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Public and private blockchain in construction business process and information integration

Rebecca Yang[a,*], Ron Wakefield[a], Sainan Lyu[a], Sajani Jayasuriya[a], Fengling Han[b], Xun Yi[b], Xuechao Yang[b], Gayashan Amarasinghe[a], Shiping Chen[c]

[a] School of Property, Construction and Project Management, RMIT University, Australia
[b] School of Science, RMIT University, Australia
[c] Data 61 CSIRO, Australia

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ABSTRACT

Blockchain as an emergent decentralized digital technology has been widely explored in many sectors to remedy the deficiencies of centralized solutions It has been recognized that blockchain technology has great potential to facilitate business activities spanning the whole life cycle of a building project in the construction industry, such as better communication or understanding, documents sharing, stage transition and quality endorsement. A comprehensive review of the literature regarding the application of blockchain in the construction domain found that there are few studies and applications of blockchain in construction practices, and most of the current research involves qualitative studies only. In this paper, we aim to explore the feasibility of applying both public blockchain and private blockchain technologies in the construction industry using two industry cases. Two business process cases (i.e., Case 1 and Case 2) were selected and used to drive the blockchain-based software system architecture design. The proposed architectures were demonstrated using Hyperledger Fabric (a private, permissioned and open source blockchain platform) and Ethereum (a public blockchain platform) respectively, to reflect the different requirements of the two use cases. This pilot study also illustrates the process, benefits, and challenges of adopting private and public blockchain technologies in construction domain. This research provides insights to researchers and practitioners regarding the adoption of blockchain technology, especially in construction industry.

1. Introduction

The construction industry is a vital sector contributing to the national economic growth. It provides many infrastructures for other sections such as health, education, and transportation, leading to more jobs and income for the whole sociality. For example, the Australian construction industry produces more than $350 billion in revenue and contributes to 8% share of the total GDP [1]. Thus, improving the efficiency and productivity of construction projects should be a key focus of any government. However, the construction industry is facing many challenges as collaborative operations. Poor communication and collaborative information sharing are one cause of many failed projects worldwide [2]. Money transaction and/or information exchange are frequently performed along with project progressing. However, the loss of management control when a significant percentage of project activities (e.g., prefabrication) offsite or offshore, and inconsistent payment terms and cash-flow arrangements, have raised numerous disputes and litigations problems on payments withheld, quality fraud and data authenticity in construction business processes. Lack of transparency and accountability in construction project business processes are widely recognized by researchers and practitioners [3]. Due to the fragmentation and discontinuity in the processes of design, manufacturing, storage, transportation and assembly on site, an open trustworthy, transparent, and traceable information resource across the supply chain does not exist. As a result, clients and contractors have difficulties to verify and validate the true information, in terms of interactions between these collaborations, such as professional qualification, building material certification, and project deliverable timing and quality. The inefficiencies related to time, cost and quality of construction projects may result in client dissatisfaction and then it can impact the national economy in broader sense.

Blockchain is a potential technology to overhaul and address the above issues in the construction industry. Blockchain technology can help to make the business processes efficient, traceable, transparent and

* Corresponding author.
E-mail address: rebecca.yang@rmit.edu.au (R. Yang).

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accountable across all stages of the project life-cycle [4]. Unlike traditional transactions which rely on the central authentication of high credit units such as banks and governments, blockchain is a decentralized P2P network connected via a consensus protocol, which means transactions on the network are validated and shared among all participating nodes (computers) in the network [5]. The blockchain networks can be categorized into public, private, and federated blockchains, based on the network management system adopted and the permissions allowed [6–8].

However, in terms of adopting blockchain technology, the construction industry still lags behind other industries (e.g., healthcare, finance, and business). While there are a wide range of case study examples based on public blockchain and private blockchain platforms [9–11], most blockchain studies in the construction domain are still at conceptual research level. Very few studies have applied blockchain technology in real cases or ready for industry trials. The opportunities for public blockchain platform-based system and private blockchain platform-based system have also seldom been identified and compared. Therefore, the aim of this demonstration study is to explore the feasibility of applying public and/or private blockchains in the construction industry according to real requirements. The advantages and limitations of using public blockchain and federated blockchain in construction domain are discussed in this paper.

Having identified the above research gap, the main purpose of this study is to develop blockchain platform for construction industry along with their limitations in various applications. Initially, we conduct an extensive literature review to explore the existing literature undertaken on blockchain in relation to construction industry and on different blockchain platforms in Section 2 and Section 3. Section 4 will present the two case studies along with their business processes and demonstrate the two systems. Section 5 will discuss the benefits and challenges. Finally, the conclusions are drawn.

2. Blockchain networks

A blockchain is a type of Distributed Ledger Technology (DLT) where all the transactions are digitized and decentralized. It is a database recording all the transactions or digital events that are executed and shared among the participants in the network [12]. The blockchains has some special features as the all transactions have an immutable cryptographic signature and therefore the transactions are grouped in blocks. Any new block will be given an immutable cryptographic signature of the previous block to connect them together. It allows non-trusting members to verifiably interact in a peer-to-peer network without the need for a trusted authority [7]. It is a decentralized network where there is no central organisation to control every transaction. All the transactions are visible to every node in the network. All transactions are accessible through nodes and data are shared in a blockchain network. Anyone can check the data and track the history through a computer on the network to ensure the reliability of information. For example, a unique blockchain ownership certificate of land title can be created, and the buyer could access the information about the property through blockchain and check the trading record without any concerns about forgery [13]. As the blocks are added in chronological order and contain a cryptographic hash of the previous block, the data recorded on blockchain cannot be tampered with, altered, concealed, or falsified. In addition, as blockchains are secured by a peer-to-peer network they store immutable data [14]. Any record that is added to the blockchain cannot be deleted and all previous transactions become immutable [15]. Any user of the blockchain can easily trace any previous transactions by accessing any node in the distributed network, as each of the transactions is validated and recorded with a timestamp [8]. The recent literature has categorized the blockchain network based on many criteria [6,8,16]. Among those categories the most common categorisation is based on the network management and permissions as public, private and federated.

2.1. Public vs private blockchain

Both public and private blockchain networks are decentralized and shared among their users to record all peer-to-peer transactions without the third party customarily trusted to authorize them [17]. However, some distinct features make public and private blockchains different.

Private blockchains have a very high transaction processing rate with very few authorised participants. Therefore, shorter time is required to get the consensus for the network and more transactions can be processed within a second. As opposed the public blockchains have a very limited transaction processing rate. The consensus mechanisms such as Bitcoin's Proof-of-Work (PoW) in public blockchains need the entire network to reach the consensus on the state of transactions. Public blockchains also have risky information privacy due to their inherent nature. The public blockchains rely on an append-only data process leading to immutable data storage [18,19]. Further, in public blockchains the entire node must agree on any change as it records the same information. As such, any change should be recorded in all succeeding blocks and it takes more time to mine just one block to the blockchain [20]. In addition, to ensure the blockchain's integrity all blocks are linked back to the genesis block [21]. Private blockchains have a very strong data privacy where any change can be made simply when all nodes agree that the data can be changed by consensus [22]. Another issue with public blockchains is controlling the users in uploading information. For example, if anyone in the system uploads sensitive information into the system there is no way to change such action [23].

Although the public blockchain has an unlimited number of anonymous nodes, each actor can communicate secularly based on cryptography [24]. Each node has a pair of private/public keys. Therefore, a public blockchain does not require to trust anyone who uses the network. Everyone in the network is incentivized to act as per the contract to achieve the best outcomes of the network. As such, the validation and the verification of a transaction can be done without the need of a trusted party. This leads to another main strength of public blockchains, i.e., they are very transparent. Each of the transaction in a public blockchain is open for the public to verify. However, in private blockchains only the trusted parties can be presented in the network to verify and validate transactions. The public blockchains are more decentralized with many nodes and therefore it is harder for any bad actor to make changes to the network. However, private blockchains have fewer nodes so that it is easier to gain control over the network by any bad actor. Therefore, the risk of hacking and data manipulation is higher in private blockchains when compared with public blockchains. As such, it can be stated that the public blockchains are more secured. Further, public blockchains require no infrastructure costs to set up the network [8]. However, private blockchains require wide scale adoption and operation costs.

A federated blockchain combines the features of private and public blockchains [6,8]. According to Casino et al. [25], the main difference of the hybrid system is that a named leader is assigned instead of a single entity to verify the transaction processes. In addition, this system is a partially decentralized blockchain [6] rather than a strict public/private dichotomy. In other words, the federated blockchains constitute a hybrid network between the low-trust (public blockchains) and the single highly trusted entity model (private blockchains).

2.2. Main blockchain platforms

There are three main blockchain platforms: Ethereum, Hyperledger Fabric, and R3's Corda. Ethereum and Hyperledger Fabric can be applied in any domain, while R3's Corda is mainly used for the financial services industry [26]. Therefore, Ethereum and Hyperledger Fabric are discussed and adopted in this study.

2.2.1. Ethereum

Blockchain 1.0 was the basis of Bitcoin, the first cryptocurrency conceptualized by Nakamoto [27]. Beyond cryptocurrency, Blockchain 2.0, the next big tier in the development of the blockchain industry, introduced the concept of smart contracts in 2015 and released a second public blockchain called Ethereum, which expands the scope of blockchain application to enable the decentralisation of markets and transactions [28,29]. Ethereum is inspired by Bitcoin and a blockchain-based distributed computing platform proposed by Buterin [30]. Ethereum is a generic blockchain platform (permissonless, public and private). The consensus algorithm adopted by Ethereum is proof-of-stake (PoS), that is bootstrapped from but more efficient than PoW [31]. PoW is based on game theory and cryptographic algorithm and has been adopted by most of cryptocurrencies [32]. Different from PoW, PoS is dependent on how much stakes are held by the participants to randomly select the winner. As a general-purpose blockchain platform, Ethereum can enable users for executing smart contracts and developing cryptocurrency-related applications.

Ethereum has two types of accounts: externally owned account and contract accounts. An externally owned account refers to an account owned by people on Ethereum, which is controlled by a private key and can hold Ether. The externally owned account is able to execute a transaction with other externally owned accounts and execute a transaction through invoke functions within contracts. The contract account is controlled by contract code and code is executed by messages received from another contract account and an externally owned account. Solidity (i.e., a scripting language) is commonly used to create codes contracts accounts, which are further compiled to a stack-based programming language to execute contract accounts [33].

2.2.2. Hyperledger Fabric

Hyperledger Fabric is a Hyperledger project of blockchain frameworks and tools established under sponsorships of the Linux Foundation in early 2016 [34]. Currently, the Hyperledger consortium consists of IBM, the Linux Foundation, and other companies, promoting cross-industry blockchain-enabled development and related apps [35]. Hyperledger Fabric is modular blockchain platform (permissioned, private) [34]. This platform has been regarded as one of the most mature blockchain platforms so far and is the first platform that allows smart contracts in several general-purpose programming languages (e.g., Node.js, Java, and Go) to be executed [34]. The specific characteristic of Hyperledger Fabric different from other platforms is the execute-order-validate architecture [36]. The transaction flow in Hyperledger Fabric consists of three steps: transaction execution, ordering, and transaction validation. Different from public blockchains, all nodes in Hyperledger Fabric have an identity, which can be categorized into the following three roles [32,34,37]:

- Clients' roles: submitting a transaction proposal and sending the transaction for ordering;
- Peers' roles: executing a transaction proposal, validating the transaction, and maintaining blockchains;
- Orderers (Ordering Service Nodes)' roles: collecting transactions from clients and determining the overall order of all transactions.

