Cup-of-Water theory: A review on the interaction of BIM, IoT and blockchain during the whole building lifecycle

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Abstract

The Architecture Engineering and Construction/ Facility Management (AEC/FM) industry plays a significant role in the development of economy. In recent years, the wide application and development of Building Information Modelling (BIM) promote the development of informatization and digitalization of AEC/FM industry. However, due to the limitation of a one single tool and lack of understanding of single source of truth, the problems of the industry cannot be solved completely. Therefore, the revolution and innovation of industry can be stagnated. Internet of Thing (IoT) and blockchain can be considered as two technologies that can be integrated with BIM for AEC/FM industry. The aim of this paper is to understand and analyse the basic principles and the applications of these three technologies in AEC/FM industry through literature review. With the integration of these three technologies, the virtual and realistic object and data during the whole building lifecycle can be managed and stored in a security, transparency and convenient decentralized common data environment (DCDE). Finally, a theory named, Cup-of-Water theory is presented.

Keywords –

BIM IoT blockchain AEC/FM industry whole building lifecycle

1 Introduction

In recent decades, the development of global AEC/FM industry is slow compared with other industries, such as manufacture industry, aerospace industry or financial industry. This phenomenon results from low digitalization, loose collaboration and ineffective management methods in most building projects. Hence, it is of significant importance to use new technologies to improve the productivity and efficiency in all phases of a building project, including design, construction and operation and maintenance stages.

BIM, which represents one of the key technologies in revolutionizing the AEC/FM industry, is expected to stimulate a major change to this conventional industry with lots of waste, low productivity and low efficiency. BIM not only provides advanced visualization tools and real-time information synchronization, but also realizes multi-disciplinary collaboration and comprehensive management for a building project lifecycle. Increasing number of AEC/FM firms are having transition from CAD to BIM [1]. It can be estimated that more and more innovations will occur in the future as the building information can be easily recorded, queried and transmitted in a common data environment (CDE).

IoT is a network which allows the data collection and exchange of real objects supported by Internet or traditional telecommunication network. It is possible to use IoT to make building components to be on the network in a unified form [2]. Construction management can then be optimized since materials, equipment and other objects can be traced.

Blockchain technology is a decentralized ledger database, which is initially adopted as a bottom structure of Bitcoin system. It has a well performance on data updating, storage and protection [3].

The objective of this paper is to investigate how these technologies can interact with each other and produce new applications that can benefit AEC/FM industry. Through review and case studies, the principle, technical advantages and applications of each technology are reviewed. Based on those information, the author makes classification with regard to interaction forms, and discuss the advantages and limitations of different ways of interaction. At last, a new theory is came up with to demonstrate the integration of these technologies and how they affect a building project.

2 BIM based Building lifecycle

The lifecycle of a building, mainly contains several processes including the programming, conceptual design, detailed design, analysis, documentation, procurement, fabrication, construction, construction logistics operation and maintenance, renovation or demolition [4]. Due to the characteristics of a construction project, rich technical content, long construction period, high risk and many stakeholders, the project requires systems of good management over the lifecycle of a building. Life-Cycle Management (LCM) has been developed as a business approach for managing the total life-cycle of products and services [5].

With the integration of BIM, some problems of the traditional LCM such as lack of effective information sharing, and the efficiency of the LCM indeed increased significantly [6]. The BIM models contain actual information of the building including the geometric information and non-geometric information such as material for building components, weight, price, procedures, scale and size [7]. Information management aim to provide the right information, in the right format and quantity, at the right time, to the right person, and at reasonable cost [8]. BIM can provide semantically rich digital building models at each process of the project in the whole building lifecycle and the object-oriented concept is utilized to improve the efficiency of the information management in the building lifecycle [9].

