Automation in Construction

“Smart construction objects” empowered blockchain “oracles”

--Manuscript Draft--

Manuscript Number:	
Article Type:	Original article
Keywords:	Blockchain; Oracles; Smart Construction Objects; Smart Contract
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Abstract:	Blockchain has rapidly aroused the interests across the global construction industry, as it can enable a collaborative and trusting environment throughout the project lifecycle. However, such promises cannot be achieved spontaneously without blockchain “oracles” used to bridge the on-chain and off-chain worlds. This study presents an innovative solution to blockchain oracles by exploiting smart construction objects (SCOs). It starts with the development of a SCOs-enabled blockchain oracles (SCOs-BOs) framework. To instantiate this framework, the architecture of a blockchain-enabled construction project management (BCPM) system is developed and further validated using a case study, whereby four primary smart contracts are examined. The validation results show that by following the framework, the accurate data is retrieved against the malicious data in each request, and the corresponding reputation scores are successfully recorded. This study contributes to existing research and practice to harness the power of this promising technology in construction.
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Cover letter

Dear Editor,

We wish to submit an original research article entitled "Smart construction objects" empowered blockchain "oracles" for consideration in **Automation in Construction**.

We confirm that this work is original and has not been published elsewhere, nor is it currently under consideration for publication elsewhere.

In this paper, we report on an innovative solution to blockchain oracles by exploiting a prior development called smart construction objects (SCOs). It starts with the development of an SCO-enabled blockchain oracles (SCOs-BOs) framework. To instantiate this framework, the system architecture of a blockchain-enabled construction project management (BCPM) system is developed and further validated using a case study, whereby four primary smart contracts are examined in the context of off-site logistics and on-site assembly services. The validation results show that by following the framework, the accurate data is retrieved against the malicious data in each request, and the corresponding reputation scores are successfully recorded.

We have no conflicts of interest to disclose.

Please address all correspondence concerning this manuscript to me at [xl1991@hku.hk].

Thanks for your consideration of this manuscript.

Sincerely,

Dr. Xiao LI
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Highlights

- SCOs-enabled blockchain oracles (SCOs-BOs) framework
- The architecture of a blockchain-enabled construction project management system
- Four smart contracts are examined in the logistics and on-site assembly services
- A decentralized SCOs network avoids the single point of failure (SPoF)
- Ubiquitous SCOs as blockchain oracles bridge the on-chain and off-chain worlds

"Smart construction objects" empowered blockchain "oracles"

Abstract

Blockchain has rapidly aroused the interests across the global construction industry, as the technology is envisioned to enhance the transparency, traceability, and immutability of construction data and further enable a collaborative and trusting environment throughout the project lifecycle. However, such promises cannot be achieved spontaneously without blockchain "oracles", which are used to bridge the on-chain (i.e., a blockchain system) and off-chain worlds (i.e., a real-life physical project). This study presents an innovative solution to blockchain oracles by exploiting a prior development called smart construction objects (SCOs). It starts with the development of a SCOs-enabled blockchain oracles (SCOs-BOs) framework. To instantiate this framework, the system architecture of a blockchain-enabled construction project management (BCPM) system is developed and further validated using a case study, whereby four primary smart contracts are examined in the context of off-site logistics and on-site assembly services. The validation results show that by following the framework, the accurate data is retrieved against the malicious data in each request, and the corresponding reputation scores are successfully recorded. The innovativeness of the research lies in two aspects. Firstly, it mobilizes the ubiquitous SCOs as blockchain oracles to bridge the on-chain and off-chain worlds. Secondly, developing a decentralized SCOs network avoids the single point of failure (SPoF) problem widely existing in blockchain systems. This study contributes to existing research and practice to harness the power of this promising technology in construction.

Keywords

Blockchain; Oracles; Smart Construction Objects; Smart Contract

1. Introduction

Construction is a noble industry by materializing the built environment, boosting the national economy, and providing a large number of job positions (Hillebrandt, 1984; Pearce, 2003; Lu et al., 2013). Meanwhile, construction is widely criticized for its frequent disputes, late payment, risk aversion, mediocre quality, high cost, poor value for money, and other counter-productive consequences (Woudhuysen and Abley, 2004). Many visionary industrial leaders and researchers have attempted to understand and address the problems. For example, the industry is notoriously fragmented, with a massive amount of atomic firms and suppliers fiercely competing in the market (Egan, 1998; Turk and Robert, 2017). The procurement of construction projects has been historically favored a lowest-price win system using a design, bid, and build (DBB) model (Lau and Rowlinson, 2009). Under this DBB model, stakeholders such as architects, consultants, contractors, and suppliers are only contracted to do a parcel of the works (MacLeamy, 2008), causing the discontinuity problem. The industry is infamous for its lack of trust and a prevalent adversarial relationship (Latham, 1994). Construction data stays in different isolated stakeholders without being adequately used to facilitate communication. At times, this data lacks of accountability (Tezel et al., 2020), leading to scandals of counterfeit construction materials or craftsmanship that take place endemically (Yau, 2019). The industry is vigorously exploring various managerial (e.g., integrated project delivery[IPD], trust-building), and technological (e.g., building information modeling [BIM]; smart construction) solutions to deal with the above problems. Blockchain comes in vogue under this background.

Blockchain is a decentralized trust infrastructure that combines the technologies of distributed ledgers, cryptography, and consensus protocols (Swan, 2015). It can track and store the past and present status of tangible assets or intangible events across a decentralized peer-to-peer network, where data is saved in a set of ‘blocks’, and each block is linked to the previous one in the form of a consecutive ‘chain’. Cryptographic protocols in blockchain prevent the change of stored data in each block unless most participants in the network collude or collaborate (Kosba et al., 2016). Smart contracts run on a blockchain to facilitate the implementation of consensus protocols, allowing participants involved in the construction process to reach a consensus based on predefined rules without a trusted third party (Li et al., 2019)(Yang et al., 2020). Several applications for blockchain-enabled smart contracts have been explored in construction, including payment security (Chong and Diamantopoulos, 2020), quality management (Sheng et al., 2020), traceability of prefabricated components (Wang et al., 2020), BIM data audit (Zheng et al., 2019; Xue and Lu, 2020), and transactions of IPD project (Elghaish et al., 2020). ICE’s (2018) report well summarized the promises of blockchain technology in the construction industry.

Nevertheless, among the rhetoric, a rarely explored yet extremely important issue is about the blockchain “oracles”. A blockchain system cannot go beyond its on-chain, cyber world to directly talk to the off-chain, physical world. Rather, this has to be done via various ‘oracles’, which are middleware agents to capture and validate real-world information and feed them to a blockchain to be used by smart contracts (Al-Breiki et al., 2020). They could be software or hardware oracles, inbound or outbound oracles, or consensus-based oracles. The human can serve as oracles to trigger any communication between the on-chain and off-chain worlds, but this is interruptive, time-consuming, and error-prone. The use of software oracles, such as BIM manipulated by human operators, is possible but difficult to ensure the authenticity of external data sources. Furthermore, software oracles also bring back the blockchain's centralization problem since relying on centralized sources increases the risk of feeding erroneous data to the blockchain system. There is an essential need for oracles with autonomous and decentralized computational power scattered in key construction processes or nodes to verify the construction data's correctness and accuracy before it is fed into the smart contracts. In addition, the oracles should also ensure the privacy of the data between the smart contracts and blockchain.

It is noticed that the increasing use of smart embedded technologies has great potentials to serve as blockchain oracles to overcome the problems mentioned above. Particularly, Niu et al. (2016) developed the concept of smart construction objects (SCOs), which is to turn construction resources (e.g., machinery, tools, device, materials, components, and structures) into ubiquitous smart objects so that they convey their designated properties meanwhile with new properties of awareness, communicativeness, and autonomy to enable various smart applications. There are good opportunities to mobilize the SCOs into different hardware oracles to bridge the communication between blockchain systems and real-life construction processes. However, this area of research is largely uncharted territory.