Apart from the above nodes, the following design components are also included in Hyperledger Fabric [34]:

- Membership Service Provider (MSP): A membership service provider manages the user identities and controls access to the blockchain network. MSP uses a certificate authority (CA) to validate and authenticate users.
- Smart Contract (chaincode): A smart contract, also called chaincode, defines the lifecycle of an asset that is maintained in the world state. The chaincode contains methods to make a change to the asset and also to query the current state of the asset. It is a software component used in Hyperledger Fabric which packages one or more smart contracts together to be installed on a particular channel. When installing a chaincode, an endorsement policy needs to be defined which decides which peers (organisations) have the right to endorse a transaction in the smart contract for it to be considered valid and committed to the ledger.
- Transactions: A transaction is an action requested by a client to be executed to change an asset that is in the current state. A transaction may read or write the current world state and has to be validated according to the endorsement policy as defined in the chaincode.
- Blockchain Ledger: Blockchain is a ledger that is a non-modifiable journal of all the transactions that happen in the channel. By querying the ledger, an authorised client can view the chain of transactions from the beginning of an asset until the current state of the asset.
- World state: World state is the current state of each asset in the ledger. By querying the world state, a client can acquire the current state of an asset.
- Channels: different channels can be created in Hyperledger Fabric, which provides a separate communication layer for a subgroup of participants to maintain the privacy of communication and data [38].

2.3. Blockchain-based applications

The numerous benefits of blockchain technology have the potential to solve different problems, which have been reflected in the specific sectors of finance, energy, and healthcare. For instance, Andoni et al. [39] identify over 140 blockchain related projects and studies in energy sector. Their classification of these literature revealed that most popular use cases in energy sector are decentralized energy trading and cryptocurrencies, tokens, and investment. In term of platform, 60% use Ethereum as a starting point developing platform, but most developers are oriented to private platform (e.g., Fabric) as they are most appealing for enterprises. In healthcare industry that has unique requirements regarding security and privacy for protecting medical information of patients, there are a wide range of experiments in adopting blockchain-based healthcare applications and several software have been developed, such as OmniPHR, Medrec, and Pervasive social network system [40,41]. A review on 65 papers from 2016 to 2018 in healthcare sector by Agbo et al. [42] showed that blockchain technology has been mainly adopted to address the issues of management of electronic medical records, remote patient monitoring, and biomedical research and education.

3. Application of blockchain in construction domain

This section presents a review of the current state of art for blockchain application in construction domain. A comprehensive desktop search was carried out in two scientific databases, including Web of Science (WoS) and Scopus. The following search string was used in the 'title/abstract/keyword' fields: ("blockchain" OR "distributed ledger technology") AND ("construction" OR "construction industry" OR "construction management"). Peer-reviewed academic journal papers, conference papers, and book chapters were selected for review. The initial searching identified 232 articles. Titles, keywords, abstracts, and main texts of these articles were further scrutinized to determine their suitability for inclusion. The articles which did not focus on construction business process (e.g., smart city and smart energy) or blockchain were excluded. This further retained 34 articles. Among these articles, seven are literature review papers by Hunhevicz and Hall [43], Li et al. [44,45], Nawari and Ravindran [38,46], and San et al. [47], and Perera et al. [48]. The other 27 studies are listed in Table 1. The publication year, country, research topics, and type of publications are summarized. As shown in Table 1, the study of applying blockchain in construction domain is still in its infancy, because of the 1st publication in 2015.

Table 1
Publications on the application of blockchain in construction domain.

No.	Study	Research topic				Country	Type of publication	Level of adoption
		Digitization of work processes			Integrated with other digital technologies			
		Smart contract and cryptocurrencies	Supply chain management	Information management				
1	Cardeira (2015) [49]	Embed digital currencies into contract				Australia	Conference	Inception
2	Barima (2017) [50]	Instant automatic electronic payment	Construction procurement	Registration of land titles	Blockchain and IoT	Canada	Book Chapter	Inception
3	Belle (2017) [51]			Recording building performance	Blockchain and BIM	China	Conference	Inception
4	Heiskanen (2017) [52]				Blockchain and IoT	Finland	Journal	Inception
5	Mathews et al. (2017) [53]		Trust problem in procurement		Blockchain and BIM	Ireland	Conference	Inception
6	Turk and Klinc (2017) [54]			Information management for all building stages	Blockchain and BIM	Slovenia	Conference	Inception
7	Wang et al. (2017) [55]	Contract management	Supply chain	Equipment leasing		Australia	Journal	Inception
8	Lanko et al. (2018) [56]		Logistics of construction materials		Blockchain and RFID	Russia	Conference	Inception
9	Sivula et al. [57]		Opportunities of blockchain in logistics			Finland	Conference	Inception
10	Ye et al. (2018) [58]				Blockchain, IoT, and BIM	China	Conference	Inception
11	Dakhli et al. (2019) [59]	Transactional costs				France	Journal	Inception
12	Hargaden et al. (2019) [60]	Smart construction contract			Blockchain and BIM	UK	Conference	Inception
13	Kifokeris and Koch (2019) [61]		A digital business mode for construction logistics			Sweden	Conference	Inception
14	Liu et al. (2019) [62]			Information management of sustainable building design	Blockchain and BIM	China	Journal	Inception
15	Lokshina et al. [63]			System design of a smart building	Blockchain, IoT, and BIM	US	Conference	Inception
16	Luo et al. (2019) [64]	Construction payment automation				China	Conference	Inception
17	Nanayakkara et al. (2019) [65]		Supply chain			Australia	Conference	Inception
18	Shojaei (2019) [29]		Supply chain	Information management	Blockchain and BIM	US	Conference	Inception
19	Shojaei (2019) [66]				Blockchain and BIM	US	Conference	Inception
20	Singh and Ashuri (2019) [67]			Data management in design phase	Blockchain and BIM	US	Conference	Inception
21	Wang (2019) [68]		Supply chain			UK	Conference	Inception
22	Chong and Diamantopoulos (2020) [69]	Security of payment			Blockchain, BIM, and smart sensors	Australia	Journal	Proof-of-concept
23	Giuda et al. (2020) [70]	Contract execution			Blockchain and BIM	Italy	Book Chapter	Inception
24	Elghaish et al. (2020) [71]	Automated execution of all financial transactions			Blockchain and BIM	UK	Journal	Proof-of-concept
25	Helo and Shamsuzzoha (2020) [72]		Logistics and supply chain		Blockchain, RFID, and IoT	Finland	Journal	Proof-of-concept
26	McNamara and Sepasgozar (2020) [73]	Intelligent contract acceptance				Australia	Journal	Inception
27	Wang et al. (2020) [74]		Supply chain in precast construction			China	Journal	Proof-of-concept

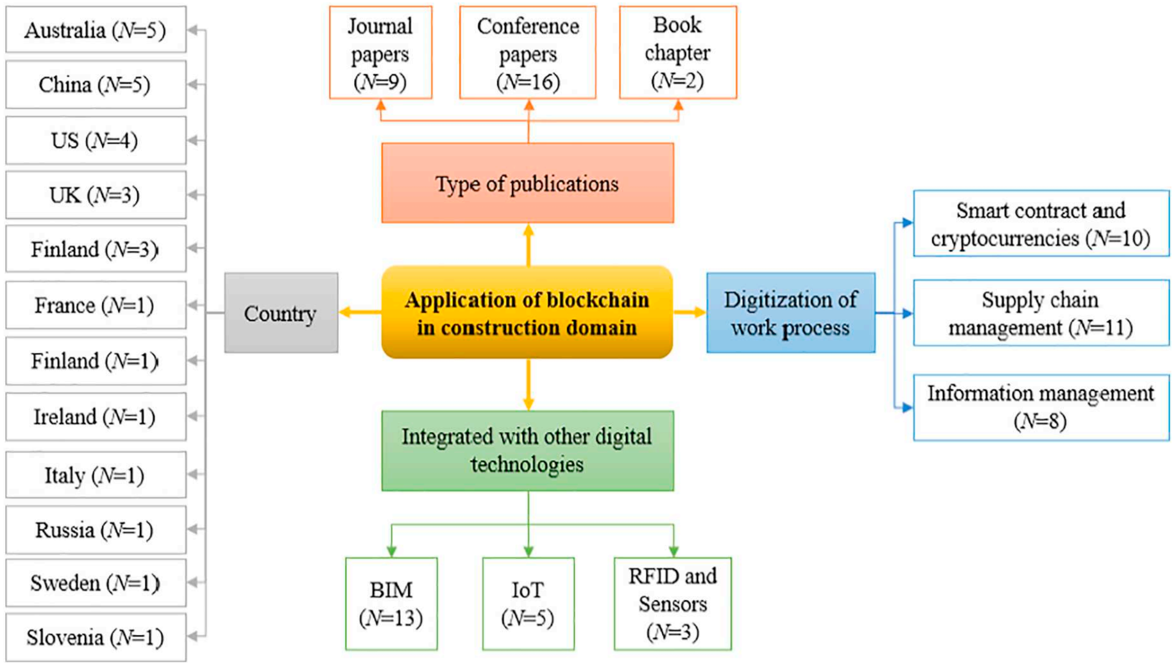

Fig. 1. Classification of the application of blockchain in construction domain.

However, increasing numbers of studies have been published since 2015, indicating a growing trend. Based on their findings and the main application areas of blockchain in the construction domain, these studies can be categorized into two groups: (a) the first group of studies mainly focus on utilising blockchain technology to improve work processes in the construction industry; (b) the second group of studies attempt to integrate blockchain technology with other digital technologies, such as Building Information Modelling (BIM), Internet of Things (IoT) and Radio Frequency Identification (RFID), to address specific problems or improve the current process. Based on the literature review, the classification of the application of blockchain in construction domain was depicted in Fig. 1.

3.1. Blockchain-enabled business process management

Some scholars consider that the application of blockchain technology can digitise the future construction business process, such as blockchain-enabled contract management [55,60], automated conditional construction payment [49,64], blockchain-enabled supply chain management [29,55], and construction information management [62].

3.1.1.1. Smart contracts and cryptocurrencies. Poor payment and contract problems have been plaguing the construction industry, resulting in numerous disputes and business failures, especially for small and medium business [55,60]. It has been proposed that contractual clauses can be coded into smart contracts, which can be self-executed without intermediaries [55,60]. Regarding blockchain-enabled construction payment, smart contracts can be used in conjunction with cryptocurrencies, allowing to create contracts with cryptocurrencies for protecting various stakeholders from the insolvency of payment withheld and not paid on time [49,55,60]. Luo et al. [64] propose a framework of automating construction payments by embedding the process into smart contracts and running them on blockchain-enabled platforms, which is demonstrated by a case-based scenario. Albreiki et al. [75] use blockchain concept with trusted oracles to create a decentralized access control system allowing a blockchain to get information from outside real world. By implementing smart contracts, Wang et al. [55] and Cardeira [49] believe that several benefits to construction contract management can be offered: guaranteeing the required funds to conduct the construction work in eliminating withheld or late payment issues, reducing contract administration time, protecting stakeholders from the insolvency of others, and reshaping trusted behaviour from human trust to coding trust. Dakhli et al. [59] reveal that the uptake of blockchain may potentially save 8.3% of total cost of residential building construction. Hasan and Salah [76,77] offer a Proof of Delivery framework for trading and delivery of digital assets by using smart contracts of Ethereum blockchain network. The proposed solution allows tracking, tracing, and logging transactions in a decentralized manner. Chong and Diamantopoulos [69] propose a framework for integrating blockchain with smart sensors, oracles, and BIM for facilitating the automated payment system based on a mixed research method, which would improve the security of payment for various stakeholders. Elghaish et al. [71] develop a framework of applying blockchain to achieve automated execution of all financial transactions for integrated project delivery though a real-life case study blockchain-based intelligent contracts

3.1.1.2. Supply chain management. The decentralized and fragmented characteristics of construction supply chains match well the decentralized properties of blockchains [29] Blockchain can act as an neutral infrastructure to ensure the transparency and traceability of supply chains [29]. Using a blockchain network for supply chain management, vendors or suppliers can easily exchange their immutable authorised certificates for their qualification to deliver specific products and/or services; and buyers can validate those certificates, examine their reputation by checking their previous track records on blockchain. As a result, buyers and vendors can establish trust easily with these evidences [29]. A scenario of the application of blockchain technology illustrated by Wang et al. [55] is the process from procurement to the final installation of a precast product. All transactions in this process can be recorded on blockchains and checked by all relevant stakeholders along the supply chain, which allows fully transparent material information and makes the re-use and recycling of materials possible. In respect of construction logistics, Sivula et al. [57] find that there are many opportunities of applying blockchain in logistics, such as better transparency among stakeholders, and encouraging new business models. Kifokeris and Koch [61] analyse the business model of construction supply chain and logistics. Lanko et al. [56] propose that the integration of blockchain, RFID, and GPS technologies in the logistics of construction materials enables the tracking of the delivery of construction materials in real time and the prediction of delivery time, which enables better project planning based on timing logistics delivery information and thus minimizes losses from delay in delivery. Helo and Shamsuzzoha [72] also design a pilot system of a cloud-based portal to track and trace the logistics and supply chains based on blockchain.