A construction project has many stakeholders. With the development of BIM, many questions and problems of BIM application are put forward during the collaborative work. Thomas [10] indicated some legal issues including the ownership of the building model, the modification rights, the distribution rights and the liability for changes or errors. Meanwhile, how to manage copyright protection and how to protect digital intellectual property are also the questions that should be of concerned for relevant stakeholders. Due to the data and information exchange between each stakeholder, the trust and networking costs are also two problems of BIM application currently [11].

3 IoT

IoT is a network of internet-connected objects that able to collect and exchange data using embedded sensors [12]. It mainly includes three key technologies. The first one is sensor technology. It can be used to convert the analog signals to digital signal. The sensors include the infrared sensor, global positioning system and other information sensing devices. The second is RFID tag. It is a kind of sensor technology combining wireless RF technology and embedded technology. Third is Network Embedded System Technology. It is a complex integration technology integrated with computer software and hardware, sensor technology, integrated circuit technology and electronic application technology [13].

4 Blockchain

4.1 Definition and principle

Blockchain technology is most commonly known as a technical base of Bitcoin system. It allows the transfer of ownership of valuable things by binding the digital currency with rights to an asset [3]. The success of bitcoin trading attracts people to explore the theory of blockchain and relate it to other fields, such as IOT, supply chain, smart contracts. In substance, blockchain is a decentralized distributed ledger database using peer-to-peer network. The data on blockchain is maintained by every node on the network, and every user preserve total history of all transactions. This mechanism eliminates the existence of central administrator. In other words, no third party would participate in the network to supervise and manage user data [14].

When user performs a transaction on their computer, which is recognized as a node in the network, the node should identify whether this transaction is valid based on rules of protocol. If this transaction deemed valid, it would be relayed on a new block. Some nodes with strong computation power would put a number of transactions together and encrypt them into a block. Due to the nodes which made encryption requires a lot of energy, money and time to operate machine to calculate hash number [15]. It resulted in the difficulty for anyone who wants to attack the network for they need to expend more to decrypt the block [16]. After transactions are assembled and new block is enclosed with a header called timestamp, the new block is added to the end of the longest chain and referenced to the preceding block. This made the time sequence of the chain clear so that less resource would be wasted due to the delay of P2P network [17]. Once the chain is updated, the new chain would be announced to all nodes on the network and every user had the same copy of ledger of transactions.

4.2 Categories of blockchain

There is always misunderstanding that all the blockchains are opened to any parties in the world so that information storing on blockchain might have privacy problems. Actually, this case refers to the most commonly seen category of blockchain, which is named public blockchains. Besides, blockchain includes two more categories: Consortium blockchains and private blockchains.

4.2.1 Public blockchains

On public blockchains, any individual or organization all around the world can send transactions and the transaction can be verified to be valid. Everyone involved in this peer-to-peer network can take participation in the consensus process. Public blockchains enable users to handle their transactions in a simple manipulation. However, the network might be slow sometimes due to too much load on it.

4.2.2 Private blockchains

On private blockchains, the network demands an invitation and must be validated by either network builder or certain rules assigned by network starter. Each transaction is recorded by the approved parties or entities, instead of all participants in the network. The blockchain creator would normally set up a permissioned network, which defined authority of participants in the network [18].

4.2.3 Consortium blockchains

Consortium blockchains are also called simply hybrid blockchains, which combines the public and private blockchains. The transaction recorders are preselected in an internal group, and the production of block is determined by all these preselected nodes [19]. The rest of access nodes just participate in the transaction, they do not interfere with the Bookkeeping process, and anyone could query the limited information on the blockchain by accessing the specified API provided by the blockchain network.

4.3 Technical advantages of blockchain

4.3.1 Decentralization

Blockchain network uses distributed storage instead of a central storage system. There is no central governor on the network, which implies the consensus could be reached without centralized control. The right and responsibility of any nodes are equal, and the data in the system should be preserved by all the nodes with maintenance function. Decentralization make the transaction on the blockchain complete without extra third parties. Consequently, it provides a reliable ledger platform which eliminate the credit risk of involvement of intermediate parties [20]. At the same time, decentralization has spared the burden whenever database administrator should make decisions on protocol rules. The participants on blockchain could make specified protocols according to property of business.

