The outlook of blockchain technology for construction engineering management

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PUBLICATION DATE

01-01-2017

HANDLE

10536/DRO/DU:30133867

Front. Eng. Manag. 2017, 4(1): 67–75
DOI 10.15302/J-FEM-2017006

RESEARCH ARTICLE

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Abstract Current construction engineering management suffers numerous challenges in terms of the trust, information sharing, and process automation. Blockchain which is a decentralised transaction and data management technology, has attracted increasing interests from both academic and industrial aspects since 2008. However, most of the existing research and practices are focused on the blockchain itself (i.e. technical challenges and limitations) or its applications in the finance service sector (i.e. Bitcoin). This paper aims to investigate the potential of applying blockchain technology in the construction sector. Three types of blockchain-enabled applications are proposed to improve the current processes of contract management, supply chain management, and equipment leasing, respectively. Challenges of blockchain implementation are also discussed in this paper.

Keywords Blockchain, contract management, supply chain management, equipment leasing

1 Introduction

Trust relations in the construction industry concern people from organisations such as clients, contractors, subcontractors, and suppliers (Lau and Rowlinson, 2010). Previous studies have shown that mutual trust helps to smooth the construction process, allows flexibility for facing uncertainty, increases efficiency and sustains long-term relationships. In practice, formal contractual rules are always developed to legitimise behaviors and strategies at odds (Kadefors, 2004). However, current contractual relationships are mainly based on confrontational situations that reflect the level of trust (or mistrust) in the contract documents, which can be the driver to increase the total cost of a specific project (Zaghloul and Hartman, 2003). Today international contracting becomes common and the complexity of the construction projects is increasing (Lau and Rowlinson, 2010). These projects require not only advanced construction technology transfer but also a shared project information environment with fair data exchange. Conventional contracting methods and information exchange technologies are far from the industry needs.

Blockchain technology which started with the popular crypto currency Bitcoin allows digital information to be distributed without copied or altered. In the conventional construction industry, data are stored at a central database which can be accessed from various places. The security problem is the main concern because the transaction data could be altered by a hacker. The blockchain technology is different, which can be treated as a database that is shared on a peer-to-peer network. Transactions are grouped together in blocks in a certain time and then added to a permanent chain. These blocks cannot be altered once they are added to the chain, which makes the chain of transactions publicly verifiable and totally unhackable (Taylor, 2017).

Trust is the key feature of blockchain technology. If the construction business or activities are executed on a blockchain system, participants involved don't need to have an established trust relationship if they trust the blockchain itself. In addition, blockchain technology takes care of the information exchange by making every participant of the project a custodian of all the information flowing through the project lifecycle. Unlike Internet information exchange where information is passed from

Received January 17, 2017; accepted March 7, 2017

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point to point, in Blockchain, the same information is passed across to the whole system. Therefore, no persons including the sender have more information than others.

A construction project is a network of hundreds of processes, participants, products, and materials. Money transaction and/or data exchange are frequently performed along with project progressing. There are a significant number of disputes and litigations occurring during construction. Although things like payment terms and data confidentiality are outlined in a contract or an agreement, disputes often arise over the stipulations of the agreed protocols (Taylor, 2017).

Current research of the Blockchain technology is limited to the digital currency (i.e. Bitcoin system) though the technology is applicable in other industries (Yli-Huumo et al., 2016). The purpose of this paper is to introduce the concept of Blockchain technology and investigate its potential applications in the construction sector to avoid these disputes. Three types of blockchain-enabled applications are proposed and demonstrated in this paper including blockchain-enabled contract management, blockchain-enabled supply chain management, and blockchain-enabled equipment leasing. Challenges of blockchain implementation are also discussed at the end of this paper.

2 Challenges in construction engineering management

The first challenge faced by the construction corporations is the trust issue. Traditional construction engineering management involves trust issues in almost every aspect of daily activities. For example, (Johnston et al., 2004) found that in the buy-supplier relationship of construction engineering management, supplier's level of trust is related to some inter-organizational cooperative behaviors, such as shared planning and flexibility. To manage project relationships, especially in a cross-disciplinary environment, a higher level of trust is expected to enhance project performance (Kadefors, 2004). Similarly, (Wong and Cheung, 2005) argued that the establishment of trust is the most critical factor that facilitates partnering success, which means that management should direct their effectors to enhance a systematic and effective trust system between various partners.

