www.itcon.org - Journal of Information Technology in Construction - ISSN 1874-4753

BLOCKCHAIN TECHNOLOGY AND BIM PROCESS: REVIEW AND POTENTIAL APPLICATIONS

SUBMITTED: October 2018
REVISED: May 2019
PUBLISHED: May 2019 at https://www.itcon.org/2019/12
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SUMMARY: *A Blockchain Technology (BCT) is an emergent digital technology that in recent years has gained widespread traction in various industrial, public, and business sectors; primarily in financial and banking realms owing to the rapid increase of cryptocurrency valuation in recent years. A blockchain Technology (BCT) is, in essence, a decentralized ledger that records every transaction made in the network, known as a 'block', the body of which comprises of encrypted data of the entire transaction history. It was introduced as the working mechanism that formed the operational basis of Bitcoin, the first digital cryptocurrency to gain extensive mainstream appeal. The introduction of decentralized technology in any industry would require strengthened security, enforce accountability, and could potentially accelerate a shift in workflow dynamics from the current centralized architectures to a decentralized, cooperative chain of command and affect a cultural and societal change by encouraging trust and transparency. It was evident that the underlying principles characteristic of BCT functional attributes and secure digital infrastructure could find application in nearly any conceivable industry. BCT aims at creating a system that would be a robust self-regulating, self-monitoring and cyber-resilient system that assures the facilitation and protection of truly efficient data exchange system.*
This research depicts a survey of blockchain technology and its applications in the Architecture, Engineering, and Construction (AEC) industry and examines the potential incorporation within the Building Information Modeling (BIM) process. Furthermore, the paper investigates how employing distributed ledger technology (DLT) could be advantageous in the BIM workflow by emphasizing network security, providing more reliable data storage and management of permissions, ensuring change tracing and data ownership. The focus on collaboration and the distributed nature of both technologies imply the suitability for implementing an integrative framework, and in extension, posit that effectively leveraging DLT's robust, reliable, and secure network infrastructure, and BIM workflow processes can be significantly enhanced. The paper examines the fundamentals of distributed ledgers, their prospective future applications and current advances, and their categorization based on intrinsic characteristics of consensus reaching and permissions. Moreover, the study investigates the potential application of BCT in improving the framework for automating the design review process such as using Smart Contract (SC) technologies and Hyperledger Fabric (HLF), as well as discussing future research areas. HLF is the underlying BCT infrastructure that can serve to highlight key postulations to elucidate the idealized BIM workflow aptly.

KEYWORDS: *Blockchain, BIM, distributed ledger, Hyperledger Fabric, Smart Contract, AEC.*

REFERENCE: *Nawari O. Nawari & Shriraam Ravindran (2019). Blockchain technology and BIM process: review and potential applications. Journal of Information Technology in Construction (ITcon), Vol. 24, pg. 209-238, http://www.itcon.org/2019/12*

1. INTRODUCTION

The blockchain is a digitized, decentralized public ledger of data, assets and all pertinent transactions that have been executed and shared among participants in the network. While it is most associated with digital cryptocurrencies such as Bitcoin, blockchain is viewed as an emergent technology that could potentially revolutionize and transform the current digital operational landscapes and business practices of finance, computing, government services, and virtually every existent industry (Crosby et al., 2015). The chief hypothesis behind blockchain is the creation of a digital distributed consensus, ensuring that data is decentralized among several nodes that hold identical information and that no single actor holds the complete authority of the network. This enables transparency of activity and enhancement of data security. FIG. 1 depicts the general schema of blockchain technology. While initially developed solely for financial transactions with an aim to create a system that enables secure data transfer between two parties without the requirement of an intermediary, the tremendous disruptive potential of blockchain was later evident with the exponentially increasing development of various cryptocurrencies in recent years. By placing emphasis on trust and cooperation between participants, blockchain radically reorganizes existing workflow paths in any organization in which it is implemented, bringing with it a plethora of benefits that include shared learning, instantaneous data exchange, automated contract execution, network security, and improved collaboration.

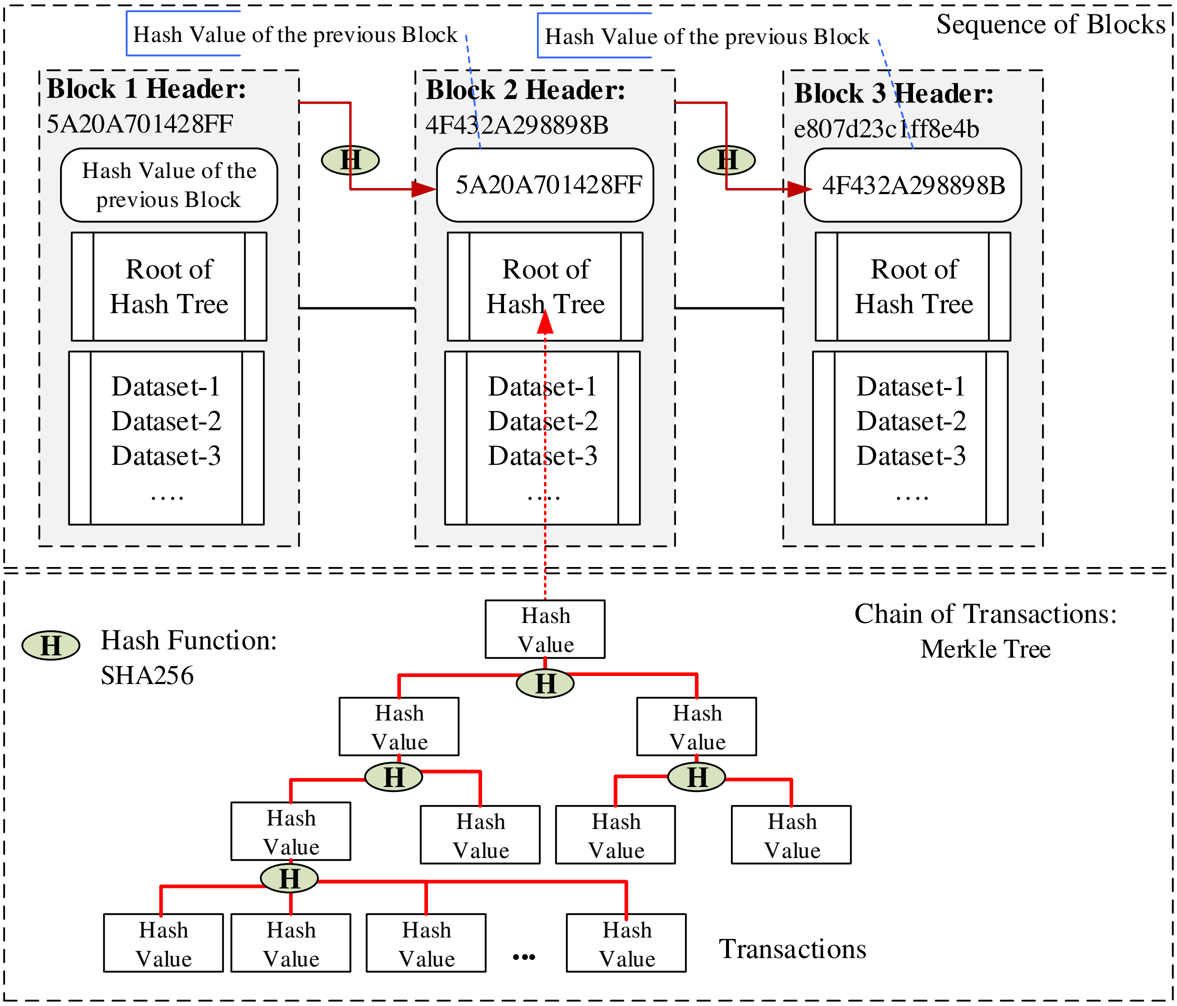

FIG. 1: Outline of the concept of blockchain technology (BCT).

FIG. 1 illustrates that blockchain is composed of a linked list of blocks of transactions. Each block within the BC is recognized by a hash, generated using the SHA256 cryptographic hash algorithm on the header of the block. Also, each block references a previous block, through the "previous block hash" field in the block header. In this fashion, each block comprises the hash of its previous block inside its header. The sequence of hashes linking each block to its predecessor generates a chain going back to the first block ever created, known as the *genesis* block. All the transactions are stored in a schema referred to as the *Merkle Tree*. Such a tree save transaction at leaf nodes, and inner nodes encompass the combined hashes of their immediate subtrees (see FIG. 1). The advancement of BC technology in the finance sector has led to a surge of investors and implementation of newer BC applications and more technological innovations such as automatically executable contracts, which is known as *Smart Contracts*.

Blockchain was first used in Bitcoin, the first cryptocurrency to achieve widespread circulation and mainstream appeal. Bitcoin was first conceptualized in a whitepaper published in 2008 (Nakamoto, 2008), outlining details required for a protocol to establish a decentralized digital currency that operates on a secure and pseudonymous network of participants. A single 'bitcoin' is essentially a tradeable asset produced by the BC system as a form of payment for its operation and maintenance by miners. Following the success of Bitcoin, the term 'blockchain' was no longer synonymous with digital cryptocurrencies as its wide area of potential applications was evident.

Blockchain 2.0 is an umbrella term denoting these new developments and widening the uses of DLT beyond cryptocurrency. The concept of smart contracts came to the realization in 2015, with the release of the second public blockchain called Ethereum by Buterin (2014). Created as an alternative to Bitcoin, Ethereum was a breakthrough in that it was a general purpose BC that provides users a flexible, general platform that can run smart contracts, and develop any conceivable application related to digital currency. Ethereum also features an active developer community involved in building distributed applications (DApps) (Buterin (2015), IBM, 2018).

The next major innovation in the BC technology was the introduction of the 'Proof of Stake' (PoS) method for reaching consensus, which presents several advantages and savings over the current 'Proof of Work' (PoW) method. The PoW is a mechanism that determines the node that writes a block on ledgers using a combination of game theory, cryptography, and incentive engineering (Zhang, 2017). On the other hand, in the PoS, the creator of the block is chosen in a deterministic method, depending on the stake held by the participants.

Currently, every node in the BC network processes every transaction. Blockchain scaling is a cutting-edge example of blockchain thinking that can circumvent this process and improve computational speed, while not compromising on security and robustness of the network. This is achieved by determining the number of necessary computers to validate each transaction and accordingly discretizing the work efficiently. While it is a difficult and ambitious solution to the problem, it is possible to attain and is viewed as the next great innovation in BC technology. Blockchain 3.0 aims to improve on the capabilities of current blockchain BC in terms of transaction time, scalability, and ease of implementation using the concept of decentralized applications (dApp) (Raval, 2016). A dApp is an open-source software platform that consists of back-end chaincode that runs on a decentralized peer-to-peer network connecting users.

The implementation of BCT in the AEC is limited in comparison to finance, e-commerce, and health sectors. Recently few researchers tackled the subject at a higher level noting the capabilities of BCT drive efficiencies in the AEC and transform industry culture and advance innovative advancements (Mathews, et al 2017; Turk, et al 2017).

In summary, three generations of blockchain technology can be distinguished: BC 1.0 which covers applications enabling digital cryptocurrency transactions; BC 2.0 which expands BC 1.0 by introduction Smart contracts and a set of applications beyond cryptocurrency transactions; BC 3.0 which enhances the capabilities of BC 2.0 in terms of transaction time, scalability, and ease of implementation using dApp;

This research contributes towards a thorough understanding of the BCT and its current state-of-the-art applications, particularly its relationship to the AEC industry. Moreover, the paper provides new approaches for integrating BC with BIM workflow such as enhancing the framework for automating the design review process.

