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LEVERAGING BLOCKCHAIN TECHNOLOGY IN A BIM WORKFLOW: A LITERATURE REVIEW

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ABSTRACT Building Information Modelling (BIM) involves the exchange of models and information between stakeholders and within collaborating teams. This information is prone to contractual, legal, security and system issues amongst others. The existing practices aim to address a digital concept such as BIM with solutions from the paper world – contracts and other documents, which do not solve the problem completely. A recent advancement in database management – Blockchain Technology (BCT) aims to provide a new stream of solutions to industries across various sectors. BCT is a system of recording a database that stores information chronologically and distributes a copy of it over a network of computers that maintain its authenticity and security collectively. This paper first reviews the literature on the issues of information exchange in a BIM workflow and next explores the concept of BCT and its connection with BIM. The literature indicates that BCT shows high potential for solving challenges during the design phase of the project by clarifying liabilities, increasing the reliability of information and enhancing the security of information flow. Its ability to incorporate self-executing contracts enable many more applications around ownership and payments. Finally, the paper discusses a few of its challenges with scalability, user acceptance amongst others.

1. Introduction

Building Information Modelling (BIM) is regarded as the step-change the Architecture, Engineering, Construction, Owner and Operator (AECOO) industry needed (Industry Training Group, 2016). The use of BIM has increased from 3D visualisation to better information modelling and work process comprehension (Likhitruangsilp *et al.*, 2014). The PAS 1192-2: 2013 by British Standards Institution (2013) has proposed three levels of BIM maturity where an increase of level indicate a better technology integration and an increase in collaborative work culture. Majorly, the segment of the industry that is currently hoping to reap the benefits of BIM is working at level two. At this level, the stakeholders are required to build BIM models in silos and exchange their models at various stages to finally create a non-clashing federated model. Depending on the type of procurement model, the chronology and frequency of BIM information exchange vary, and risks creeps in for the participating stakeholders, such as issuer liability, the vulnerability of information to unethical modification, misuse of information amongst others (Hudson, 2016; Wong and Lam, 2010). Hence, these risks account for a range of contractual, legal, security and system challenges that hinder the growth and ease of adoption of BIM at the industry level.

This paper reviews a recent advancement called Blockchain Technology (BCT), which displays potential for a new strategy for addressing some of these challenges. BCT at its core is a digital information recording method (Conte de Leon *et al.*, 2017). It uses an approach, which is similar to what the construction industry is quite familiar with – the logbook. The information recorded on this database or ledger is ordered and incremental, and instead of storing the ledger on one single system, this technique requires it to be shared across several devices using a predefined set of rules to update it, called a protocol. Therefore, BCT is essentially a form of Distributed Ledger Technology (DLT) (Giancaspro, 2017). A distributed ledger system (based on DLT), Conte de Leon *et al.* (2017) explain is a computer-based system in which a set of computer processes representing agents or users connected to a digital network operate collaboratively on a set of distributed ledger data structures. Swan (2015) places the analogy of a giant interactive spreadsheet, which everyone has access to, updates, and confirms that the digital records are unique. What has brought this technology to light is the clever combination of existing techniques used in database and network sciences.

BCT finds its origins in the 2008 whitepaper by a pseudo-author(s) named Satoshi Nakamoto titled ‘Bitcoin: a peer-to-peer electronic cash system’ (Nakamoto, 2008). Although the terms block and chain were not used together in the paper, the concept and functionality of the cryptocurrency, bitcoins, is derived from a protocol Bitcoin (‘B’ in capital) which uses the concept of what today is referred to as Blockchain Technology. It is worth noting that the system of Bitcoin is only an application of BCT and this study will discuss BCT devoid of Bitcoin.

BCT primarily sets out to solve the problem of trust between interacting parties. Mathews *et al.* (2017) assert that with the advent of working systems based on network structures rather than hierarchy, BCT enables participants to read and write data to its ledger without a trusted intermediary. Security of such a ledger is managed by cryptography protocols rather than human administrators. BCT solves the trust aspect of an ancient human ritual "the handshake", an agreement for a value transaction (Robles and Bowers, 2017). The industry report from Arup by Kinnaird and Geipel (2017) concurs that BCT is a revolutionary technology that disrupts trust so much that it is not needed anymore. Tapscott and Tapscott (2016) raise a bold comparison between the advent of the internet as the first set of digital revolution and blockchain as the second generation of revolution and call it the internet of value. In line with this are authors Ibáñez *et al.* (2017) who agree that BCT has the potential to re-decentralise the internet.