This study thus aims to investigate the extended use of smart construction objects (SCOs) as trustworthy oracles for blockchain applications in the construction industry. It has three specific objectives: (1) to establish a deployment framework for linking SCOs as decentralized blockchain oracles; (2) to instantiate the framework by proposing a practical system architecture of SCOs-as-oracle blockchain-enabled construction project management (BCPM) system; and (3) to validate the framework and system architecture by using a case study. The rest of the paper is organized as follows. Subsequent to this introductory section is Section 2 to elaborate on some basics on blockchain and its oracles. Section 3 is to delineate an SCO-enabled blockchain oracles (SCOs-BOs) framework, followed by the system architecture of the BCPM system elaborated in Section 4. Section 5 is a case study to use logistics and on-site assembly traceability services to validate the smart contracts used in the BCPM system. Discussions are conducted in Section 6, and conclusions are drawn in Section 7.

2. Blockchain and Oracles

2.1 Blockchain

Blockchain is a digital trust infrastructure with the features of mass collaboration, openness, decentralization, and immutability, which can be achieved by integrating various existing technologies such as consensus protocols for distributed governance, distributed ledger for data storage, peer-to-peer network for decentralized communication, cryptography for tamper-proof, security, and privacy. In the blockchain, data (e.g., transactions) can be recorded in the blocks, and each block is a package data structure that comprises the header and its data (Gupta, 2017) (See Fig.1). The header consists of metadata, including index, timestamp, nonce, hash, previous hash, and Merkle root. The key to keeping blockchain data secure is through hashing and Merkle tree (Nakamoto, 2019). When data with any length has been verified and put in a block, it will use a hash algorithm to convert it into a fixed-length of unique numbers and letters. As each data in a block is hashed, then combined and hashed again, this process forms the Merkle tree and the final root hash. A hash value of a block can be considered a fingerprint or digest of the current block data. The previous hash included in the current block as a reference to enable the blocks to structure a chain. Thus, any small change to data, hash values in the whole chain need to be changed.

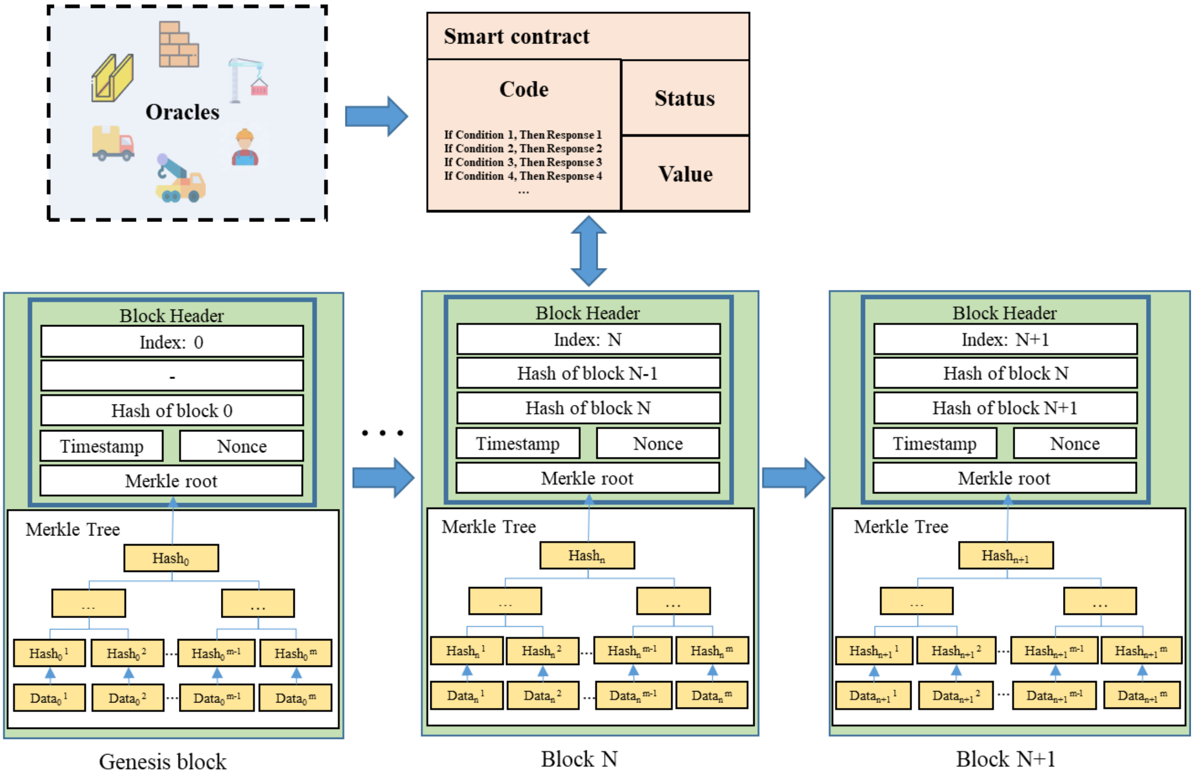


Figure 1. Structure of blocks and smart contracts

However, it should be noted that the immutability of data on the blockchain relies on the strong consensus rules (Sankar et al., 2017). Consensus protocols are introduced to solve the Byzantine general problems by approving and confirming the data in the distributed system of untrusted participants through a set of mechanisms, such as Practical Byzantine Fault Tolerance (PBFT), Proof of Work (PoW), Proof of Stake (PoS), and Delegated Proof of Stake (DPoS). Given such mechanisms, once data put in a block, this change will be passed to all participants by sharing a copy through the peer-to-peer network. Blockchain typically can be classified into public, private, and consortium. A public blockchain is entirely decentralized, and everyone can access the network, such as Bitcoin and Ethereum. A private blockchain is always established within the organization. A consortium blockchain is most suitable for the construction management as the network is limited to various participants who can form an alliance for the best project delivery, such as Hyperledger Fabric (Androulaki et al., 2018).

2.2 Smart Contracts

Cryptocurrencies delegated the first application of blockchain “Blockchain 1.0”, whereas smart contracts are the primary advancement of “Blockchain 2.0” to make blockchain bloom in more sectors (Buterin, 2014). Smart contracts are self-executing contracts that run on an ‘if-then’ basis. It can track on-chain, cross-chain data changes, and off-chain data sources in a real-time manner and automatically respond under the preset trigger conditions (See Fig.1). Smart contracts can be either deterministic or non-deterministic. The former could be independently executed in the blockchain without interaction with the external world, such as the tokenization of assets. The latter is widely needed as all industry applications require off-chain data to trigger execution. For example, the location data of each prefabricated housing product can be captured from the mounted GPS sensors. When it arrives at the construction site, the smart contract can extract the off-chain location data to activate the blockchain's product status change. In previous studies, Zheng et al. (2019) use the blockchain to store the historical process of BIM data modification. Wang et al. (2020) use the smart contract in blockchain to update the precast components status and operation information, and Sheng et al. (2020) also explore the smart contract for handling construction quality information. Das et al. (2020) and Elghaish et al. (2020) investigate the smart contract applications of payment and transactions among construction stakeholders. However, these off-chain data's quality and authenticity have not yet been investigated before inputted to the blockchain. In particular, some of the data in construction processes are with noise or even in a miscellaneous nature. To address this issue, blockchain oracles can serve as a trustworthy intermediary to facilitate such data exchange between the on-chain and off-chain worlds. Without blockchain oracles, smart contracts have to trust only data already within the chain. The functions of blockchain would be seriously constrained.