The rest of the paper is structured as follows. In section 2 the purpose of the study and research questions are described. The objectives of this work are given in section 3. The methodology employed to conduct a systematic literature review is introduced in section 4. The findings and evaluation of the retrieved literature are presented in section 5, while in section 6 the limitations are addressed. In section 7, the applications of blockchain technology in different domains are discussed. Also, section 7 examines the BCT and BIM work process and the ability to integrate them. The discussion about BCT, applications, potentials, and trends is given in section 9. Conclusions and future research areas are covered in section 10.

2. PROBLEM STATEMENT

This research aims to review the fundamentals of Blockchain Technology (BCT) and its application in the Architecture, Engineering, and Construction (AEC) industry focusing on Building Information Modeling (BIM) workflow. BCT has been successfully applied in several fields such as data management, finance, supply chain, and health (Zheng et al. , 2016; Tama et al., 2017; Brandao et al., 2018). However, there are limited research and applications of BCT in the AEC industry, a limitation which is the chief driver for conducting this research.

The advent of BIM software platforms in recent years has been the most important development in the digital transformation of the AEC industry. Its framework and structure center on a collaborative approach to solving problems, monitoring errors, and coordinating tasks between multidisciplinary teams. BIM still has certain flaws that need to be addressed such as cybersecurity, interoperability and data ownership in a collaborative environment (Shourangiz *et a*l., 2011; Bryde et al., 2013; Volk et al. 2014; He et al., 2017; Turk, et al. 2017). The implementation of BCT in various industrial and business sectors has been gaining traction in current years and integrating BC in the BIM environment could solve some existing problems as well as offering new areas of applicability. Thus, the hypothesis of this work is that conducting a systematic review of BCT and its current applications would assist in defining the potential implementations of BCT to enhance the BIM workflow" The paper seeks to explore the potential applications of BCT in BIM processes. In particular, the study aims to address the following research questions: (i) How BCT develops over time (ii) What are the fundamentals of BCT and its areas of applications? (iii) Is there any potential of integrating BCT with BIM to enhance the work process?

3. OBJECTIVES

The main objectives of this research project are: i) to perform a systematic survey of BCT and its applications as well as its relationship to the AEC industry; and ii) to analyze the prospective integration of BCT with Building Information Modeling (BIM) workflow with respect to network security, data storage and management of permissions, and data ownership;

4. METHODOLOGY

The research method is based on an organized review and evaluation of the current advancement of Blockchain Technology (BCT), and the retrieval of the relevant data from the literature sources. The process includes identifying the research, selecting the relevant studies, assessing the quality of the content, extract data, and synthesizing the data. A comprehensive investigation of the current literature is essential to further the knowledge base of prominent topics, and enabled the formulation of a viable narrative, and justified the necessity, research goals, and direction of this paper. Fig. 2 depicts the overall approach implemented in this research. The first phase of the research protocol focuses on the scope identification and the survey background on the current state of BCT and its applications. This phase covers the existing knowledge base, to provide background on the historical developments of prominent BCT, significant development of key features, market impact and uptake. Knowledge of ongoing research efforts could provide a fair sense of prediction of future developments. The second phase screens the literature review relevant to the goal of the research. This helped to ascertain the upper and lower limits of relevant fields with terms to current capabilities and limitations for BCT and BIM. This includes classifying the publications according to the main categories: BCT related only, BCT and the AEC, BCT, and BIM, Hyperledger Fabric, and SC. Thirdly, the collected literature is evaluated, and findings are formulated and presented. The third stage is a mixed study review since there has been minimal overlap between the fields of BCT and BIM (or between computational studies and AEC in general), it was necessary to develop a cache of descriptive data and conceptual underpinnings pertaining to both fields. This review helped to strengthen the research question, clarify the scope and objectives, and validate the direction of the paper. Finally, conclusions about the potential applications of the emerging BC technology in the AEC industry are presented as well as proposing a new conceptualized framework resulting from integrating BCT and BIM that could facilitate the automation of design review processes.

The scope identification centers around collecting evidence through extensive literature review. The literature review provides definitions, background, historic development, current knowledge areas, and ongoing research efforts on each relevant area identified. The most prevalent fields discussed and researched currently are used to identify the keywords, which served to widen the search process in search tools such as Google Scholar, Mendeley, Microsoft Academic, Bielfeld Academic Search Engine (BASE), arXiv, WorldWideScience, RefSeek, Science.gov, ResearchGate, and Virtual Learning Resources Center. The first set of literature collected was checked for relevancy from their abstracts. A closer look into the papers' abstracts determined the relevancy of the papers. A preliminary study of research papers suggests that cybersecurity, interoperability, collaboration, Smart Contract (SC), and HLF are the main areas of emphasis. Extensive literature is studied that address these areas with respect to both BIM and BCT. The research suggests that BCT, BIM, and BCT, cybersecurity, HLF, and Smart Contract (SC) are the main aspects of the scope of this research. An extensive literature has been studied that address these areas and is summarized in Tables 1.

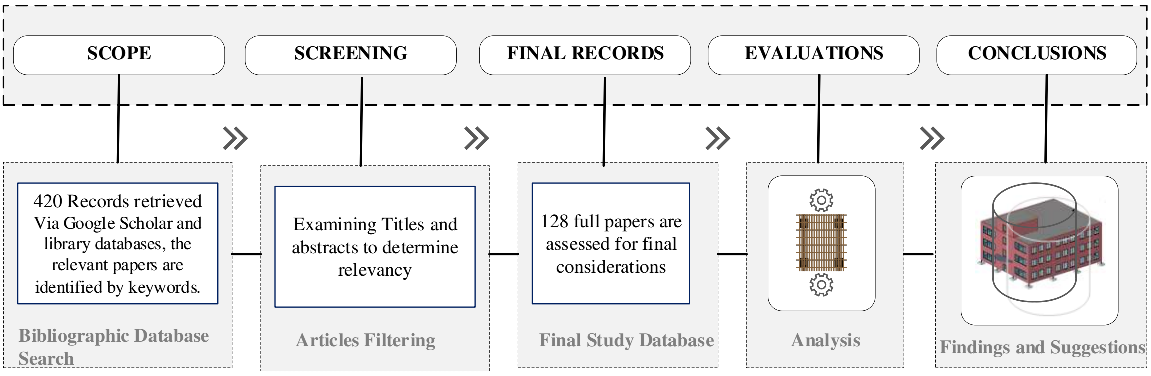

FIG. 2: The General research approach.

TABLE. 1. Summary of the literature related to the concept's indicators.

Sources	Key Aspects						
	BCT	BCT + AEC	BCT + BIM	Smart Contracts	Cybersecurity	Hyperledger Fabric (HLF)	Design Review
Peer-reviewed journal articles	38	4	2	2	18	6	8
Patents	1						
Conference/symposia proceedings	6	4	2	3	5	1	10
Dissertations	4	3	2	4	5		
Newspaper article (relevant time)	1						
Correspondence	1						
Websites and blogs	4					1	
Original documents/research	1	1			1	3	1
Govt/Organizational records	3						
Misc. (literary, art, audio, speech)	4						
Books							2

While ample of publications exist that tackle the fundamentals, operational mechanisms, and research directions of BCT, limited research papers are published addresses areas of BCT overlapping with application in the AEC industry. Even fewer publications are available that deal specifically with the use of BCT in BIM processes since both areas are relatively new in conception and usage. However, the current number of papers tackling these subjects are reassuring, as many research results published in the last three years suggest the employment of BCT, specifically its Smart Contract (SC) concept, to achieve different solutions in BIM environment.

5. EVALUATIONS AND INFERENCES

5.1 Blockchain Fundamentals

Blockchain concepts, functionality, present implementation, mining, cybersecurity, transaction protocols are discussed by many researchers such as Crosby et al. 2015, Feig, 2018, 2014, Zheng et al, 2017, Swan, 2015, Brakeville et al. 2016, Puthal et al. 2017, Hasan and Salah, 2018. BCT fundamentals, potential applications, and emergent DLT frameworks are addressed by Atkins, et al. (2013), Cong et al. 2018, Wang et al. 2018, Li, et al. 2018, Boyes et al. 2014, Andersen et al. 2017, Coyne et al. 2017. The advantages of using different types of BCT are studied by Mathews et al. 2016, Mason et al. 2017, Hammi, et al. 2017, Mahamadu et al. 2017, Mason 2017.

The BCT consists of a chain of sequentially arranged *blocks* of discretized, encrypted data, that is created and stored with cryptographic hashes upon validating a transaction. The two main parts that constitute an individual block are (see Fig.1):

- *Block header*, consisting of the block version, a timestamp, Merkle tree root hash equivalent of the transactions, nBits, Nonce, and a parent block. A *Block version* indicates the set of the block validation. *Timestamp* displays the current universal time. *Nonce is* a 4-byte field that generally starts from zero, and increases by one for every hash calculation, thus acting somewhat as a transaction counter. *Parent block hash* is the 256-bit hash value that references the *parent block*, i.e. the sequentially preceding block to the one in the discussion. The first block in the chain that does not have a precursor is called the *genesis block.*
- *Block body,* which contains the actual transaction data. This is the part of the block that effectively dictates the upper limit of possible transactions, as well as the transaction time (Zheng et al. 2017).

The digital infrastructure of the blockchain network can be divided into two layers of code: (Glaser, 2017)

- *Fabric layer:* consists of the actual blockchain code base, communication protocols, public key infrastructure, data structures for database maintenance, smart contract capabilities. Since the BC network is owned and controlled by the developers, the fabric layer cannot be tampered with;
- *Application layer:* contains application logic of smart contracts. It is collectively controlled by the participants who deploy the code onto the BC network when it is operational. Any participant that holds access and control of the deployed code can write the application layer.

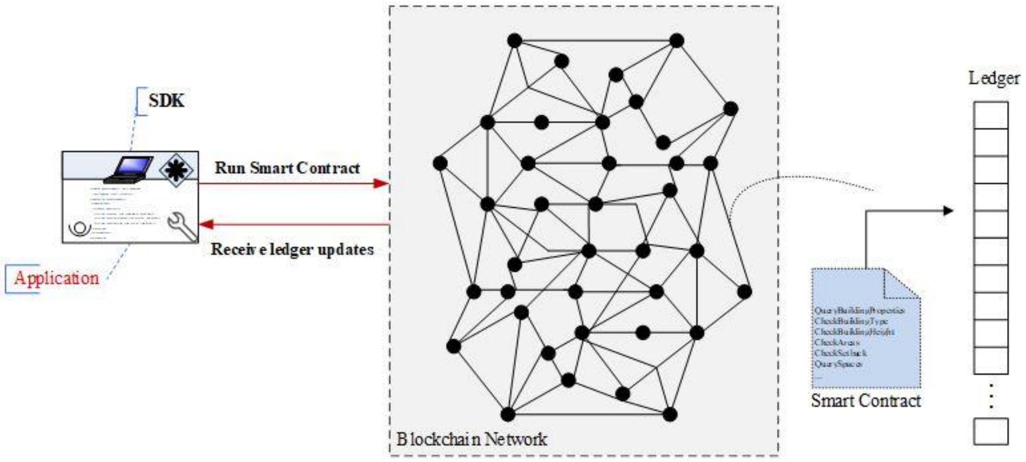

FIG. 3: Overview of blockchain infrastructure

The BC networks can be defined in several ways. These are typically organized according to the network's management and permissions such as public (permissionless), private (permissioned) and federated (Buterin, 2015; Zheng et al., 2016; Christidis and Devetsikiotis, 2016; Wood, 2016). It is worth mentioning that in a public BC any entity can join as a new user and perform operations such as transactions or authentications.