This paper reviews literature to explore how a BIM workflow can leverage the advantages of BCT. First, it reviews the challenges of an ineffective BIM-based workflow. Next, the properties of BCT are discussed with a review of the potential advantages of integrating BCT with BIM. Finally, it discusses the current limitations of BCT before concluding the discussion.

2. BIM workflow and its challenges

Manley (2001) and Winch (1998) identify the construction industry as a 'complex product systems industry'. Hobday (1998) defines this as 'any high cost, engineering-intensive product, sub-system, system or construct supplied by a unit of production – be it a single firm, production unit, a group of firms or a temporary project-based organisation.' This fits well as construction projects require individuals or entities (stakeholders) of different skillsets from multiple industries to work with each other for the duration of their association with the project and discontinue on completion (Zhu and Augenbroe, 2006). A report by Tribelsky and Sacks (2011) on journal logs used for 14 projects, found a total of 70,048 transactions, of which 90% were exchange of drawings and schedules – mostly in DWG and PDF formats, 8% were technical specification documents and the remaining 2% included meeting summaries, requests for information (RFI), client's memo and budget directives. This exemplifies the sheer volume of technical information that is exchanged on average in construction projects. Hence, there is a constant exchange of dialogue, information and deliverables between the stakeholders. For example, the design teams are composed ad-hoc for construction projects, and they belong to multiple firms trying to work towards producing a coherent design through collaborative work. The fact that the design teams do not co-locate for the project and they are contracted only with the client and not among themselves leaves collaboration and coordination to informal relationships and tacit understandings between the team members (Ford and Sterman, 2003; Love *et al.*, 2002). Information produced in the design phase influences the construction of the project and information produced in the construction phase may influence future design, client requirements or may require the construction process to be amended (Yang and Baldwin, 2013). Hence, this process is not linear. Ballard and Koskela (1998) assert that perceiving the design process as a flow of information rather than a rigid segmentation and sequencing of design tasks can lead to a better design management approach. Hence, it is better suited to use the term workflow, which is defined as the flow of information, specifications and other design resources between the project participants (Al Hattab and Hamzeh, 2016). Designers use information as raw material, and information flow is an enabler for them to perform effectively and efficiently (Tribelsky and Sacks, 2011). They also directly link with the amount of rework that happens in construction projects. Khan *et al.* (2016) extend the discussion that timely and accurate information during the production phase reduces delays, the likelihood of contractual claims, disputes and the requirement of change orders and RFIs. Rao (2006) calls for a complete and adequate electronic project information system and concurs that Information is regarded as 'probably the most important construction material'. 'Information systems' recognise the criticality of the flow among the project participants, and improving the flow of information across different stakeholders leads to better performance (Khan *et al.*, 2016). They form a significant contributor to the success of the project (Lam and Wong, 2011). The Network for Construction Collaboration Technology Providers regarded construction industry as 'highly dependent on information' and asserted that team members in a project require timely, most accurate and latest information exchanged between them to ensure success of projects – 'the right information needs to go in the right form to the right person at the right time' (Shelbourn *et al.*, 2007). In 1995, the National Science and Technology Council (NSTC) identified information and decision technology, which includes integrated databases and information systems, as one of the most critical drivers of a competitive construction industry (Wong and Lam, 2010).

Adoption of IT in construction to improve information exchange is confirmed and reported across the literature (Behzadan *et al.*, 2008; Fukai, 1997; Nitithamyong and Skibniewski, 2004; Zhu and Issa, 2003). A study by Wong and Lam (2010) has indicated that the industry users welcomed novel technology for information exchange. With the advent of Building Information Modelling (BIM), information has taken the shape of parametric 3D models and other digital forms. Typically, the architect creates an architectural model first, and then other participants use this model as the basis for creating their domain-specific models. Subsequently, meetings among the parties are conducted to coordinate the models and evaluate the constructability perspective (Staub-French and Khanzode, 2007). Traditionally, this process is sequential and is time-consuming. With demand for faster delivery of projects, there is a trend for these processes to be carried out concurrently. This means that with such complication of information moving between multiple parties and without a sequence of approvals, the process of information exchange needs to be more efficient than ever before (Rao, 2006).