3.1.1.3. Information management. Scholars have also pointed out that blockchain technology enables the storage of a wide range of information or data in the construction domain, such as recording building performance [51], equipment leasing information [55], and sustainable building design information [26]. Singh and Ashuri [67] propose a blockchain-based framework for design phase to decrease the barriers of BIM with a transparent, secure and traceable data store and management. Since the comparison of building performance is difficult to achieve, Belle [51] points out that smart building components can be programmed with the help of blockchains for initiating maintenance and repairing routines automatically. Wang et al. [55] suggest that blockchain technology can help increase the efficiency of equipment leasing process. They propose that the identity of heavy equipment can be registered on the leasing blockchain and transactions on equipment leasing can be updated on the blockchain. Chaer et al. [78] explore the potential integration of blockchain features with 5G services. Furthermore, Liu et al. [55] propose and validate a two-level conceptual architecture of a blockchain and BIM-based system for sustainable building design information management, which may help to improve information management and realize sustainable designs.

3.1.2. Integrated blockchain with other digital technologies

Digital technologies can be applied in various stages of a construction project. This requires integrating blockchain technology with other digital technologies (e.g., IoT, AI and BIM) [51–54,60,62]. IoT can be used on large building components to provide real-time material monitoring, better site management and improved construction efficiency [52]. A combination of blockchain and IoT as complementary developments has been advocated to benefit each other [52]. For example, Suliman et al. (2018) employ blockchain technology to monetize IoT data and has developed a system to automate payments without an involvement of any intermediaries. Blockchain is ideal for IoT interactions and integration to achieve reliable data sharing and avoid falsification and cheating. Further, blockchain concept has been applied for Artificial Intelligence (AI). Salah et al. (2018) review the prevailing research emerging blockchain applications in the area of AI and has discussed the potential applications in explainable AI, digital twins, automated machine learning, hybrid learning models, and lean and augmented data learning. BIM is becoming a standard platform where all parties (e.g., architects, engineers, and construction professionals) work together on a single and shared model for collaboration. Some shortcomings of BIM work process can be addressed by integrating with blockchain. One of the main challenges in applying BIM-based system is that data are distributed on several versions of the BIM model, resulting in fragmented and inconsistent management of model use and confused ownership of a BIM model [54,58]. By applying smart contracts, only party having the permission of intelligent contracts is allowed to use the BIM model and all operations are stored on blockchains. As a result, responsibilities and intellectual property rights are effectively assigned, and information is integrated on blockchain [51]. Ye et al. [58] suggest that only certain specific transactions need to be written by smart contracts in a BIM workflow, as the workload and technical requirements of transferring all contracts to smart contracts may exceed the ability of project teams. They further propose the cup-of-water theory that BIM is the bottom of the cup to manage the digital information, blockchain is the cup wall to redefine the method of storage, and IoT is the water in the cup as the entity of object and data. Lokshina et al. [63] also regard blockchain, BIM and IoT as complementary technologies which work together to enable secure storage and management of data and information of building construction.

Studies of blockchain-based systems in the construction industry have emerged in recent years. These studies have explored how the construction sector can benefit from adopting blockchain technology. They have highlighted the drivers and key benefits of blockchain technology in the construction domain for facilitating project organisation and transparency during the design and construction stages and identified limitations and obstacles as adopting blockchain as new tools. Currently, most approaches in these blockchain publications are related to conceptual studies and/or proposed frameworks. Very few studies have provided demonstration on the application of public and private blockchain platforms by industry cases. Many steps need to be taken and practice-related obstacles need to be overcome to make blockchain a vital part of the business process of construction projects. While most of these studies have not detailed the process of applying blockchain, they explored the potential and shed light on future directions of blockchain studies.

4. Case study

Two construction project cases were selected based on the discussion with key stakeholders to demonstrate the use of public and private blockchain technologies in enabling the transparent and traceable business processes in the construction domain. Case 1 is the design process of the external cladding of a large-scale apartment. The design process of a suitable cladding system for the apartment project is very important in Australia. The combustible cladding fuelled Grenfell Tower disaster in London that killed 72 people. Similarly, the fast-moving fire that damaged the Melbourne 43-storey apartment Neo200 and 21-storey Lacrosse building have ignited the urgency of checking and replacing high-risk flammable cladding across Australia, considering hundreds of buildings have such flammable cladding [79]. Building a construction supply chain traceability system for key construction materials and products is becoming more and more urgent. Thus, the project team recommended the business process of selecting the cladding for a large-scale apartment project in Australia as the case study. Since the cladding design process is a common practice in the company business process for other similar projects, and the stakeholders have established relatively long-term collaboration relationship, the company prefers private blockchain system as a standard infrastructure to be invested, and potentially connected with other existing platforms. Case 2 is the procurement process of an important equipment of an international mega project. The smart payment is important for both sides of the procurement. This business process is generally a one-off action with limited stakeholders involved, so public blockchain is tested in this case to avoid complexity. The business processes for these two cases are presented in the following sections.

4.1. Case study 1

4.1.1. Business process of Case 1

The application of a permissioned blockchain network for the process of designing external cladding for an apartment project is explored through a case study. The key participants and their scope of work in this process are described in Table 2.

Fig. 2 shows the business process of selecting cladding of Case 1. Initially, the architect hand over the concept design specification to different suppliers to select a suitable product for the project. The architect checks product compliance with the Building Code of Australia, Australian Standards for cladding, the Australian Standard for non-combustibility and the codemaker's certification. Subsequently, the architect discusses with the façade engineer to check the adaptability of

Table 2
Key participants and their scope of work.

Key Participants	Scope of Work
Architect	Coordinate certification with different parties and finalize design drawings
Suppliers	Provide different cladding material for the project
Façade engineer	Check the adaptability of the selected cladding material with the framing requirements
Building surveyor	Check the compliance of the selected material with required standards
Town planner	Check the compliance with town planning and council requirements

the selected cladding system with the framing requirements. The architect shares the cladding material specification and the cladding test results with the project team. After confirming with the façade engineer, approval from the client is required in relation to colour, maintenance and replacement etc. If the client approves the product, the architect approaches a relevant building surveyor for approval. Building surveyor then confirms that the selected material complies with the Building Code of Australia, Australian Standards for cladding, the Australian Standard for non-combustibility and the codemaker's certification. After approval by the building surveyor, the architect then approaches the town planner with the facade drawings and product specifications. The town planner checks product compliance and colour compliance with town planning, council requirements and neighbourhood characteristics. Once the cladding material is approved by town planning, the design drawings can be implemented with different rounds of revisions. Finally, the design drawings are finalised with a discussion with the client.

4.1.2. System architecture of Case 1

According to the workflow for selecting cladding in Fig. 2, the overall architecture for the proof-of-concept blockchain solution for the architect selecting cladding for a building project is proposed and illustrated in Fig. 3, in which the open source Hyperledger Fabric platform was used to build the overall solution. The smart contracts (chaincode) and the user-facing applications were developed in Java.

In this architecture, there are six main stakeholders, including *Architect* (R1), *Supplier* (R2), *Engineer* (R3), *Client* (R4), *Building surveyor* (R5), and *Town planner* (R6). In addition to these main stakeholders, an ordering service organisation (*Orderer*) and an independent *Observer* organisation were also created, as shown in Fig. 3. *Architect* and one *Administrator* have been assigned to be the network initiators.

In the permissioned blockchain network Hyperledger Fabric, separate channels for interactions between different organisations can be created and access to the channel (as well as to the overall network) is controlled via the certificate authorities and cryptography-based authorisation. Channels allow organisations to use the network, while maintaining separations between multiple blockchains. Only the members on the channel (including the stakeholders and *Observer*) can see the specifics of transactions performed on that channel, whereas other members of the network cannot see the transactions on that channel.

As per the above workflow in Fig. 2, six channels among main stakeholders were established as they need to have private communications within the overall network. For instance, the *Architect* organisation and the *Supplier* organisation need to conduct transactions between each other in order to acquire a cladding sample as per the compliance standards. Since the interactions between a supplier and architects may not be disclosed to other parties in the network, a

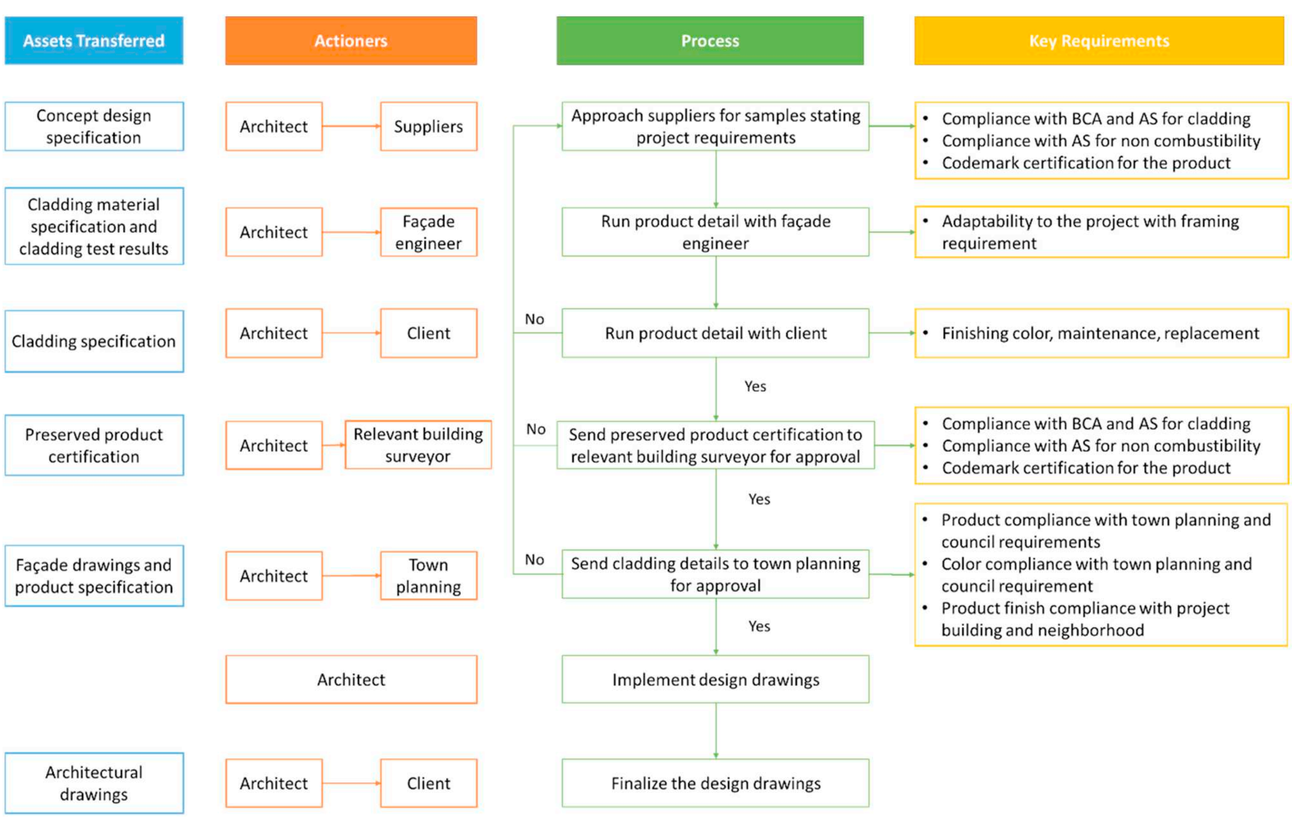

Fig. 2. Business process of selecting cladding.