5.2 Decentralized authority and data distribution

A centralized network is one that tasks a single central node with monitoring, controlling the flow of information between the other nodes, and dictating operational controls. From personal standpoint, one decision-maker could reduce the likelihood of conflicts and disagreement, but on the other hand – there are several other factors that could affect coherent interoperability and collaborative decision-making, such as if even one of the two parties is acting with malicious intent, or is negligent, or incompetent.

A Decentralized Ledger Technology (DLT) is a peer-to-peer network generally incorporates a decentralized consensus mechanism, distributing the computational workload across multiple nodes present throughout the network, facilitating the nodes to create connections, and they ensure the connections stay alive, while also ensuring every node in the network receives and transfers out data (Nakamoto, 2008; Zheng *et al.*, 2017; Wang et al. 2018). This mechanism excludes the likelihood of a system failure or a complete network blackout. DLT usually achieve this by integrating a decentralized consensus structure prior to the blockchain initiating transaction operation. The network participants agree in advance and decide on a consensus mechanism appropriate to their requirements. Every endorsing node in the network runs the exact same consensus algorithm, thus, the system does not need any third-party administrator to oversee the transaction operations (Brakeville, et al, 2016). *FIG. 4* delineates the different architectures of these network system such as centralized, distributed, and decentralized ledger networks.

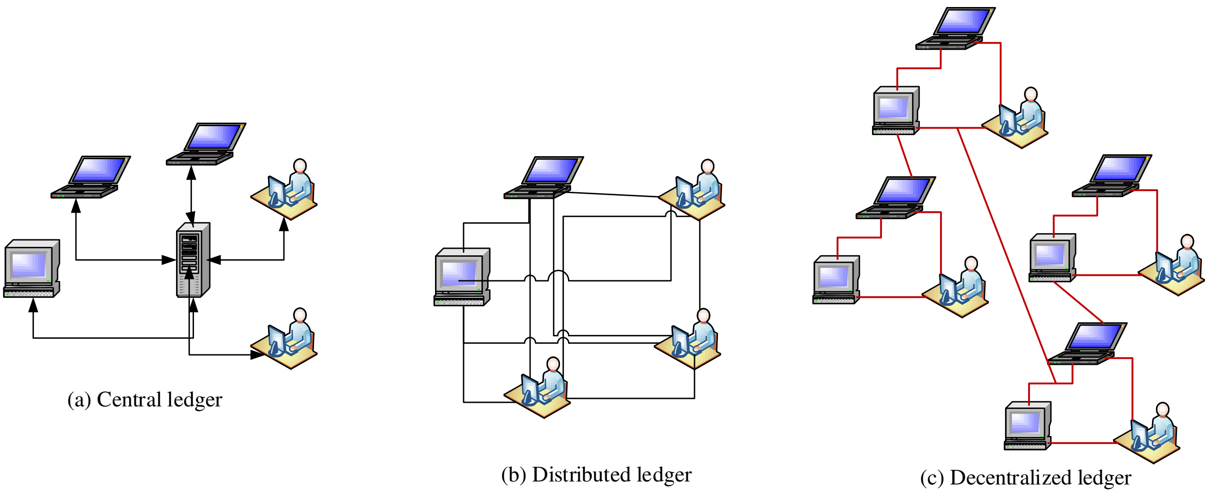

FIG. 4: Different types of network architectures.

5.3 Trust (Consensus)

Members of the network must prove themselves as legitimate members. Thus, reaching a consensus agreement is one of the key features of a distributed technology (Brakeville et al., 2016). A consensus between all participants in the BC network is agreed on prior to the implementation of the BCT and this ensures that the ledger is shared, unchangeable, and immutable throughout its life.

After agreement on the consensus mechanism, the peers execute the consensus protocol to validate transactions, create blocks and hash chains. The ledger is updated and appended in the event of the occurrence of errors, instead of overwriting them. New transactions recorded on the ledger are validated by miners. A block is mined every few minutes. The Byzantine Generals (BG) problem is central to determining consensus in a BCT, and all consensus mechanisms are developed with the aim to overcome this issue. The Byzantine General Problem was a security flaw in distributed systems developed prior to Bitcoin, in which the nodes aim to reach a consensus despite having a faulty component (Xu et al. 2017). This increases the possibility of malicious intent or network irregularities.

The different mechanisms through which consensus is reached are:

- *Proof of Work:* 'Mining' or the Proof of Work (PoW) mechanism works by determining the node that writes a block on ledgers using a combination of game theory, cryptography, and incentive engineering (Zhang, 2017). The nodes in the network compete to solve a mathematical puzzle (generally a computationally difficult but easily verifiable pattern) to record a transaction. Upon resolving the puzzle, a consensus is reached by broadcasting the resolved solution to other nodes in the network, thereby ensuring transparency, robustness, and incorruptibility of the network. Consequently, the group with larger total computing power dictates the decision-making and reaching consensus. The two most popular BCT systems, Bitcoin and Ethereum operate on PoW mechanism. However, this involves expensive transaction fees, extensive computing tower, and cumbersome mining processes to create new blocks;

- *Proof of Stake:* The creator of the block is chosen in a deterministic method, depending on the stake held by the participant. An algorithm is employed to determine collective decision-making and level of privacy between participants. This mechanism requires the credibility of data, which is denoted by proof of ownership of cryptocurrency coins. If a created block can be validated, the cryptocurrency will be returned to the original node as a bonus. This method involves no block rewards but operates solely on transaction fees. It is thus an energy-saving alternative to PoW and presents several economic benefits. (Zheng et al., 2017). Ethereum aims to shift the paradigm by transitioning to a PoS mechanism;

- *Practical Byzantine Fault Tolerance (PBFT):* This is a Byzantine agreement consensus method that can tolerate a maximum of 1/3 malicious byzantine replicas. A primary is selected in each round and is responsible for ordering the transaction. A node enters the next phase if it receives 2/3 of votes from the remaining nodes in the network. (Zheng et al. 2017) Thus, PBFT requires each node to query other nodes. Hyperledger Fabric uses the PBFT algorithm;

- *Delegated Proof of Stake (DPOS):* Stakeholders elect representatives to validate blocks. Since this mechanism features a relatively small number of nodes, the processing of transactions is quicker (Zheng et al. 2017). The delegates are authorized to modify the network parameters.

5.3.1 Mining

Mining is the mandatory process of recording transactions on the blockchain network using the computer's processing power. The subset of nodes in the network that are equipped with special software that validate the transactions to be added on the blockchain is called *miners* (Cong et al., 2016).

5.3.2 Privacy

Blockchain can address accessibility and visibility of the data in a secure and efficient manner since the ledger is distributed (Clack, et al. 2016, Seijas, et al. 2016, Frantz, et al. 2016, Brakeville, et al. 2016). It facilitates setting different levels of privacy as every participant is essentially a stakeholder and no single participant has full administrative privilege. Thus, formulating and enforcing consensus is crucial to the blockchain operation, with terms to data updates, error-checking and collective decision-making. The selection of which BCT to uses depends much on the method of the agreement to reach consensus.

Based on the privacy, blockchains can be classified as (see Table 3):

- *Permissioned blockchains:* Permissioned BCs restrict the actors that can contribute to the consensus of the system state. Only a restricted set of users have the rights to validate transactions and may also restrict access to approved actors who can create smart contracts. HLF is an example of this permission type;

- *Permission-less or public blockchains*: Blockchains that are permission-less allow any participant to create consensus, as well as smart contracts, and uses the PoW mechanism to reach a consensus. They typically use a native cryptocurrency or none to validate transactions. Bitcoin and Ethereum blockchains are good examples of this type of permission.

TABLE 3: Comparison of the different types of permission management in blockchain technology.

Blockchain Privacy	Permissioned Blockchain	Permission-less Blockchain
Privacy	Only permissioned actors have access to the blocks of transactions.	Any participant can read access to all blocks of data. This is convenient for a shared database.
Scalability	Permissioned BC can build a simplified PoS model to establish consensus by burning computational cycles.	Uses PoW mechanism to reach consensus.
Fine-Grained Control	Allows fine-grained control by restricting access to a few participants.	Not possible to ensure fine-grained control.

5.4 Security Risks to Blockchain:

The blockchain is still susceptible to certain forms of security problems. While it is difficult to compromise a blockchain system, it is important to note that the system is still not completely infallible. Some of the threats to a blockchain application are:

- Double-spending: Two parallel transactions transfer the same data to different recipients, thus creating a new, invalid transaction. This can be prevented by enforcing a PoW consensus, where all participants agree over the order of transactions that have taken place;
- 51% attacks: When a participant controls over 51% of the network, that participant does have a high chance of tampering with the blockchain without any consequences, since he or she controls the majority of the network and thereby gaining more power in dictating the consensus. Thus, smaller networks are more susceptible to attacks since a single participant can gain relatively more power in the blockchain's early stages (Yii-Huumo et al, 2016);
- *Inadvertent centralization:* Since security is partly dictated by the participants in the blockchain, it is impossible to stop the weakest participants from transferring assets to a centralized system of exchange. These often occur due to a third-party that has amassed large amounts of assets and is storing them on behalf of the users. In addition, assets in pure blockchains can also be centralized. An example is the cryptocurrency Ripple, large amounts of which are owned by a small number of founders and large multinational organizations.
- *Lack of privacy due to pseudonymity of user: It* is crucial to choose which information is to be made private and which can be accessible to the public. It is also impossible to achieve complete privacy since one can infer the data to a particular user by studying their transaction patterns.
- *Data malleability:* The integrity of digital signatures used to validate transactions cannot be guaranteed. In such a scenario, the hacker would intercept a transaction, modify it, and broadcast it to the network (Yii-Huumo et al., 2016).

5.5 Smart Contracts

Smart contracts are contracts programmed with the blockchain that automatically executes upon the fulfillment of certain conditions. This removes the requirement of a third-party intermediary for overseeing the transaction in real-time (Clack, et al. 2016, Seijas, et al. 2016, Frantz, et al. 2016, Bhargavan, et al. 2016, Dhawan, 2016). They are an extension of the blockchain that can independently enforce rules without requiring manual intervention. FIG. 5 illustrates the concept smart contract in a blockchain application.

The following is a definition for the concept of Smart Contracts (Cong and He, 2018): "Smart contracts are digital contracts allowing terms contingent on the decentralized consensus that is self-enforcing and tamper-proof through automated execution." The introduction of smart contracts in blockchains has opened many new possibilities such as complete lifecycle management of legal contracts, automated execution of contracts, and personalization of customizable contracts.

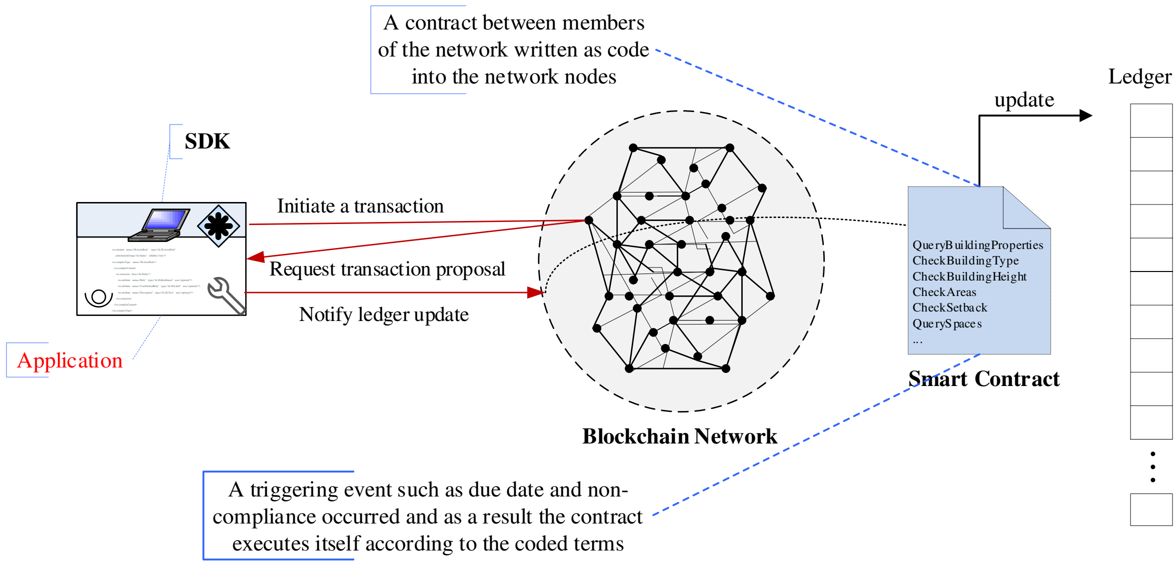

FIG. 5: The concept of smart contract in a blockchain network.