4.3.2 Peer-to-peer network

Peer-to-peer network is a network system without central server and exchanging information by user groups. It realized the information transfer between each two nodes on the blockchain [21]. Unlike central network systems with central servers, each user terminal of a peer-to-peer network is both a node and a server function. In the blockchain, each node has a complete set of historical transaction books. The peer-to-peer network of blockchain solves the problem of data correctness caused by a single data source. Each user node has a history record so that the overall database could remain static even one node is attacked.

4.3.3 Immutability

Blockchain always maintains a growing chain, once the information is verified and added to the blockchain, it will be permanently stored. The transaction on blockchain can only be added and cannot be modified. Therefore, the data stability and reliability of the blockchain are much higher.

4.3.4 Consensus mechanism

The consensus mechanism solves the problem of data block being encrypted by any node in the network, so as to prevent the blockchain from being bifurcated, and there always exists the unique longest chain. Because most blockchains are open, the anti-attack and stability of the consensus protocol is critical. Current workload proof (PoW) and equity Certificate (PoS) are two of the most common consensus mechanisms.

4.3.5 Secure encryption system

Taking advantages of asymmetric encryption and hashing, blockchain ensures that transactions cannot be denied and destroyed, and the privacy of user information and records is protected as far as possible.

5 Interaction of BIM, blockchain and IoT

Overall, BIM, blockchain and IoT are advanced technologies in three various categories. BIM digitalizes the building information while IoT connects realistic objects with Internet, and blockchain transmits data on a decentralized network. When considering how these technologies can contribute to a building project, it is difficult to analyse benefits of a single technology. In other words, it is interaction of different technologies that breeds new applications, and therefore improves the way the AEC industry generates single source of truth for digital information. In this paper, the enhancement from interactions of these three technologies can be concluded below.

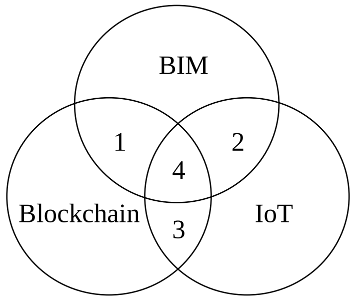

Figure 1. Interaction of BIM, IoT and blockchain

Note:

1. BIM and blockchain: contract, supply chain, modification record.
2. BIM and IoT: green and smart building, construction site safety, e-Commerce
3. IOT and blockchain: Decentralized IOT database, privacy, external collaboration
4. Integration of BIM, IOT and blockchain

As shown above, the interaction of BIM, blockchain and IOT could bring about technical and management innovation throughout the life cycle of construction project. It is necessary to analyse the potential benefits and restriction of these applications following the order as listed above. After that the value of interaction of BIM, blockchain and IoT can be realised.

5.1 BIM and blockchain

5.1.1 Smart contract

In construction project management, there existed many issues relevant to transaction and documentation. First, payment delay or not paid on time have been stressed out as one of the main factors causing conflicts and disputes between each party [1]. Secondly, the traditional contract signing in a construction project required a complex procedure with confirmation of different parties. And the documentation of a contract is a time-consuming process considering various forms of contracts and different properties of transactions. However, smart contract, which is an important innovation enabled by blockchain technology, might be helpful in construction.

Szabo, the proposer of smart contract, described that “smart contract is a computerized transaction protocol that executes the terms of a contract” [22]. It should have several functions that meet fundamental contractual conditions, such as payment and liens. At the same time, smart contract can reduce or eliminate the influence of third party and can improve the efficiency of signing. At that time, digital technology is not mature so that smart contract was only at conceptual level. Today smart contract can be computer program coding based on blockchain system that executes the predefined terms without intermediate. Digital currency like bitcoin or ether are used to achieve payment or exchange with realistic asset.