However, there seems to be a problem of building such a systematic and effective trust system in traditional construction engineering management. Traditional construction engineering management uses lump-sum contract and lowest bidder will normally be appointed. If the lump-sum contract is used, many aspects of the building design will not be measured accurately in verifiable terms, which may affect the completion of the project (Kadefors, 2004). In addition, as (Kadefors, 2004) pointed out, the constant change of requirements will also impede the establishment of a trust system. The level of trust that is required for successful completion of the project is also very difficult to be determined. For example, according to (Wicks et al., 1999), it is expected that the extrinsic and economic incentives of other people's work will normally be overestimated and the intrinsic and non-monetary incentives, such as social recognition, will be underestimated. From a rational point of view, participants in construction engineering management tend to emphasize their own economic self-interest. As such, building a systematic and effective trust system may be difficult. It may be beneficial to investigate project success in an environment where no trust is required in single entities.

Supply chain issue is the second main challenge. Many studies in the construction engineering management discipline have focused on improving supply chain management performance between manufacturers, distributors, contractors and customers (Simatupang and Sridharan, 2005). According to (Kopczak and Johnson, 2003), the ultimate goal of supply chain management is to achieve seamless and agile supply chain to meet customers' needs at lowest cost. However, because of the conflicting interest of various participants in the supply chain, this ultimate goal is very difficult to achieve.

There are a variety of reasons leading to ineffective and inefficient supply chain performance in construction engineering management. However, it is argued that the transparency and traceability of products should be highlighted as the basis for further improvement (Abeyratne and Monfared, 2016). At the moment, it is very difficult for end-users to track the origination of the products, their delivery, storage as well as distribution. This problem is amplified in a complex project where second-tier suppliers and subcontractors are involved. In a complex project, transparency in the supply chain requires that the information of every product in the supply chain be documented in a centralised system so as to understand the effects and consequences of an isolated decision on the overall supply chain performance (Abevratne and Monfared, 2016). It requires accurate data collection, input, storage and analysis between various participants in the supply chain. At this moment, there are very limited studies which focus on visualizing the transparency of supply chain (e.g. see Bonanni, 2011). However, it should be noted that these studies rely upon an established trust system between various participants. In addition, the company that owns the centralised supply chain performance system will gain significant power by obtaining such valuable data, which may potentially damage other companies. It seems that there is a need for a de-centralised system in managing supply chain data, which can help improve supply chain management performance without building a trust system between participants.

The other important aspect of supply chain management is related to information sharing, including information sharing support technology (such as the software used to record supply chain data), information content and information quality (Zhou and Jr. Benton, 2007). As stated earlier, there are many studies which focus on using advanced IT applications for supply chain management. However, such applications require a centralised company to record and manage the data, which other participants may not be willing to provide. Information quality refers to the degree to which the shared information can be trusted and used to meet the needs of the supply chain (Petersen, 1999). It can be measured by accuracy, frequency, credibility and availability (McCormack, 1998). However, it should be noted that traditional construction engineering management practices may not be sufficient to help achieve such information quality. For example, it is necessary to have an established mechanism to identify false information and providing false information should be penalized.

The third one is related to asset management, which is of critical importance in construction engineering management, especially for sectors where much attentions are directed toward operation and maintenance. As such, many studies have focused on asset management in construction engineering management. Similarly, asset management in construction engineering management shares some of the aforementioned challenges, such as sharing data between different parties, as well as reducing the needs of duplicative data. In addition, it is recommended that such data should be collected by a distributed ledger, which is defined as geographically spread digital data across multiple sites (Shah et al., 2016). It can help reduce the risk of a single entity owning the whole asset data.

In addition, current asset management practices are that each company constructs their own asset management platform using their own internal database. Such practice has created some challenges around interoperability, especially when multiple asset management platforms are involved. The interoperability issue, which can be solved by creating assorted API solution, of an industry-wide or even cross-industry collaborations will be too complicated. In addition, the company who owns the API solution or the cross-industry asset management platform may intentionally reduce its interoperability with other platforms in order to gain a strong economic advantage (Mattila et al., 2016). While this may be good for the API owner, it may damage the overall productivity of the whole industry.