2.1 Challenges of a BIM workflow

The standard forms of contracts have always been tested with the development and integration of technology into projects, and adoption of BIM is no exception. Unlike CAD, which is considered as a tool, BIM is a new process that has not been tested enough in courtrooms to establish legal history (Arensman and Ozbek, 2012). For example, in the traditional procurement method, the architect retains the copyright over the design and the drawings, expressing that the designs are licensed to other design stakeholders to do their work. This means there is a clear identification possible of who did what. With the introduction of BIM and collaborative work, this process is disrupted. This scenario is especially visible in procurement techniques such as Integrated Project Delivery (IPD) method where collaboration and contribution of the project participants during design development are vital to the delivery method itself (Mathews *et al.*, 2017). Hence, increasing the complexity to establish liability and causations.

Moses *et al.* (2008) state how a balance needs to be struck between the data verification and time required for it. The authors discuss how once the data leaves the collaboration system, the security applicable to the objects and documents is lost, which allows anybody who gains access to the information to view or amend it. Wong and Lam (2010) discuss that the construction professionals shared worries of employees sharing confidential or sensitive information to competitors and an unreliable user authentication mechanism. Likewise, Alshawi and Ingirige (2003) also shared that a central database of project information where IP was kept for downloading freely could result in copyright infringement and this made the designers very anxious.

Below tabulated (in no particular order) are a few of the challenges of an ineffective information system in a BIM process.

Challenges	Reference
Waste of time - Spent on coordinating the exchange of information - Designers wait for information	(Anumba *et al.*, 2008; Khan *et al.*, 2016; Tang *et al.*, 2008; Tribelsky and Sacks, 2011)
Waste of cost through data loss	(Anumba *et al.*, 2008)
Incompatibilities in semantics, process and software used for collaboration or interoperability	(Abukhder and Munns, 2003; Ashcraft, 2008) (Hurtado and O Connor, 2008; McAdam, 2010; Simonian and Korman, 2010; Winfield, 2015)
Traditional project management tools fail	(Mathews *et al.*, 2017)
Contractors (small to medium) suffer	(Kangari, 1995)
Rework	(Moses *et al.*, 2008; Tribelsky and Sacks, 2011)
Over design	
Design information is still commonly communicated or submitted in documents (2D), whether electronic or paper	(Abukhder and Munns, 2003; Anumba *et al.*, 2008; Dawood *et al.*, 2002; Park and Lee, 2017; Tribelsky and Sacks, 2011)
Unused information	(Tang *et al.*, 2008)
Inability to evaluate the value of stored information	
Paucity of information	(Chen and Kamara, 2008)
Frequent variability of accuracy and reliability of information	(Khan *et al.*, 2016)
Difficulty with establishing - Intellectual Property (IP) rights - Causation, Liability, Indemnity - Model ownership - Insurance claims - Traceability - Reliance	(Arensman and Ozbek, 2012; Ashcraft, 2008; Azhar, 2011; Beth and Chatswood, 2014; Collaborate, 2016; Group, 2011; Hudson, 2016; Hurtado and O Connor, 2008; King's College, 2016; Mathews *et al.*, 2017; McAdam, 2010; Olatunji, 2011; Parrott and Bomba, 2010; Savage, 2014; Simonian and Korman, 2010; Winfield, 2015)
Security implications - Unauthorised viewing or amending data - Data leakage - Unreliable user authentication mechanism	(Hudson, 2016; Moses *et al.*, 2008; Wong and Lam, 2010)
Copyright infringement	(Alshawi and Ingirige, 2003)

Solving these issues is a necessity for true collaboration to exist in the industry. Demian and Walters (2014) add that cumulative coordination of information exchange is a critical requirement in the overall improvement of the information management system in a project or an organisation. Despite the technology offering solutions at a brisk pace, the legality of this innovative methodology and tools are far from being risk-free.

3. Potential of Blockchain Technology

Since Blockchain Technology (BCT) is a recently introduced technology, there is limited academic literature surrounding this concept, and the volume drastically drops further when we look at its application in the construction industry. A study by (Yli-Huumo *et al.*, 2016) that reviewed 41 papers related to BCT reflected no research on the use of BCT in the building design or construction. Hence, there is very little academic work published on BCT in the AECOO industry.

