, as explorative studies, concentrated on formulating Blockchain 1.0 or 2.0 frameworks to store CPM data, leaving the critical point of practical utilizations for distributed CPM activities. Two application gaps of Blockchain 1.0 and 2.0 are summarized: 1) a blockchain holding a large amount of data becomes lengthy, associated with performance loss and slow synchronization; 2) stable Internet is required for data transactions and queries, leading to failed offline functions.

Thus, this research aims to develop a Blockchain 3.0 paradigm for fast synchronization and offline functions, including efficient communication, indexing for combinatorial query, remote analytics, and digital authorship, for localizing distributed blockchain for distributed and dynamic CPM activities.

3 ChainPM for CPM digital twins

The research methodology of the study is shown in Figure 1. The first step aims to analyze the existing dilemma in CPM DT by reading the literature and supplementing it with hands-on experiences. Then, in the next step, the study presents ChainPM as a Blockchain 3.0 paradigm that extends Blockchain 2.0 with innovative indexing, querying, and analysis feature sets for key CPM data to address the dilemma. Then, ChainPM is implemented in a case study of modular construction with a CPM DT of 952 volumetric modules. Finally, experimental results gauge the performances of the proposed ChainPM in contrast with the traditional Blockchain 2.0.

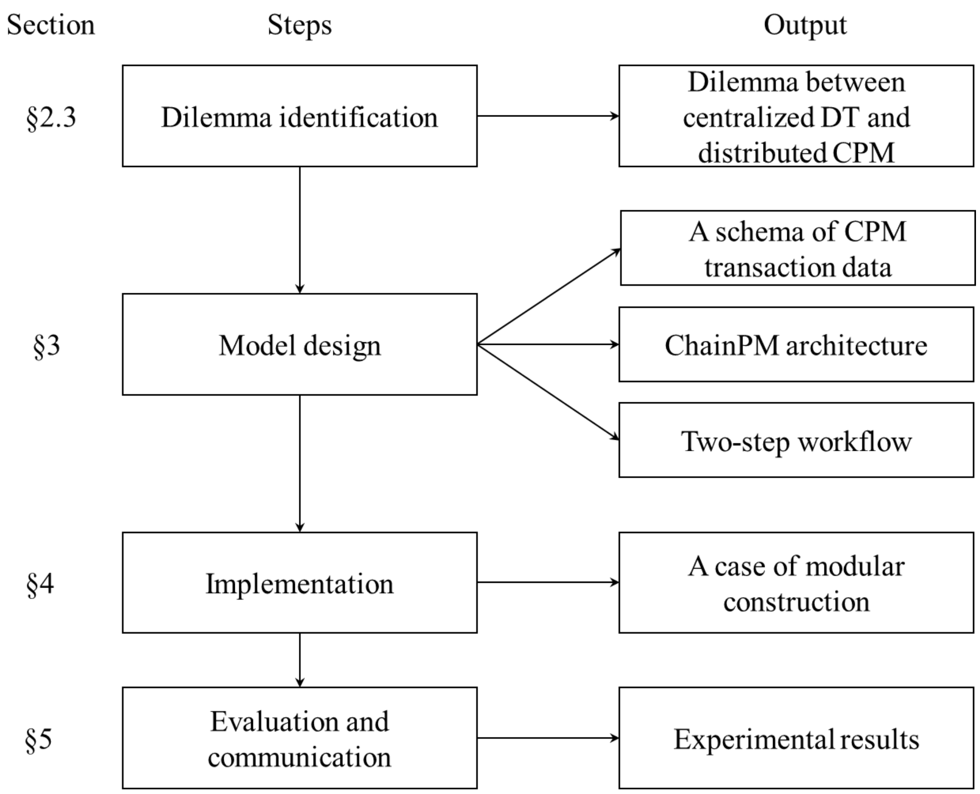


Figure 1. Research methodology in this study

3.1 A schema of CPM transaction data

First, a general schema of CPM transaction data is designed, as shown in Table 2. Regardless of the various CPM activities, four common keys are defined:

- *DT channel*: a private channel dedicated to a particular DT involving two or more stakeholders,
- *component ID*: the unique ID of a construction component,
- *transaction time*, and
- *user ID*: the user who submitted the transaction.

Besides that, other transaction data are organized as *general data* in a semi-structured format, such as JSON format. Different types of data, such as numbers, texts, and images, are compatible with the semi-structured format.

Table 2 Example of the CPM data transaction schema in this study

DT channel	Component ID	Transaction time	User ID	General data (semi-structured)
Channel A	ID001	2022-02-28 14:21	User A	{“taskID”: 1, “task”: “Inspection”, “deviceID”: 53, “photo”: [BLOB], …}
Channel B	ID002	2022-03-02 16:37	User B	{“taskID”: 2, “task”: “Transportation”, “vehicleID”: 994, …}

3.2 The ChainPM architecture

Figure 2 shows the ChainPM architecture. ChainPM has three layers: application, smart contract, and Blockchain 3.0. The design of the three layers is compatible with existing Blockchain 2.0 paradigms. However, what makes ChainPM unique is the sublayer Cached Twin, designed to bridge the conventional Blockchain 2.0 framework and the smart contract layer.