Other than interoperability issue, traditional asset management practices which rely on data input into a centrally controlled platform are not appealing to all participants. Providing data to a platform which is owned by other companies leads to the reluctance of participants. Although this problem can be addressed by using a trusted agent who is not a direct participant of the project (e.g. using the asset management platform provided by individual software developers), it should be noted that the direct participants of the project will lose values in terms of control of the platform (e.g. if the individual software developers decide to stop updating the platform). As such, it seems that a decentralised system is required in asset management so that all participants are equal and they can all gain values out of the system by providing accurate and reliable data.

3 Blockchain technology

Blockchain, mostly known as the technology running the Bitcoin cryptocurrency (Nakamoto, 2008), is a public-permissioned-distributed ledger system maintaining the integrity of transaction data (Yli-Huumo et al., 2016). According to the Allens (2016), the distributed ledger can be public or private. A public ledger has no central owner which can be accessed and maintained by any member of the public. Identical copies of the ledger are distributed to everyone in the network. A private ledger is one with limited or pre-selected participants that are authorised to transact and interact while subject to some form of external control.

The blockchain information exchange is disintermediated and every individual in the ecosystem has access to the same information as the other participants. The essential feature of blockchain is the maintainability of the data and information without any organizations or governmental administration in control. Swan (2015) classified the blockchain technology into three categories: Blockchain 1.0, 2.0 and 3.0. Each of them is explained in detail as follows.

Blockchain 1.0 is for the decentralisation of money and payments. Bitcoin is a typical application in this category. The core functionality of blockchain 1.0 is that any transactions can be sourced and completed directly between two individuals over the Internet. Unlike fiat currencies for which governments can print more money, the money supply of Bitcoin grows at a predetermined rate. The new currency is being issued at a regular and known pace, with about 13.5 million units currently outstanding, growing to a capped amount of 21 million units in 2040.

Blockchain 2.0 is for the decentralisation of markets more generally, and contemplates the transfer of many other kinds of assets beyond currency using the blockchain, by the creation of a unit of value whenever it is transferred or divided. Blockchain 2.0 can include Bitcoin 2.0 and its protocols, smart contracts, smart property, Decentralised Applications (Dapps), Decentralised Autonomous Organizations (DAOs), and Decentralised Autonomous Corporations (DACs). All financial transactions could be reinvented on the blockchain, including stock, private equity, crowdfunding instruments, bonds, mutual funds, annuities, pensions, and all manner of derivatives. Public records (i.e. property ownership certificates, business licenses, and vehicle registrations), digital identities (i.e. identity cards, passports and driver licenses), and private records (i.e. loans, signatures and escrows) can be migrated to the blockchain and stored. Attestation can be executed via the blockchain for proof of insurance, proof of ownership, and notarised documents. Physical assets such as houses and cars, and intangible assets such as patents and copyrights, can also be encoded, protected, and transferred via the blockchain.

Blockchain 3.0 is for the justice applications beyond currency, economics and markets, particularly in the areas of government, health, science, literacy, culture, and art. The freedom attribute associated with the blockchain becomes more pronounced in Blockchain 3.0, which is fundamentally a new paradigm for organizing activity with less friction and more efficiency. The coordination and acknowledgment of all manner of human interactions, and a higher order of collaboration between human and machine can be significantly facilitated through the blockchain 3.0. Blockchain government is an important application of the blockchain 3.0, which uses the blockchain as a universal, permanent, continuous, consensus-driven, publicly auditable, redundant, record-keeping repository to provide decentralised government services.

4 Potential applications of Blockchain in construction engineering management

Potential applications of the blockchain in construction engineering management can be classified into the following three categories:

(1) Notarization-related applications to eliminate the verification time of documents' authenticity. Corporations operating within the construction sector face mounting pressure to meet increased industry and government regulations. Notable resources including time and labor are assigned to preserve the integrity and authenticity of construction documents during storage and retrieval. With the implementation of the blockchain, every document can be stored in a distributed ledger, there is a perfect notarization of each creation, deletion, and updating across the system. The whole blockchain system knows exactly what the source of the information is and the technology enables the authentication. Such type of applications can be used for recording construction quality data including the quality of the raw materials and installation, construction progress information (i.e. daily, weekly and monthly), and resource consuming data such as concrete, scaffold, formwork, steel, and equipment.