There are two kind of properties a complex system with many users or agents may have – intrinsic and, emergent and desired properties. The characteristics such as immutability, the exact copy of ledger with all users, among others are not intrinsic but desired and emergent properties. Conte de Leon *et al.* (2017) emphasise the difference between these two kinds of properties and adds that proving the emergent properties of a complex system with multiple users, some of which cannot be trusted, is a difficult task to achieve. This paper will first look at a few of the intrinsic and emergent properties.

Cryptographic security: Information recorded on the blockchain is considered authentic where it does not lose its integrity. All the data added or modified to this ledger is crowd consented. The verification of transactions is validated by a series of cryptographic screening procedures, for example, 'proof-of-work' (Giancaspro, 2017). The quality, accuracy and the integrity of the data are not dependent on trusting a single authority but based on a mechanism which acquires consensus from all bookkeepers using that blockchain.

Distributed database: BCT is designed as a peer-to-peer, non-intermediated architecture. It mitigates the risks of a centralised system such as: there is no risk of single-point-of-failure, unnecessary control over data by an untrusted authority and breach in security of this centralised system, among others.

Data provenance: BCT's logbook based data recording method enables assured data provenance. The transactions once recorded on to the ledger are cryptographically linked with other entries, and this enables a highly secure record of the origins of any piece of information. Compared to other systems of information recording, such as cloud databases, blockchain address the issues of security concerns much more effectively (Liang *et al.*, 2017).

Immutable database: BCT adopts the advantage of a physical ledger that data can only be added and can never be changed or removed. Any attempt at changing or removing a single entry in an older block would mean rewriting the entire history of transactions after that block (Kinnaird and Geipel, 2017). The only way to manipulate existing data is to manipulate the ledger across the entire network, almost simultaneously. The probability the attacker will ever catch up drops exponentially as the number of the blocks by which the attacker lags behind increases. This way the blockchain mechanism solves the relaxed version of Byzantine Generals Problem and the Sybil Attack Problem as proved by Miller and LaViola Jr (2014), and Man-in-the-middle attack (MitMA) (Lemieux, 2016).

3.1 Blockchain technology and BIM

An integration of technologies is not a new phenomenon and has been the basis of many recent developments not only in the construction industry but also many other fields. Mathews *et al.* (2017) believe that BIM, when powered by other emergent technologies such as BCT, Artificial Intelligence, Internet of Things, Machine Learning (and Big Data), might provide the opportunity the AECOO industry needs for a systematic change. BCT provides a tamper-proof exchange of value and information layer on top of the existing internet infrastructure, and this is why Kinnaird and Geipel (2017) believe its impact will be as vast as the impact the World Wide Web had a few years ago. Mathews *et al.* (2017) assert that information stored in a BIM model at the end of the day is data which can be open to the same level of manipulation as any other form of data. They further add that a construction project could probably provide for a best-case scenario for BCT implementation with multiple untrusting parties looking for a means to form a trusted secure record of information that is independent of a third party and open for verification by the participants. It provides the users with visual evidence of 'value transactions' that occur between untrusting stakeholders through its system of a trusted database.

Turk and Klinc (2017) assert that the major difference between using BCT for a cryptocurrency platform (like Bitcoin) and using it for BIM is the difference in ratio between the number of transactions, the number of participants and the size of the data to be managed. Bitcoin transaction data are tiny in size but huge in volume, on the contrary, BIM has a much lesser volume of transactions which include files of enormous sizes. The author discusses four scenarios of integrating BCT within a BIM setup.

- In the first scenario, the blockchain records BIM model data that is then distributed with other stakeholders. The problem with that would be storing such large BIM models along with their parametric data on the blockchain is currently not feasible with the existing infrastructure. This will make management of the blockchain database highly challenging to manage.
- In the second scenario, not all the stakeholders keep a copy of the database, instead only the essential members do. For all the other participants they use a "wallet software" which will enable them to cache the files locally when opened from the blockchain.
- Explaining a more practical approach for the third scenario, the author explains that instead of the complete information being recorded on the blockchain, the project can choose to only record a fingerprint of the file on the blockchain along with all the metadata of transactions happening on it. The actual complete BIM files would instead be stored in a centralised cloud or a file management server. This would enable the participants to verify the file version and its modification details. However, the author rightly points out, in this case, the overall security of the file content will be dependent on the file management server or the cloud storage facility used.
- Finally, the author introduces the fourth scenario and believes that the right way to integrate BCT in a BIM workflow is an alliance between a BIM server and the blockchain database. This is not discussed further and hence how this would affect the overall performance and security of the system is still to be determined.