In the context of BCT taxonomy, two different definitions for the term 'smart contracts' are given since the term is used interchangeably for the written code and the binding contracts (Clack et al., 2016):

- *Smart contracts codes:* They are software agents fulfilling pre-set obligations and exercising certain rights and may take control of certain assets within a shared leger;
- *Smart legal contracts:* This term focuses on the expression and implementation of the software and encompasses operational aspects and issues pertaining to the composition and interpretation of the contract.

A high-level definition that combines both aspects of the smart contract and based on automation and enforceability is given as (Clack et al., 2016):

"*A smart contract is an automatable and enforceable agreement, automatable by a computer, although some parts may require human input and control, enforceable either by legal enforcement of rights and obligations or via tamper-proof execution of computer code.*"

The two widely used programming languages for writing Ethereum Smart Contract (SC) are *Solidity* and *Serpent*. Also, there are a number of emerging contract-oriented high-level language that is under development such as *Viper*, *Lisk*, and *chain*.

In Hyperledger Fabric, SC is known as Chaincode. It is executable code, deployed on the network, where it is invoked and validated by peers during the consensus process. The common programing language used in developing chaincode is Go, Ruby, Java, and NodeJS (Hyperledger, 2018).

5.5.1 Key characteristic features of Smart Contracts:

A list of the main characteristics of a smart contract generally include:

- *Automation:* Automation is accomplished by linking the legal prose to the smart contract code via parameters that generate instructions regarding the final operational details;
- *Enforceability:* The smart contract code must execute successfully, accurately, and within a reasonable timeframe. A smart legal contract must include legally enforceable obligations and rights that are expressed in complex, time-dependent, sequential, context-sensitive prose. These may also include overriding obligations based on the fulfillment of certain conditions;

5.6 Hyperledger Fabric (HLF)

Hyperledger Fabric is a platform for generating distributed ledger blockchain systems, supported by a modular design, offering an elastic and extensible digital framework, that delivers high levels of confidentiality, and scalability. It is designed to support pluggable implementations of different components and accommodate the complexity and details that exist across the economic ecosystem. The Hyperledger blockchain aims to be a general purpose, enterprise-grade, open-source DLT that features permission management, pluggability, enhanced confidentiality, and consensus mechanism and is developed through a collaborative effort. HLF is one of the blockchain projects within Hyperledger. Like other BCT, it has a ledger, uses smart contracts, and is a system by which participants manage their transactions.

Hyperledger was founded by the Linux Foundation in 2015 to advance cross-industry BCT. It was the first blockchain developed that enabled the development of distributed applications written in standard general-purpose programming languages (Androulaki et al., 2018). Presently, the Hyperledger consortium involves IBM, the Linux Foundation, and other organizations that contribute to the BCT development and related apps (Seijas et al, 2016). The open source nature of the BCT is augmented by the lack of necessity of mining cryptocurrency or expensive computations to validate transactions. The HLF was the first blockchain developed that enabled the development of distributed applications written in standard general-purpose programming languages (Androulaki et al, 2018). It is founded by IBM and is aimed to be a platform for developing applications with a modular architecture. It permits for plug-and-play components and leverages containers to host smart contracts called chaincode that comprise the business logic of the application.

The fundamental differences between HLF and other blockchain systems are that it is private and requires permissions. In contrast to an open permission-less system that allows unknown identities to participate in the network (necessitating rules like PoW to authenticate transactions and secure the network), the nodes (members) of a HLF network join through a trusted Membership Service Provider (MSP). Furthermore, HLF offers several pluggable options such as ledger data can be stored in multiple formats, consensus mechanisms can be exchanged in and out, and diverse MSPs are supported.

Moreover, Hyperledger Fabric has the ability to create channels, allowing a subgroup of participants in the network to establish a separate ledger of transactions. This is an especially important option for BIM workflow where subcontractors can exchange data within the only subgroup of the network. For example, the structural engineer of record of the project can exchange information with steel connection subcontractors only while still being part of the HLF network and sharing those transactions with the rest of the nodes.

The HLF has several design components (FIG. 5) that provide the comprehensive, yet customizable, enterprise BC (Xu, et al. 2017; Zhao et al. 2016; Singh et al. 2016; Bartoletti, et al. 2017; Androulaki et al. 2018):

- *Assets*: Assets can range from physical objects (real estate and hardware) to the intangible (BIM models, contracts, and intellectual property). Hyperledger Fabric provides the ability to modify assets using chaincode transactions;
- *Ledger*: It is comprised of a blockchain to save the immutable, sequenced records in blocks, as well as a state database to preserve the fabric state. There is generally one ledger per channel. Each node sustains a copy of the ledger for each channel of which a node is a member. The shared ledger encodes the entire transaction history for each channel and includes SQL-like query capabilities for efficient processing;
- *Privacy*: Channels enable multi-lateral data exchanges with the high degrees of privacy and confidentiality required by the AEC specialized and other regulated industries that exchange data on a shared network. A ledger exists in the scope of a channel - it can be shared across the entire network (assuming every participant is operating on one common channel) - or it can be constrained to only contain a specific set of participants;
- *Security & Membership Services*: Permissioned membership provides a trusted blockchain network, where participants know that all transactions can be detected and traced by authorized regulators and auditors;
- *Consensus*: It is defined as the full-cycle of verification of the correctness of a set of transactions comprising a block in a distributed ledger system. In HLF consensus covers the entire transaction flow, from proposal and endorsement to ordering, validation, and commitment. Hyperledger Fabric

has been designed to allow a new application to select a consensus mechanism that best characterizes the relationships that exist between participants in the network;

- *Smart Contracts*: Hyperledger Fabric smart contracts are written in chaincode and are invoked by an application external to the BCT when that application needs to interact with the ledger. In most cases, chaincode interacts only with the database component of the ledger, the world state (querying it, for example), and not the transaction log. Chaincode can be implemented in several programming languages. The currently supported chaincode language is Go with support for Java and other languages coming in future releases.

5.7 Summary of BCT

In summary, blockchain systems are generally comprised of four building blocks: 1) a shared ledger, 2) privacy, 3) trust, and 4) smart contracts (see FIG.6).

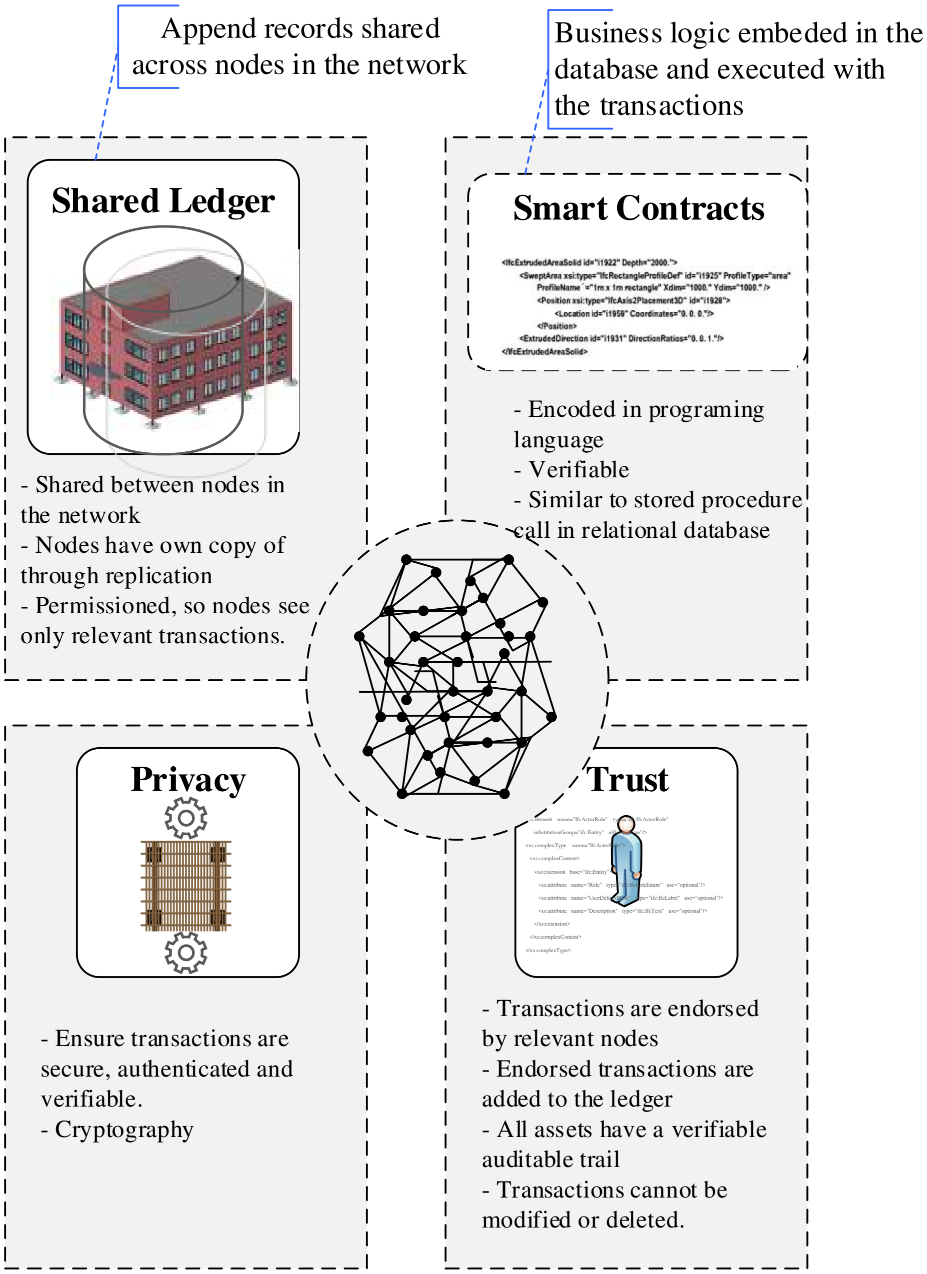

FIG. 6: Main components of BCT.

These main blocks are briefly explained below:

Shared ledger: It refers to the distributed transaction records in the network. With a bitcoin blockchain system, the intent was to publicizes visibility and transparency of data exchanges; however, enterprise blockchain systems requires a different approach due to the regulation of consumer data.

Privacy: Privacy is achieved through cryptographic encryption of data and it does ensure that transactions are authenticated and verified. It is a crucial part of the BCT to ensure hardening security and making the network more difficult to breach the distributed system.

Trust or consensus: Trust means using the power of the network to verify data transaction. The trust model (consensus) is truly the heart of blockchain applications. It is what delivers the tenets of trust, exchanges, and ownership. Trust is what enables blockchain to displace the transaction system, but this can only happen when trade and ownership are addressed by distributed/shared ledgers. The trust system is modified whenever new participants join the blockchain network and apply BCT to a new use case or change. There's still much work needed to define an optimized trust system for various use cases.