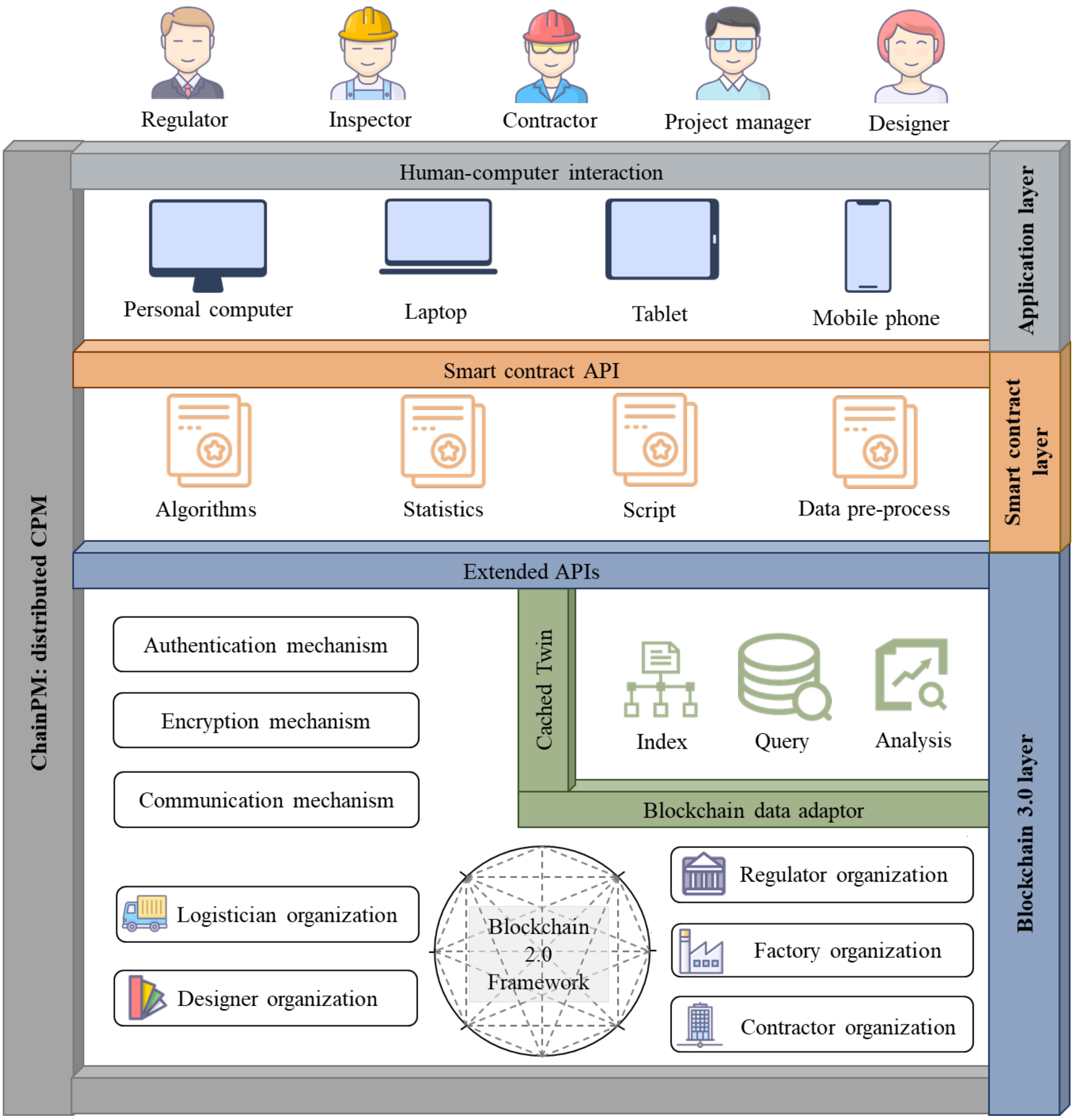


Figure 2. Blockchain 3.0 architecture of ChainPM

Application layer. This layer offers practical CPM functions for users in terms of smartphone (or web page) graphical applications. When the Internet is unavailable, Internet-reliant actions, such as saving data on the chain, will be queued and executed in the temporal order once the Internet resumes. After a short time of enqueuing the action, users can proceed with their other offline operations without worrying about loss of requests and data. Each user is required to have a unique ID associated with a certificate and a private key issued from the certification authority to access the application layer's functions in ChainPM.

Smart contract layer. This layer realizes smart contracts, consisting of algorithms, statistics, scripts, and pre-processing, for CPM DTs. The smart contract layer aims to build a bridge between the application layer and the Blockchain 3.0 layer for data transfer and analysis. Multiple algorithms are included in the smart contract to implement the different functions of CPM, such as adding records and querying records. CPM statistics (e.g., volumes, ownerships, and progress) depict the CPM DT in general based on multi-source data without unfolding all the blockchain transactions and cryptographic hashes. Scripts can help users more easily update and deploy smart contracts for possible security hazards. Based on the features of smart contracts, CPM information can be pre-processed and analyzed automatically. The algorithms, statistics, scripts, and pre-processing together also ensure data integrity, eliminate duplication, and improve data security for CPM.

Blockchain 3.0 layer. Three sublayers are integrated into this layer:

1) Blockchain 2.0: ChainPM includes and extends the Blockchain 2.0 sublayer. For example, *Hyperledger Fabric* is a matured Blockchain 2.0 with a versatile design and many functional modules. For CPM DT, the Blockchain 2.0 sublayer can reuse the off-the-peg consensus mechanism for data security and membership services for multiple stakeholders.
2) Cached Twin: The Cached Twin sublayer aims to improve the indexing and analytics functions, particularly for fast synchronization and offline functions. Indexing and analytics are vital to Blockchain 3.0 in ChainPM. Usually, a query to a three-node blockchain network consumes a few seconds, which is much higher than most users' expectations for productivity and response (Nah 2004).
3) Data adaptor: The role of the data adaptor sublayer is to exchange transactions between Blockchain 2.0 and the Cached Twin. The data adaptor regularly handles the synchronization between the on-chain and off-chain data against different scenarios (e.g., two synchronization requests every second). The success of the synchronization depends on the availability and speed of the Internet connection.