2.3 Blockchain "oracles"

In ancient Greece, an oracle was the messenger to pass the advice from God to people. However, any accurate source can be considered as an oracle in modern society (Al-Breiki et al., 2020). In the blockchain, an oracle is a middleware agent that queries, verifies, and authenticates external data sources and then delivers them to the blockchain and subsequently used by smart contracts (Kochovski et al., 2019). The data transmitted by oracles in the construction processes can come in many forms, such as safety and health information from the workers, operation and energy information from machinery, location, and quality data from material and components, cost and progress status, and even BIM models. These oracles can also be classified depending on the source of data (software, hardware, and human), the direction of information flow (inbound and outbound), the design pattern (request-response, publish-subscribe, and immediate-read), and the trust model (centralized and decentralized) (Beniiche, 2020). Since oracles are not built-in functionality of blockchain, and they do not have the consensus mechanisms. If oracles are compromised, smart contracts will also be compromised. Thus, the centralized oracles with a single data source may suffer from the well-known single point of failure (SPoF). Some off-the-shelf solutions of decentralized oracles for commercial applications, such as Witnet (De Pedro et al., 2017), Augur (Peterson et al., 2015), Chainlink (Ellis et al., 2017), ASTRAEA (Adler et al., 2018), and Aeternity (Hess et al., 2018), have been developed considering the reputation system, voting game, or consensus mechanism. However, the research on blockchain oracles so far shows a lack of decentralized blockchain oracles customized for construction management by improving the quality, privacy, security, accountability, scalability, and semantics of construction data.

3. A framework for smart construction objects enabled blockchain oracles

3.1 SCOs as Oracles: Definition & Properties

Smart construction objects (SCOs), proposed by Niu et al. (2016), represent a robust Internet of Thing (IoT) model with the capacities of sensing, processing, and communicating to facilitate information exchange among various construction resources. Here, construction resources could be machines and materials. The core properties of SCOs are awareness, communicativeness, and autonomy (Niu et al., 2017). The awareness shows the ability of SCOs to sense and record their real-time situation and that of the surrounding vicinity. Communicativeness indicates the power of SCOs to exchange information they have obtained through their awareness. Autonomy refers to the ability of SCOs to alert people of the need for actions or take actions autonomously based on predefined rules. These properties of SCOs are well matched with the design patterns of blockchain oracles (See Table 1). For example, the activity-aware with passive autonomy and pull communicativeness is similar to the request-response pattern for oracles, where they can monitor, retrieve, and record the data when the specific activity or event requests to oracles are triggered. The policy-aware with active autonomy and push communicativeness is identical to the publish-subscribe pattern, where they can broadcast real-time conditions when the changes compile with rules and regulations. The process-aware with mixed autonomy and mixed communicativeness works the same as the immediate-read pattern, where they can store data to be available for any immediate need in any construction process.

Table 1. The core and sub-properties of SCOs

Properties	Description	Oracles Design Patterns
Awareness		
Activity aware	To aware and response when an activity or event is triggered.	Request-response

Policy aware	To aware the situations complied with published rules and regulations	Publish-Subscribe
Process aware	To immediately aware of activities in workflows and processes.	Immediate-Read
Communicativeness		
Pull	To offer information on request	Request-response
Push	To proactively issue updated information or alerts in a regular interval	Publish-Subscribe
Mixed	To immediately offer and issue information	Immediate-Read
Autonomy		
Passive	To assist in making decisions and taking action upon request	Request-response
Active	To proactively take actions based on the change in a regular interval	Publish-Subscribe
Mixed	To execute autonomy in both passive and active manner	Immediate-Read

SCOs can work in a way similar to oracles in construction blockchain. SCOs can act as data feed providers to sense and capture data from various construction resources and scenarios and serve as oracle node operators to process and transfer the accurate, reliable, and verified data to blockchain systems. IoT sensors installed on SCOs can serve other relevant purposes. For example, inertial measurement unit (IMU) and air pressure units can compensate the Global Position System (GPS) locations on accurate motions and height data. Moreover, a supplement of passive Radio Frequency Identification (RFID) and Quick Response (QR) codes can stick to the construction objects for a lifelong period for facility management. For different construction tasks, a combination of different SCOs design profiles can offer the optimal performance-price ratio. Fig. 2 shows a detailed SCO plan for construction processes with two types of models:

- *Model 1:* Low-energy, single GPS sensor for location-based service in off-site production and transportation.
- *Model 2:* High-frequent, multiple motions and environmental sensors for on-site assembly.

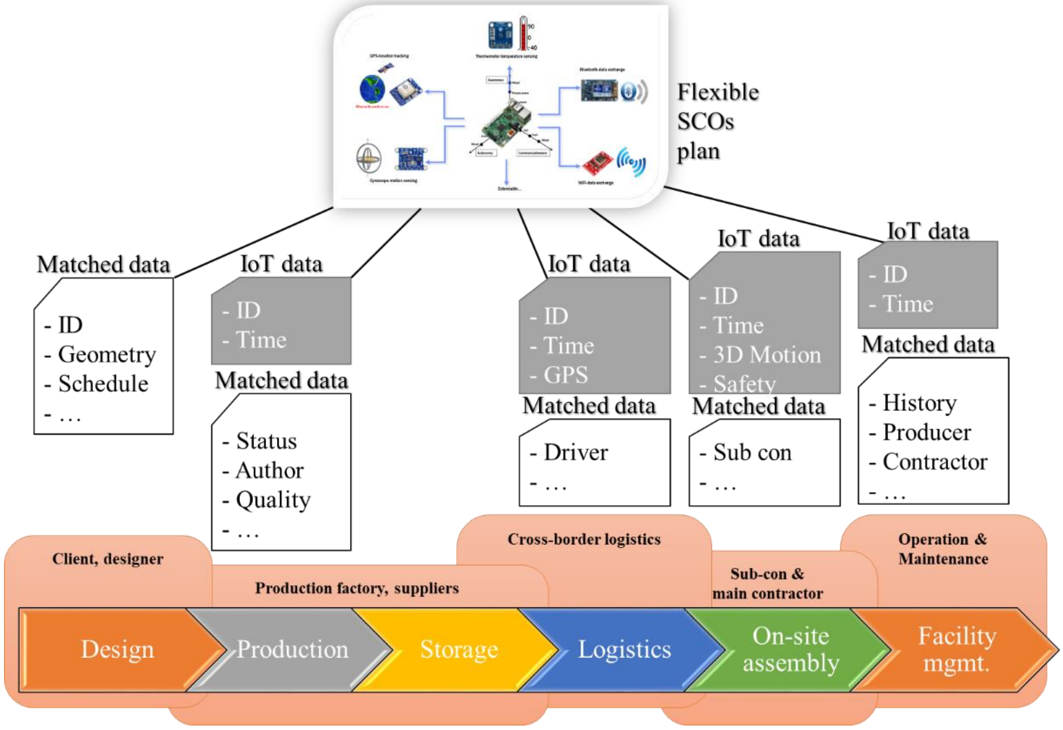


Figure 2. An SCO plan for construction processes: Off-site logistic production and transportation and on-site assembly services

3.2 The SCOs-BOs Framework

This section proposes a framework named 'smart construction objects enabled blockchain oracles' (SCOs-BOs), which provides a decentralized oracle solution with multiple smart contracts to manage the interactions and data access. It can help randomly select and monitor the oracles for specific service in construction processes and offer reputation scores to each oracle by cross-reference. The framework tries to improve two bottlenecks in the data exchange between the physical construction processes and the cyber blockchain worlds: (1) single point of failure (SPoF), which means only relying on one source of information from the centralized BIM platform (Li et al., 2017); and (2) the need for trustworthy data with good quality.

