When permissioned blockchain meets IoT oracles: An on-chain quality assurance system for off-shore modular construction manufacture

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***Abstract*—Advanced information technologies such as the Internet of Things (IoT) and Modular Construction (MC) bring new potentials to the construction industry. The trustworthiness is critical for MC quality assurance (QA), particularly in the off-shore manufacture stage. The emerging blockchain technology which enables transparent, traceable, and immutable information exchange in distributed systems opens a new avenue for managing off-shore MC. However, the real-time data collection and update, as well as permitted data access are two critical concerns in utilizing blockchain for MC. The permissioned blockchain and IoT is considered as feasible solutions. Thus, this paper presents a three-tier architecture of permissioned blockchain with IoT oracles: the infrastructure layer, platform layer, and service layer. IoT devices in the infrastructure layer act as oracles of the blockchain, feeding real-world data from MC components promptly on time through trusted APIs. A permissioned blockchain network in the platform layer provides authentication functions to ensure authorized access to QA-related channels. A mobile-based application named e-InStar in the service layer provides user-friendly UI for multi-stakeholders to access the QA system named e-inspection 2.0. The three-tier architecture design can thus respond to the data access and data updating needs for MC QA, specifically for multi-stakeholders cooperation requirements. An application case of a housing project validated the permissioned blockchain in the e-Inspection 2.0 system in two aspects: (1) system transparency and security, and (2) users' satisfaction with data collection and QA functions.**

***Index Terms*—Permissioned Blockchain, Internet of Things, Quality Assurance, Modular Construction, Oracle**

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I. Introduction

Modular Construction (MC) is a trending distributed construction method [1], [2], in which most construction components are manufactured remotely in an off-site, sometimes off-shore factory, and assembled into a 3D module before transporting by specialized vehicles to the construction site [3]. The MC is deemed a promising solution for many countries that have confined building space but urgent needs for construction, such as Singapore and China.

Inefficient and ineffective execution of MC projects may severely impact construction productivity in terms of cost, quality, and timeliness. Quality in MC is associated closely with safety and property [1], and the Quality Assurance (QA) acts as a vital 'gatekeeper' to the MC project. It is a systematic operation that ensures checking items in accordance with the quality standards to meet a set of targets, such as compliance, schedule, and function [4]. Therefore, QA is a time-consuming task that must be completed during the construction and pre-construction manufacturing phases [5].

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The authorized individuals and parties, such as contractors, supervisors, and developers, frequently perform the inspection part [6]. Furthermore, the physical presence is indispensable during inspections due to the MC's nature of the distribution. Moreover, file-based QA remains the primary mode of information recording, revising, and sharing [2]. As a result, inspectors from different parties must record inspection data on-site and subsequently enter the data at the office. However, the lock-downs of COVID-19 undoubtedly makes traveling and on-site working troublesome or even impossible.

The recent advancement in Information Technologies [7] has brought potential opportunities for digital QA [8]. For example, Wu et al. [9] developed a method to facilitate efficient QA by adopting Building Information Modeling (BIM) and IoT on a mobile device. A collaborative system integrating BIM and indoor positioning can eliminate errors and cursoriness in QA [10]. However, the lack of integrated data recording and confidence in the authenticity have led to the incomplete and inaccurate report of QA, hindering a trustworthiness and efficient QA [5]. The existing approaches mentioned in the literature are still limited by centralized governance from contractors, resulting in low inspection efficiency and stakeholder collaboration [1], [11]. Furthermore, the process, results, and responsible individuals sometimes are ambiguous; contractors, as the project's general data manager, can sneakily modify records to exonerate them from unexpected quality issues, leaving original or modification records untraceable and easily tampered with [12].

Blockchain is a promising technology to realize decentralized storage that chronologically and securely records data [6], [13], [14]. It has been adopted in several construction industrial applications, such as smart contracts [15], collaborative detection [16], and logistics management [17]. However, public blockchains have some serious problems, involving prone to attacks, the latency of data transmission and updating, which hurdle wider application in the construction industry [18]–[20]. A permissioned blockchain generally involves a federation of organizations in which transactions are blocked together and verified by authorized peers rather than anonymous miners. With a granted access control, transactions with consensus can be achieved in an attack-proof manner. The IoT technology has been utilized in contributing to promise better strategies in construction practice. For example, the social reputation capital in IoT was optimized using a blockchain-based group formation strategy [21]. IoT oracles guarantee the "true provenanc" and real-time updating of data are two issues for implementing permissioned blockchain in construction industry [22].