ChainPM is designed for utilizing DTs for distributed CPM. Stakeholders are authorized to join the ChainPM as nodes. Smart contracts provide stakeholders with trusted transactions without a third party. A ChainPM node determines the authenticity of each transaction according to predefined rules and the consensus protocol, while certain rules are designed as well for offline mode. Integrating the transparency and immutability features of Blockchain 2.0 and the low latency and rich analytics from the new sublayer, the proposed ChainPM can ensure timely access and analysis of CPM DTs. Last but not least, the information in the Blockchain 3.0 Layer in ChainPM is as equally accurate and secured as the employed Blockchain 2.0 backbone.

3.3 Two-step workflows in ChainPM

ChainPM has unique two-step workflows that return results twice. In existing Blockchain 2.0 frameworks, smart contracts follow a sequential execution order based on a consensus protocol setup, where the data connection between the application layer and smart contract closes when the response is received. The two-step workflows in ChainPM return an immediate response from the Cached Twin before the blockchain's final response, as shown in Figure 3, which are different from those in Blockchain 2.0.

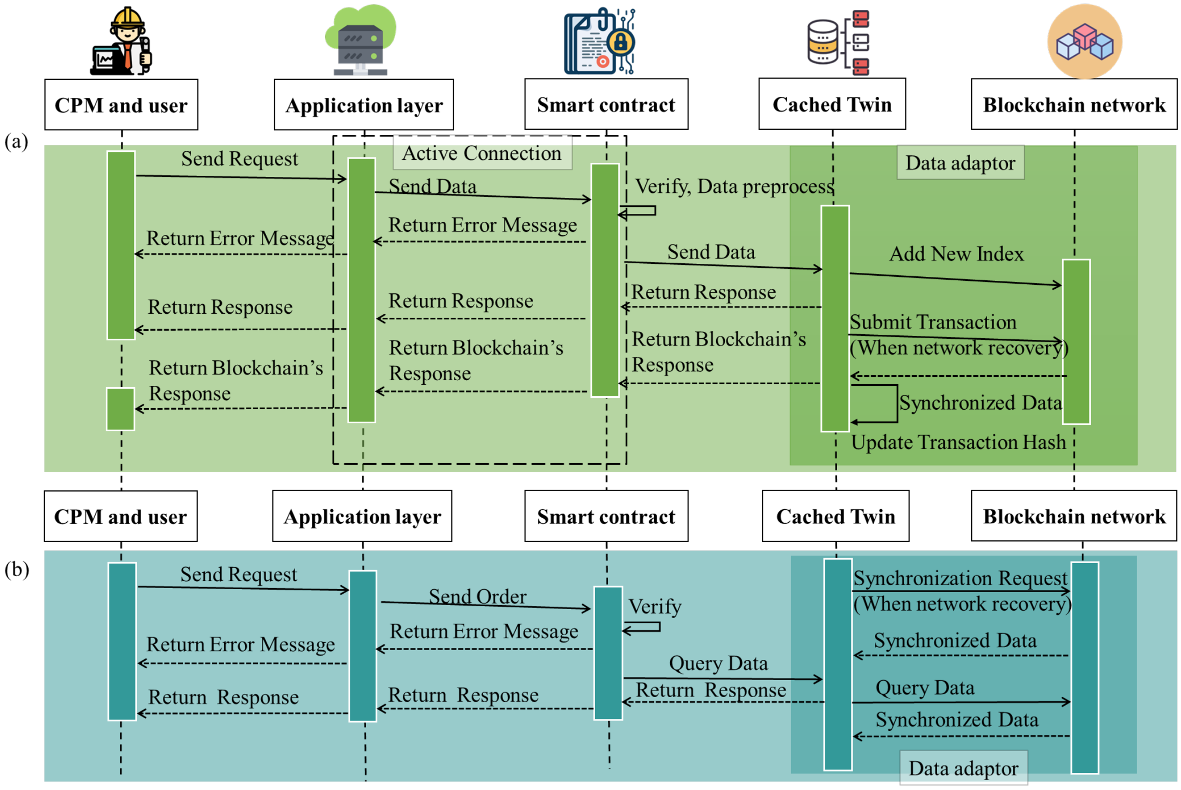


Figure 3. Message sequence charts of two-step workflows in ChainPM. (a) Upload records; and (b) queries and analytics

Figure 3(a) shows the message sequence chart of the two-step workflow of uploading records. The smart contract verifies the function and pre-processes data first according to the predefined contract before sending pre-processed data to Cached Twin. Cached Twin acknowledges the request promptly and then communicates with the data adaptor for synchronization with the Blockchain 2.0 network. After the impacts on the blockchain, the blockchain's result is returned as the second response. In the meantime, the new data are indexed asynchronously. The time-consuming executions of block packaging and key data indexing do not block the application layer because the application layer receives the acknowledgment of the request; therefore, the unnecessary waiting time for blockchain packaging in conventional Blockchain 2.0 is avoided.