Smart contracts: It is a business agreement embedded into the transaction database and executed automatically with transactions. Contracts consist of rules that are required in any commerce activities to define the flow of values and the state of transactions. The contract is smart because it's a computerized protocol to execute the terms of the contract. Various contractual clauses (such as collateral, bonding, delineation of property rights, and so forth) can be transformed into machine language to enforce compliance with the terms of the contract and ensure a successful transaction. Smart contracts are intended to guarantee one party that the other will satisfy their promise. Part of the objective of such contracts is to reduce the costs of verification and enforcement due to the lack of an intermediary party to oversee transactions.

Smart contracts must be transparent (indicating that participants can see or prove each other's actions pertaining to the contract), confirmable (meaning that members can prove to other nodes that a contract has been completed or breached), and private (implying that knowledge of the contents/performance of the contract should involve only the necessary members required to execute it). These advances made it possible for complex business contracts to be codified in a blockchain system.

6. LIMITATIONS

On one hand, there are notable advantages of BCT that include: trust system (Consensus, mining, and the public ledger), secure communication on open networks using Cryptography and encryption; transparency; removal of Intermediaries; decentralization; reduced costs; and increased transaction speed. On the other hand, there are also downsides and risks associated with the standard BCT that can be ignored at this time. These limitations may involve (Crosby et al. 2015, Feig, 2018, 2014, Zheng et al, 2017, Swan, 2015, Brakeville et al. 2016, Puthal et al. 2017, Kshetri et al, 2017; Hasan and Salah, 2018):

Lack of Privacy: Decentralized public blockchains lack privacy, which will make full acceptance difficult. Not only is the information not private, but it is also readily accessible at any given moment to anyone using the system This is also concerning considering that the computers running a large amount of the blockchain networks are in countries such as Russia and China where computer crime is high and personal information may be used against people living or traveling to those countries. This is particularly an issue for Bitcoin and Ethereum systems.

Security Concerns: Blockchain-based assets are like cash, if the cash in your wallet is stolen or lost, then it’s gone. Blockchain-based systems use advanced cryptography and encryption that are more secure than standard internet passwords or number access codes. However, more security can sometimes result in a system being less secure. There are countless examples with cryptocurrencies where someone has forgotten their private key and can’t access their money. With blockchain-based systems, transactions can’t be altered or reversed, and there is no intermediary to assist you if fraud occurs on your account. If you sent funds to the wrong account number (wallet) on the blockchain, then those funds are gone. If someone gains access to your private key, they can access other members data easily.

Lack of Centralized Management Entity: The control is placed with most members of the network, creating issues with regards to control of the blockchain network. The decentralized nature of many blockchains means that the system must agree and decide the future direction of the blockchain system. With a traditional network and software, if an organization wants to make a change, they can make that change after approval from relevant departments within the organization. With a decentralized public blockchain system like Bitcoin, changes must be agreed to by a certain majority of the networks' participants. This may be over 50% but could be as high as 70% to 80% of the nodes of the network. No single entity has control over the changes or direction of decentralized blockchain system making them risky for businesses to use as they can't manage any changes to the system.

Risk of 51% attack: If someone were able to control over 50% of the computers on a blockchain network, that person would control the transactions on the blockchain network. A malicious user controlling over 50% of the computers on a blockchain network is known as a "51% attack." Leveraging this control over a cryptocurrency network, they would theoretically be able to block new transactions from confirming, reverse transactions, and allow for moving assets freely in a Bitcoin network.

Cost: The Proof-of-Work (PoW)algorithm that many blockchain networks use requires proof that computing power and resources were contributed to the network before a block is added to the network. This proof is in the form of an answer to a puzzle that is attached to the block for the network to confirm it is correct. Solving this puzzle requires an enormous amount of computing power and electricity.

Lack of scalability: At the current rate of energy consumption, the electricity costs of running certain public blockchain system such as Bitcoin and using the PoW algorithm make it unfeasible to handle the number of transactions (for example, by credit card companies like Visa and MasterCard). This is one of the factors that is presently affecting the scalability of blockchain networks.

7. APPLICATIONS OF BLOCKCHAIN TECHNOLOGY (BCT)

7.1 BCT in Different Sectors

FIG 7 delineates the current and emerging areas of BCT applications. In the following sections, some of these areas are described.

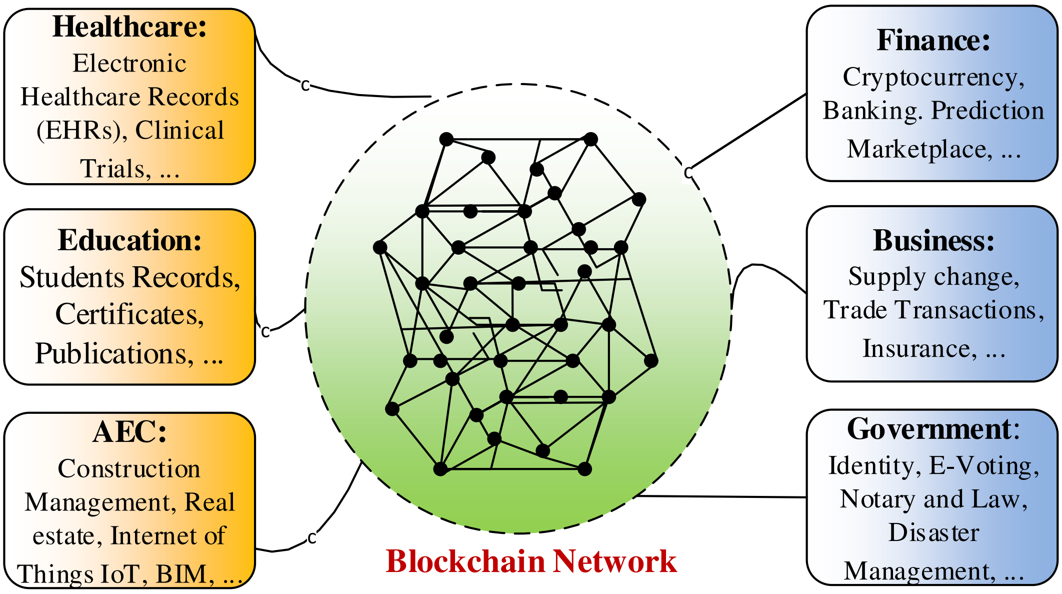

FIG 7. Classical and emergent areas of BCT applications.

7.1.1 Business

Implementing BCT can streamline business transactions by obtaining multiple approvals at once with the minimal required supervision, as opposed to the cumbersome process of sequential verification. Blockchain technology is expected to enhance transparency and accountability in supply chain networks (Ahram et al., 2017; Kshetri, 2017; and 2018). BCT can be utilized effectively in logistics, identifying counterfeit products, decreasing paper load processing, facilitating origin tracking and enabling buyers and sellers to transact directly without manipulation by intermediaries and improve the intra-organisational processes (Kennedy et al., 2017; Lee and Pilkington, 2017; Toyoda et al., 2017; Tan et al., 2018; and Subramanian, 2017).

The application of BCT in data management indicates a number of innovative solutions. For instance, García-Barriocanal et al. (2017) propose the use of a decentralized BCT solution for metadata supporting crucial functions such as secure data distribution, management, and sustainability of digital archives. Yang et al. (2018) discussed the needs of trust in the big data processing and proposed a reliable big data sharing model based on BCT and SC to safeguard the movement of data resources. Moreover, Do, and Ng (2017) suggest a BCT framework that permits secure and distributed client data management employing cryptographic primitives along with keywords query solution.

7.1.2 Finance

Currently, BCT is applied to a wide variety of financial sectors, including business services, settlement of financial assets, prediction markets and economic dealings (Haferkorn and Quintana Diaz, 2015). Blockchain is expected to play an essential role in the sustainable development of the global economy, bringing benefits to consumers, to the current banking system and the whole society in general (Nguyen, 2016).

The international financial system is looking into ways of utilizing BCT applications for securities, fat money, prediction market system, and derivative contracts (Fanning and Centers, 2016; Nijeholt et al., 2017; Paech, 2017). For instance, BCT provides an enormous change to capital markets and a more efficient method for performing exchange operations such as securities and derivatives transaction (Van de Velde et al., 2016; Wu and Liang, 2017), digital payments (Papadopoulos et al., 2015; Beck et al., 2016; Min et al., 2016; Yamada et al., 2017; English and Nezhadian, 2017; Lundqvist et al., 2017; Gao et al., 2018), loan management systems (Gazali et al., 2017). Remarkably, a group of the world's largest banks, including Barclays and Goldman Sachs have joined forces with R3 to establish an operating blockchain-based framework for the financial market (R3, 2015; Crosby et al., 2016). Moreover, the Global Payments Steering Accountants can manage client accounts in real time upon adoption of BCT owing to its immutable record-keeping. Thus, the adoption of BCT could be instrumental in accelerating the shift from monthly cycles to instantaneous transactions and accountants (Brakeville et al, 2016).

7.1.3 Insurance

Insurance companies can use BCT to automate insurance claims, verification of qualifying criteria and execution of privileges. This would be advantageous in saving cost by significantly minimizing the workload by insurance agents who are tasked with manually scrutinizing and cross-referencing insurance claims with factual data, and thus also eliminating fraud and counterfeit claims (Brakeville et al., 2016). BCT would also benefit clients by ensuring efficient pay-outs through instantaneous transactions and providing comparisons between policies for better-informed decision-making (McNulty, 2018).

7.1.4 Public Sectors

BCT can have wide applications in the public sector in areas such as voting and identification, land registration and monitoring real estate, management of medical records, transportation, disaster management, education, and enabling transparency with non-profit organizations (McNulty, 2018).

Recently many government agencies around the world are aiming at utilizing BCT due to the secure, distributed, open, and inexpensive database technology to reduce cost and bureaucracy, increase efficiency and for authenticating many types of official documents (Nordrum, 2017; Chiang et al., 2018).

Governmental organizations working in disaster management often aims to secure sensitive data and make sure any conceivably lifesaving data being sent promptly to the needed communities. Rohr (2017) indicated that: "*Disaster situations call for the absolute transparency that only a distributed network can provide*." BCT can be a boon in disaster management efforts as it can behave as the distributed system of all the operations. All the respective parties can come together and join the blockchain network making it a transparent and distributed way of help provision. The BCT systems empower the key players/associations during disaster management to communicate adequately and securely and follow up on time.

7.1.5 Academia

BCT application can offer a secure system for storing educational data records about students and teachers (Turkanović et al., 2018) by addressing the issues of vulnerability, security, and privacy in any learning environments (Dennis and Owen, 2015.; Bdiwi et al., 2017). For example, teachers can add blocks into the blockchain network storing data about students' learning achievements (Devine, 2015). Educational certificate management system will be significantly improved by blockchain data security and trust in digital infrastructures (Xu et al., 2017d).

Furthermore, BCT applications can provide several benefits to the digital accreditation of personal and academic learning (Grech et al., 2017). Blockchain-based school information system can likewise be established for collecting, reporting, and analyzing data about students, teachers, and staff to assist in the decision-making process (Bore et al., 2017). Lastly, as for the research publications BCT can be employed for improved handling of manuscript submissions and for performing relevant peer-reviews in a timely manner as well as for manuscript authentication (Spearpoint, 2017; Gipp et al., 2017).