This paper will review the use of BCT in BIM in three phases of the project - pre-construction, construction and post-construction.

Pre-construction phase: BCT enables the ability to store an immutable record of changes that a stakeholder makes to a BIM model. These records can be stored permanently with a time-stamp and tamper-proof guarantee. The history of modification as well as the metadata (timestamps, author information) is protected with the equivalent of a cryptographically secure digital signature (Turk and Klinc, 2017). As of now, different software packages handing BIM offer the option of saving these changes internally or on a centralised storage platform, but with BCT, stakeholders working on projects can share these records with external stakeholders (Kinnaird and Geipel, 2017). Therefore, the records of who did what and when are more authentic as they are on a blockchain database that operates on public consensus, unlike the current BIM's centralised storage, promoting disintermediation. This can be used as a basis for any legal arguments that might occur over information exchange and manipulation as it enables traceability of errors, minimises non-repudiation and increases liability control. Through clever coding, one can also build a platform which enables control over modification rights on the BIM model and hence restrict unauthorised changes from happening in the first place.

Considering the current path of progress of BIM towards level three maturity, stakeholders will be expected to work on a single shared model with contributions related to their domain of work. At this stage, BCT can help with stakeholder integration through multi-signature transactions and inter-organisational record keeping (Barnett, 2016; Turk and Klinc, 2017). Stakeholders can take advantage of the provenance tracking ability of BCT to publicly prove the ownership of Intellectual Property of components within the shared model such as Revit families and other components (Kinnaird and Geipel, 2017). In her book, Swan (2015) discusses a project called Ascribe (no longer active) which built an infrastructure for IP registration in the digital art and copyright protection sector. This service set out to address the issues of digital work piracy on the internet. Hence, a potential system using such a service could enable BIM files to use a service such as Ascribe in the background which would help to prove the rights of Revit families. Copying and unauthorised use of BIM files have so far been a problem which now could be addressed through smart contracts and digital currencies to securely and publicly record the ownership, and also transfer ownership in exchange for payment. Kinnaird and Geipel (2017) explain this through an example: An AHU designed by an MEP engineer associates this component to an address on a blockchain and includes it in the shared model. At this point, no other stakeholder can edit or claim ownership of this component and the rights remain with the MEP engineer. When this ownership needs to be transferred, say to the contractor, the MEP engineer does this by sending a tiny amount of bitcoin on the blockchain to the contractor's address, thereby transferring the ownership of the family. Hence, transfer or licencing of ownership between the stakeholders can happen securely without an intermediator and at a negligible cost. Therefore, Swan (2015) explains that blockchain is like a giant spreadsheet which maintains a register of all assets and an accounting system for transacting them on a global scale. Satoshi Nakamoto had initially indicated this use through the examples of escrow transactions, bonded contracts, third-party arbitration and multiparty signature transactions (Nakamoto, 2008).

Further, BCT can also be used as an alternative to a central cloud-based data repository, sometimes referred to as the Common Data Environment (CDE). The problem with a centralised cloud service is it is vulnerable to hacking and data leakage. Generally, in projects that are related to national security or which include sensitive information such as banks, prisons and so forth centralised CDEs are not the ideal option. One company that aims to provide a distributed or decentralised cloud storage facility is Storj (Storj Labs, 2018). It provides end-to-end encryption where the data is shredded to small pieces called shards and stored in a global network of computers. This enables faster, cheaper, secure storage than centralised cloud services. Since this is the beginning of such services user-friendliness is not the best and is expected to get better with time.

A project working towards integrating the BCT capability in a BIM workflow is BIMCHAIN. The solutions offered by this French firm is still in its prototype stages and are built on infrastructure that is in line with the third scenario from the previous discussion (Turk and Klinc, 2017). BIMchain works on creating digital proofs of various transaction scenarios in a BIM workflow and append these proofs on a public blockchain such as Ethereum. Owing to the nature of a public blockchain, these digital proofs are undeniable, inalterable, inviolable, public, perennial and not controlled by a third party (Gueguen and Haloche, 2018). At this moment, BIMchain offers five different proofs –

- Proof of ownership: Stakeholders digitally sign-off their creations to maintain authenticity and anteriority of publication (precedence) to prevent disputes around copyright and ownership.
- Proof of context: Establishes proof that the work performed by stakeholders is built on verifiable inputs and enables better control over liability.
- Proof of handshake: This creates an electronic agreement where stakeholders can commit to working on synchronised versions of the file through digital signatures.
- Proof of consistency: Exchange of digital outputs from a BIM model as deliverables between stakeholders is common in projects, and this proof enables the outputs to be tracked back to the source model which makes the model a 'single source of truth.'
- Proof of certifications – Objects and families used in a BIM model can be digitally certified by the issuing stakeholder and passed on to the recipient as proof of compliance.