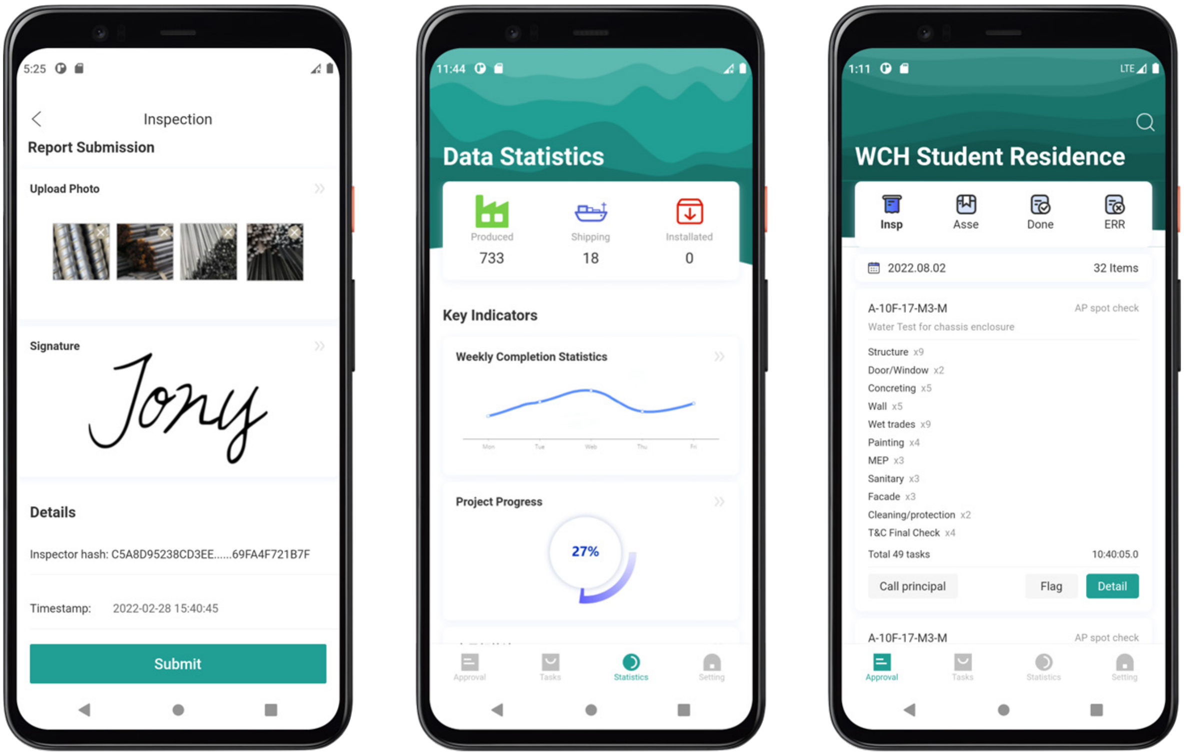
Figure 3(b) shows queries and analytics are handled by the smart contract in two steps. First, the Cached Twin in ChainPM immediately returns the indexed data for the smart contract. Then, it confirms the slow-but-trustworthy results from the blockchain network using the indexed hash value. If no results are found in the cache, the query request is forwarded to the blockchain for a full-chain query. In the offline situation, the data will be temporarily stored in Cached Twin. When the network is recovered, the data adapter will synchronize with the blockchain network at regular intervals. In CPM DT, synchronization and data querying are particularly important (Martínez-Rojas et al. 2016).

4 A case of modular construction

4.1 Three application functions

A modular construction project was selected in Hong Kong, focusing on quality and safety inspections to validate the proposed ChainPM. The project was a student residence at the Wong Chuk Hang site for the University of Hong Kong with two 17-story towers, including 952 prefabricated dormitory rooms and support facilities, such as prefabricated restrooms and common areas. First, a manufacturer, Yahgee Modular House Company Limited, produced modular components in Zhuhai, China. Then, the components were shipped and pre-assembled into a volumetric module plant in Tuen Mun, Kowloon. Later, the assembled modules would be delivered in batches to the construction site in Wong Chuk Hang District on Hong Kong Island. Thus, the DT, in this case, involved spatially and temporally distributed CPM activities.

Three typical CPM functions were included for validating the functionality for different stakeholders without loss of generality. Figure 4 shows the screenshots of the DApp of ChainPM. The first function was designed for manufacturer users to upload inspection records of new modules to the CPM DT. The records involved a variety (consisting of facts, signatures, and photos) and a big volume (> 500 MB) of inspection data. Each upload operation, therefore, took roughly 5 to 10 minutes to store on a Blockchain 2.0 framework. It was a painful practice in that the average number of uploads was about 40 per day. Figure 4(a) shows that ChainPM works well with various data types for CPM DT for manufacturer users.



(a) (b) (c)

Figure 4. Screenshots of demanded CPM functions of ChainPM. (a) For manufacturer users; (b) for main contractor users; and (c) for government regulator users

The second function was project statistics for main contractor users, as shown in Figure 4(b). The main contractor demanded to check the modules' production, delivery, pre-assembly, and installation information on the chain for transparent and traceable project progress. Figure 4(b) shows the statistical overview of the work-in-progress modules at different stages. For example, Figure 4(b) shows that 733 prefabricated components have been produced, 18 of them are in shipping, and no components have been installed. The weekly statistics are represented in a wave chart, while the project's overall progress is shown in a gauge chart.

The third function was the approval of records for government regulator users, as shown in Figure 4(c). The regulatory authority is expected to review and approve the documents submitted by stakeholders, including the quality inspection records and assembly records. Figure 4(c) shows daily inspection records pending approval on the DApp interface of ChainPM. Records' details, such as signatures of endorsers and inspection photos, are available from the blockchain network as well.

4.2 Implementation of ChainPM

ChainPM was implemented with several software environments, including *Node.js* (version 16.15.1) for smart contracts, *SQLite* (version 3.31.1) for indexing in the Cached Twin, and *Hyperledger Fabric* (version 2.2) for the Blockchain 2.0 framework, which consisted of three organizations (i.e., a manufacturer, the main contractor, and regulatory authority), as shown in Figure 5(a). The cryptogenic of *Hyperledger Fabric* is shown in Figure 5(b). At the same time, channel configuration includes organization and profile configuration, as shown in Figure 5(c). The default asymmetric encryption was employed for safety and effectiveness.