7.1.6 Healthcare

BCT has incredible potential to advance the healthcare industry with several applications in areas such as public healthcare management, longitudinal healthcare records, automated health claims settlement, online patient access, sharing patients' medical data, user-oriented medical research, drug counterfeiting, clinical trial, and precision medicine (Peterson et al., 2016; Chamber of digital commerce, 2016; Al Omar et al., 2017; Capgemini, 2017; Emrify Inc., 2017; Shae et al., 2017; Zhao et al., 2017; Mamoshina, 2018; Mytis-Gkometh et al., 2017; Borioli and Couturier, 2018; Lee and Yang, 2018; Xia et al., 2017a, 2017c; Yue et al., 2016; Juneja et al., 2018). Employing Smart Contract (SC) in healthcare blockchain applications can address issues related to scientific reliability of findings (such as missing data, endpoint switching, data dredging, and selective publication) in clinical trials (Nugent et al., 2016) as well as issues of patients' informed consent (Benchouf and Ravaud, 2017; Benchouf et al., 2017). Further areas of applications include managing Electronic Healthcare Records (EHRs). The BCT can advance EHRs by the distributed storage nature of BCT, data security and integrity (fewer risks of hacker, viruses, data corruption or breach), data is updated and always available (Azaria et al., 2016; Young, 2016; BurstIQ, 2017; Sullivan, 2017; Medicalchain, 2017; Center, 2017; Xia et al., 2017b).

7.1.7 Oracle

Oracles or validation oracles are agents that import external states from external sources to evaluate conditions not expressible within blockchains (Xu et al., 2016). Oracles can exist independent of a BCT and in its absence, a human arbitrator can periodically inject data to update the variables in a contract. Oracles are necessary because most BCT systems generally do not allow contracts to query externally sourced data. Oracles can act as an interface between smart contracts and the external data source. Hence, this involves trusting in a third-party organization to send the data (Bartoletti et al., 2017).

7.2 AEC Industry

In the following sections, the application of blockchain technology in the AEC industry is explored, navigating the advantages and potential applications.

7.2.1 Overview

While the digitization of many designs and engineering processes in the AEC industry has seen advances in recent years, it should be noted that it has the slowest rate of digital transformation, just above agriculture and hunting (Belle et al., 2017). Changes are largely impeded by the fragmented nature of the construction sector, stemming from the current organization of teams and projects, featuring a collaborative process for a project. This is counterproductive in that, each party may aim to merely deliver the minimum work order, prioritize profit margins, and minimize liabilities (Belle et al., 2017). Thus, the modern economy favors an adversarial environment where firms would be better incentivized by minimizing information exchange between parties. However, in the future, data exchanges in networks can help to achieve significant savings in cost, time, error, and labor, as well as stimulate collaborative learning. Moreover, efforts to develop an information support system for investment and construction market players can have a significant impact in the AEC industry (Ablyazov & Petrov, 2019).

There is yet clearly inadequate education at the firm level and workforce to present an overall holistic picture of how updating current trends could lead to several advantages. Several organizations have not yet recognized the potential and significance of adopting Building Information Modeling (BIM) techniques and conclude that this would, in fact, complicate existing practices while disregarding the long-term benefit and overhead savings. Further, the collaborative design process in BIM could create difficulties in assigning responsibilities and liabilities due to the overlap of roles and responsibilities, ensuring intellectual property protection, risk allocation, privacy, and third-party reliance and software agents (Eastman et al. 2011, Turk et al. 2017). The focus of firms on return on investment, the complexity of projects, large initial capital, firm reputation, untrained personnel, legal considerations, and government restrictions are other factors that still impede digitization.

7.2.2 Current Advances

In recent years, there has been an increasing push to transition existing construction practices into digitization and automation, and consequently the development of investment and construction activity information system(). The adoption of BCT in the AEC domain is expected to both increase competitiveness in businesses as well as overall systemic efficiency while achieving synergy and enhancing the communication protocols between the entire network, and streamlining payment systems (Ablyazov & Petrov, 2019). An example of BCT applicatin in the AEC is delineated by the Agreements of Participatory Construction Interest (APCI) project. The project was implemented by Rosreestr together with AHML and Vnesheconombank (VEB). The APCI network was used to register the purchasing apartments iagreement by using a consensus agreed upon by the applicants and stakeholders. When the agreement concluded using BCT was validated, it refers to the authorization sanctioned by the builder for the APCI corresponding to the requirements of the Russian Federation law (Ablyazov & Petrov, 2019). A further example is the Tinkoff Bank and AHML agreement in 2018 to develop a BCT application to deal with mortgage credit and support for e-processing platform. This application aims to improve the interaction of the construction domain in terms of participation, involving a system of automatic finalization of mortgage requests by AHML standards, signing credit, granting credits, and online registration (Ablyazov & Petrov, 2019).

The advent of Building Information Modeling (BIM) has facilitated a collaborative work environment with a single centralized model so that the structure can be analyzed and checked for compliance and can be rectified of errors in the design stage prior to actual construction. Adopting BIM presents a novel way of integrating all pertinent data into a shared digital model with geometric, temporal, financial and asset management dimensions. BIM software like Revit and ArchiCAD also include a plethora of plug-in tools that can simulate and assess several important aspects of a building structure, such as operational energy analysis, life-cycle costs, occupancy behavior, connection design, interior climatization, building envelope, quantizing ecological footprint, etc. Thus, one can simulate scenarios and focus on one or more specific variables in real-time for every stage in the building life-cycle. This not only avoids unforeseen circumstances and errors in future stages but greatly saves time, manual labor and need for excessive paperwork.

7.2.3 Blockchain in Construction Management

Blockchain technology, while still in its nascent developmental stages, has the potential to accelerate and streamline much of today's design and engineering practices with a multitude of benefit to the firm, individual, industry, clients, and society. The implementation of BCT could lead to effective management and utilization of several tools that would drive efficiencies, transform industry culture, and advance futuristic advancements such as (Mathews, et al 2017):

- Building information modeling software for intelligent and collaborative 3D design and modeling;
- Cloud-based technology allowing for real-time creation and coordination of a visualized database and serving as a platform for multi-disciplinary collaboration;
- Smart contracts, a set of coded instructions that can automatically execute upon the fulfillment of certain conditions;
- Reality capture technology allowing verification and conversion of digital assets into real value;
- Managing the Internet of Things (IoT): The distributed wireless sensor networks, are playing vital role in construction projects and recently researcher indicated that blockchain architecture might enhance IoT by minimizing its shortages and capitalize on its potential (Kshetri, 2017; Liao et al., 2017; Buccafurri et al., 2017a; Fabiano, 2017).
- Functionally, permissioned blockchain that facilitates consensus-based collaboration.

BCT can considerably slash administrative costs, effectively protect Intellectual Property Rights, and eliminate cumbersome paperwork, manual verifications, and contract execution. A potentially new stream of revenue for design professionals could be created by evaluating and selling designs and workflows. This, however, would also include addressing future problems that might arise, drop in quality standards, and continued liability (Mathews et al., 2016).

Building reputation is an important asset to any organization, which is difficult to quantify and compare. BCT can facilitate the creation of a registry consisting of past achievements and qualifications, to enable comparison of team constellations and thus aiding in decision-making processes for clients and project managers to select a well-balanced team with diverse skill sets, experience, and versatility (Mathews et al., 2017).

7.2.4 Blockchain and BIM Workflow

This section addresses issues related to the potential capabilities of BCT in enriching the BIM process. It explores various aspects of existing BIM workflow that could benefit from the integration of blockchain technologies.

BIM is at the forefront of digital transformation in the AEC industry, encouraging collaboration and trust, and simplifying data exchange. McGraw-Hill reports that BIM adoption has increased to 71% in 2012 from 49% in 2009 (Atkins et al., 2013). BIM models present a comprehensive design model of the building that can include all aspects of the structure like architecture, structural, and MEP design areas. Further, several built-in plug-ins in BIM platforms like Autodesk Revit enable the simulation of external site conditions, geography, weather, as well as carry out energy analysis, building energy modeling, structural analysis, etc. In the future, BIM development will eventually aim to unify all design and analysis tools in one platform.

In terms of the benefits incurred from the adoption of BIM in the AEC industry, Cannistrato (2009) studied, data from 408 projects over 6 years totaling $558,858,574 to quantify how much BIM contributed to saving money. The report indicated that BIM saved more money as the project team gets more collaborative in the process. Another example is the study by Bryde et al., 2013 indicated similar results. Their investigation covered a set of 35 case studies between 2008-2010 that indicate cost savings due to BIM usage. The study has also noted reduced times in project schedules, improved communication, greater information exchange, and higher levels of coordination. The data clearly implies that initial costs such as hardware upgrades, software implementation, and training of personnel are offset on the long term upon BIM implementation. However, the BIM process still bears a number of shortcomings.

These include some limitations in the schema, technical toolset, and managerial aspects of the current BIM process. More specifically, these deficiencies involve:

- an insufficient toolset or methods that can efficiently comment or mark upon Requests For Information (RFIs) (Shourangiz et al. 2011),
- no archival of BIM model change and modification history,
- impracticality in the generated list of design errors (Miettinen et al. 2015),
- inapplicability of the integrated model for co-designing in real-time (Miettinen and Paavola 2014), (Miettinen et al. 2015),
- a clear generation of comparative deviation reports contrast design changes between different file versions (Shourangiz et al. 2011),
- Detailed open model templates (Cerovsek 2011),
- insufficient communication standards and BIM model sharing that can lead to interoperability issues between different BIM tools (Nawari, 2012a; Nawari, 2012b; Nawari & Alsaffar, 2015),
- Lack of tools to map complex collaborative workflows and insufficient levels of interoperability (Ahn, Kwak, and Suk 2015),
- difficulties in assigning responsibilities and liabilities due to the overlap of roles and responsibilities, ensuring intellectual property protection, risk allocation, privacy, and third-party reliance and software agents (Eastman et al. 2011; (Turk and Klinc 2017),
- insufficient cyber-resilience of the software platform and consequent risks and liability to data theft, tampering, and other cyber-attacks,
- Time-consuming re-modeling, conversions, and other repetitive tasks through the project phases that could be automated (Ahn, Kwak, and Suk 2015),
- lack of legal framework detailing model data ownership and legal contractual issues (Ahn, Kwak, and Suk 2015).

Many of these shortcomings can be addressed by the implementation of BCT in BIM work process. One such example is bcBIM that explores extending the combined integration of these emergent technologies aiming to primarily incorporate mobile cloud data into BIM architecture (Zheng et al., 2019), particularly in maintaining historic records of BIM modification by getting the hash value of BIM uplink data and calculating Merkle tree roots. This model, therefore, ensures data integrity and can generate a unified format in favor of transparent, open sharing, guarantee cybersecurity for the transaction of financial services in the AEC industry, credit reporting, ownership management, resource sharing, and trade management (Zheng et al., 2019). Another example is the BCT-based solutions for BIM introduced by a French tech start-up company, focusing on the immutability and they aim to bridge both these technologies into a cohesive, seamless conjunctive integration and move on from a simply third-party usage of the tool, ultimately targeting to decentralize the entire process of BIM and shift the paradigm from the current central common data environment (CDE) that forms its operational basis (Cousins, 2018).

7.2.4.1 Collaboration

The replacement of a hierarchical organization with an inherently collaborative network could seem to be inevitable due to its effectiveness in isolating faults by tracing alternate paths around these areas. This is one of the key advantages of BIM, making it the current best solution for collaborative creation, data storage, and asset management. Stakeholders can reach a consensus by providing evidence of trust, such as collaboration centered on a shared BIM model, and integration of a distributed decentralized ledger based on BCT. This cooperation culture change can address issues of unclear responsibilities and liabilities by prioritizing collaboration and sharing risks and rewards among the participants (Mathews et al., 2016). Integration of BCT in BIM software addresses current issues like confidentiality, non-repudiation, traceability, change tracking, provenance tracking and data ownership (Eastman et al. 2010; Ahn et al., 2015; (Turk and Klinc 2017). This 'Evidence of Trust' can be an effective and stable cornerstone for the collaborative design process and the Integrated Project Delivery (IPD) strategies.