This paper aims to introduce a permissioned blockchain-enabled IoT system named e-Inspection 2.0 to offer an adaptable solution to achieve secure data access, as well as trusted data provenance and updating for MC QA. Compared with the traditional insufficient inspection and inflexible manners, a transparent, secured, and traceable framework was designed to streamline and digitalize the QA procedures, for facilitating co-management by stakeholders. At last, a case study of practical application is deployed to validate its performance.

II. The Permissioned Blockchain-Backed IoT Platform

A typical MC project usually involves one or several manufacturing factories, due to the fragmented construction process and distributed stakeholders, the data sources are discrete and variable for QA. The e-Inspection 2.0 system aims to collect mass production data of MC projects through IoT oracles and support trustworthy decision-making by leveraging a permissioned blockchain. The three-tier structure of the system is shown in Fig. 1.

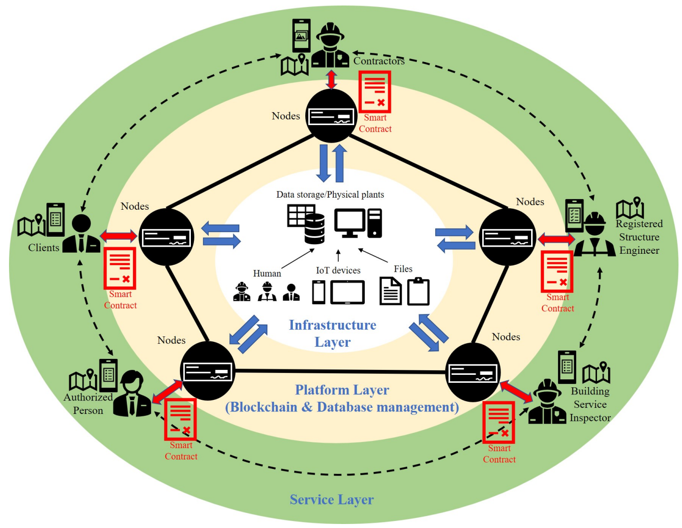


Fig. 1. The three-tier structure of e-Inspection 2.0 system

The infrastructure layer integrates IoT sensors and provides web and application servers, networking resources, and data storage physical plants. In this layer, the IoT sensors/devices serve as oracles of the second-tier blockchain network to collect real-world data from distributed MC processes. The infrastructure layer enables blockchain and database to deploy quickly, and data from different resources such as human beings, IoT devices, and files of the MC project can be stored and computed efficiently.

A permissioned blockchain is implemented in the platform layer. An open-source permissioned distributed ledger platform Hyperledger Fabric and the J2EE data web services running on server Resin are employed. This layer serves as the middleware of e-Inspection 2.0 system that involves the database management tools, backend services, and deployed blockchain ledgers. In this layer, all components serve as a bridge for the communication between users and data, and a parallel data exchange system using Java Database Connectivity and smart contracts is developed. The inspection records of materials and production processes of modules, as well as dynamic BIM models of the target MC project, are processed as quality assurance contracts (QAC) to support trustworthy consensus-based collaboration among stakeholders. The structure of the ledger is shown in Fig. 2.

The service layer provides a mobile-based application named e-InStar. Users can make intelligent decisions based