The framework is shown in Fig. 3, including the oracles pool, oracles sidechain, services blockchain, and stakeholders consensus:

- *Oracles pool*: Stakeholders can provide and register new SCOs in the oracles pool. The SCOs for specific service in the oracles pool will be randomly selected and registered in the oracle smart contract (OSC) to form a decentralized oracle network.
- *Oracles sidechain*: Since oracles may not be reliable due to the lack of properties as blockchain, the sidechain is an alternative to package the oracles network as a side blockchain, which can communicate with the main blockchain (Singh et al., 2020) (Uriarte et al., 2020). The sidechain includes oracles smart contract (OSC) and aggregator smart contract (ASC). The former provides a frequently used interface to select SCOs from the oracles pool by using an unbiased sortation algorithm for specific construction management services (Zhou et al., 2019), and these selected SCOs can register in OSC. This registration process will be verified by all stakeholders. Their data are also hashed and return to ASC. ASC receives all data hashes from OSC, cross-references their hash values, and broadcasts reputation scores for each involved SCO to reputation smart contract (RSC).
- *Service blockchain*: It includes a service smart contract (SSC) and a reputation smart contract (RSC). The former receive ASC's reputation scores to compute and record the average reputation scores for all SCOs in the oracles sidechain and then select the winner SCO for SSC. Also, the updated reputation scores are returned to the SCOs in OSC. The SSC is triggered and can call upon the ASC's selection interface when the specific need arises (e.g., the logistics service is used to monitor prefabricated products' location status).
- *Stakeholders consensus*: the stakeholders in the construction processes can request data from SSC. All service smart contracts and registered SCOs in OSC should reach a consensus from all stakeholders before executed in the services blockchain and oracles sidechain.

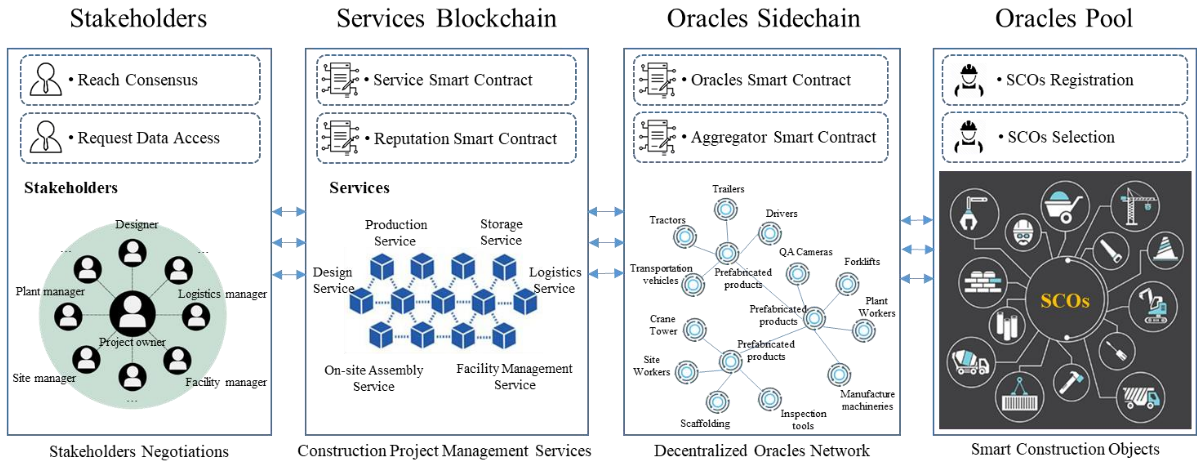


Figure 3. The SCOs-Bos framework

The interactions between the different components in the framework are summarized in the sequence diagram, as shown in Fig 4. These interactions can occur on-chain, cross-chain, or off-chain. Stakeholders are responsible for deploying SCOs and reach a consensus when SSC is ready and selected SCOs are registered. For example, in the logistics stage, all the stakeholders can make a service consensus on SSC to monitor prefabricated products' real-time position status. The logistics manager should arrange for embedding GPS sensors (e.g., Model 1 of SCOs plan) into the prefabricated products, tractor, trailer, and driver in the transportation process. Furthermore, these SCOs can be registered into OSC, where will be agreed upon by all stakeholders. Stakeholders can send the data request to SSC, and SSC conducts permission verification. If the stakeholder has valid access permission, the request proceeds as follows:

- SSC forwards stakeholder request to ASC
- ASC invokes the interface of OSC, and OSC randomly selects from the off-chain oracles pool.
- All selected SCOs can be registered into the OSC to form a decentralized sidechain, and each registered SCO hashes its data and sends it back to ASC.

- ASC introduces a cross-reference method on all received data hashes from SCOs, gets the most similarity on returned hashes, and reports each SCO's reputation score to RSC.
- RSC updates reputation scores for all SCOs in the oracles sidechain and selects a winner SCO based on the highest reputation score for SSC.
- SSC delivers the data in the winner SCO to the stakeholders.