Despite the increasing understanding of the significance of BIM, the rate of mainstream utilization and implementation has been relatively slow. The best stage for implementation is between the transaction processing component of the BIM server and its storage functionality. The complete scope of possible applications from adopting BCT is not yet fully realized, and it is by no means completely foolproof or at this point. Despite all the advantages, the written code is only as dependable as the accepted collaboration and agreed upon consensus. While varying levels of centralization and establishing a chained or unchained implementation of BCT in BIM can yield certain benefits, Turk and Klinc (2017) suggest that completely integrating BCT in a BIM setting to record all transactions would be the ideal solution to leverage all potential advantages from using a DLT. Furthermore, recent research efforts on the employment of BCT in BIM platforms has indicated that the properties of recordkeeping, immutability, and transparency seem to signify apt implementation and potential for expansion in the construction domain (Shen & Pena-Mora, 2018).

Choosing the appropriate type of BCT based on privacy levels (public or private) is vital while implementing DLT in the construction sector (Li et al, 2016). This process depends on the suitable consensus mechanism that could be applied, and that would cover all operational necessities of all participants and stakeholders since it forms the basis of establishing the BCT.

A framework proposed in a study by Xu et al. (2018) to choose the appropriate BCT depending on application requirements since current development levels of smart contracts necessitates reaching a compromise in a trade-off between scalability, permissions, computational power, and other characteristics. The process of choosing of BCT is elaborated below:

Fabric Layer Design Considerations:

- *Scalability:* Larger block sizes will require off-chain data storage to draw on application logic or data, while smaller transactions can be transmitted as scalable metadata on the BCT. BIM model data may be too large and might incur high latency rates, and hence using off-chain data is a better option;
- *Consensus mechanism:* PoS, Practical Byzantine Fault Tolerance or PoW may be used depending on the nature of the organization. In the AEC industry involving several parties involved in a common project, a PoS mechanism can work since each project member has his design contributions to the model to offer as the stake. PBFT is also a suitable mechanism if a slightly decentralized approach is required, and the managers alone can be granted access to reaching consensus.

Application Layer Design Considerations:

- *Data storage:* On-chain data storage uses limited computational power, features limited data storage, and can verify computational data. This is suitable if hashed metadata is adequate for sharing. As discussed earlier, BIM model data might require greater computational power for addition in the BCT and hence, off-chain storage may be required. This is also suitable if the information is sensitive in nature, and confidentiality is vital. Using off-chain data will also be relatively inexpensive since the mining of blocks is reduced;
- *Privacy:* In the case of the AEC industry, a private BCT like a permissioned or consortium blockchain is a better option since it features permission management and ensures data privacy;
- *Single or Multiple chains:* Using a single chain translates to better management of blockchain and permissions but data management is more difficult. Using multiple chains, on the other hand, can prove useful when information isolation is essential while compromising on chain and permission management. This decision depends on the nature and confidentiality level of the project and participants;
- *External or internal validation oracle:* BIM projects usually involve teams that assemble only for that particular project and hence a human arbitrator who can be tasked with periodically injecting external state into the blockchain. This may, however, feature incur high latency rates;
- *Permissioned vs. Permission-less blockchain:* Permission-less blockchains cannot preserve data privacy and all data is visible to all participants on the network. Hence, for a legal contract platform, it is more appropriate to use a permissioned blockchain that allows developers to explicitly grant permission to the participants. Besides, the information on the blockchain may require encryption to preserve privacy. In this case, the key needed to be generated and stored off-chain. The BCT does not have enough information that can be used by the components without permissions to access the sensitive data.

7.2.4.2 Data ownership

BIM can address the issue of conversion of intrinsic value to digital values by creating added value, coupled with BCT's featured to provide reward mechanisms in the form of virtual currencies that hold validity long after the project completion. #AECoin is a recently developed cryptocurrency coin specifically created for design and engineering transactions (Mathews et al., 2016). This effort can contribute to addressing the difficulties in assigning responsibilities and liabilities due to the overlap of roles and responsibilities, ensuring intellectual property protection, risk allocation, privacy in current BIM workflow (Eastman et al. 2010; Ahn et al., 2015; Turk & Klinc, 2017). #AECoin can be used to measure the added intrinsic and intangible value of a physical artifact and accurately calculate rewards earned by the participant by assessing individual/collaborative project contribution over the product life-cycle. This concept of monetizing designs through the life-cycle would ensure a superior outcome and can more effectively motivate engineers and architects to deliver their best efforts by providing proportionate incentives. The application of BCT in BIM workflow will simplify the design and construction by tracing the process of construction, design and quality monitoring, and objects ownership by leveraging the Smart Contract technology (Ablyazov & Petrov, 2019).

7.2.4.3 Cybersecurity

7.2.4.3.1 Current security levels in BIM

Most industries currently rely on the "security through obscurity" approach to secure engineering, which emphasizes on the confidentiality of the implementation and mechanisms of the cybersecurity system. Thus, a small leak of information could potentially endanger the entire network (Kshetri et al, 2017). BIM offers a diverse multifunctional workspace which addresses asset management, performance monitoring, and change management through the life-cycle apart from overlooking the planning, design, and construction phases of the structure. To facilitate continuous collaboration among all parties, BIM makes use of Common Data Environment (CDE), which provides a single repository for project information that is used to collect, manage, and distribute data for multi-disciplinary teams. (IET Cyber Security Consortium Report, 2014). It requires auditing, monitoring, and tracking of data through the CDE, which will develop throughout the project life-cycle. Hence, it is vital to provide suitable governance and curation to address information management and uphold data security, quality, and integrity. Since BIM involves complex interactions involving collaborative actions and information exchange between actors, technology, and processes and inter-relationships, it is crucial to consider cyber-security implications, assess current levels of reliability, address current drawbacks, and reinforce security. In current usage, all BIM data is electronically shared across a common data environment. It is essential for all project members to understand and abide by cybersecurity rules (Hammi et al., 2018). There are lesser trust issues among BIM actors compared to traditional information sharing. However, BIM's complicated collaborative framework creates security issues with terms of data leakage, information theft, and information protection while dealing.

Both permissioned and permission-less blockchains have their respective advantages and drawbacks, and the BCT for use must be chosen appropriately based on the desired functionality and level of privacy needed. Concerning BIM workflow, there are generally several different parties working simultaneously on one model. In such cases, implementing a permission-less BC could bring positive effects such as improved communication, transparency of work, and presenting opportunities for collaborative design processes. However, the current socio-economic environment of the AEC industry may necessitate tighter management of permissions due to concerns like data theft, conflicting interests, misuse of information, and others arising from the number of third-parties involved in a typical construction project which usually entails high levels of copyrights, budgets and accountability to government bodies and regulatory entities. Hence, employing a permissioned BCT is a far more realistic option for most BIM projects.

Cybersecurity is "the collection of tools, policies, security concepts, security safeguards, guidelines, risk management approaches, actions, training, best practices, assurance and technologies that can be used to protect the cyber environment and organization and user's assets." (Boyes, 2014) The cyber environment includes the Internet, telecommunication networks, embedded processors, controllers, sensors, data storage and control devices, as well as the information, services, collaborative and business functions that only exist in cyberspace.

Cybersecurity threats that can potentially affect BIM workflow and its connected systems could be classified into three categories:

- *External threat agents:* unconnected malicious outsiders, criminal entities attempting to access data for reconnaissance, hackers, intellectual property theft, leak of sensitive or confidential information, malware that can attack BIM database;
- *Internal threat agents*: involved participants who may bear malicious intent, abuse of authorized access to steal, leak, or corrupt information to disrupt BIM operations, human errors like omissions, ignorance, negligence of work;
- *Systems and business failures*: natural causes by extreme weather, interference from animals, storage device failures, poor maintenance of the centralized IT infrastructure, bankruptcies, and business failures.

7.2.4.3.2 Advantages of using BCT for Improving Cybersecurity

The elimination of the requirement of a designated intermediary party to oversee transactions in the network offers several improvements over existent systems in terms of cybersecurity levels. Blockchain networks ensure that no single node in the network has complete access to all the information. Multi-signature (multisig) protection can add another layer of security by authorizing transactions by accepting more than one key. Hackers can gain complete access in the network only if more than 50% of the nodes are compromised (Kshetri et al, 2017).

Effective interoperability can be achieved by ensuring identifiability and authentication of participants and establishing a ubiquitous and secure infrastructure that serves as a repository for data storage, as well as a reliable platform that facilitates data exchange subject to required permissibility levels. Key features of BC such as utilizing secure cryptography, asset sharing, auditing trails of data access and a resilient peer-to-peer network present a novel and promising emergent method to address cybersecurity and collaborative issues. However, it should be noted that the implementation of BCT does not directly ensure infallibility. Further, BCT can enable a secure and transparent method of Proof of Delivery (PoD) with terms to the transport and delivery of physical assets (Hasan and Salah, 2018).

7.2.4.3.3 Compliance and Trust

The immutable, instantaneous, and transparent nature of DLT emphasizes compliance and trust between all involved parties on the network. The current economy that is inherently adversarial incentivizes the minimal exchange of information between parties involved in the completion of a project with a view to protecting one's interests. The advent of BCT is increasingly disruptive to the existing paradigm and will shift work culture in a direction that rewards collaboration and proves advantageous in the design process by facilitating better-informed decision making, collaborative learning, and easier debugging of errors. This change can be accelerated by the ability of BC technology to reward the intrinsic value of any data through an #AECoin cryptocurrency (Mathews et al., 2017). BC can facilitate the creation of a registry comprising of past achievements and qualifications of individuals with a view to enable comparison of team constellations and thus aiding in decision-making processes for clients and project managers to select a versatile and well-balanced team with diverse skill sets and experience.

The BCT platforms can primarily serve as recordkeeping tools to record changes in the BIM model throughout the design and construction phases of the structure. Moreover, smart contracts can be programmed to automate awarding or revoking privileges based on the satisfaction of certain terms, as well as store an immutable record of all modifications in the BIM model data, along with other associated information (Wang et al., 2017). The tamper-proof append-only nature of the records in a DLT also help to enforce compliance among workers. The transparency of the DLT coupled with the database properties of BIM (Wang et al., 2017) can introduce an '*evidence of trust'* (Matthews et al., 2017), which would create a new value proposition for the AEC industry.

7.2.5 Hyperledger Fabric and BIM workflow

Given the multidisciplinary nature of a BIM project with teams who may belong to different organizations and considering other project participants with varying levels of functions and privileges, a permissioned blockchain is most suitable for collaborative BIM environment. Thus, the study proposes the HLF framework since they rely on permissioned blockchain. A permissioned blockchain provides a way to protected data exchanges between groups of entities who share a mutual goal, but they have the intellectual properties that they need to secure while exchanging data. A permissioned BC relies on the identities of its peers, and thus, they can use the traditional Byzantine-fault tolerant (BFT) consensus mechanisms. BFT is a protocol that has been widely used in IT solutions to reach a consensus on the state of faulty nodes of a network.

The Hyperledger Fabric (HLF) is based upon modular and extensible architectures. An example of possible modules that can be plugged in and implemented in Hyperledger Fabric include (see Fig 8):

(a) *Membership services*: This module deals with a permissioning and serves to create a root of trust during network formation. Also, this module is vital in managing the identity of members participating in the blockchain network. It provides a specialized digital certificate authority for issuing certificates to members of the BC network.