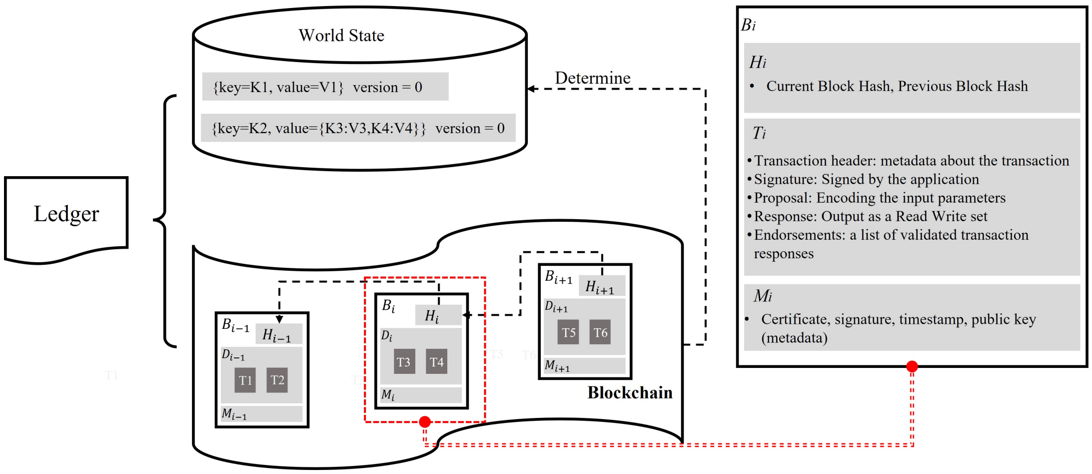


Fig. 2. Ledger service model in the platform layer (Adapted from Li et al. 2021 [6])

on the process management and QA of the off-site manufacturing activities of MC projects. Typical QA stakeholders involve manufacturers/contractors, registered structural engineers, building service inspectors, authorized people, and clients. Different roles contain different authorities in the app, and Fig. 3 illustrates the transaction flow, which is based on the consensus mechanism.

In this architecture, As shown in Fig. 3, the transaction flow consists of three phases: the proposal phase, the ordering and packaging of transactions phase, and the validation/submission phase. In the first phase, the client application with different authorities sends a transaction proposal to a subset of peer nodes that will invoke a QAC to generate a proposed ledger update and then approve the results. For example, the main contractor delivers a production inspection report of door/window installation through the app; this action invokes a chain code to generate a transaction T1 and submits it to qualified peers, then receives an endorsed transaction proposal response. In the second phase, app clients submit transactions T1 to the ordering node to create blocks of transactions that will eventually be distributed to all peers of the QA channel. In the last phase, peers connected with the ordering node validate each transaction in block B2 independently, and the validated transactions update the ledger's state (add block B2 to ledger L1).

To avoid malicious users and guarantee the exact access to the QA channel, the certificate authority (CA) and membership service provider (MSP) supported by Hyperledger is utilized. A CA dispenses certificates to users through the key-pair mechanism, and a MSP is a trusted authority to prove the identity and grant specific privileges an actor has on a node or channel. Thus, only the project-related organizations and their colleagues with different authorities are able to transact on the QA channel.

The IoT oracles, such as prefabricated MC components with QR codes, can be captured and recorded through smartphones. With the help of the developed application, users with different roles and authorities can scan the QR code or NFC (Near Field Communication) chips on the module to record and upload the related data to the system. As Fig. 4 shows, stakeholders of an MC project can update the inspection data everywhere, and related peers in the permissioned blockchain QA channels are able to monitor these data changes timely.

III. Implementation and Evaluation

A. A case study

An MC project of a new student residence at the University of Hong Kong (HKU) was used to test the e-Inspection 2.0 system regarding remote quality assurance. The student residence comprises two 17-floor tower buildings with 952 prefabricated modules, of which the QA includes 40 tasks to conduct at the off-shore manufacturing factory. Traditionally, the QA practices were achieved by sending a troop of inspectors from Hong Kong to Mainland China where the parts of MC were manufactured. However, the COVID-19 pandemic and the control measures, such as long-term border control and strict quarantine policies, made the traditional QA practices surprisingly tricky. The e-Inspection 2.0 is deployed as an innovative way for remote and digital QA.

The primary stakeholders in this MC project include the Real Estates Office of HKU (owner and clients in Hong Kong SAR, China), Paul Y. engineering (main contractor in Hong Kong SAR, China), and Yahgee Modular House (manufacturer in Zhuhai, Guangdong, China). The 40 inspection tasks for QA can be categorized into five types in accordance with stakeholders:

- 40 items for the main contractor (Paul Y.),
- 12 items for RSE (Registered Structural Engineers),
- 7 items for AP (Authorized People),
- 5 items for BSI (Building Service Inspectors), and
- 17 items for CR (Client Representative).