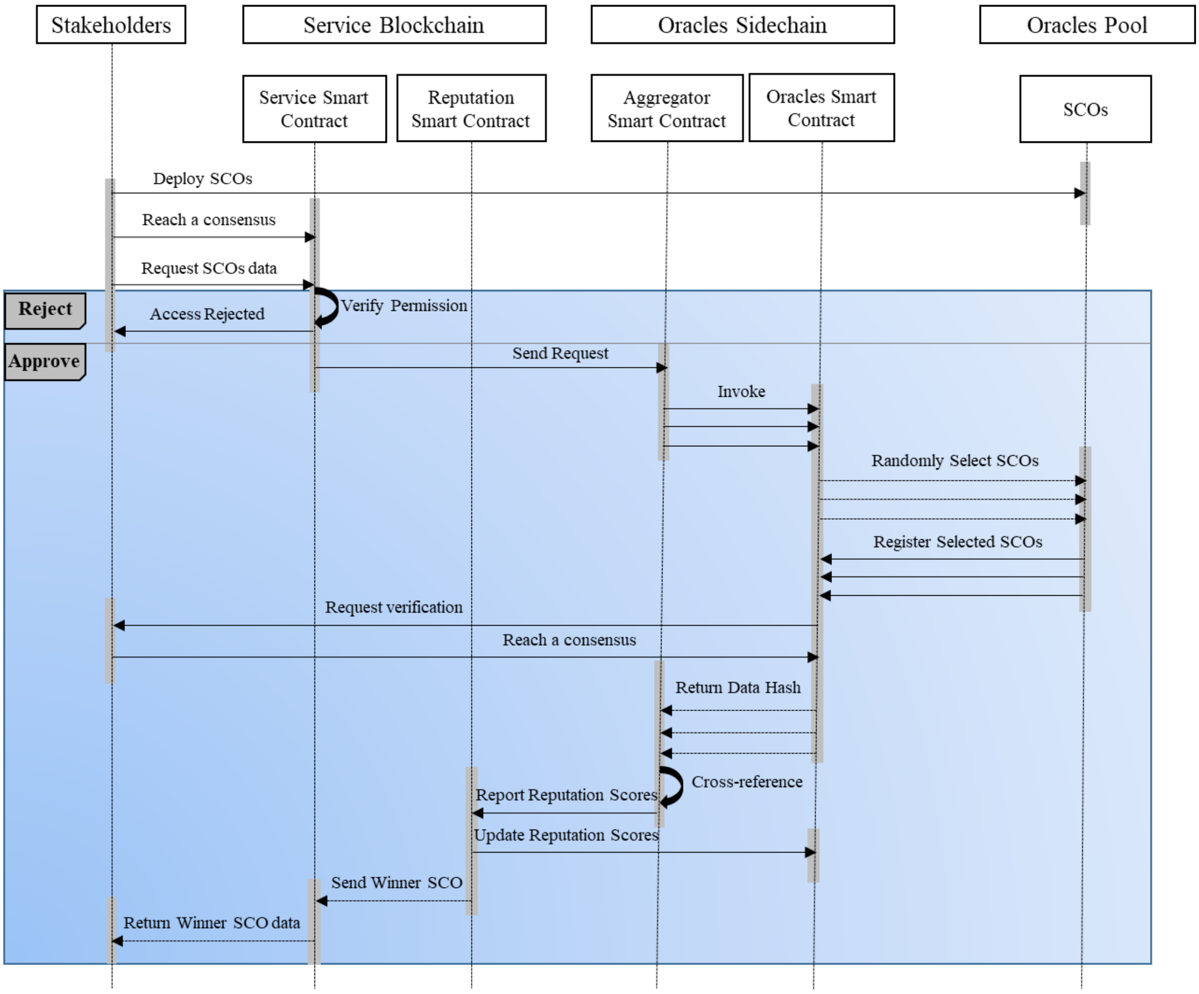


Figure 4. Sequence diagram for the proposed framework

4. System Architecture

This section instantiates the SCOs-BOs framework by developing and enriching a blockchain-enabled construction project management (BCPM) system. The supporting stakeholders and main services are also explained below.

4.1 Overview

Fig. 5 shows the architecture of the BCPM system, which comprises four main layers: (1) smart construction objects (SCOs), (2) oracles sidechain network, (3) service blockchain network, and (4) services.

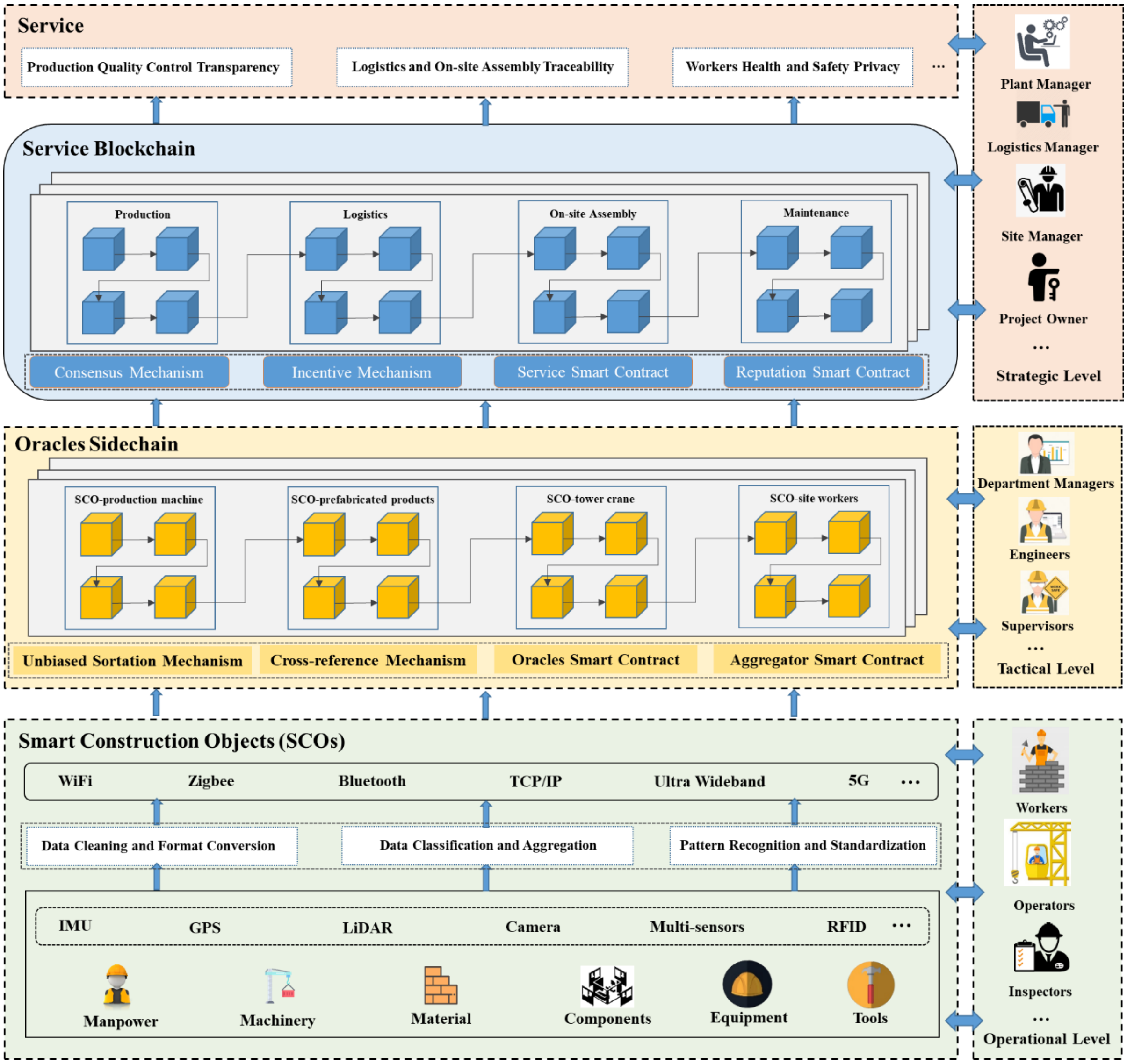


Figure 5. The architecture of blockchain-enabled construction project management system

SCOs serve as the foundation of this architecture. SCOs are the construction resources in the BCPM system, which can be equipped with smart IoT devices (Zhong et al., 2020). For example, site workers' data, including heartbeat, heat stress, location, motions, can be monitored and tracked by wearable devices such as smart wrists, vests, and helmets. These collected construction data can also be retrieved and broadcast through the communication channels in the SCOs layer, such as ZigBee, Bluetooth, WiFi, Ultra-wideband, 5G, and Transmission Control Protocol/ Internet Protocol (TCP/IP). Furthermore, the procedures of data cleaning and transformation, aggregation and classification, standardization, and pattern recognition are also processed in each SCO. This layer mainly has the capacities in awareness, autonomy, and communicativeness of multimode data from different IoT sensors promptly and accurately.

In the oracles sidechain network layer, an unbiased sortation algorithm is then used to randomly select the SCOs for a specific service (e.g., production quality assurance), and these selected SCOs can be registered and used to form a set of blocks. Each block in the oracles sidechain comprises a header and the selected SCOs' data. A cross-reference method is applied in this layer to find out the authentic data and report their reputation scores (e.g., 0 or 100) based on whether it is similar to the authentic data.

In the service blockchain network layer, a reputation system is adopted to elect the SCO with the highest reputation scores as the winner and updates the reputation scores of other SCOs in the oracles sidechain network layer. The data from the winner SCOs are used for establishing a set of blocks. Each block in this network comprises a header and the winner SCOs' data, such as the location of prefabricated products, physiological signals of workers, and operation status of the tower crane. In the blockchain network establishment process, a consensus mechanism named Practical Byzantine Fault Tolerance (PBFT) is used to ensure collective decision-making and reduce the faulty nodes' influence. Moreover, an incentive mechanism is also devised to reward stakeholders who deploy SCOs in the construction processes.

In the service layer, numerous service-oriented applications for the BCPM system are deployed, such as production quality control transparency, logistics and on-site assembly traceability, and workers' health and safety privacy. These services are supported by the service blockchain and oracles sidechain, using the data from SCOs.