Compared with traditional contractual ledger, smart contract has several advantages on built environment.

a) As mentioned above, payment not being completed on time is a serious problem causing loosen collaboration and decreased working efficiency. Smart contract can effectively prevent such cases by binding the payment together with contract. Once the work has been done, the fund stored on the contract would be released and sent to a contractor.

b) Smart contract can be executed automatically following its code. It saves a lot of time which people should spend executing or supervising the contract manually.

c) Due to the decentralization property of blockchain, the data of smart contract is of high security and immutability. Further, decentralization eliminates the trust risk from the involvement of intermediate party [23].

d) If the logic and content of contract could be written properly in the program, the software would accurately execute the items step by step. It reduces the possibility of some manual errors.

In BIM workflow, it is a perfect state provided that every contract can be written as a smart contract. However, the workload and technical requirement might exceed the capability of project team to achieve it. At the beginning when project team start using smart contract, it is suggested that smart contract should be applied on some specific transactions, which can raise the efficiency, security and collaboration of a project at most.

a) BIM model management

One of the main obstacles to replace traditional document-based construction process by BIM-based construction process is that information is distributed on more than one version of a BIM model, model reviews and digital documents [24]. It results from fragmented management of model usage, their associated right and ownership of a BIM model. The Using smart contract, each party in a project team can only access BIM model under the permission of such intelligent contract, and their operation can be recorded on the blockchain. By this way, the responsibility and right can be effectively allocated, and information can be integrated on blockchain database.

b) Property and land ownership transfer

In a construction project, there are amounts of property transfer transactions, like equipment purchase or prefabrication procurement. Otherwise, there also exists land ownership transfer events when the building area is modified. It is significant to use smart contract to transfer the property and land ownership since smart contract provides an authentic platform without redundant cost.

5.1.2 Modification record

Due to the immutability of blockchain, the record is permanent [23]. As many people and teams working in one project, the modification of one BIM model at same time is unavoidable. The tamper proof and time-stamped data can be record by using blockchain not only for internal member but also for external collaborators [23,25]. Immutable public record of all model modifications can be stored [22]. With the application of this record the efficiency of the data sharing can be significant increased, the efficiency of management can be improved [26], the collaboration and trust between each participant can be enhanced [23].

5.1.3 Supply chain and logistics

In the traditional construction supply chain, the collaboration between each partner is temporary, the cooperation period is short, and the number of participants is huge. Therefore, the unstable relationship can cause the lack of transparency and traceability [27]. The problem of trust between each participant in supply chain leads to a low efficiency and low level of productivity [28]. The blockchain can be considered to solve these problems through an immutable digital ledger system [29]. This system is authenticated and the information on this system is more reliable than the conventional [26]. Based on the reliable information and without the participation of third party, more companies can be considered to hire as contractors or subcontractors. A reliable, open and competitive market is a positive motivation for the companies and people in the industry [30]. The efficiency of the procurement can be increased [31]. Moreover, blockchain can provide consistent report for each participant in supply chain including owners, contractors and subcontractor. It helps managers to track the progress of the project and the logistics timely.

5.2 IoT and BIM

IoT can be applied in different processes in the building lifecycle based on BIM. In terms of the green and smart building design, some sensors can be used to measure the temperature, air quality, humidity; monitor the location and movement or control the system respectively to provide safety and thermal comfort with limited energy consumption intelligently and automatically [30, 32]. With respect to the application of IoT in construction site, the wearable sensor can be used to monitor the acting of workers to make the workplace safer and more efficient [33]. In terms of the construction supply chains and logistics, the RFID sensor can be used to monitor various aspects of product and their environments [34]. Meanwhile, the IoT have potential to promote the application of e-commerce in procurement process [35]. In terms of the facility and asset management, the IoT can improve the efficiency of O &M; reduce the track cost and process in real time through the RFID technology [36].