(2) Transaction-related applications to facilitate automated procurement and payment. It is easy to perform title transfer for any properties including tangible and intangible whose ownerships are controlled by the blockchain. In the construction sector, there are numbers of disputes that are related to payment, technology transfer, equipment leasing, and house selling. With such applications, significant time and cost can be saved if all of the processes are automated and neutral.

(3) Provenance-related applications to improve transparency and traceability of construction supply chains. Since every transaction is visible in the blockchain ecosystem, it is easy to trace backward of the supply of each product or service with authenticity from a compliance or quality assurance perspective. This is of particular importance in global construction projects. For instance, during operation and maintenance stage, if a serious defect of a product is found, the histories of the total supply chain are always available from the raw material preparation to offsite manufacturing, transportation, site construction, and until the final commissioning. The responsible party of the occurred defect can be quickly identified and confirmed without tedious arguments because all of the records stored in the blockchain system are authentic and non-editable. There are no chances, in theory, to hack into the system and manipulate the records to suit one party.

To demonstrate how to use the blockchain technology to address the three challenges mentioned in Section 2, three types of blockchain-enabled applications are proposed, respectively. For the trust challenge, contract management is selected as an example to show the capabilities of the blockchain. The application of blockchain-enabled contract management developed in this paper belongs to the category of the notarization-related applications. To solve the issues of transparency and traceability in the supply chain management process, a blockchain-enabled supply chain management system is proposed which belongs to the category of the provenance-related applications. In terms of the challenge faced by asset operators, due to the broad area of the asset management, in this paper the authors only choose a small sub-topic of the asset management (i.e. equipment leasing) to illustrate the underlying mechanism of the blockchain. The proposed blockchain-enabled equipment leasing system belongs to the transaction-related applications.

4.1 Blockchain-enabled contract management

A blockchain-enabled contract, also called smart contract, is an agreement that can execute a part of its function by itself (Swan, 2015). The self-executing component is built based on the blockchain technology and requires the expression of terms in logic statements. Figure 1 illustrates a simple example which is developed based on the Ethereum blockchain platform (Ethereum, 2016). The contract states that if the temperature of the construction site is higher than 40 degree centigrade, then the client pays to a certain amount of dollars (allowance) to the construction contractor. With such a smart contract implemented, three significant improvements can be achieved in the current construction sector. Each of them is described in detail in the following paragraphs.

SOLIDITY CONTRACT SOURCE CODE

```
pragma solidity ^0.4.2;


contract MyContract {
    /* Constructor */
    address public contractor;
    uint256 public allowance;
    uint256 public temperature;

    mapping (address => uint) public balanceOf;
    event Transfer(address _from, address _to, uint value);


    function token(uint supply) {
        balanceOf[msg.sender] = supply;
    }

    function transfer (address contractor, uint256 allowance) {
        if (temperature < 40) throw;
        if (balanceOf[msg.sender] < allowance) throw;
        if (balanceOf[contractor] + allowance < balanceOf[contractor]) throw;

        balanceOf[msg.sender] -= allowance;
        balanceOf[contractor] += allowance;
        Transfer (msg.sender, contractor, allowance);

    }
}
```

Fig. 1 A smart contact example

The first one is eliminating the payment and cash-flow issues. Payments withheld or not paid is a serious problem in the current industry, and has been highlighted as the main cause of business failures and escalating disputes. With a smart contract, the funds or cryptocurrencies can be embedded into the contract against the insolvency of the late payments so as to protect general contractors, subcontractors and suppliers. Moreover, these smart contracts can be interlined with each other to create a web of payments. For instance, when a construction project achieves a payment milestone such as structure completed to building Level 10, the general contractor will get an automated payment through the smart contract with the project client. This event will also automatically activate all the related payments, such as the smart contracts between the general contractor and their subcontractors or suppliers, based on the contract conditions.