4.2 Supporting Stakeholders

In this BCPM system, there are three kinds of stakeholders, including strategic level, tactical level, and operational level, which can support and facilitate the implementation of the related layers.

Front-line workers and operators are the representative stakeholders at the operational level. All the SCOs fresh data for the BCPM system comes from operation tasks. For example, supported by the deep camera and laser scanner in the production plant, the dimensions and smoothness of prefabricated products can be detected and recorded. These point cloud data can be further used for assembling the prefabricated products on the site. Operational level stakeholders should verify the authenticity of data in the selected and registered SCOs. For example, truck drivers should verify whether location signals of on-transport prefabricated products are consistent with them.

Department managers and construction engineers are the representative stakeholders at the tactical level, aiming to ensure data exchange reliability between oracles and blockchain by designing specific smart contracts with various algorithms and models. For example, the reputation mechanism and cross-reference method are designed by the tactical stakeholders. These data can be further used for service blockchain when all tactical and operational stakeholders agreed and verified on the data from SCOs-BOs.

Project owners and senior managers, such as plant managers, logistics managers, and site managers, are the strategic level's representative stakeholders. They are accountable for forming the service blockchain, including the provision of SCOs, and the design of incentive and consensus mechanism. They are also the decision-makers of the construction supply chain for specific strategies using the information from the service blockchain network.

4.3 Critical Services

To instantiate the SCOs-BOs framework, three construction management services are possibly achieved through the above-proposed system architecture.

- *Production quality control transparency* refers to quality inspection information in each production process of prefabricated products readily available to stakeholders. This service enabled by SCOs-BOs in our system architecture can facilitate remote stakeholders (e.g., contractors and project owners in Hong Kong) to access the detailed quality information in the off-site manufacturing plant (e.g., plants in Jiangsu province, Mainland China) during the Covid-19 pandemic. The deep camera and laser scanner can work as SCOs-BOs to compute and retrieve quality inspection information in each production process, such as formworks (e.g., smoothness, cleanliness, and dimensions), steel reinforcing bars (e.g., size, pattern, fixing and layout, spacers, and concrete covers), concrete (e.g., placing and compaction), finished products (e.g., surface, size, and dimensions, anchor bar). These data recorded in blockchain can increasingly improve the accountability of inspection in the production process.
- *Logistics and on-site assembly traceability* enable stakeholders to track the latest and historical status of construction resources and events. For example, this service enabled by SCOs-BOs can assist site managers in tracking the real-time location status and assembly progress of prefabricated products. The low-energy, single GPS sensor for

location-based logistics service can be mounted in each prefabricated products. These location data can be cross-referenced, and the one with the highest reputation scores is recommended to record in the blockchain for further decision-making.

- *Workers' health and safety privacy* is a service concerned with the privacy issues for monitoring the health and safety data of construction workers. The health and safety data, such as images or sensor signals of fatigue, unsafe motions, heartbeat, heat stress, locations, can be captured and processed by the SCOs-BOs. Furthermore, federated learning is used for decentralized SCOs-BOs (Yang et al., 2019), where a model can be trained by using the local health and safety data samples in each SCOs-BOs, without extracting them. Only the high-level insights from the data are retrieved and stored in the blockchain.

5. Case Study

A case study using cross-border logistics and supply chain management, focusing on the services of off-site logistics and on-site assembly traceability, is conducted to verify the SCOs-BOs framework and the system architecture of the BCPM system. According to Wan et al. (2020), blockchain can offer clear accountability and make the construction supply chain more traceable, transparent, and immutable among all participants involved in the project. In this case, the low-energy, single GPS sensors mounted in the prefabricated beams as SCOs were transported from Mainland China, to Hong Kong, for a prefabricated construction project, comprising five high-rise public housing residential towers and one commercial center in the middle. We implement four primary smart contracts: SSC, RSC, ASC, OSC, by using the GPS data of prefabricated beams for the commercial center to validate the proposed SCOs-BOs framework and system architecture. Although this project has already been completed (nine highlighted beams have been erected as shown in Fig.6), the full record of GPS data (shown in the green data list of Fig.6) for nine beams (named from C1023 to C1031) in the same batch can be put into the oracles pool for this validation.

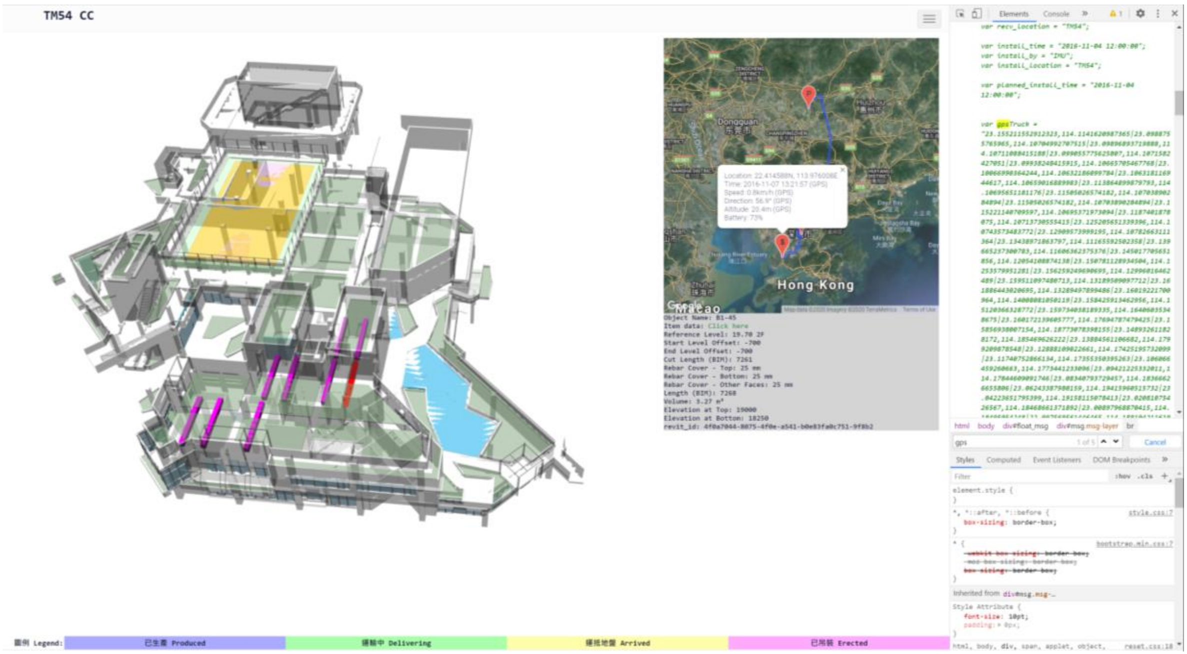


Figure 6. Service for off-site logistics and on-site assembly services

5.1 Implementation

Four smart contracts in SCOs-BOs were implemented using Chaincoder, the IDE in hyperledger, to provide rich features for testing and debugging smart contracts before deployment. Four smart contracts are programmed in Javascript. The main functions and interactions of these four smart contracts in this case study are illustrated in the following.

(1) Service Smart Contract (SSC)

Service smart contract (SSC) manages the on-chain interactions that can help check if the site manager, project owner, or other stakeholders can access the location data from SCOs and then send data requests. Each service matches with one smart contract, and each stakeholder in the service blockchain can request the location data by providing the address of stakeholders and

SCOs, and the required number of SCOs. To reach a more than 51% consensus on getting the accurate location data, the required number of SCOs should no less than three. Table 2 presents the algorithm of the main function for SSC. Once the stakeholder sent a request, the SSC will check if the stakeholder can access data and then check if the SCOs online. Once the stakeholder's request is approved, SSC will generate a token which includes (1) Request for data, which is created from hashing the name of stakeholder, address of SCOs, Number of SCOs, block timestamp, and using Sha 256 hashing algorithm, (2) address of stakeholder, (3) address of SCOs, (4) Number of SCOs. The token is generated and then deliver to the aggregator smart contract (ASC). After the implementation of ASC, OSC, RSC, SSC get the final data through cross-chain interaction.