In addition to this, BIMchain is working on improving workflows in BIM by creating a Deliverables Management System that integrates BCT into the regular flow of information exchange between stakeholders on the existing BIM platforms. It also visions use of smart contracts for enabling payments in the future, and use of a decentralised project cloud for sharing information through a blockchain secured peer-to-peer protocol. Its vision is to enable stakeholder collaboration through a single BIM model that can itself act as the contract for the project (Gueguen and Haloche, 2018).

Construction phase: In the construction phase of a project, BCT can be used to improve the reliability and authenticity of records such as works performed, materials used and other such information that can be integrated to the BIM model. The current system using BIM is unable to reliably verify if specific information has been authorised by the issuing party and creates a lag between the event occurrence and its reporting. Kinnaird and Geipel (2017) explain through an example where the foreman could digitally sign off each dataset in near real time, and a hash of this could be added to the blockchain with a timestamp and this can be further counter-signed by other team members to validate the information through the use of a common data environment (CDE). This creates consistent reporting for stakeholders such as the subcontractors,

contractors and owners which is of prime importance. In cases where there is a need to modify sections of the design, blockchain can help log not only these changes but also incorporate the physical implementation of these changes. Such a system can be used for controlling disputes on whether the work was completed in time or not, which are usually tried to fix with the use of incomplete paper records and based on memories of the individuals. Authors also note that using a suitable IT system, the identity of the digital signature can be controlled concerning its visibility to the other project participants. Hence, BCT can be valuable to minimise the risk of making mistakes and of overlooking information (Gordge, 2018).

Mathews *et al.* (2017) point out the AECOO industry is different from the financial and software industry in a way that at the end of a project the deliverable is a real-world physical artefact. BCT can be used to link the physical components constructed to its digital counterpart on BIM. Kinnaird and Geipel (2017) explain that when the technology is combined with Internet of Things (IoT) it enables microchips can be used to track components from the manufacturer to the site. This will also help in reducing waste and carbon emissions that could be caused due to over-production. Another idea presented is called the 'product passport' proposed by the Buildings As Material Banks Project (BAMB, 2018). The product passports are to hold information about the materials that building products contain, and define their characteristics. This information can be stored on a readable label or a QR code or something similar, which enables the reuse and recovery of such products. In both these scenarios where blockchain comes into play is instead of storing the linked information onto a central server where it could be prone to attack and other security issues, the information could be stored on a decentralised blockchain database. The authors believe a system that enables the linkage between the digital and physical counterparts has an immense potential to create a truly live BIM model that can receive information from more than a single source or medium. This will open an entirely new paradigm for BIM (Kinnaird and Geipel, 2017). The use of such a model during and after construction is of great value.

Post-construction phase: On project completion, all the final changes are recorded in the BIM model, and this becomes a highly valuable asset during the operation of the structure for the facility manager. This will form the basis for any further upgrades for the facility and a reliable source of information and records for its maintenance.

BCT can offer better security of sensitive information storage collected during the operation phase that can include data received from sensors (Turk and Klinc, 2017). It also facilitates a maintenance log integrated on the facility's BIM model which can be way more reliable thanks to the immutable nature of this log. Inspections and audits can happen seamlessly, and the records maintained by the facility manager are more trustworthy and secure.

In the future, it can also be predicted that facility managers can use IoT and smart contract enabled fixtures to self-maintain and regulate itself based on pre-defined parameters (Saleem, 2018). For example, in a scenario where an HVAC fixture fails or malfunctions, the device sends out distress signals to service contractors within the vicinity. Based on the signals, contractors quote their repair or replacement price (maybe on a blockchain marketplace), thereby sending return information to the fixture. The most suitable quote is accepted and called in for repair or replacement. Once the work finishes, the device releases currency units for their service or replacement charges almost instantaneously. Hence, this automates the actions required to be carried by a building manager, and technician in a more straightforward, faster, cheaper and trustworthy way.