The second one is improving the efficiency of the contract administration process. A smart contract is expressed as a software code which is unambiguous and predictable when compared with the traditional contracts. Massive time in terms of contract registration, monitoring and updating can be saved because of the automated process and tamper-proof system.

The third one is reshaping the trusted behavior from the human trust to coding trust. The cost of building trust among different parties in a construction project is very high because every project is one-off and the project team is always temporary. In the traditional way, construction lawyers play a key role in creating and managing the enforcement of many of business rules through contracts and litigation. To maximise their profits in a real project, corporations rely on in-house lawyers or large firms to help them stay on the right side of the law and execute their contracts appropriately. Blockchain makes it easier for two parties to trust each other without a third-party enforcer. The blockchain-enabled contract can be stored in a non-editable format. Together with the self-executing codes, neither party has the upper hand to tamper or prevent the execution of the contract. With right code and secure code executing across a peer-to-peer network of databases, the "trust" function that a legal team currently plays becomes redundant, which can lead to significant time and cost savings.

4.2 Blockchain-enabled supply chain management

The main challenge of the traditional supply chain is the shortage of an open and trustworthy information resource across the supply chain. Customers and buyers have no reliable ways to verify and validate the true value of the products they purchase because of the lack of transparency and traceability. A typical supply chain is a series of bilateral contractual links that are put next to each other to form a supply chain such as: buyer-vendor link for the procurement of materials or equipment, production-distribution link for transportation of the products, and inventory-distribution link for the optimal inventory levels. Every link in the supply chain is a bottleneck for information sharing and trust erosion.

The Blockchain technology has the potential to tackle these challenges through the use of the open permissioned ledger system. Figure 2 shows a blockchain-enabled supply chain for an off-site fabricated instrument from procurement to the end of the final installation.

The system starts with the purchase order developed by the project owner. The manufacturer who fabricates the instrument receives the information and send the raw material requirement to their suppliers. The system then sends a notification to the inspection agency which records the details of the raw materials to be inspected. During the manufacturing process, records related to the quality of cutting and drilling, welding, surface treatment, and assembly are also uploaded to the blockchain system. Once the inspection agency has issued the certificates to approve the delivery, the shippers can arrange to ship the instrument and issue the delivery status in the system, such as alongside ship, on board and ship's arrival. When the instrument is unloaded in a material offloading facility, a notification of quarantine inspection will be sent to the specific department. All of these records are available to the supply chain participants and can enable any audits on quality issues faced in the downstream supply chain. Since the information input to the blockchain system is authenticated, the reliability of the information is significantly higher than the traditional. In addition, the extended supply chain traceability can be also achieved, for instance, each part of the instrument can be traced to the provenance.

4.3 Blockchain-enabled equipment leasing

With the increased complexity of the construction projects, there is a large demand of using heavy equipment to help deliver their jobs such as cranes, compressors, excavators, and loaders. Due to the high cost of these heavy equipment including maintenance and repairing cost, most of the construction contractors face financial constraints to purchase. Therefore, instead of making huge investments in buying them, leasing is a lucrative option for both large and small contractors to cut down their expenses on construction projects.

Conventional leasing process is time-consuming and inefficient, which includes lengthy negotiation cycles, insurance quoting procedures, burdensome financing applications, and reams of paper documents need to be signed and maintained. Figure 3 illustrates an example of a crane leasing which is developed based on the IBM Blockchain Platform (IBM, 2016). For a new crane to be produced, the manufacturer needs to record the crane first in the blockchain system. To begin the process, a prospective construction contractor (i.e. leasee) chooses the crane they want to lease after checking and evaluation according to their requirement. The crane's identity is then registered on the leasing blockchain (i.e. the secure ledger database) to record transactions over broadly-distributed computer networks. After that the construction contractor will choose a lease option for the crane (i.e. short-term, long-term, or finance lease). This is all in turn updated on the Blockchain. They then choose their insurance options in a familiar way, and the Blockchain would again be updated. The customer then links their payment details to pay for the lease and insurance, and crane payments will be covered automatically like operational training, maintenance and repairing services. All of the above processes will take a mere matter of minutes. Together with sensing technologies, the operational status can be tracked and recorded in the blockchain such as abnormal breakdown events, daily lifting load and frequency, and electricity consumption.