Other users include the architect, structural engineer, and building services consultant. All these stakeholders had corresponding rights to access the system, for example, the workers from the main contractor or building services inspectors access the system via a smartphone application, as shown in Fig. 4.

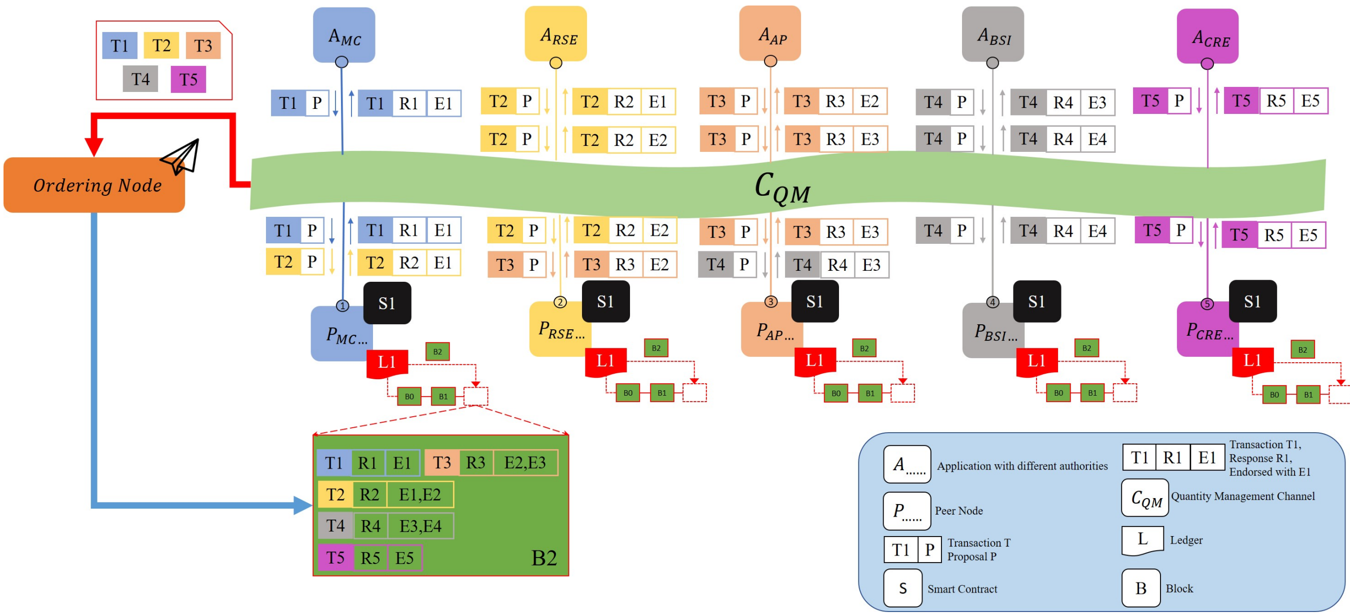


Fig. 3. Transaction flow of the presented e-Inspection 2.0 system

Fig. 4. The smartphone application interface of e-InStar (Adapted from Lu et al. 2022 [1])

In this project, Paul Y. monitored the quality of the pre-fabricated modules during production through photography and then submitted these photo records to AP or RSE for validation. Each submission of the inspection photo records invokes a transaction (proposal) in the blockchain network, as Fig. 5 shows. For roles with permissions such as AP or RSE, the commitment results of inspection tasks are sent to the inspector with an endorsed response in a limited time. Otherwise, the endorsing process will be done automatically. After all the inspection tasks are finished, users deliver the inspection report to the blockchain server and publish it to all peer nodes. In this way, stakeholders in the QA channel can access the inspection record anywhere.