Turk and Klinc (2017) conclude that BCT does provide solutions to many current problems in construction information management; however, it is most likely that the technology will be built into the generic IT infrastructure on top of which construction applications are built. Design and construction software solutions provider giant, Autodesk (Sheppard, 2018) has confirmed their investigations on BCT to enable automation in the future, which indicates its potential application in BIM as well. Swan (2015) asserts that the technology is not just a better organisational model functionally, practically and quantitatively – by requiring consensus to operate, but also promotes greater liberty, quality and empowerment qualitatively.

3.2 Limitations of blockchain technology

The fact that the technology is in its infancy and still in development is an area of concern as this indicates that the technology is not at the maturity level as other well tried and tested technologies. Issues include:

Accuracy of the information: One of the biggest concerns with blockchain technology is that the participants can validate the digital signature of the receiving party based on the public key or the 'address' assigned to that party but the correctness of the content cannot be verified (Kinnaird and Geipel, 2017). Considering the third and fourth scenario stated by Turk and Klinc (2017), the blockchain only stores the hash of the data that is being digitally signed but the content of the data is not on the blockchain itself. This can be problematic if smart contracts are triggered based on files with incorrect content. Stakeholders will have to resort to conventional methods to sort out such issues.

Scalability: BCT's consensus mechanism, although secure and sound, comes with its limitations of difficulties to scale in the future. The effect of the ever-increasing size of the linear blockchain means the size of the transactions ledger is growing beyond what is acceptable as it is necessary for the protocol that every node maintains a copy of the complete register to participate in the network. In terms of speed, the fastest growing bitcoin network transacts a single transaction per second with a theoretical maximum of seven transactions per second (Luu *et al.*, 2015). This can be compared with other financial transactions processed by leading vendors such as Visa which is designed to take 2000 transactions per second with a maximum of 10,000 transactions per second at peak times such as holidays (McConaghy *et al.*, 2016). Ideally, a blockchain network will be required to support such massive amounts of data generated each second without being concerned about the scalability of the networks. The functioning of public blockchains such as Bitcoin or Ethereum requires an enormous amount of energy to run. This is estimated at $15 million per day (Swan, 2015). Although the use of computational power is what ensures the security and trust behind the blockchain, there has to be a more efficient form of arriving at consensus than using such levels of energy.

To address these issues, there is a relatively new concept which is still under tests is called the IOTA project. IOTA is built with the Internet of Things in mind, which will have billions of devices running on the network. How this technology progresses and how adaptive it is to transactions that are possible in different industries is something to wait and watch for (Popov, 2018).

Sensitive information: Data stored on a blockchain ledger are pseudonymous, that is, the data is accessible to all participants but does not reveal the identities of the transacting parties. This can be problematic for applications that require a higher level of privacy than this. Another issue is that when undesirable or error-prone transactions are embedded into a blockchain, this cannot be removed due to the immutability of the blockchain. Although this is what powers the blockchain with its ability to record unchangeable records, sometimes sensitives information could be uploaded which becomes impossible to retract. However, the downside is mitigated by the fact that the sensitive data is buried amongst other information and would need to be specifically searched for. Kinnaird and Geipel (2017) argue that this is no different to what is present on the World Wide Web, where personal information can be uploaded to a website and can never be entirely removed unless intervened by the government.

Consensus mechanism: The current leading blockchains of Ethereum and Bitcoin are based on a Proof-of-work (PoW) consensus scheme where the participants have to agree on a common ledger and also have access to all the transactions ever recorded. However, this affects the overall performance of the system negatively (Patel, 2018). There have been cases where the authors have considered storing more than just the transaction hashes and have commented on how the size of a blockchain is a limiting factor when just the transactional data is recorded (Croman *et al.*, 2016; Wilkinson *et al.*, 2014). The research community is proposing new mechanisms for the leader election for DLS (Conte de Leon *et al.*, 2017). Other reasons why it is important to find alternatives to PoW is because of the increasing use of energy for the computational power and the high monetary costs to maintain it. The author emphasises that the distributed systems research community need to consider these concerns as this could lead to an unsustainable and economically unviable system.