Table 2 Algorithm of the main function in SSC

Algorithm 1 SSC_Data Request

Input: Stakeholder.address, SCOs.number, SCOs.address

Output: Token

State: signData, token

Require: SCOs Online, Is (Number of SCOs $\geq$ 3)

```
function DataRequest(SCOs, Stakeholder) {
    const timestamp = Date.now();
    let signData = [stakeholder.address, SCOs.address, timestamp, SCOs.number]
    if (SCOs.state !==0 && stakeholder.state ==“Y”){
        GPSSignData = CryptoJS.SHA256(signData).toString();
        token = jwt.sign (GPSSignData, stakeholder.address, SCOs.address, SCOs.number);
        setRequestHeader (‘Authorization’,’BasicAuth’+token);
    }else{
        return null
```

```
        }
    }
```

(2) Aggregator Smart Contract (ASC)

ASC coordinates the cross-chain interactions between oracles smart contract (OSC), SSC, and reputation smart contract (RSC). SSC forwards stakeholder's location data requests to ASC, which receives the requests and invokes the oracles to satisfy them by retrieving and validating SCOs' responses from OSC. ASC finally reports the reputation scores of selected SCOs to RSC. Table 3 presents the algorithm of the main function for ASC. A minimum of three SCOs should be sent to ASC for SCOs cross-referencing, in which at least 51% consensus on the same location data should be reached. Otherwise, the ASC can not decide the results sent from the OSC. ASC cross-references the SCOs data based on 51% agreement and reports a binary reputation score to the RSC. If greater than 51% of SCOs send back the same result, these SCOs will receive a 100 reputation score, and other SCOs that return different results will get zero reputation score. If less than 51% of SCOs return the same result, a new aggregation round can be conducted.

Table 3 Algorithm of the main function in ASC

Algorithm 2 ASC_Reputation Scores and Cross-referencing

Input: SCOs.address, DataHashes

Output: Authentic_SCO.Score, Authentic_SCO.address

State: SCOs_Data, DataHash_Agreement, Matches.number, Counter

```
async invokeChaincode({stub},SCOs_Data,DataHash_Agreement) {
    const {Authentic_SCOs} = stub.getFunctionAndParameters();
    const results = await stub.invokeChaincode('Data_Request', Authentic_SCO]);
    let DataHashes = results.payload.toString('utf8');
    let DataHash_Agreement = []
```

```
      forEach(data in DataHashes => {
        if (DataHash_Agreement[data]!= 0){
          DataHash_Agreement[data] = DataHash_Agreement
          data++
        }else{
          DataHash_Agreement[data]=1
        }
        forEach(Counter in DataHash_Agreement  => {
          if(DataHash_Agreement[Counter] > Matches.number ){
            Authentic_SCO.sender_name_auxiliary = SCOs_Data[Counter]
            Authentic_SCO.Score = 100
            continue;
           }
        });
      });
      return [Authentic_SCO.sender_name_auxiliary, Authentic_SCO.Score]
 }
```

(3) Oracles Smart Contract (OSC)

OSC manages the off-chain interactions to select SCOs from the oracles pool for retrieving the location data. An unbiased random sortition algorithm (RSA) is developed to ensure that SCOs selection processes from the oracles pool to the sidechain are independent and random (See Table 4). It is also vital to guarantee that stakeholders reach a consensus, and selected SCOs can not represent the counterparts' benefits. RSA in OSC uses a verifiable random function (VRF) of Algorand (Gilad et al., 2017) for the oracles pool (A set of SCOs), and they can generate a hash, a proof, and priority score for each SCO. The lucky SCOs, aligned with the required number, can be selected and recognized in the OSC of the sidechain.

Table 4 Algorithm of the main function in OSC

Algorithm 3 OSC_ Unbiased Random Sortition

```
Input: SCOs_Set, SCOs.number
Output: SelectedSCOs
State: SelectedSCOs, [value, proof, priority_score]
Require: Is(Number_of_SCOs ⩾3)
funcation unbiasedRandomSortition(SCOs_Set){
    var str = SCOs.number
    var inputJSON = JSON.stringify(str);
    if (SCOs_Reputation>0 && SCOs.number !== null){
                let publicDer = key.exportKey ("pkcs8-public-pem")
                let privateDer = key.exportKey("pkcs1-private-pem")
          Const[value, proof, priority_score] = vrfjs.ecvrf (SCOs_Set, publicDer, privateDer)
          SelectedSCOs = vrfjs.sortition (value, proof, priority_score)
       return SelectedSCOs
    }
    return null
}
```

(4) Reputation Smart Contract (RSC)

RSC aims to compute each SCO's accumulative reputation score and return the winner SCO with the highest accumulative reputation score to SSC. RSC receives an input array of authentic SCOs addresses, and it sends back an output array address of the winner SCO to SSC. Table 5 presents the algorithm of the main function for RSC.

Table 5 Algorithm of the main function in RSC

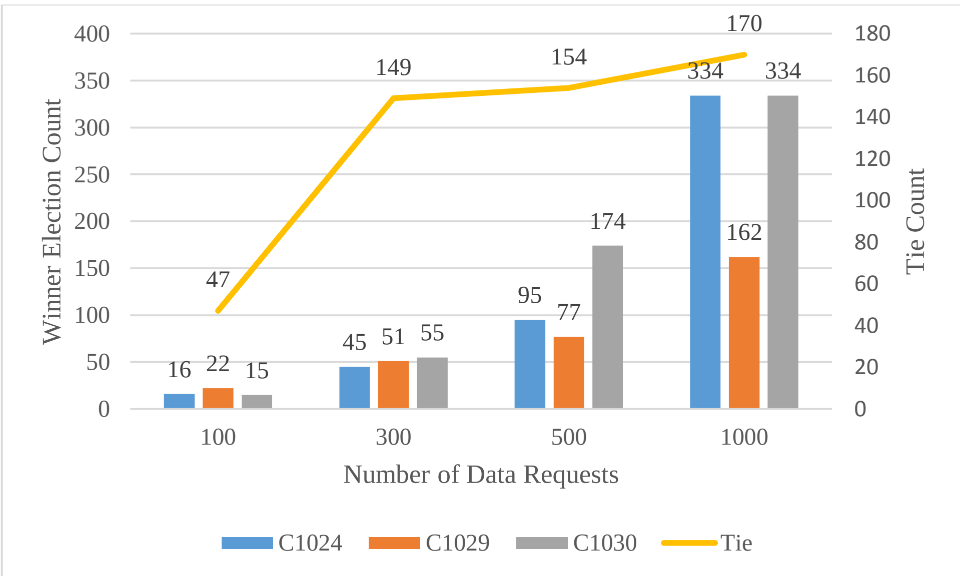
Algorithm 4 RSC_ Select Winner SCO

```
Input: Authentic_SCO.address
Output: Winner_SCO.address
State: SCOs
function selectWinnerSCO(SCOItemArray) {
   let Maxacum_Scores = 0
   let Currentacum_Scores = 0
   SCOItemArray.forEach(function(item)) {
      Currentacum_Scores =  item.score
      if (Currentacum_Scores >= Maxacum_Scores) {
         Maxacum_Scores = Currentacum_Scores
         let Winner_SCO.sender_name_auxiliary=item.sender_name_auxiliary
       }
   return Winner_SCO.address
   });
```