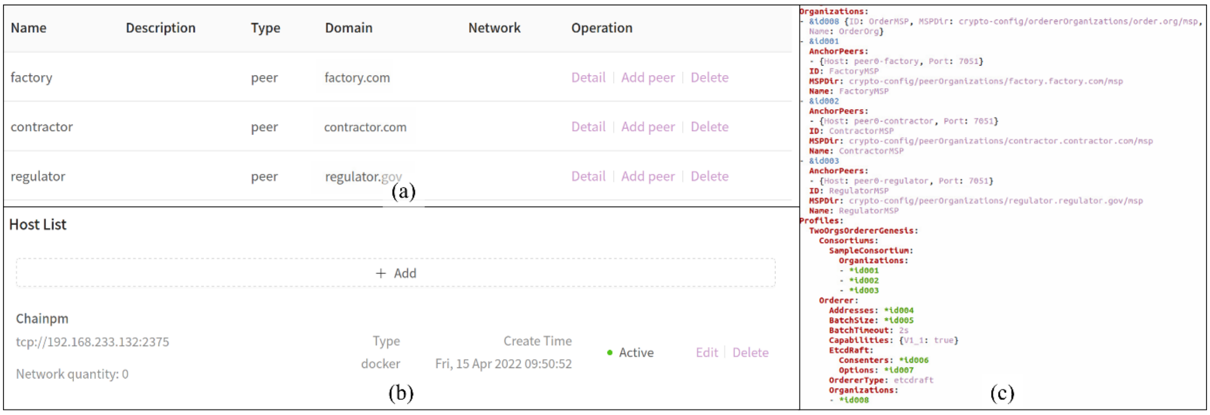


Figure 5. Blockchain 2.0 network configuration in ChainPM. (a) Organizations; (b) host; and (c) channel configuration

The Cached Twin sublayer adopted a relational data structure for indexing the CPM DT, as shown in Figure 6. Figure 6(a) shows that two more keys, i.e., *taskID* and *taskType*, were indexed for the case study. Besides, *tranID* was the unique code referring to a transaction ID, as shown in Figure 6(c). Figure 6(b) shows a set of examples of indexed data. Then, Cached Twin utilizes a lightweight SQL service, SQLite, to index all the selected CPM on-chain data.

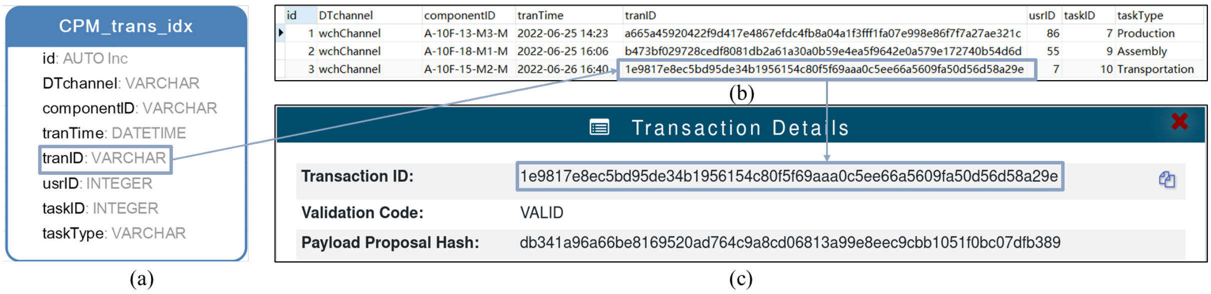


Figure 6. Example of indexing tables in ChainPM. (a) Keys to index for on-chain data transaction; (b) data in Cached Twin; and (c) transactions in the blockchain network

With the Cached Twin sublayer and supporting data adaptor, ChainPM elevates the conventional Blockchain 2.0 to a 3.0 paradigm, emphasizing synchronous data indexing and advanced queries for DApps. First, the smart contract layer automatically synchronizes the CPM transactions with the Cached Twin sublayer without user interventions for data sorting or block packaging. Advanced queries, such as ‘selecting all the records uploaded by User 55 on 25 June 2022,’ are therefore enabled by the Cached Twin. The combinatorial conditions can be applied to all the columns in Figure 6(b). Furthermore, the DT’s digital authorship is cached as an enormous network of component-time-author nexus, using *componentID*, *tranTime*, and *usrID*. Consequently, multiple analyses can be realized based on the transactions and data sources, such as monitoring project schedules, worker productivity, and digital authorship.

ChainPM safeguards data authenticity in the Cached Twin using a data adaptor module, as shown in Figure 7. Figure 7(a) shows the indexed keys, which extended the general schema defined in Sect. 3.1. A block in the Blockchain 2.0 framework comprises three parts, specifically a block header, block data, and block metadata, as shown in Figure 7(b). The list of ordered transactions of the current block is contained in block data. The data adaptor in ChainPM synchronizes the transactions in block data to Cached Twin. Figure 7(b) shows the attributes of an example transaction, including all the key columns in Table 2 and privacy data like *signImg,* which is the user’s signature photo encoded in Base64 format. Such privacy data were waived from indexing in Cached Twin and can only be verified for authorized persons (e.g., government regulators) via the *tranID*. Moreover, the semi-structured *formValue* is a JSON dictionary comprising the submitted transaction details.