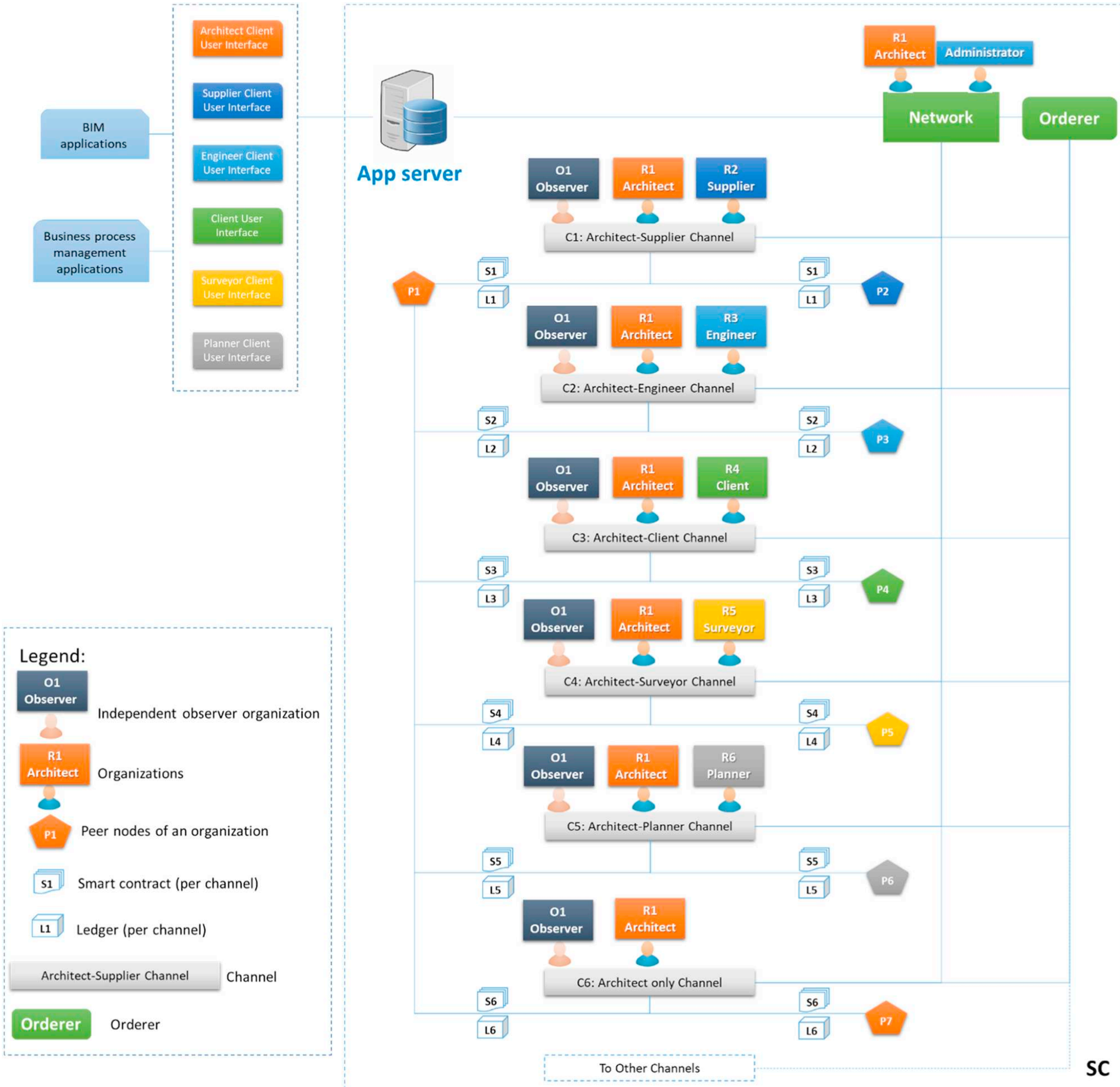

Fig. 3. System architecture of private blockchain-enabled process of Case I.

separate channel is established between the two organisations. These two organisations are able to endorse a transaction according to the pre-agreed smart contract installed on the channel. However, to ensure transparency, we also added an independent *observer* organisation to the channel who does not have any rights to endorse the transactions but can query any transaction that has already been committed to the blockchain. This results in a faster endorsement of transactions while maintaining the transparency of the overall operation. Following the same approach, other channels were also established for all the interactions between the organisations in our solution, including an *Architect-Engineer* channel, an *Architect-Client* channel, an *Architect-Surveyor* channel, an *Architect-Planner* channel, and an *Architect* only channel. All these main stakeholders can use their client applications to access ledgers through relevant smart contracts in the relevant channels.

In this network, all organisations, including *Architect*, *Supplier*, *Engineer*, *Client*, *Surveyor*, and *Planner Architect,* have their client applications. *Architect* can conduct business transactions with stakeholders *Supplier*, *Engineer*, *Client*, *Surveyor*, and *Planner,* in channel *C1*, *C2*, *C3*, *C4*, and *C5*, respectively. Similarly, the stakeholders *Supplier*, *Engineer*, *Client*, *Surveyor*, and *Planner* also can conduct business transactions in channels *C1*, *C2*, *C3*, *C4*, and *C5*, respectively. Peer node *P1* maintains a copy of the ledger *L1* regarding *C1*, a copy of the ledger *L2* regarding *C2*, a copy of the ledger *L3* regarding *C3*, a copy of the ledger *L4* regarding *C4*, a copy of the ledger *L5* regarding *C5,* and a copy of the ledger *L6* regarding *C6*. All six channels are governed based on the policy rules specified in each channel configuration.

In addition, *Orderer* (an ordering service) is the administration point of the whole blockchain network and can use the system channel. *Orderer* supports all six channels *C1*, *C2*, *C3*, *C4*, *C5*, and *C6* to order transactions into blocks for distribution. *Orderer* is initially configured and started by the administrators of the network.

This ensures not only an immutable record of these crucial data, but also enhances trust and accountability across all stakeholders. Moreover, relying on the blockchain system, all the information on products is transparent and open to relevant stakeholders and observers.

```
################################################################################
#
#   Section: Organizations
#
#   - This section defines the different organizational identities which will
#   be referenced later in the configuration.
#
################################################################################
Organizations:

    - &OrdererOrg
        Name: OrdererOrg
        ID: OrdererMSP
        MSPDir: crypto-config/ordererOrganizations/blockchain.rmit.edu.au/msp
        Policies:
            Readers:
                Type: Signature
                Rule: "OR('OrdererMSP.member')"
            Writers:
                Type: Signature
                Rule: "OR('OrdererMSP.member')"
            Admins:
                Type: Signature
                Rule: "OR('OrdererMSP.admin')"

    - &Architects
        Name: ArchitectsMSP
        ID: ArchitectsMSP

        MSPDir: crypto-config/peerOrganizations/architects.blockchain.rmit.edu.au/msp
        Policies:
            Readers:
                Type: Signature
                Rule: "OR('ArchitectsMSP.admin', 'ArchitectsMSP.peer', 'ArchitectsMSP.client')"
            Writers:
                Type: Signature
                Rule: "OR('ArchitectsMSP.admin', 'ArchitectsMSP.client')"
            Admins:
                Type: Signature
                Rule: "OR('ArchitectsMSP.admin')"
        AnchorPeers:
            # AnchorPeers defines the location of peers which can be used
            # for cross org gossip communication.  Note, this value is only
            # encoded in the genesis block in the Application section context
            - Host: peer0.architects.blockchain.rmit.edu.au
              Port: 7051
```

```
################################################################################
#
#   Profile
#
#   - Different configuration profiles may be encoded here to be specified
#   as parameters to the configtxgen tool
#
################################################################################
Profiles:

    TwoOrgsOrdererGenesis:
        <<: *ChannelDefaults
        Orderer:
            <<: *OrdererDefaults
            Organizations:
                - *OrdererOrg
            Capabilities:
                <<: *OrdererCapabilities
        Consortiums:
            ArchitectSupplierConsortium:
                Organizations:
                    - *Architects
                    - *Suppliers
                    - *Gov
            ArchitectEngineerConsortium:
                Organizations:
                    - *Architects
                    - *Engineers
                    - *Gov
            ArchitectClientConsortium:
                Organizations:
                    - *Architects
                    - *Clients
                    - *Gov
            ArchitectSurveyorConsortium:
                Organizations:
                    - *Architects
                    - *Surveyors
                    - *Gov
            ArchitectPlannerConsortium:
                Organizations:
                    - *Architects
                    - *Planners
                    - *Gov
            ArchitectsOnlyConsortium:
                Organizations:
                    - *Architects
                    - *Gov
```

Fig. 4. Screenshots of part of configurations used for Case 1.

4.1.3. System demonstration of Case 1

As per the business process of selecting cladding depicted in Fig. 2, smart contracts for six channels were written and deployed, allowing users to create transactions in the Hyperledger Fabric network. Fig. 4 presents parts of configurations used for Case 1. This simulation consists of the following seven steps and the relevant channels used are outlined in Table 3.

Screenshots of interfaces and the corresponding records in the ledgers of stakeholders of each step are shown in Fig. 5. In this figure, the first column shows categories of business processes, the second column presents the channels used by stakeholders, the third column shows the blockchain users (e.g., architect, town planner, client and supplier), the fourth column depicts the interface of user's actions, and the last column presents the screenshots of corresponding transactions recorded on the blockchain ledger. This study focusses on three main aspects in this demonstration: business process, interface integration, and information integration.

Table 3
Steps and corresponding channels in Hyperledger Fabric simulation.

Steps	Channels
Step 1: Create a new cladding sample request	*Architect-Supplier*
Step 2: Send cladding details to façade engineer	*Architect-Engineer*
Step 3: Send cladding details to client	*Architect-Client*
Step 4: Send cladding certification to building surveyor for approval	*Architect-Surveyor*
Step 5: Send cladding details to town planner for approval	*Architect-Town Planner*
Step 6: Implement design drawings	*Architect only*
Step 7: Finalize design drawings	*Architect-Client*

4.2. Business process

4.2.1. Business processes among main stakeholders

Various blockchain-enabled business processes of stakeholders are achieved in this simulation.

- o Stakeholders in each channel can input cladding requirements and supporting assets (e.g., screenshots I-1, I-3. I-5, I-10, I-15);
- o Options can be provided to stakeholders in blockchain-enabled systems. For instance, in Step 3, after the architect sends the cladding details to the client for approval, the client has two options (i.e., accept this type of cladding or reject it). Screenshot I-6 shows that the client selected "Reject" and the architect immediately receives the notification "Client has rejected the cladding sample" (see screenshot I-7). The architect needs to re-select a cladding sample. Similarly, in Step 4, the building surveyor is also provided with two options (i.e., approve the cladding or not approve the cladding) after the architect sends the cladding details (see screenshot I-11).