5 Discussion

Blockchain technology is no doubt a disruptive innovation

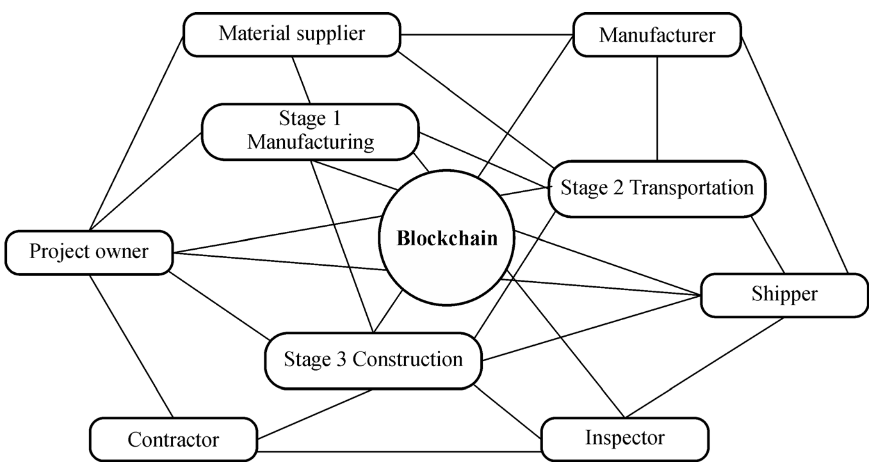

Fig. 2 Blockchain-enabled supply chain

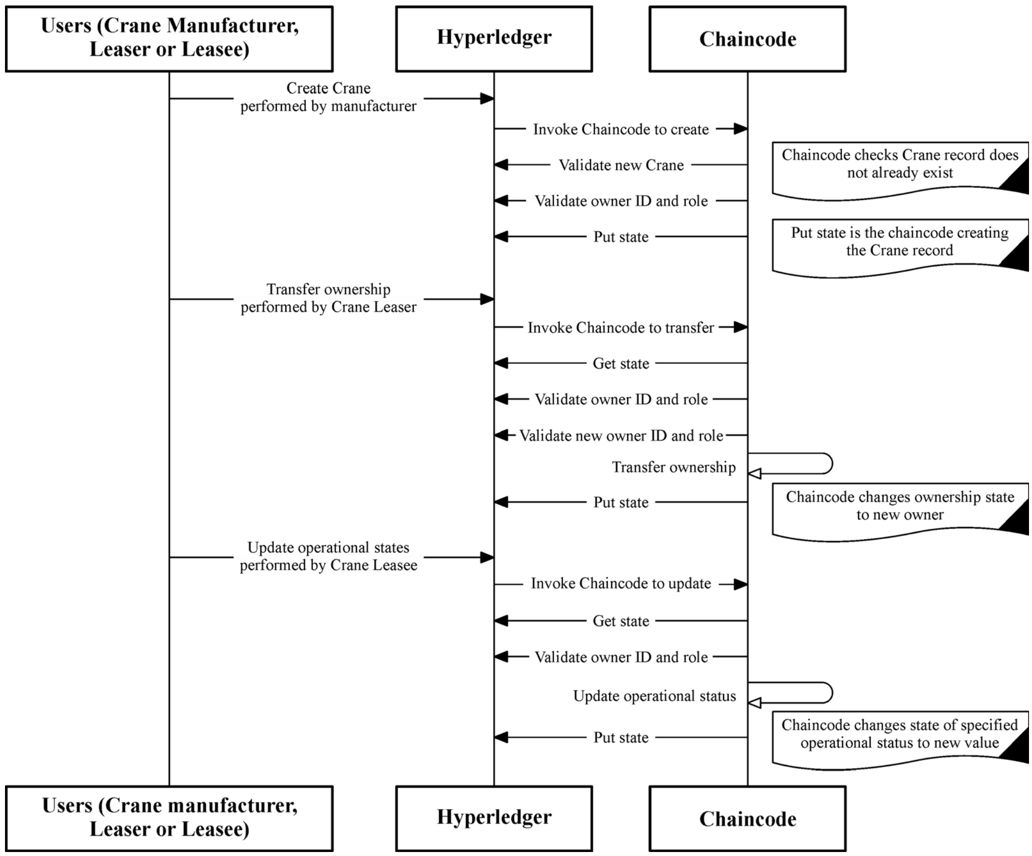

Fig. 3 An example of a blockchain-enabled crane leasing

that has the potential to revolute current practice of construction engineering management. Compared with conventional methods of performing contract management, supply chain management and equipment leasing, the three proposed blockchain-enabled applications can significantly avoid disputes and litigations due to the immutable data record. Time and cost can be also reduced through process automation. However, there are still lots of challenges when implementing it into real construction projects. Three main types of challenges are discussed as follows.