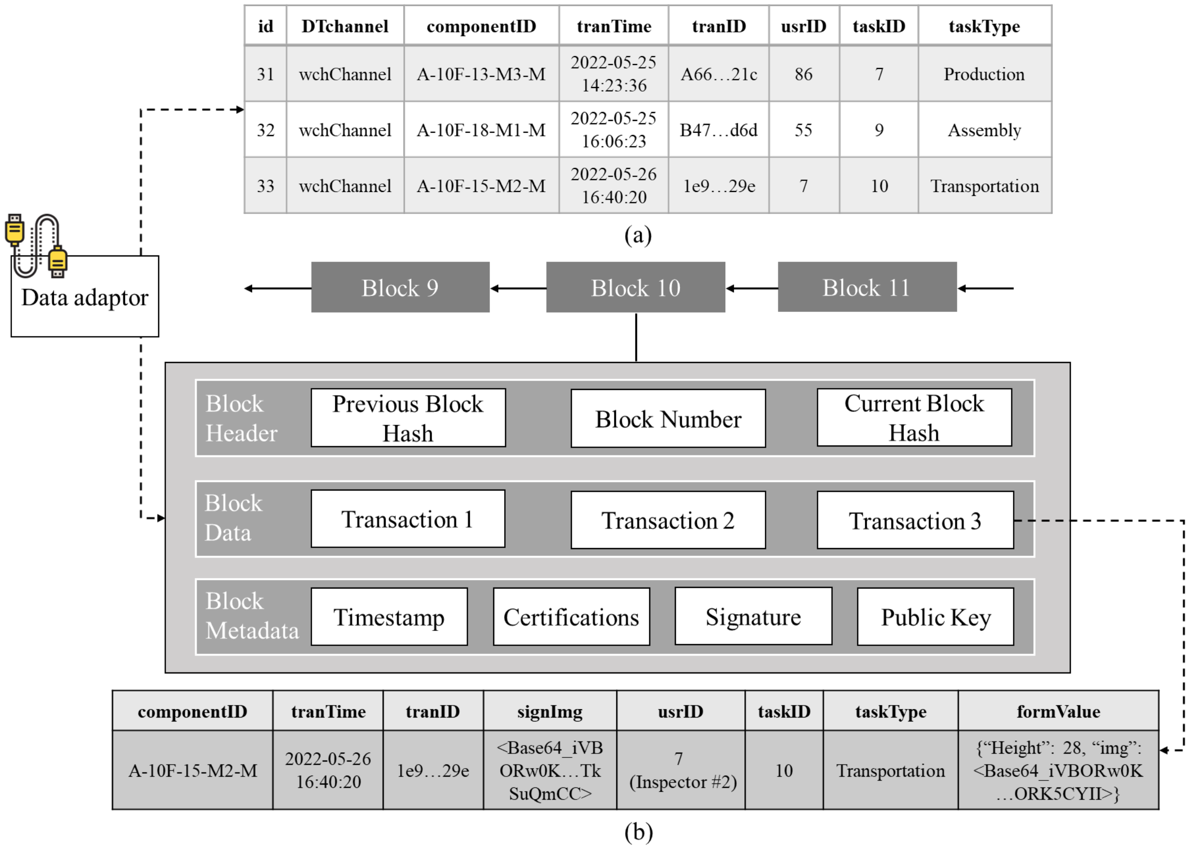


Figure 7. Example data for blockchain data adaptor. (a) Target structured CPM data to index; and (b) source blockchain data

5 Experimental results

5.1 Experimental settings

All experiments were conducted on a Docker engine (version 19.03.13) with an Intel i7-12770KF CPU (3.6 GHz, 8-thread), 16 GB memory, and Ubuntu 18.04.1 LTS (Linux version 5.4.0-58) operation system. For gauging the efficiency of synchronization and offline functions, the performance metrics in this study included storage cost and response time, which were adopted from Blockchain 2.0 applications in the literature, such as Kuzlu et al. (2019) and Li et al. (2021b).

Storage was calculated by measuring the space changes in the operating system hard disk. The configuration of *Hyperledger Fabric* was set to default, where the maximum block interval was 2 s, the maximum number of block transactions was 500, the maximum capacity of each block was 2 MB, and if the size of a transaction exceeded 10 MB, the transaction would not be packaged (Elli et al. 2018). Experiments on storage costs were conducted with 100,000 same data transactions recorded independently for Blockchain 2.0 and ChainPM, where 100,000 was the approximate ceiling number of all project tasks for all the 952 modules.

Response time refers to the smart contract API's waiting execution time in milliseconds for a transaction, which is a key performance measure of the project management system. Response time was measured through the system Unix timestamp. The first response time of ChainPM indicates the time the user needs to get feedback from Cached Twin, while the second response time indicates the time the blockchain needs to finish data storage. The metric offline response time, which is new to the existing studies, aimed to gauge the performance of the proposed ChainPM without Internet connections. The expiration time for the smart contract to identify the offline mode was set to 5,000 ms. The experiments on the response time were conducted with 100 independent requests of (i) uploading new inspection reports, (ii) listing the records of all modules, and (iii) listing specific records of a given new module for gauging the performances.

5.2 Experimental results

5.2.1 Storage cost

The results showed that ChainPM consumed more disk space than conventional Blockchain 2.0. In the experiments, the conventional Blockchain 2.0 took 297.0 MB of extra space to store the 100,000 data transactions. In comparison, ChainPM occupied 505.2 MB of extra disk space, which was about 1.7 times the size of conventional Blockchain 2.0. Modern smartphones and DApps can handle both sizes effectively and efficiently.

5.2.2 Response time

Figure 8 shows the box chart of the response time of uploading inspection records of new modules (100 independent requests). The first response time of ChainPM was 3.53 ms on average, while the average second response time was 2,258.4 ms. For Blockchain 2.0, the online response time was 2,212.2 ms on average and relatively stable, whereas the offline response time was over 5,000 ms, according to the settings. On average, ChainPM saved > 99.8% response time against conventional Blockchain 2.0, while the second response time was almost the same as that of Blockchain 2.0.