4.2.2. Parallel business processes by Observers

In parallel to the existing business processes among main stakeholders, independent Observers can query any channel of which they are members based on the need to verify and check the transactions in the channel or ledger. In this case, since Observer *O1* is a member of all six channels (see Fig. 3), the Observer *O1* can query any of these six channels. Screenshot I-22 shows that Observer *O1* selects the *Architect-Supplier* channel to query and the history of transactions in this channel recorded on the blockchain is presented in screenshot R-22. Similarly, screenshots I-23 and R-23 show the interface of *O1 selecting Architect-Planner* channel to query and records of transactions in this channel on blockchain, respectively. Note that in this query the observer can also check the transactions that occurred when the Planner rejected the

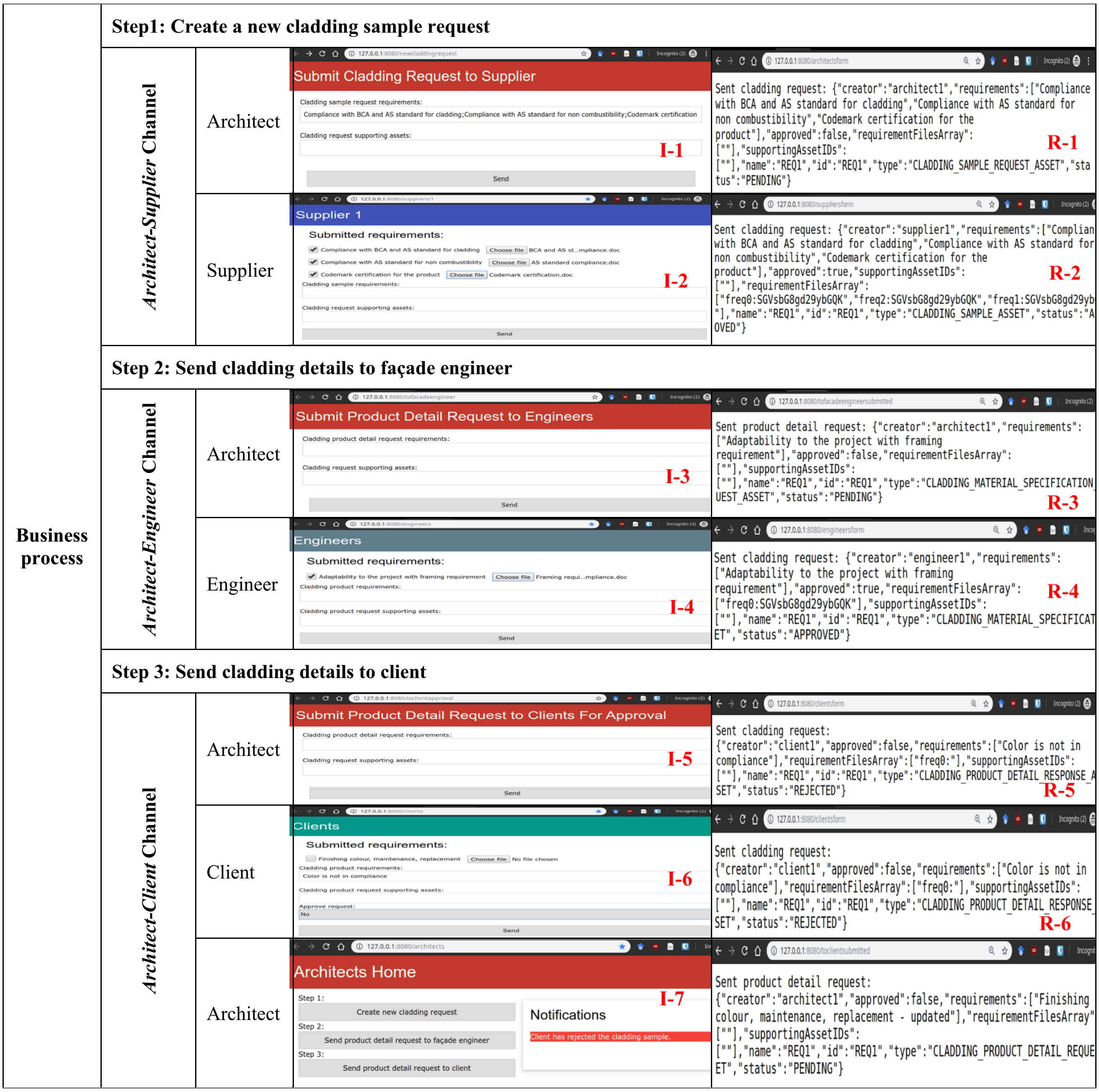

Fig. 5. Screenshots of stakeholders' and Observer's interfaces and corresponding records

initial request from the Architect due to non-compliance. Furthermore, Observer *O1* can query all channels (see screenshot I-24) and transactions in all channels are presented (see screenshot R-24).

4.3. Underlying the existing work interface

Blockchains are usually combined with other components in a broader system. Since blockchains can underlie the current work interface of stakeholders, users can record key transactions without adding workload or interrupting their current work.

4.4. Information database

In the construction domain, blockchain technology can be a database of information, which provides benefits, such as reducing the possibility of tampering, time and cost saving, transparency and traceability. In this case, stakeholders can select and upload the relevant standards for cladding and products in their channels in various formats, such as doc., gif., and pdf. For instance, the supplier submitted the BCA and AS standards for cladding and codemark certification in doc. Format in the *Architect-Supplier* Channel (i.e., screenshot I-2) and the corresponding record on blockchain is shown in screenshot R-2. The engineer, client, and building surveyor can also upload the required documents in their channels (see screenshots I-4, I-6, and I-11).

4.5. Case study 2

4.5.1. Business process of case 2

Case 2 is derived from an international engineering, procurement, and construction management (EPCM) project. The distillation tower, an important piece of equipment in this mega project, needs to be purchased overseas and installed as per the scope of work of the

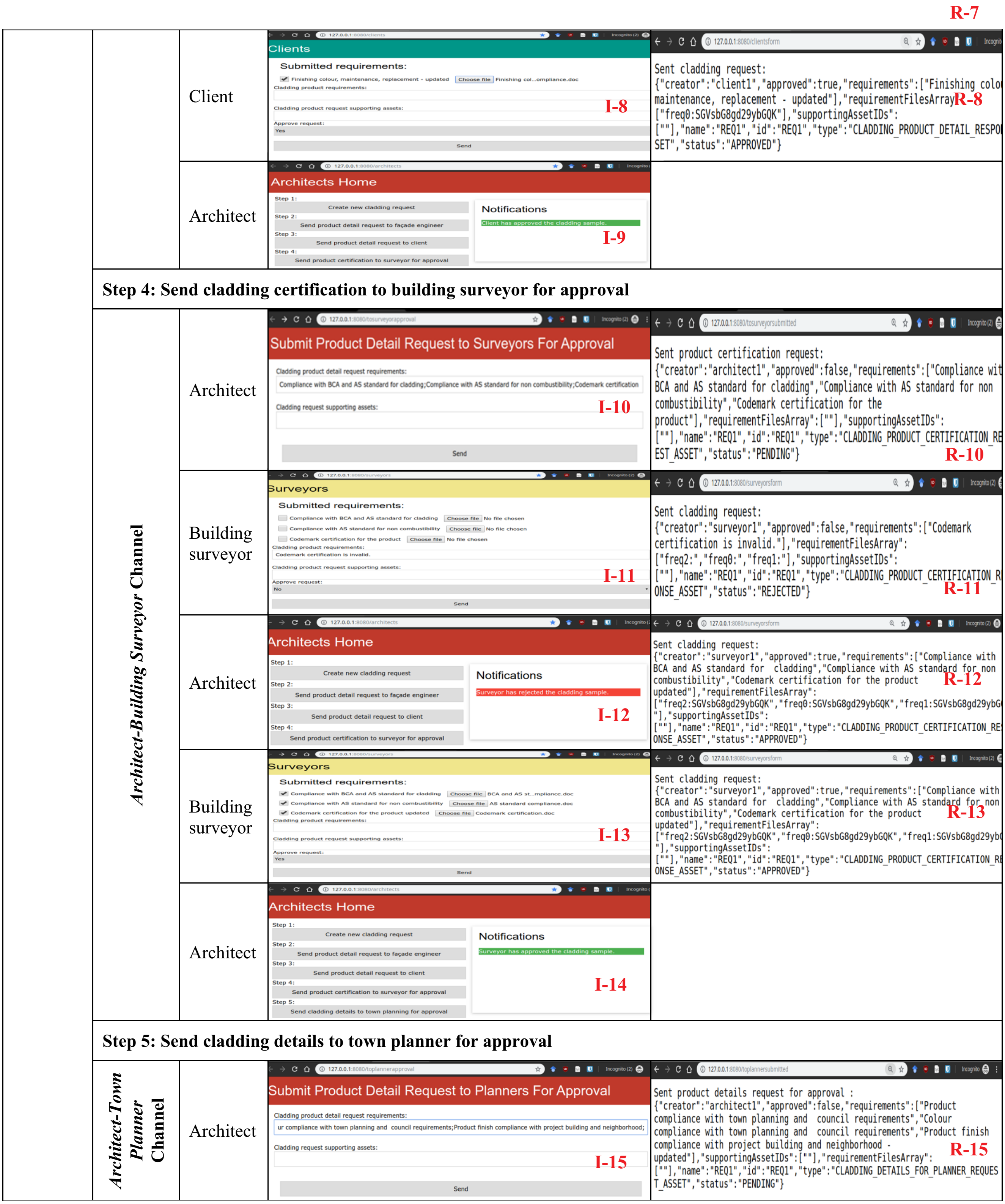

Fig. 5. (*continued*)

construction contract. The business process of Case 2 is depicted in Fig. 6. The procurement team is responsible for procuring this equipment. The procurement team of the EPCM contractor needs to sign a supply agreement with the supplier/vendor. The total contract price of the distillation tower is AU$43,000. The procurement team will pay 30% of the contract price as a deposit to the vendor. After the vendor receives the deposit, they need to supply and deliver the equipment based on the supply agreement. Once the equipment is delivered to the nominated warehouse, the procurement engineer of the EPCM contract and the nominated subcontractor check the quantity and visible damage jointly. The parties sign the acceptance form, and responsibility for care and custody then transfers to the nominated subcontractor

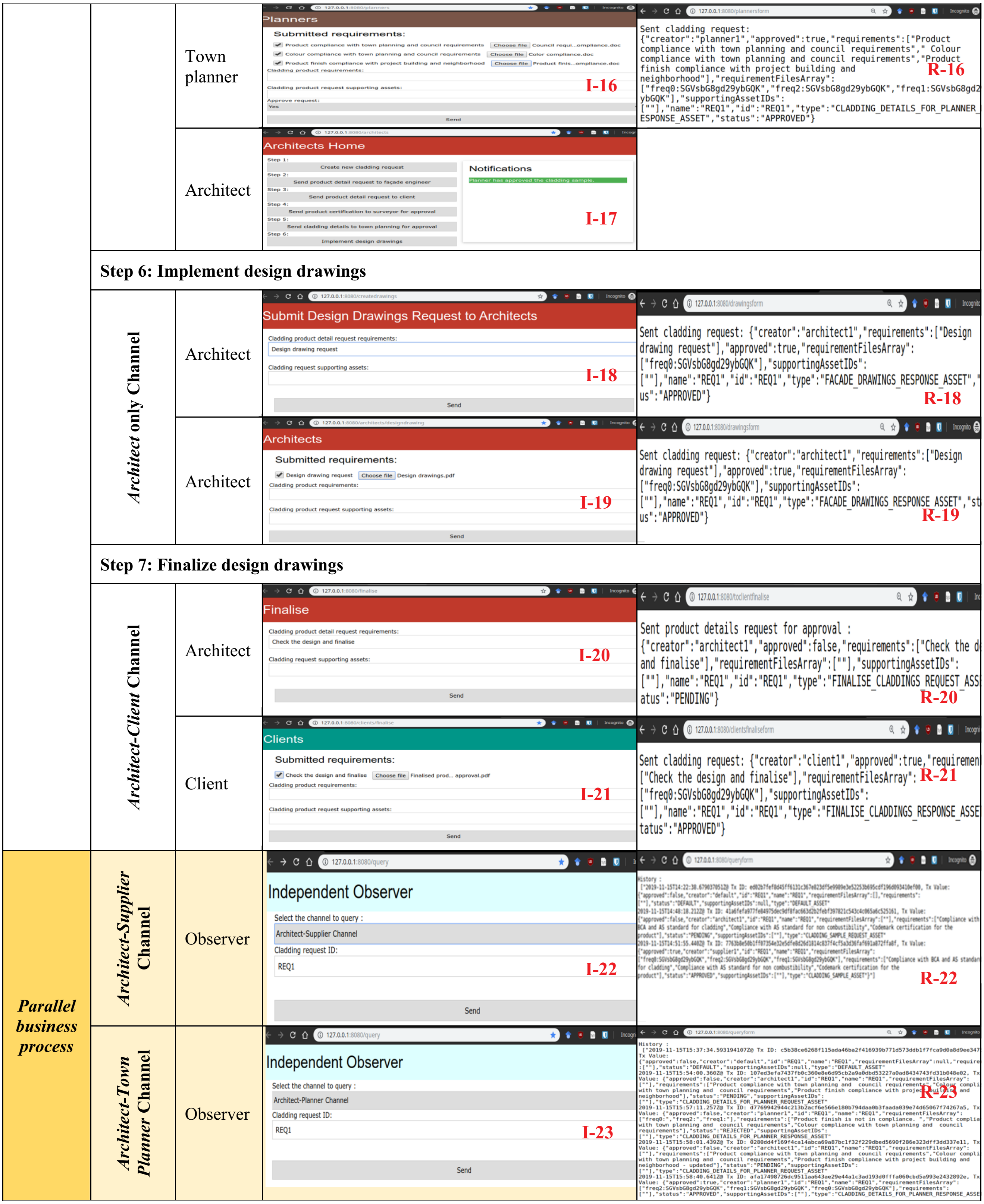

Fig. 5. (*continued*)

under a condition of the construction contract. Otherwise, the procurement team should instruct the vendor to remedy damaged material or equipment. Once the procurement team receives and inspects the equipment, they will pay the remaining 70% of the contract price (AU$ 30,100) to the vendor and complete the procurement.