B. Evaluation

The presented e-Inspection 2.0 system was tested in the study case with practice production data. At the time of reporting, 421 (about 43 percent) modules were produced with detailed inspection records in the study case. This section describes two performance indicators, namely, the security and transparency of the system and satisfaction reported by users.

a) System security and transparency: The e-Inspection 2.0 system utilizes permissioned blockchain that only stakeholders of the MC project could join the network, the membership service provider of Hyperledger Fabric is used in this paper to certify the authorized peers. In this way, the system provides a granted access control function and prevents the

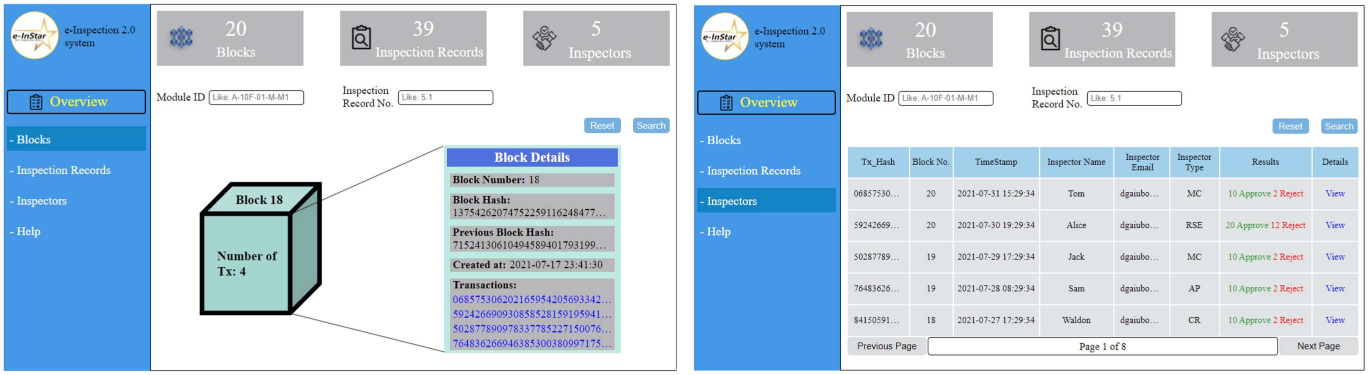
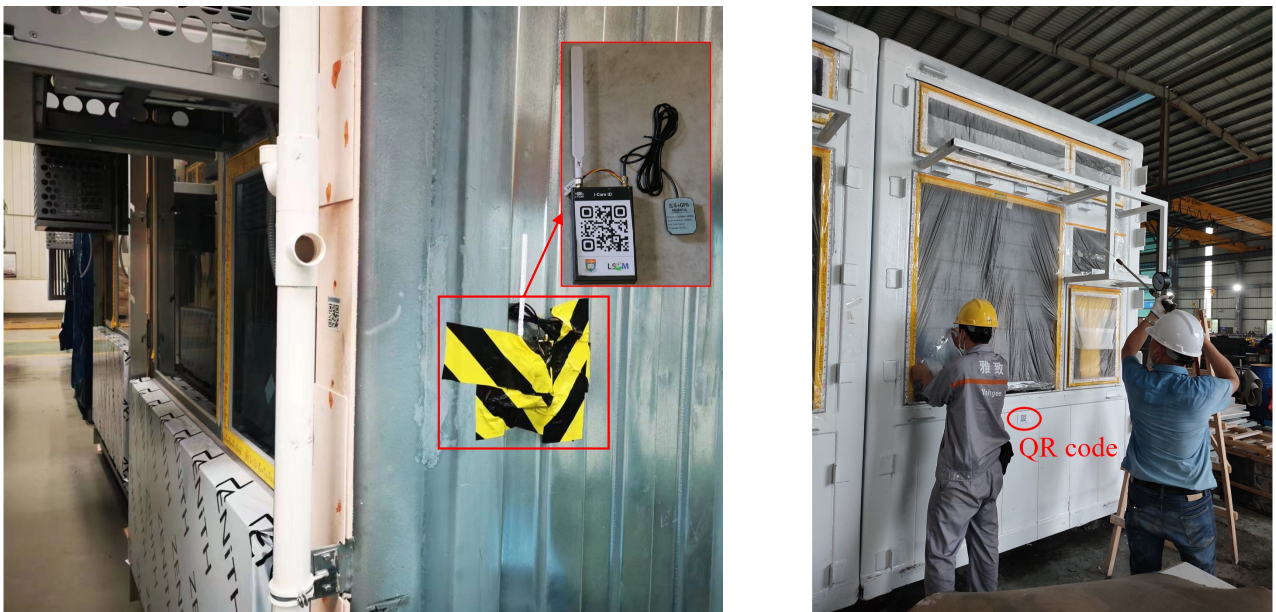