(b) *Chaincode services:* Chaincode or smart contract is an application-level code stored on the ledger as a part of a transaction. Chaincode runs transactions that may modify the data on the ledger. Business logic is written as chaincode (often in the Go or Java languages). Chaincode is installed on network members machines, which require access to the asset states to perform reads and writes operations. The chaincode is then instantiated on particular channels for specific peers. Ledgers are normally shareable across entire networks of peers or include only a specific set of participants. Peers can participate in multiple BC channels.

(c) *Consensus services:* These services are at the heart of any BC application. They enable a trust system. The consensus service permits digitally signed transactions to be proposed and validated by network members. The consensus is normally pluggable and tightly linked to the endorse-order-validation model that the Hyperledger proposes. The ordering services in HLF represent the consensus system. The ordering service groups multiple transactions into blocks and outputs a hash-chained sequence of blocks containing transactions.

A transaction in Hyperledger is simply a request to the blockchain to invoke a function on the ledger. The function is implemented by a chaincode (smart contract). Cryptography ensures integrity and security of transactions by linking the transaction to previous blocks and by linking the cryptogram or hash from previously linked blocks. Each channel in HLF is its own blockchain. A smart contract functions as a trusted, distributed application and gains its security from the BC and underlying consensus among its network nodes.

The SDK (Software Development Kit) enables the development of applications that deploy and invoke transactions on a shared ledger. Currently, the Hyperledger Fabric supports both Node.js and Java SDK. The SDKs are critical in BCT application development. With the SDK one can create the application client, chaincode, users, and events in the HLF.

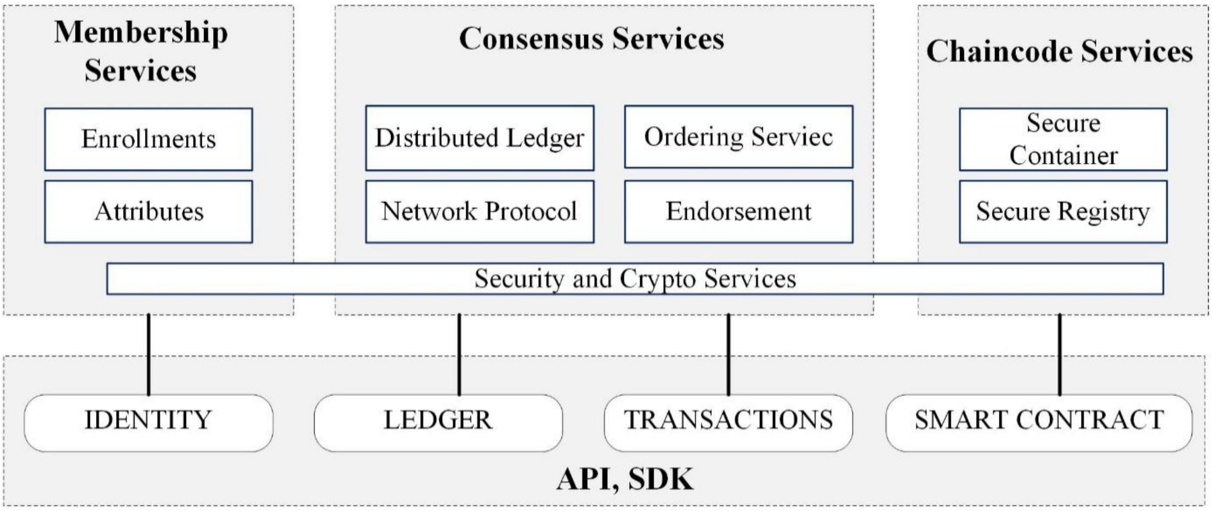

FIG. 8: Hyperledger Fabric (HLF) Architecture.

This study suggested a framework that store regulatory texts and BIM model data off-chain and facilitates the chaincode to function as the model checker tool. The details of this approach include:

a) The building codes or regulations upon which the BIM model data is to be checked must be processed into a computable language. A smart contract (chaincode) can be programmed to process the rules from natural language into computable terms. This contract must be defined carefully to account for all clauses, terms, and variables used in the building code. After conversion of the rules, the smart contract generates a second appended smart contract that can now be used by the model checker. If the smart contract capabilities do not support adequate levels of semantic enrichment, the rules can be directly expressed in the scripting languages;
b) The BIM model data is exported from the platform in IFC format and is converted to the scripting language used by the smart contract platform (Java, or Go languages). The BIM model data file expressible in Java is now generated and used as off-chain data;
c) A model checker is programmed in the form of another smart contract that can extract information from the BIM model data upon calling and verify them against the translated rules created in the previous step (a);
d) The model checker invokes the code-checking process and creates another smart contract where the results are reported and send to respective participants.

8. DISCUSSION

Blockchain systems provide a secure way to initiate a data exchange that helps verify ownership and availability of the asset to transfer in the form of hashes and digital signatures. In essence, it is a progression of encrypted data records pinned together over a distributed environment that vastly limits the probabilities of extortion. Thus, Blockchain technologies can play a vital role in improving the workflow in the AEC industry. For instance, BCT application emphasizes a framework that keeps transaction data, value, and state inherently close to the business logic that can be expressed in smart contracts (SC). Furthermore, they provide secure execution of data exchanges and validation through privacy and trust mechanisms, in a secure process that facilities speedy robust transactions. The cryptographically enforced interconnectivity in the blockchain applications fosters the stability and security of distributed ledgers.

Blockchain applications generally provide three layers of data security. The first one is through the physical IT infrastructure layer, which may include network, and infrastructure isolation requirements. The second layer contains requirements for crypto modules, encryption levels, encryption on data storage, transfer and data at rest, and visibility of data between participants in the network. The third layer of security is the trust system layer (consensus), which is essential to blockchain and necessary to assure basic data store properties. Consensus certifies that a minimum number of nodes agree on the order in which transactions are appended to the shared ledger. It provides a guarantee that all network nodes are operating on an identical blockchain. It maintains both the integrity and consistency of transactions in a blockchain network.

FIG. 9 illustrates the comparison between several application and research efforts in different domains. Finance and government applications seem to depict the highest growth whereas in the AEC related fields more research and innovations are needed. The surveyed BCT applications indicated that about 33% of them are in finance and business, 20% are in the data management domain, 30% are in healthcare and government, 10% are in education, and about 5% in the AEC related industry.

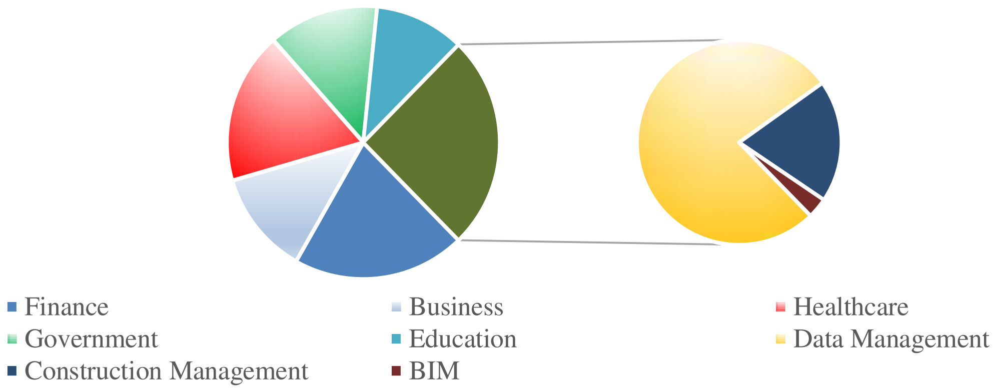

FIG. 9. BCT applications in different domains

Blockchain technologies can be grouped into two main categories, namely permissionless (such as Ethereum) and permissioned blockchain (such as Hyperledger Fabric). When comparing HLF to permissionless blockchain, the Fabric is more beneficial because nodes assume different roles and tasks in reaching a consensus, and are classified according to their roles as clients, peers or orderers. Hyperledger Fabric is established by IBM and is designed to be a platform for developing applications or solutions with a modular architecture. It permits for plug-and-play components, such as consensus and membership services, and leverages containers to host smart contracts called chaincode that comprise the application logic of the system. This modular architecture of HLF allows customization into various applications depending on the domain. The protocol of Fabric operates through two kinds of peers:

- *Validating peers*: These are nodes tasked with operational functions such as running consensus, validating transactions, and maintaining the ledger;
- *Non-Validating peers*: These nodes connect the clients that make the transactions to the validating peers.

These key features of the Hyperledger Fabric (HLF) can extend the BIM workflow and offer potentials for future innovative solutions. A conceptual example has been presented that integrates HLF with the BIM process. This proposed framework aims to address some of the main issues associated with the current BIM workflow such as cybersecurity, privacy, the speed of transactions, difficulties in assigning responsibilities and liabilities due to the overlap of roles and ensuring intellectual property protection.

The mechanisms of the data exchange in a HLF network begins with the client sending the request to all its connected endorsers who agree to reach consensus and initiate the update. The client collects the approval of all the endorsers and sends an approved transaction to the orderers who then reach consensus on the transaction block and forward it to all the peers holding the ledger. The peers then commit the transaction to the ledger.

It is important to note that HLF does not require built-in cryptocurrencies like Ethereum since mining is not required to reach a consensus. Every transaction is executed (endorsed) only by a subset of peers, allowing for parallel execution and addressing potential non-determinism and scalability issues. However, It the creation of digital currency is possible in a HLF application with chaincode (smart contracts), that implements the business logic and runs during the execution phase. Chaincode serves as the central part of a distributed application in Fabric and may be written in any programming languages. The chaincode is invoked within an environment that is loosely coupled with the rest of peers and support plugins.

One of the main limitations of HLF is the lack of defined standards to promote interoperability between multi-domain BCT applications. AEC applications that adopt HLF technologies in their workflow will, therefore, need to build competency so that they can contribute to further innovation and help with necessary blockchain standards development.

9. CONCLUSIONS

A blockchain is defined as a decentralized database that records every transaction complete in the network, known as a 'block'. Each block comprises encrypted data of the entire transaction history. The main concepts behind Blockchain Technology (BCT) are the creation of a digital distributed consensus, ensuring that data is decentralized among several nodes in the network that hold identical information and that no single node holds the complete authority of the network. The application of such decentralized technology in any industry would require augmented security, enforce accountability, and could potentially accelerate a shift in workflow dynamics from the current hierarchical structure to a decentralized, cooperative chain of command and effect a cultural and societal change by encouraging trust and transparency. This paper presents a comprehensive survey of BCT and its applications in various domains and examines the potential integration with building information modeling (BIM) workflow. The study examines how commissioning distributed ledger technology (DLT) such as the Hyperledger Fabric (HLF) could be advantageous in the BIM working processes by reinforcing network security, providing more reliable data storage and management of permissions, ensuring change tracing and data ownership. The example presented indicates that the application of BCT in BIM workflow creates a system that is built on the principles of decentralization, open governance (or self-governance), and transparency, a system that rewards innovation and eradicates disintermediation. Moreover, such systems provide secure execution of BIM data exchanges and validation through privacy and trust mechanisms, in a secure process that facilities speedy robust transactions. The cryptographically enforced interconnectivity in the blockchain applications fosters the stability and security of distributed ledgers.

HLF is a BCT that can be particularly suited for enhancing the BIM workflow due to its ease of programming (using SDK), flexibility, user-defined smart contract (chaincode), robust security, identity features, and modular architecture with pluggable consensus protocols. Using HLF can address many of the current concerns such as data security, privacy, speed of transactions, and change tracing and permission management that arise from using centralized BIM work processes. Future research work will focus on HLF applications in enhancing automating code-checking and compliances in the BIM workflow environment.

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