5.3 IoT and blockchain

With the development of IoT, the limitations of it is gradually exposed. Firstly, due to the centralized of the currently IoT system, the central database is vulnerable to attack. With the exponential growth of data, the cost for operation and maintenance of database is increased rapidly. Secondly, credit mechanism is hard to build without the third party. The cost of the collaboration work between external partners is high. Meanwhile, the privacy of participants could be leaked via the third party. Based on the characteristics and advantages of the blockchain, the limitations can be solved.

5.4 Integration of BIM, IoT and blockchain

The applications of integration between two of these three technologies are came up gradually. However, the application of integrating BIM, blockchain and IoT is rarely mentioned. One of building maintenance systems based on “Decentralized Autonomous Organizations” (DAO) can be considered as a meaningful approach that adopts BIM, IoT and blockchain technologies in the construction industry. This example shows the feasibility and the value of integration between these three technologies.

5.4.1 Building Maintenance System （BMS） based on DAO

An efficient operation and maintenance system of a building can save labour and management cost as well as reducing health and safe issues. A new building maintenance system based on DAO is expected to perform well rather than existed systems in the future [37]. DAO is the abbreviation of “Decentralized Autonomous Organizations”, which is an organization that runs through rules encoded as computer programs [38]. This organization does not have any human governor. It follows completely the rules of a smart contract. On the other side, BMS takes advantages of IoT technology to retrieve the operation information of every building component. Once BMS could monitor the performance of building and get prepared to react to any abnormal conditions based on a fixed contract, a set of troubles on operation and maintenance stage can be solved in an abbreviated time [39].

Supposed an elevator in a large office building breaks down, the sensor from BMS could quickly find the problem and detect which part of the lift got damaged. Then transaction would be uploaded onto blockchain network. DAO could make responses to this event according to the scheme of the smart contract, such as writing facility damage report, connecting with service provider, or purchasing new component with supplier. As a consequence, the broken elevator could soon get repaired and return to operation. It prevents hundreds of staff in the building from having to walk on fire passage, which leads to safety concerns [40].

From this example, it is of great significance to apply blockchain along with IoT during operation & maintenance of a BIM life-cycle. IoT provides the opportunity to access the dynamic data of building while DAO make automatic reaction to any situations based on predetermined programs. The absence of any of BIM, blockchain and IoT technologies could make BMS unable to work.

6 Discussions

In the UK, the Digital Built Britain national strategy describes the plan to create a mature digital economy for built environment and lead to a smart cities, services and grids [41]. It requires a large amount of digital information, new commercial model, interoperable and safety working environment. This strategy indicated that the informatization and digitization are the tendency of the development of the future AEC/FM industry in the UK. As one of most advanced countries in the development of construction and BIM standards, the HM Government's strategy can be used for reference in the global construction industry. Meanwhile, the development of informatization and digitization of AEC/FM industry are also mention in the 13th Five-Year Plan of China. The advance technologies are required for the development of economic and social [42]. Both national strategies can indicate a digitized and informationalized world in the future. Those mass of data and information need to be well managed without wastage, excessive transfer and unnecessary cost burdens [43].

BIM, IoT and blockchain are three advanced technologies that are explored to achieve the informatization and digitization of AEC/FM industry. These three technologies can be considered to be complementary.

Without linking to IoT, the correctness of project data is poor. Considering that a smart contract was made to manage the equipment lease, it is essential to collect the dynamic data of equipment in order to ensure the performance and safety of a machine. The virtual 4D BIM data could only provide some static data such as manufacturer or provider information of the equipment. Manual recording and uploading of these dynamic data of equipment generate problems. For instance, the updating is not real-time, and the data accuracy cannot stay on a prominent level, which could lead to execution error of a contract. Therefore, it can be realised that blockchain technology can improve the trustfulness of virtual BIM data, but the independent interaction of these two technologies still lacks support from real world data. Meanwhile, IoT can improve the level of intelligentization and automation of the supply chain and logistics through sensors and RFID. It ultimately increases the efficiency of these applications with the participation of IoT.