A trade-off between fast, open and secure: Most of the blockchains based on current technologies lack one of the three: fast, open and secure (Kinnaird and Geipel, 2017). This is illustrated with an example of Bitcoin (or we can also consider Ethereum) where the network is open and secure but cannot be fast due to the various mechanism involved in its protocol to make it secure and open. On the other hand, when we consider a private blockchain, which will enable the blockchain to be fast with a different protocol to arrive at the leader election. However, since this is a closed or permissioned blockchain, it will lack the ability to be open and can only guarantee partial security as compared to the open blockchain. Taking this discussion forward with an IOTA network, which is based on directed acyclic graphs, it presents us with an opportunity for a network to be fast, due to its tangle nature, secure, as every attempt to spam it makes it even stronger and also open as it is distributed as an open network, similar to blockchain (Popov, 2018).

Industry users' acceptance: One of the significant drawbacks of the system include the complexity of the security model and an unclear regulatory environment. The end user experience becomes very crucial when considering such a complex system. Patel (2018) discusses how the framework requires the users to generate and manage key pairs, provide cryptographic signatures and post transactions authorising access to the data. The majority of the users are expected to be unfamiliar to cryptographic concepts, hence the complexities of the system will need to be hidden under a user-friendly interface. While using smart contracts, it is a challenge to gain buy-in from the construction industry on decentralise applications or the Dapps. The current way of working with a period of payment on completion enables a particular way of cash flow, which may no longer be accessible under the use of Dapps (Gordge, 2018).

Security: The science behind cryptography is ever-changing, and the resilience of a good cryptographic function is not a static property. Hence, a function designed today to resist certain computational power will not be of the same capability a few years from now. This is a challenge for software creators to design systems that can adapt itself to the changes in computing technology. The authors believe this can be possible through a nested blockchain approach and it requires research in this space (Conte de Leon *et al.*, 2017). Next, the blockchain database system designed is only as good as the code used to design that protocol. Owing to the short coding history of BCT and Dapps a sound and secure design and implementation of code is a challenge.

The immutability of a blockchain is based on the logic that the distributed users who consent over a block of information are always the majority. Nevertheless, it is theoretically possible that an alliance of attackers who are users on the blockchain can pool together their computational power to reach 51% of the entire network (Tosh *et al.*, 2017). This will compromise the authenticity of any value transactions on the database hence breaking its immutability. Hence, BCT should be better referred to as mutable-by-hashing-power (Conte de Leon *et al.*, 2017). In addition to this, reliance on asymmetric cryptography does not allow for a recovery mechanism when the user loses the private key for access to the information on the blockchain. This is sorted through off-the-chain solutions, which again compromises the security aspect (Patel, 2018).

4. Conclusions

There is evidence that points to the growth of blockchain technology (BCT) as a solution to the problem of trust. Claiming this technology can revolutionise the use of internet infrastructure is a long shot and cannot be accurately answered with the available evidence. Although industries such as the finance, banking and supply chain are benefitting from the application of BCT, the construction industry is yet to find its roots. This paper reviewed the challenges of a BIM workflow and examined the limited literature available on the potential of BCT in BIM.

BCT has more potential of application in the pre-construction stage where the use of BIM is at its maximum. BCT seems to enhance stakeholder confidence by enabling change tracking and establishing clear liabilities. It facilitates true collaboration through multi-signature transactions and inter-organisational record keeping. It provides visual evidence of information ownership and reduces disputes over information authenticity. It enables a secure platform for exchanging sensitive information and information subject to Intellectual Property rights. A distributed database avoids concentration of ownership and eliminates misuse and corruption of information making it suitable for legal proofs. The example project of BIMchain and Autodesk's announcements have proved that the industry can soon expect some of the identified challenges in information workflow to be addressed using BCT. The literature suggests BCT is best implemented when its integration is concealed within the BIM interface.

The idea of linking physical construction to its digital counterpart on this platform opens a new paradigm for BIM and is definitely worth researching. The use of smart or self-executing contracts running on blockchain is a potential solution to saving enormous time and money in projects during and after construction. As the industry progress towards BIM level 3, it increases the need for stakeholder integration and a clear division of responsibilities. At this stage, BCT can help keep liabilities clear and back them up with evidence without having to rely on the contracts as often. Further research on this is needed as the industry needs to be well equipped to take on the next digital revolution. Will BCT prove its mettle in the days to come? Is BCT the right solution for the construction industry of the future? These questions are open to be addressed.

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