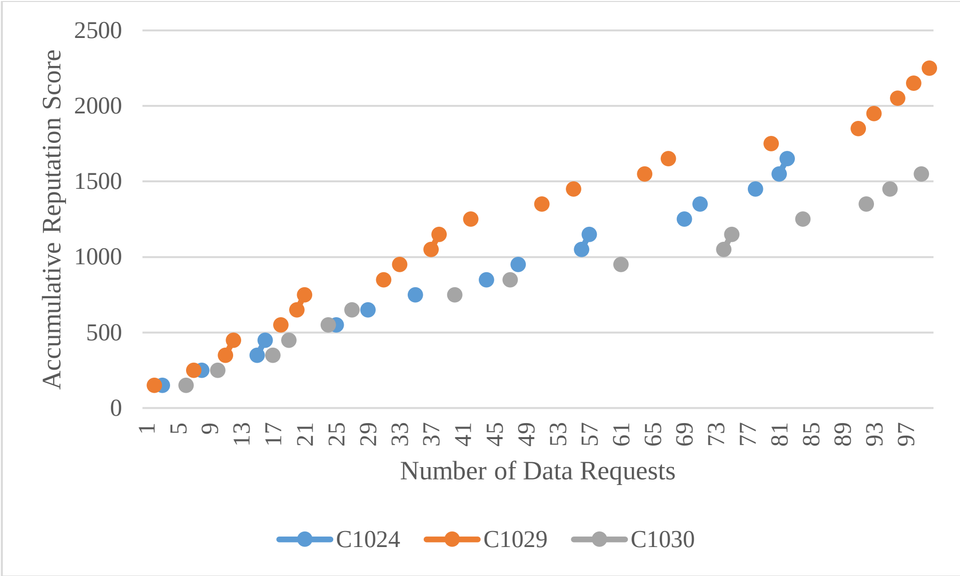
5.2 Evaluation

The most critical design philosophies in SCOs-BOs are to avoid the single point of failure (SPoF) and offer the authentic construction data from SCOs to the service blockchain. To this end, the evaluation in this case study is conducted to prove its usability of screening the malicious data and offer the authentic one to the blockchain. We assume the total number of SCOs is nine, three of them are authentic (C1024, C1029 & C1030), two of them are malicious (C1025 & C1026), four of them are offline (C1023, C1027, C1028 &C1031), and these SCOs were transported in the same batch, which means they should be shipped in the same vehicle with identical location data given ignoring GPS accuracy error. We suppose that the total number of data requests is 100, 300, 500, and 1000, the required number of SCOs in each request is 3, and the default reputation score is set to 50 for each SCO. The accumulative reputation scores and winner election count are used as the index to validate its usability.

As shown in Fig.7 (a), all three authentic SCOs are elected under a different number of data requests, and the tie count is also significant, which indicates that each selection is independent and random. The results proved that SCOs-BOs could avoid SPoF and reject malicious data when authentic data occupy the majority. However, when malicious SCOs hold the majority and form the collusion, it would limit the automatic capacity of retrieving authentic data, even though oracles sidechain can record data history of each selected SCO. Fig.7 (b) shows the records of all three authentic SCOs' accumulative reputation scores under 100 times of SCOs requests. As 47-round requests reach a tie (all selected location data are different), C1024, C1029, C1030 only receive their reputation scores 16, 22, 15 times, respectively. It is also interesting to find that C1029 with the most winner election count under 100 times of SCOs requests but falls to the lowest one under 1000 requests.



(a) Winner election count and tie count



(b) Accumulative reputation score at 100 times of requests

Figure 7. Evaluation of SCOs-BOs usability

6. Discussion

Compared with the previous studies, there are three aspects to the proposed SCOs-BOs framework's novelty summarized as follows.

- Firstly, blockchain oracles are yet to be fully investigated in the construction context, which relies highly on massive data from human, hardware, and software for real-time project management. SCOs provide an alternative to working as oracles. The innovative devising SCOs as blockchain oracles can satisfy the design patterns of oracles and facilitate the data exchange between blockchain and the real-world construction process.
- Secondly, construction data for existing blockchain systems mainly relies on human inputs or a centralized BIM platform. The innovative establishment of a decentralized SCOs network as a sidechain has been proved to avoid the SPoF in the case study. The registration of SCOs can make them more accountable when compared with

unregistered SCOs. The unbiased random sortation mechanism is also deployed to ensure the fairness of selecting and registering SCOs for the sidechain.

- Thirdly, the cross-reference mechanism was proposed together with the reputation system work well on screening out the malicious construction data in the evaluation section. This innovation provides support to obtain trustworthy SCOs and sustains their on-chain reputation.

Despite these innovations, our study still has several limitations.

- Firstly, the only request-response pattern is designed in the smart contracts for SCOs-BOs. As limited by the case study scenarios, the patterns of publish-subscribe and immediate-read have not been explored in this study.
- Secondly, the cross-reference mechanism in this study sets a 51% consensus on the data. However, there is a risk that malicious data may also have a certain degree of possibility to reach 51% agreement when the quantity of data or SCOs is small enough. Thus, a more flexible consensus rate range (e.g., from 51% to 67%) in the cross-reference mechanism should be devised and matched according to the required number of SCOs.
- Thirdly, we only test the usability of the SCOs-BOs by using the index of average reputation scores and winner election count in a case study. Enabling multiple SCOs reporting the same data streams may increase the cost of the overall system. Thus, other performance metrics, such as cost, throughput, latency, and scalability, will be considered in the future.

7. Conclusions

With the characteristics of decentralization, immutability, and consensus, the blockchain can improve the fragmented construction process coordination and collaboration in an isolated deterministic network. In contrast, smart construction objects (SCOs) have the capacity of capturing, processing, verifying, and taking action with the external construction environment in a real-time manner to offer data for blockchain. The harness of SCOs as the blockchain oracles has great potential to enable massive value-added services in construction but also faces numerous Gordian knots, such as single point of failure (SPoF) and malicious data. Blockchain’s power may be limited when the offered data heavily rely on a single centralized source or low-quality sources.

This study presents a SCOs-enabled blockchain oracles (SCOs-BOs) framework to offer a decentralized SCOs network and related data authenticity mechanism. SCOs-BOs includes four parts: stakeholder, service blockchain, sidechain, and oracles pool, which can interact with each other under the request-response pattern in an on-chain, cross-chain, or off-chain manner. Accordingly, a system architecture of a blockchain-enabled construction project management (BCPM) system is developed to instantiate SCOs-BOs. The services, such as production quality control transparency, logistics and on-site assembly traceability, workers' health and safety privacy, are illustrated. A case study for logistics and on-site assembly traceability service with four main smart contracts are implemented to evaluate its usability. OSC helps form the decentralized SCOs network and select the SCOs from the oracles pool randomly and independently. ASC works as the aggregator to cross-reference the data and report the reputation scores. Then, RSP manages the authentic SCOs and selects the winner. SSC monitors the data requests and responses in an overall process. The evaluation results show that the accurate data are retrieved against the malicious data in each request, and the corresponding reputation scores are successfully recorded.

Future research works are recommended to enrich the SCOs-BOs framework. For example, logics in the four smart contracts can be developed and extended for publish-subscribe and immediate-read patterns. A cooperative game theory-based reputation system can be used to improve the performance of rating scores for SCOs. The data semantics enrichment can be enhanced to ensure the cross-chain, off-chain, and on-chain communication. More tests are needed for different services, such as production quality control transparency and workers health and safety privacy.

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"Smart construction objects" empowered blockchain "oracles"

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Conflicts of Interest Statement

Manuscript title:

"Smart construction objects" empowered blockchain "oracles"

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