4.5.2. System architecture of Case 2

According to the workflow in Fig. 6, an architecture based on the public blockchain Ethereum platform was also built up, which offers Turing-complete and programmable scripts to support complex modelling and computing. As outlined in Fig. 7, two main stakeholders were

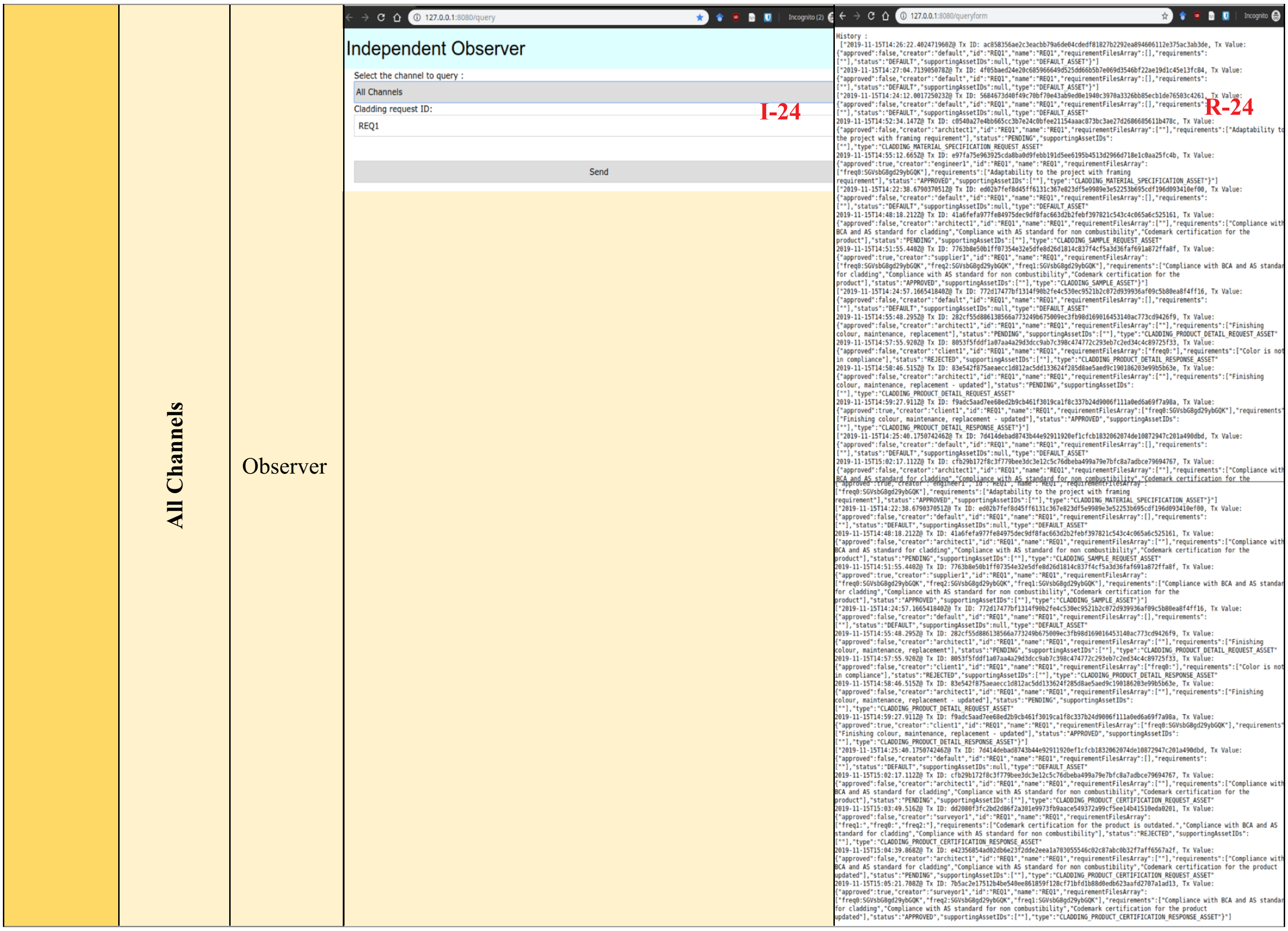

Fig. 5. (*continued*)

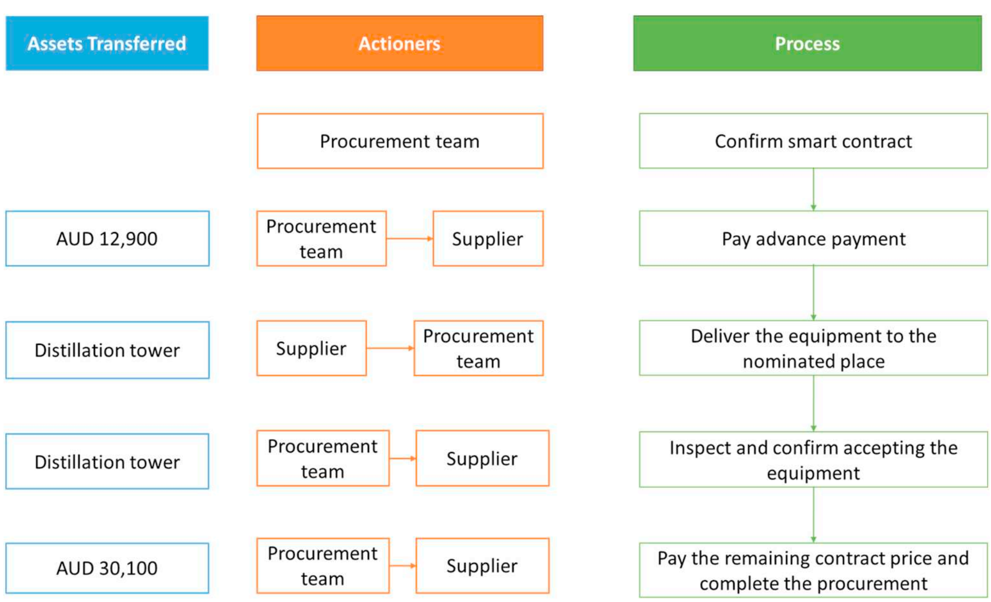

Fig. 6. Business process of purchasing equipment.

involved in this architecture, i.e., the procurement team of the contractor and the supplier. These organisations have unique externally owned accounts on Ethereum and create smart contracts which contain functions that can be executed by external accounts. In Ethereum, Ether is one kind of crypto-currency which needs to be used to pay for transactions, as Ethereum ensures security by an incentive-based model.

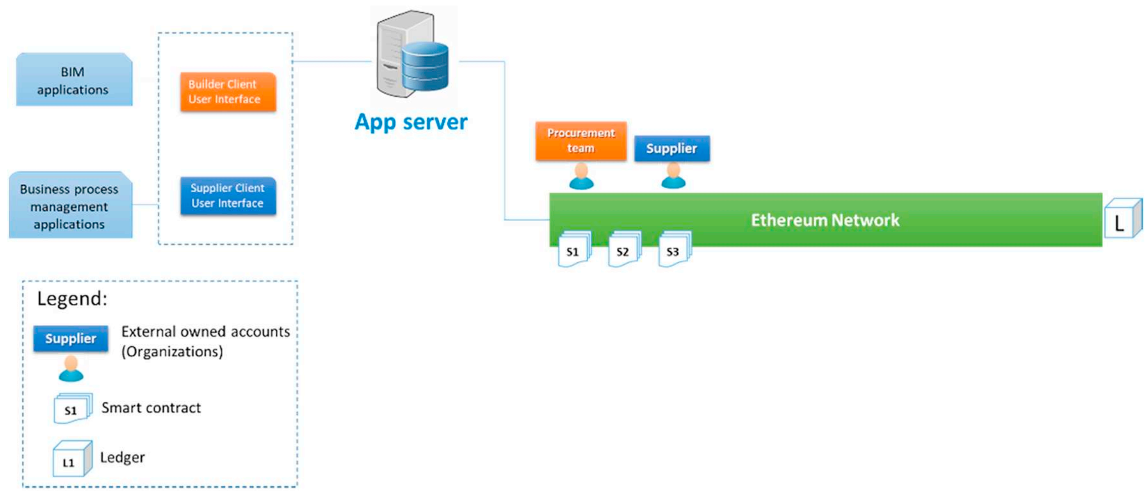

Fig. 7. System architecture of public blockchain-enabled process of Case 2.

4.5.3. System demonstration of Case 2

Based on the business process of Case 2, a testing smart contract is created, as shown in Fig. 8. The vendor and procurement must register to the contract to get access and administer the work interface, respectively. An equipment supply contract is created once the electronic contract is compiled and run successfully on the blockchain platform Ethereum. The main procedures for applying blockchain technology in the procurement of a distillation tower can be divided into the following stages. A total of five transactions are added to the blockchain through the five steps of procurement. The status of the deployed contract, transaction fee and the created block in Case 2 are depicted in Fig. 9.

4.6. Step 1: confirm smart contract

After contract deployment, the vendor's account (i.e., a string of letters and numbers that represents different people), the name of the equipment, and the price are input into the system according to the supply contract. As shown in Fig. 9, after the procurement team confirms the contract (see screenshot C-1), they pay a transaction fee to Ethereum (see screenshot F-1) for creating the contract in blockchain and then the confirmed transaction (see screenshot R-1) is added into the latest block of the blockchain.

4.7. Step 2: pay deposit

When the procurement team performs the purchase action, AUD 12,900 (30% of the contract price) is paid to the vendor as the advance payment for the equipment according to the pre-defined rules of the supply contract. If the advance payment is less or more than AUD 12,900, the system will generate an error warning. After the correct Ether coin is successfully charged from the procurement team's account, the buy action is successful, and the status of the contract is updated and shown in screenshot C-2. In addition, the procurement team needs to pay a transaction fee to Ethereum (see screenshot F-2) and the record of the buy action is added to the blockchain (see screenshot R-2).

4.8. Step 3: equipment delivery

After the vendor receives the advance payment, they are responsible for transporting the equipment to the place nominated by the procurement team. In the system, the vendor needs to carry out the “send” action, and the status of the deployed contract is updated (see screenshot C-3). The vendor also needs to pay a transaction fee to Ethereum (see screenshot F-3) for adding the record on blockchain. Thus, the transaction regarding equipment delivery is added to the blockchain (see screenshot R-3).