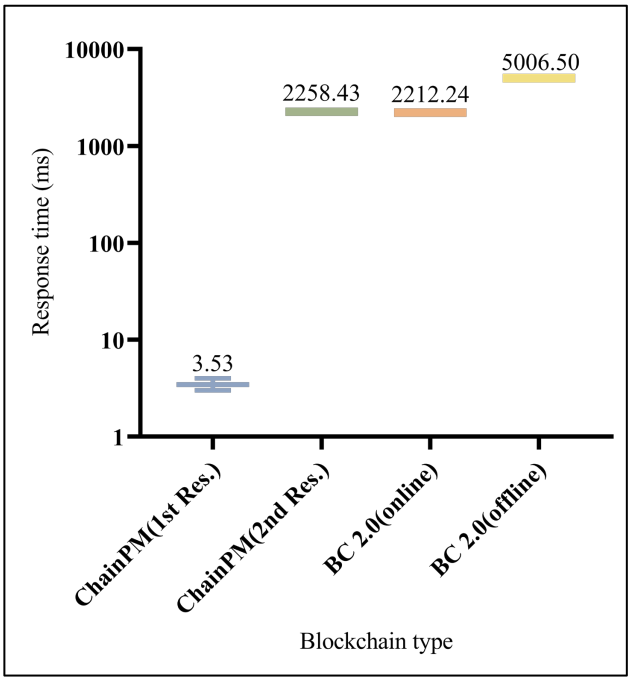


Figure 8. Box chart of the response time of uploading inspection records of new modules (100 requests per test)

Figure 9 shows the box chart of the response time of querying the records of new modules. Figure 9(a) illustrates that Blockchain 2.0's native query function was about 150.1 ms on average for listing the records of all modules; Figure 9(b) shows that querying the records of a specific new module was, on average, 157.9 ms, slower than listing all modules. In contrast, ChainPM took merely 1.1 ms for both tasks, in which the time cost saved was > 99.2%. Furthermore, ChainPM's 1.10 ms for a specified module was faster than listing all data (1.13 ms) due to the efficiency of SQLite indexing for the 100-run experiments. The significant (99.2%–99.8%) time-saving confirmed the fast synchronization of the proposed ChainPM framework as a Blockchain 3.0 paradigm.

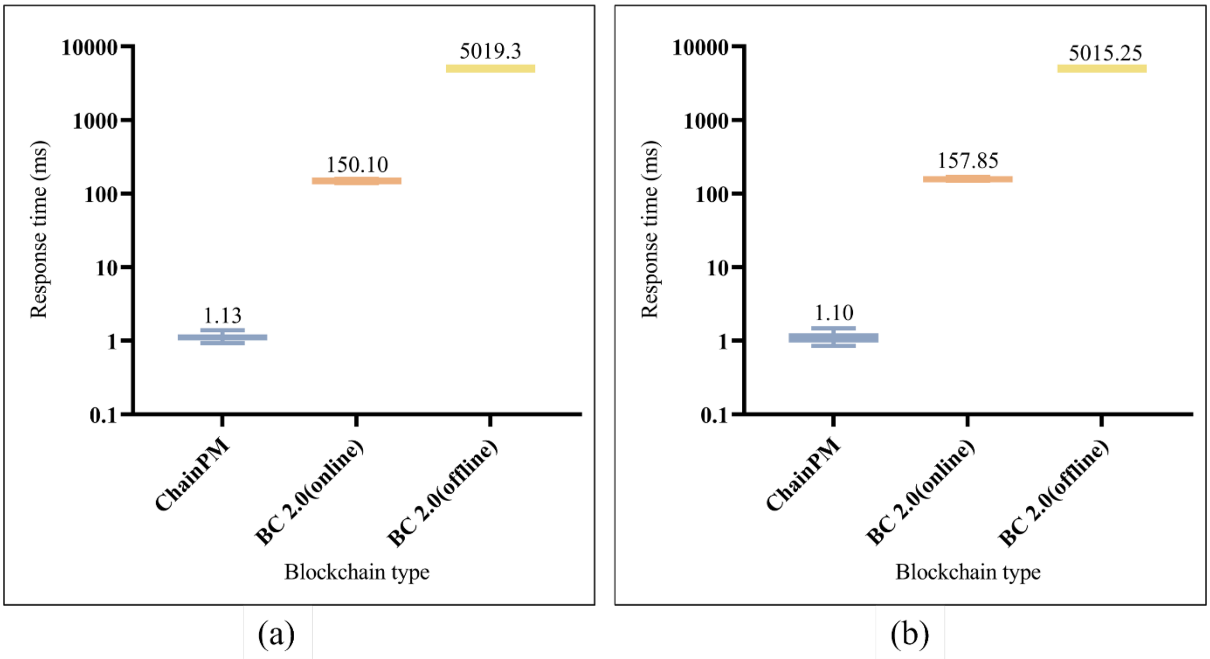
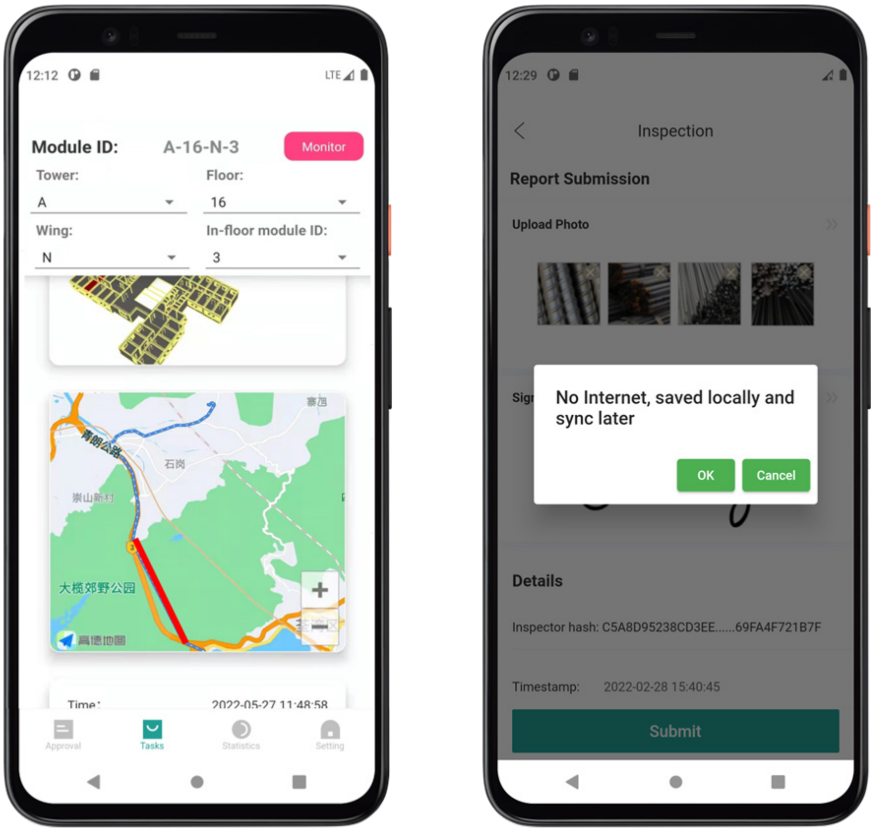