(1) Technical challenges: The blockchain technology is still in the early stages of development and faces a number of technical limitations such as throughput (a theoretical current maximum number is 7 transactions per second), latency (each block takes 10 min to process which means at least 10 min needed for your transaction to be confirmed), and size and bandwidth (long time needed to download the entire blockchain). Detailed information can be found in the Swan (2015).

(2) Construction business-related challenges: Companies in construction sector had got accustomed to maintaining their business activities in their own ledger in the last many centuries. It is very hard to change the way to a permissioned distributed ledger. Moreover, most of the companies have incurred heavy investment on building their Enterprise Resource Planning (ERP) systems in the last few decades. The position of blockchain has a conflict with these internal ERP systems, which makes the transformation become more difficult. Another significant challenge is the significant initial investment if a private blockchain solution is selected, which means companies involved in a construction project need to develop a full ecosystem to provide the entire value chain of service delivery. Due to the one-off characteristic of the construction projects, the reuse of existing private blockchain solution becomes difficult.

(3) Human-related challenges: Blockchain is still an emerging technology to most construction people. Lack of awareness and understanding prevents the diffusion of this technology. There are many issues to be resolved before individuals would feel comfortable storing their personal records in a decentralised manner with a pointer and possibly access via the blockchain. In the current blockchain architecture, if a personal secret key is stolen, the implications could be staggering for an individual who would no longer have his identity at all due to the identity theft.

The blockchain technology is still quite new to construction corporations. Many firms are still in an exploratory phase due to the numerous technical and regulatory uncertainties. Construction corporations that want to assess the viability of the blockchain technology for specific applications, such as supply chain management, should consider a number of factors, such as anticipated time and cost reduction in goods delivery, current supply chain management costs, and blockchain deployment cost. The next step is to clearly identify risks and challenges. Only then should a corporation begin developing a detailed blockchain roadmap, determining user scenarios and creating an implementation schedule. In the meantime, construction corporations should consider which uses would benefit most in the near term, explore the technology closely, and engage with one another in test cases to create blockchain-enabled distributed ledgers (Accenture, 2015).

In terms of blockchain integration with other innovative technologies, such as Building Information Modeling (BIM), there are few pieces of evidence from both academia and industry sectors. BIM has been widely used in current construction industry to improve collaboration, data exchange, information flow, and project delivery (Chong et al., 2016; Shou et al., 2015; Wang et al., 2015a; Wang et al., 2015b; Wang et al., 2016). The blockchain technology can provide a useful tool for managing and recording changes to the BIM model throughout the design and construction phases by using smart contracts to negotiate editing privileges and storing an immutable public record of all modifications to the model (Lohry and Bodell, 2015). Moreover, blockchain combined with the database properties of a BIM model can provide a vital, visible and permanent chain of "evidence of trust" which in turn can lead to a new value proposition for the construction industry and the clients its serves (Mathews, 2017).

6 Conclusions

This paper has shown the potentials of how to apply the blockchain technology to improve current construction industry. Through the investigation of the technology itself and considering the challenges faced by construction corporations, three types of blockchain applications are discussed which are: Notarization-related applications to eliminate the verification time of construction documents' authenticity, Transaction-related applications to facilitate automated procurement and payment, and Provenance-related applications to improve transparency and traceability of construction supply chains. This paper also demonstrates three blockchain-enabled user scenarios including contract management, supply chain management, and equipment leasing. In the near future, more case studies in the construction sector will be conducted to assess the effectiveness of the blockchain system. This may include partnering with local industry partners, and testing the blockchain in their real projects. Detailed benefits and technology limitations will be also measured.

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