4.9. Step 4: receive the equipment

When the distillation tower is transported to the appointed warehouse, the procurement team needs to check the quantity and quality. If there is no problem, the procurement team needs to conduct a “receive” action in the system and the deployed contract is updated accordingly (see screenshot C-4). The procurement team also needs to pay a transaction fee to Ethereum (see screenshot F-4) for adding a new transaction regarding confirmation of acceptance of the distillation tower and the corresponding transaction is added (see screenshot R-4).

4.10. Step 5: completion of the procurement

In the last step, once the “receive” button is clicked, the procurement team will be automatically charged the remaining AUD 30,100 to the vendor's account and the status of the contract is also automatically updated to “completed final payment and ready to install” (see screenshot C-5). The procurement team pays a transaction fee to Ethereum (see screenshot F-5) to add the record of this action to the blockchain (see screenshot R-5).

5. Discussion and reflection

This study uses two business processes which can represent the generic actions in similar scenarios to explore the opportunities and experiences to apply public and private blockchain systems. Feedback from key stakeholders and experiences from the system development are summarized in the following subsections.

5.1. Benefits of blockchain-enabled business process

5.1.1. Extended transparency, traceability, and auditability

Blockchain-enabled business process has the potential to improve the transparency and traceability of supply chains of key materials. In Case 1, blocks have been created for each transaction along the design and procurement process of cladding, and critical information and data such as the concept design specification, cladding materials specification and test results, product certification and relevant drawings have been recorded in blockchain system. These transactions and records are immutable and easily traced back if necessary. The case manager recommends this process to be extended to other major or critical materials and products. All transactions along blockchain-enabled supply

```
    address payable public vendor;  //0x439d61956bC06FAbB4F3d2C3cdA004bdE6b508D2
    address payable public procurement; //0x75873eDB8Ab42aA0B933BC86B27C7776a1EA7CE3
    uint256 internal deposit;
    uint256 public remaining;


    modifier onlyVendor() {
        require(msg.sender == vendor);
        _;
    }
    modifier onlyProcurement() {
        require(msg.sender == procurement);
        _;
    }

    string public productName;
    uint256 public price;
    string public status;



    //
    // initial the contract
    //
    // as a founder
    // enter vendor address
    // enter procurement address
    // enter product name
    // enter product price
    constructor(address payable _vendor, string memory _name, uint256 _price) public {
    //constructor() public {

        procurement = msg.sender;
        vendor = _vendor;
        productName = _name;
        price = _price;
        deposit = price * 3 / 10;
        remaining = price;
        status = "started";
    }

    //
    // complete whole transaction
    // only the procurement can run this function
    //
    // make the deposit (Product price * 0.3) of the Product
    function buy() payable public onlyProcurement{

        require(statusIs("started"));
        require(msg.value >= deposit);

        transferETH(vendor);
        remaining = price - msg.value;

        status = "paid deposit";
    }
```

Fig. 8. Screenshots of part of smart contract in Case 2.

chain are fully auditable. Such level of traceable and immutable record-keeping is helpful for enhancing the transparency and traceability of key materials and ensuring their authenticity and legitimacy [80]. Providing much needed transparency can alleviate the quality fraud problems and improve confidence and trust of the public in construction quality.

5.1.2. *Project supervision*

Independent observers can be added in blockchain. Observers are unable to submit or validate any transaction and can only query the status of and information on transactions in their channels. In the construction domain, these observers can be government, quality assurance firms, building surveyors, regulatory agencies or even the public to monitor and investigate transactions of relevant stakeholders at different stages. In Case 1, the observer can detect whether the builder is purchasing cladding which meets the required standards. This not only provides a single window concept for project governance, but also increases company's credibility in tendering especially in public projects.

5.1.3. *Automated payment transactions*

Smart contract has features of automation and enforceability through an automated protocol [46]. In Case 2, smart contract was used for the procurement of an expensive equipment for an international mega project. For cryptocurrencies, public blockchains (either permissionless or permissioned) are required, allowing people to access the blockchain network, such as Bitcoin (run on a public, permissionless network), Ether (run on a public, permissionless network), and XRP (run on a public, permissioned network) [81]. The status of a deployed smart contract will only update when the pre-defined requirement(s) is fulfilled at different stages, such as if buyer cannot order an item if he/she did not have enough deposit, and the remaining digital currency will automatically have transferred once the buyer received the item. This helps to eliminate disputes and litigations on payments withheld

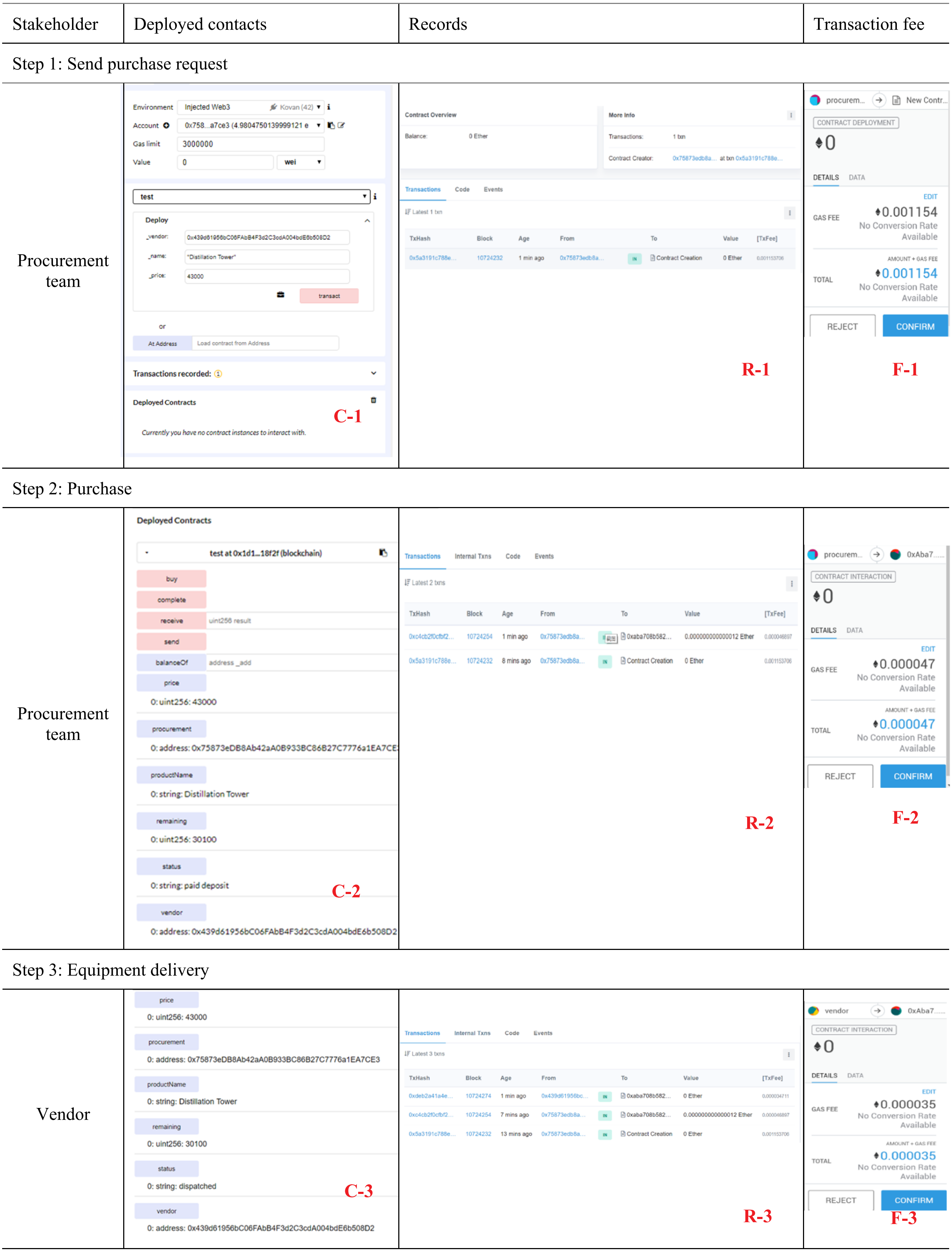

Fig. 9. The status of deployed contract, transaction fee, and created block in Case 2.

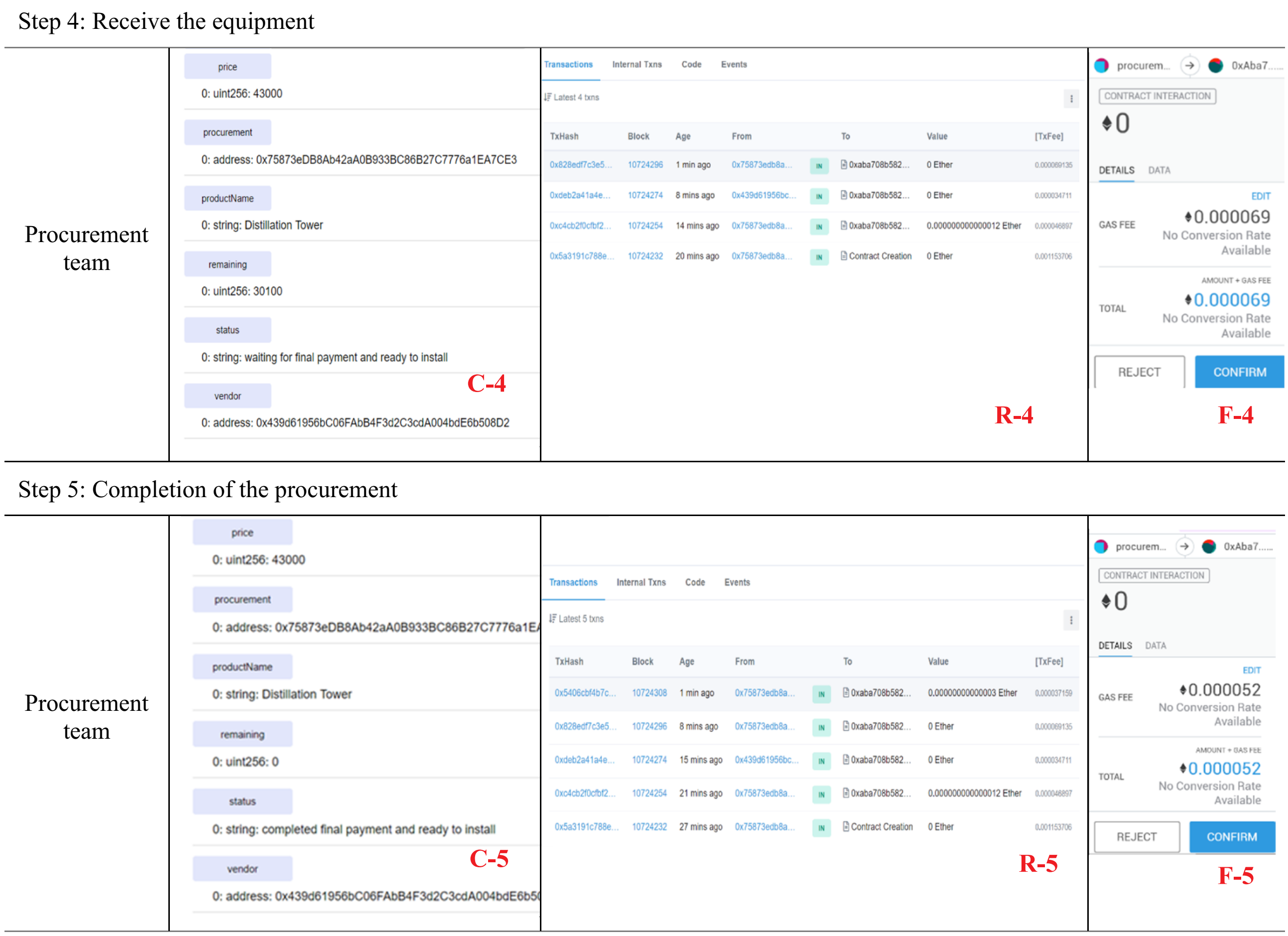

Fig. 9. (*continued*)

problems and improve efficiency of contract administration. Smart contract is suitable for the temporary and fragmented construction projects involving numerous stakeholders for tracking the progress status and settling financial payment, especially for international businesses such as Case 2, where the trustfulness among geographically dispersed parties may not be easily established. There are many cases in the construction industry that project retentions are unpaid, and the collaborative relationship is collapsed. Although the blockchain technology cannot solve the entire problem, it provides more confidence for product/service providers to run international businesses or be protected in small trades.