Figure 9. Experimental results for data query. (a) Listing the records of all modules and (b) regulator's specific record query of a new module (100 requests per test)

Regarding the offline settings, ChainPM returned the same results in the same computational time, whereas Blockchain 2.0 failed to work. As shown in Figure 10, the average time cost of Blockchain 2.0 for the offline cases was slightly over 5,000 ms, which indicated the user had to wait more than 5 seconds for a 'no Internet' message. Figure 10(a) shows the offline mode identified by ChainPM through a long tunnel; Figure 10(b) displays the offline mode simulated on a smartphone emulator.



(a) (b)

Figure 10. Example screenshots of offline ChainPM. (a) Offline mode identified through a long tunnel; (b) offline mode simulated on a smartphone emulator

Overall, experimental results confirmed that ChainPM is efficient and stable for bridging the emerging blockchain technology and DTs for distributed stakeholders and CPM activities. Thus, ChainPM can facilitate project stakeholders in terms of communication and collaboration, particularly where the Internet connection is unstable. The proposed ChainPM framework and the case DApp realized a Blockchain 3.0 paradigm for CPM DTs.

6 Discussion

In contrast with the existing Blockchain 2.0 frameworks in the literature, ChainPM has three advantages. Firstly, experimental results demonstrated that ChainPM has high-level flexibility for variant types of DT information and meets the demands of distributed CPM. Secondly, existing Blockchain 2.0 frameworks rely heavily on the Internet, though the Internet connections are unstable on real construction plants and sites. In contrast, the proposed ChainPM synchronizes the key index data with Cached Twin for online and offline settings, while the subsequent data synchronization operation can be performed immediately when the network is available. Thirdly, the DApp realizing ChainPM confirms that the Blockchain 3.0 paradigm is feasible and adequate for CPM—for example, in building component quality inspection, project progress monitoring, and government regulation. Therefore, CPM researchers and practitioners can refer to the ChainPM to adopt DTs and tackle the advent of the blockchain era.

However, ChainPM also has several limitations. Firstly, as an exploratory study, the ChainPM system lacks large-scale experiments. Therefore, unexpected situations were not considered thoroughly, necessitating further explorations in future research. Secondly, the indexed keys in the Cached Twin sublayer were a subset of structured data selected from the CPM data transactions. Due to the encryption mechanism of Blockchain 2.0, the full data transactions were not accessible even though their briefs (as the indexed keys) were listed in offline mode. Thus, another tractions cache can be designed for hosting the recent or highly likely 100 transactions. Thirdly, ChainPM does not fully utilize multidimensional BIM; subsequent research thus is suggested on integrating semantically rich BIM and city information modeling (Xue et al. 2021). Fourthly, the proposed ChainPM introduces the public smart contract design in Hyperledger and a single-chain multi-node blockchain network. A future direction is thus recommended on extra privacy protection and cross-chain and multi-chain methods to ensure the blockchain's security, scalability, and performance. Lastly, the Cached Twin in the case study involved two additional structured data columns, i.e., taskType and formValue, which led to manual SQL database alternation by an expert. A user-friendly Cached Twin 'remote controller' will be developed in the future.

7 Conclusion

Traditional CPM is challenged by inadequate integration, laborious data accessibility, and unsatisfactory information security. The current adoption of ICTs and DTs has brought opportunities for upgraded information digitization and data integrity. Harnessing blockchain technology is a potential solution to fill the gaps. The explorative applications (i.e., Blockchain 1.0 and 2.0) can theoretically solve the problems regarding proof of non-repudiation and traceability for distributed CPM. However, Blockchain 2.0 also relies on a smooth network. Yet, unstable Internet connections, especially in complex physical environments in construction sites, can jeopardize DTs and blockchains of serviceable uses.

Therefore, this paper proposes a ChainPM framework for CPM DT. ChainPM incorporates three innovative layers: (i) a smart contract layer for handling DTs with Blockchain 3.0 using two-step workflows, (ii) a distributed Cached Twin sublayer with CPM indices and analytics, and (iii) a blockchain data adapter layer optimized for an unstable Internet environment. Through the unique two-step workflows in ChainPM, on-chain CPM data transactions can be efficiently indexed and analyzed with Cached Twin services for the first response for stakeholders' access while not losing the authenticity and trust backed by the blockchain network (via the second response). ChainPM explores an uncharted domain of designing and applying Blockchain 3.0 for CPM DTs, which is vital to the practical adoption of blockchain in the construction industry and, in turn, contributes to the scalability and extension of blockchain theory studies in the literature.

Experimental results showed that ChainPM saved > 99.8% response time in uploading new records and > 99.2% time in querying CPM data, respectively, where the baseline was the well-known Blockchain 2.0 system on *Hyperledger Fabric*, while ChainPM used 70% more disk space. In summary, ChainPM drastically improved the time performance of Blockchain 2.0 at a tolerable cost in disk size. Future research can be directed to (i) larger-scale experiments with real projects, (ii) building another tool for hosting the most recent transactions, and (iii) multidimensional data sources such as OpenBIM and city information modeling (Li et al. 2022a), and (iv) more privacy preservation means other than data channels in consortium blockchains.

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