Without blockchain, the integration system of BIM and IoT is lack of security and correctness due to the single source of truth. Due to the various data format between each technology, the information exchange is complex. With the regular format data in blockchain, the collaboration can be more efficient in an integrated system. Overall, with the construction industry, the generation rate of data is exponential from a number of stakeholders along the life cycle of the building. These data and information need to be transferred, stored and shared by an efficient and safe method. Blockchain is a reliable technology to process data. With the blockchain, the data and information can be managed well.

Without BIM, all the information in the whole building lifecycle is hard to be digitized. Paper-based document cannot be used in IoT and blockchain directly. BIM is the first step and the basement for AEC/FM industry to convert and manage digital information through-life.

In conclusions, BIM, IoT and blockchain are complementary. With the integration of these three technologies, the traditional AEC/FM industry can become a digital and informationized industry in a high efficiency and secure environment.

In order to clearly illustrate the interaction of these three technologies and how they rely on each other in a building project, a "Cup-of-Water" theory is came up with to graphically show the importance of integrating them together.

7 "Cup-of-Water" theory

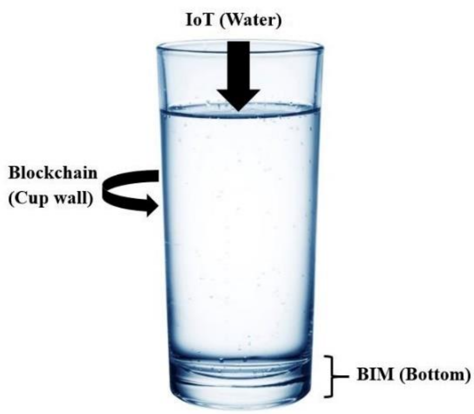

Figure 2. Cup-of-Water Theory

The information carrier, entity and flow can be taken as a cup filled with water, where water is building data and cup is the approach how these data are stored, transmitted and shared.

BIM (Bottom): The management of digital information for whole building lifecycle is the baseline of the revolutionary AEC/FM industry.

Blockchain (Cup wall): Redefinition the method of storage of high value single source of truth for AEC/FM industry.

IoT (Water): The entity of the object and data.

Three components are all compulsory in this system for the industry. Without BIM, the "water" cannot be conserved and managed. The method for regulating the object and data is meaningless. Without IoT, the cup is empty. The system is out of sync with reality. Without Blockchain, the 'water" cannot be conserved and managed in a security, transparency and convenient environment. The integration of these three technologies is the future of the AEC/FM industry.

8 Conclusions

In this paper, the definition, characteristics of BIM, blockchain and IoT in AEC/FM industry are presented through literature review. Then the interaction between these three technologies are analyzed with regard of their applications, benefits and limitations. The integration of BIM and blockchain can improve the safety and efficiency of the contract signing, project modification, asset management and supply chain management. But the applications lack dynamic realistic data of project without IoT. The integration of IoT and BIM brings about comprehensive data in the whole life cycle of a project, but these various formats of data require a stable method to be stored and transmitted. The sole combination of IoT and blockchain without BIM is infeasible because the project data cannot be digitalized. The integration of all these three technologies can access and organize the digital information of building project in the most effective and safe way. An example of building management system based on DAO shows the feasibility of integrating these technologies and huge significance to the building. Cup-of-Water theory is concluded to illustrate the structure of the relationship between BIM, IoT and blockchain during the whole building lifecycle. In this theory, BIM can be taken as "cup base", which is the fundamental of a digital building project. IoT is described as "water", which is entity of object data from the real world. Blockchain plays a role as "cup wall". It is cup wall that preserve water in a transparency, secure and convenient environment. At last, the national strategies of China and UK both promote a digitized and informationalized AEC/FM industry in the future. These three technologies are complementary and the "cup of water" have potential to lead an innovation AEC/FM industry in the future. Currently, the integration between BIM, IoT and blockchain is a complex and diversified process. The detailed methods for integration and integrated system structure need to be further developed.

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