5.1.4. Interface and information integration

Although this pilot shows only a simple interface, this interface of smart contract can be incorporated into the existing enterprise management or procurement systems. These system users do not need to significantly change their working processes, as a blockchain platform works as a strong backbone system sitting behind the interface layer of current work applications. After a smart contract is designed accordingly and incorporated into current work interfaces, non-IT practitioners can operate them easily without having knowledge of the blockchain technology and adding much workload. In the two cases in this study, the interfaces are very easy to use. The users can upload required information or documents to the blockchain. The World Economic Forum categorizes digital technologies for various stages of construction projects into user interfaces and applications, software platforms and control, and digital/physical integration, and emphasizes the importance of technology integration and cyber security [82]. Blockchain technology can be integrated with most of these technologies (e.g., IoT sensors, RFID, drones, and BIM) to act as data platforms for companies which need data and transactions to be recorded and stored securely. Although the integration of blockchain technology with other technologies was not demonstrated in this study, this demonstration shows that evidence/documents in Microsoft Word format can be uploaded on blockchain (see Case 1). Data and documents in other formats, e.g. videos, images, and BIM models, can also be uploaded and stored. In this way, information on every transaction (e.g., cargo certificates, different standards, certificates, specifications, and regulatory compliance) from various stakeholders (e.g., manufacturers, suppliers, transporters, builders, and project owners) along supply chains can be logged and traced on blockchain. It is expected that this information integration will bring numerous benefits, including reducing the high level of fragmentation of construction supply chains, decentralized data storage, reducing time, improving scalability, and ensuring transparent, traceable and accountable data storage and sharing [4,83].

It should be noted that the main use case of using blockchain is not to store the data/assets but to record different status of these assets. The ledger does not directly store the business objects/assets, instead keep track of all the transactions that every member committed, that lead to the current state of each asset. Therefore, an external database is associated with each blockchain solution/ledger which stores all the assets or the business objects (e.g., cladding details and drawings) and the ledger stores the transactions that manipulated the assets (e.g., attaching proof of compliance to a cladding request). The amount of data that can be stored is subject to the required transaction speed and throughput. By limiting the access to the database via the blockchain platform only, we can make sure that other integrated solutions cannot manipulate the assets outside the platform.

5.2. Challenges of applying blockchain

5.2.1. Business variations

The construction industry has many variations. The governance of public blockchain platforms needs the consensus of majority of participants in the network, while private blockchains only need the stakeholders on that channel to validate changes. The speed of validation on public blockchain is likely slow compared to private or consortium blockchains. Through the study, we learnt that at this stage, it is still too early to establish blockchain systems for all project management activities. However, for the businesses which have relatively less variations and are critical, construction firms can consider it. Also, tools/templates are required to enable businesspeople with less computer skills to write smart contract for business.

5.2.2. Identity

Since there are many stakeholders and objects involved in construction business process, a standard identity format needs to be agreed and developed initially. Blockchain system also needs to identify the user and object quickly during business dynamics. In Hyperledger Fabric, each actor, i.e., peer, oracler, client, and administrators, has an identity associated with it by default encapsulated in a X.509 digital certificate which is issued by a trusted authority, also known as MSP with the use of the traditional public key infrastructure (PKI). The certificates are issued by a certificate authority (CA). The organisations who are members of the network can either use their existing certificate authority for issuing certificates or create their own new Hyperledger Fabric CA for this purpose. Each organisation is recommended to have one to one mapping between an organisation and an MSP to ensure that the identities of different actors from different organisations do not collide or undesired access is not granted. The identities of each actor that accesses the network has to be stored in a wallet (which can be stored in memory, file system or a database.). Each actor has its own wallet and uses the identities stored in this wallet to acquire memberships from different MSPs in the network and later to interact with the network. It is up to each organisation or the actor to decide how the wallet is managed (For example, an organisation can establish a policy that all the wallets are stored in a secure file system).

5.2.3. Cost of adopting blockchain system

Cost is a major concern in adopting blockchain systems. The transaction costs of using blockchains can be categorized into initial platform building, onboarding or deployment costs, cloud costs, ongoing maintenance costs, and monitoring costs. In the two demonstrations reported in this study, the initial costs of the private blockchain are higher than the public blockchain. Although users need to pay transaction fees to Ethereum per transaction, ranging from 0.000045 to 0.00154 Ether, the average transaction cost is still lower than that of the private blockchain. Ernst and Young [84] estimated that if the average transaction volume per day is lower than 1912, the average transaction costs of private blockchains are much higher than those of public blockchains, while if average transaction volume per day is higher than 1912, the average transaction costs of public blockchains are higher than those of private blockchains. For instance, if average transactions per day are 25 and 160, the transaction costs of private blockchains are approximately 12 and 6 times higher than those of public blockchains [84]. Transaction volume refers to the number of activities performed on the blockchain, which are related to the size and complexity of construction projects, businesses, and contracts. These factors should be taken into account when designing blockchain systems. It should also be noted that when deciding the feasible blockchain platform, multiple key criteria should be considered such as the normalised total transaction cost for the project duration, transaction speed and volume, ease of adaptability for the use case and integration into existing tools/infrastructure, and data privacy.

5.3. Vulnerability and security

As a smart contract normally involves high-valued assets, it is of great importance to ensure that the smart contract code is not vulnerable to attacks. Thus, testing the smart contract code is necessary, which can be realized by using security analysis tools to check the bugs and vulnerability, such as Oyente [77,85].

For public blockchains, transactions posted to blocks are visible to all users in that platform. Every node in public blockchain can access all the information on the blockchain without any permission [48]. Considering that data privacy is one major concern to using public blockchain, digital signatures, encryption and decryption have been proposed to ensure confidentiality, such as a secure Sockets Layer session after a successful handshake by Hasan and Salah [77]. Although some techniques can be adopted to protect confidentiality in Case 2, there are still some weaknesses regarding key management and extra costs and services, which are concerns of non-IT background professionals. The establishment of good confidentiality for public blockchain platforms is challenging. In this respect, private blockchains are favourable in most cases.

5.4. Complexity in adoption

The adoption of a new technology (e.g., blockchain) is always a challenge to traditional industries due to the learning curve. Learning curve is a disadvantage common to every blockchain platform which can be mitigated by providing trainings and technical support. Hyperledger Fabric has multiple steps such as endorsement policies and orderer service to ensure the consensus is met between all the peers. Non-uniform consensus and transaction contents collisions should also be considered.

The uptake of blockchain is not easy and requires the collaboration of multidisciplinary experts. As shown in Fig. 10, the aspects of regulation, construction industry trust, business, and technique should be considered to design and prioritize blockchain systems for the construction industry. Prior to designing a blockchain-based system, we can better determine that what kind of information should we stored on-chain, which can be accessed by public (e.g. the status of each asset), and what data we must store off-chain and keep them as a secret (e.g. privacy and sensitive data of stakeholders). The blockchain-based application/system may be easier than BIM, because for project-based applications, once project stakeholders consent to the business process and a blockchain system is developed, it does not require much in terms of new skills or changes in current business processes. The blockchain-based technology sits behind the current work system.

5.5. Scalability

Most of public blockchain platforms have scalability problems, such as transaction processing rate and data transmission latency [48]. The current public blockchain Bitcoin and Ethereum can process an average of 4 and 12 transactions per second, respectively [86,87]. Such processing rate is relatively low compared with payment service VISA (24,000 transactions per second) [88] and Facebook (millions of transactions per second) [86]. To accelerate the performance, side chains have been adopted and consensus algorithms are improved (e.g., PoS, and DPoS) that is helpful for the adoption of blockchain in the construction industry, but more work is required to address scalability issues [86]. For Hyperledger Fabric, in our use case a transaction time was generally between 30–60s. However, this would largely depend on the performance of the infrastructure, the size of the network, block size, transaction size, etc.

6. Conclusions

The blockchain technology is still relatively new but is widely

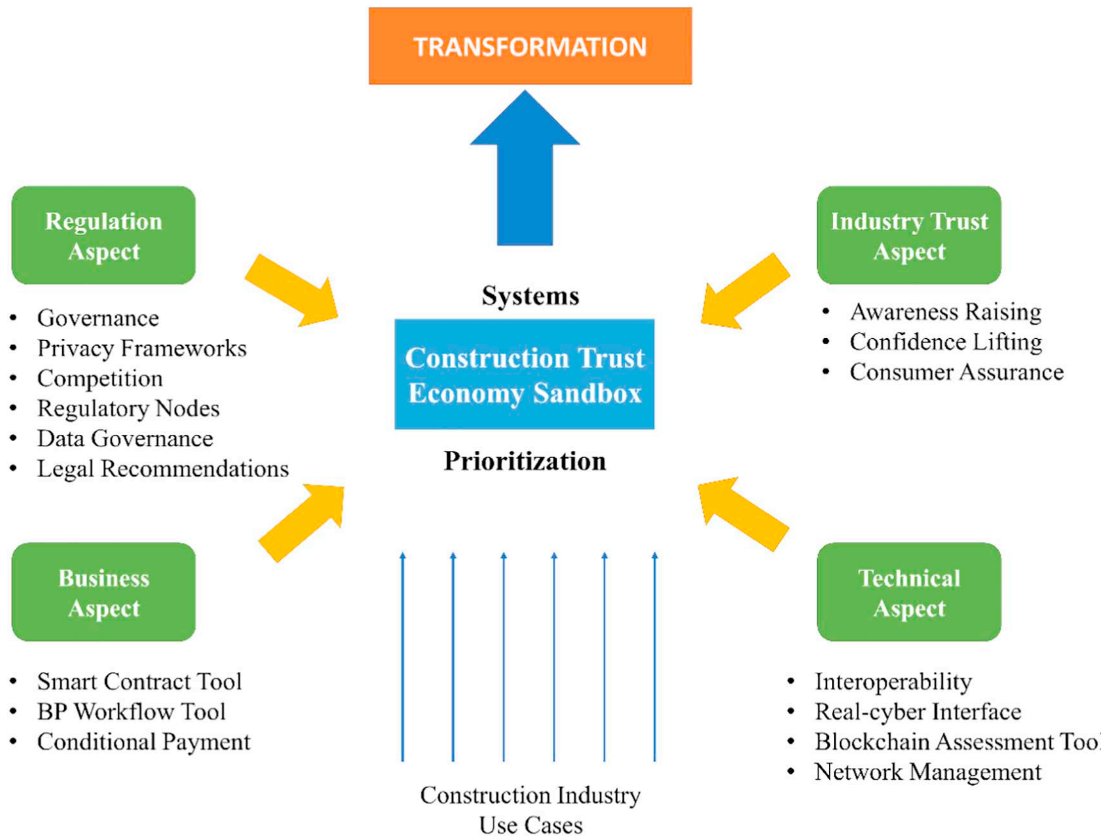

Fig. 10. Blockchain application framework in construction industry

regarded to have potential to solve many business problems. Many organisations and governments are attempting to incorporate blockchain technology into their business processes. A wide variety of pilot studies in some industries exist, which can provide insights to researchers and practitioners. However, such case studies are very limited in construction industry. In this paper, we adopted two existing business processes as real case studies and compared a public blockchain-based system architecture and a private blockchain-based system architecture by discussing their advantages and disadvantages of the two architectures. The challenges of adopting blockchain technology in construction industry are also discussed to point out future research directions. Two of the most industry faced public and private blockchain/distributed ledger platforms were adopted in this study which are also openly available to be used out of the box. Although many other blockchain platforms exist, it is beyond the scope of this study to compare all major blockchain platforms. A future study may consider the other major blockchain platforms that have many overlapping functionalities to Ethereum or Hyperledger Fabric appropriately while also acknowledging the contrasting features in each of them.

Declaration of competing interests

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

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