Fig. 5. Example of the pilot-floor on-chain transactions visualization interfaces for owners and contractors



(a) (b)

Fig. 6. Examples of modules as IoT oracles (a) With GPS + tremble + env. sensors + 4G outdoor; (b)With QR codes indoor

whole system suffers from some cybersecurity attacks, such as the Sybil attack, which is a typical attack on the consensus process as the participants are anonymous and can have several identities. At the same time, the permissioned blockchain keeps all the inspection records and data transparent and immutable for a consortium of stakeholders of the MC quality assurance.

b) User satisfactions: The major stakeholders give positive feedback on this e-Inspection 2.0 system on both data collection and QA functions.

In terms of data collection, the size of inspection attachments such as photos and instruction files are 44 gigabytes (GB) for a total of 13,055 transactions. As Fig. 6 shows, there are total 975 smart MC components in the practice project that serve as IoT oracles through QR code or NFC chips. By simply scanning the QR code on the module, or communicating with NFC chips on the e-InStar app, users can achieve real-time and compatible data uploading. Thus smartphones acts as the media between users/permissioned blockchain and IoT oracles, the unique QR codes and NFC chips ensure the collection of true-provenance data. In the e-Inspection 2.0, each inspection photo record includes the original size and a thumbnail, where the average size of photos in original size is 1 megabyte (MB) and the average size of thumbnails is 20 kilobytes (KB). To guarantee the efficiency of data storage in transactions, only the thumbnails of inspection photos are stored as JSON values in Base64 encoded forms. In this way, the size of each transaction is about 50 KB which is reasonable for blockchain. Meanwhile, as Fig. 5 shows, the brief summaries of inspection records are also stored in MySQL indexing tables that enable users to browse the transaction details efficiently.

The HKU Estates Office confirmed that they understand the virtual process of transaction flow in the permissioned blockchain and feel confident about the massive volume of collected inspection data. The main contractor Paul Y. claimed, "[the] e-InStar supports various functions such as the inspection, progress monitoring, statistical analysis, and streamlined verification processes. It is an empirical evidence of blockchain rebuild trust in construction."

IV. Conclusion

Trustworthy remote quality assurance (QA) is an urgent issue for modular construction (MC) involving distributed manufacturing and construction activities. Especially the restricted border control due to the COVID-19 prevents cross-border activities such as on-site quality inspection. The recent advancement of information technologies such as IoT and permissioned blockchain has brought potential opportunities for digital QA. The permissioned blockchain provides a promising pathway for upgrading the information security and trustworthiness of a consortium of stakeholders. IoT oracles guarantee real-time data collection from the real world. So, a permissioned blockchain-backed IoT platform is presented in this paper, aiming to facilitate the security of the blockchain system and data collection efficiency. It is an empirical evidence of the claim that blockchain rebuild trust in contruction industry. The significant contributions of this study are summarized in two aspects.

a) The e-Inspection 2.0 system: An integrated quality assurance system is presented with two highlights. 1) The presented e-Inspection 2.0 system utilizes IoT MC components for real-time data collection from the MC project, which serves as the oracle of the permissioned blockchain network to ensure efficient and true-provenance data collection. The system also provides a mobile-based application named e-InStar that support QA functions for MC stakeholders. 2) A permissioned blockchain network for MC quality assurance is presented, which guarantees the privacy and authority of peers in the network and prevents the whole system from suffering cybersecurity attacks. In this way, the MC project stakeholders can comply with regulations, have complete control of data, and come to a consensus on the present data state of the ledger.

b) A practical case study: A practical MC project is used as a case study to validate the feasibility of the proposed system. The experiment's performance illustrates the reliable privacy and security of e-Inspection 2.0 system, and the users' satisfaction with data collection and QA functions prove the feasibility and efficiency of the whole system. In the future, the e-Inspection 2.0 system could be improved in terms of latency performance and smart contracts' ability to process complex transactions.

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