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Blockchain technology: Is it hype or real in the construction industry?

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ABSTRACT

The dawn of the 21st century has seen the advent of many technologies targeting commercial and financial sectors. These include Big Data, Internet of Things and FinTechs such as blockchain. Blockchain is a type of a distributed database that is used to replicate, share, and synchronise data spread across different geographical locations such as multiple sites, countries, or organisations. The main property of blockchain is that there is no central administrator or centralised data storage mechanism. Consensus algorithms govern the peer-to-peer decentralised network. Numerous benefits and applications of blockchains have resulted in it becoming popular among a broad spectrum of businesses, but is it the case in the construction industry? Given, the backward nature of the construction industry in digitalisation and its reticence to change, it becomes important to analyse the potential impact of Blockchains as a potential disruptive technology.

Although there exists a significant research gap and the potential possibility to test blockchain in the construction sector, the construction industry is historically reported as the second lowest sector to have adopted information technology. This leads to a conundrum whether blockchain is a pure technological hype or whether there is a real potential application in construction. The paper is aimed at critically analysing the application potential of blockchains in construction through a use case analysis and comprehensive literature review to resolve whether it is pure hype or real. The exploration revealed that due to the exponential uses of blockchain, investments involved, and a number of start-up businesses contributing to Industry 4.0, blockchain indeed has a credible potential in the construction industry.

1. Introduction

Blockchain is considered a potential disrupter of the status quo in the commercial sector innovating in transactions, revolutionising industries and driving economic change on a global scale. Blockchain technology is predicted to completely overhaul the digital economy [1]. Blockchains attracted attention from various industries such as finance, insurance, logistics, energy, and transportation in experimenting its applications [2]. Though blockchain is a potent disruptor in different industries, it is important to understand whether this is just hype or real when applied to real-life problems. This paper is aimed at critically analysing whether blockchain is pure hype or whether there is credible application potential in the construction industry.

The 4th industrial revolution (Industry 4.0), follows Industry 1.0 (water and steam power), Industry 2.0 (electricity) and Industry 3.0 (internet, electronic devices). It is characterised by the seamless integration of cyber-physical environments propelled by an array of technologies that enable the development of a digital and automated industry as well as the digitisation of the value chain [3–5]. Blockchain follows the egalitarian ideologies of the modern society where equality, direct dealing, openness, consensus and mutual trust play a vital role. Sikorski, et al. [6] states that blockchain technology has the potential to revolutionise the engineering industry by changing its production and procurement methodologies. A recent global report by McKinsey ranked the construction industry as the second lowest sector to have adopted information technology during Industry 3.0 [7]. Hence, there lies the conundrum, whether blockchain will create just hype or real disruption in construction, similar to the digital revolution that is taking hold in other industries.

Introduction of new technologies generally contributes to disruptive innovation, For example, Uber disrupting transport sector and Alibaba disrupting the business-to-business marketplace. On the other hand, Building Information Modelling (BIM) was expected to be such a disruptor, but was BIM successful in disrupting the construction industry? BIM-enabled to change the design paradigm [8–10], but was unable to create an impact on procurement. On the other hand, blockchain has

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more potential in addressing procurement issues fulfilling the unattended gap of BIM, whereas BIM and blockchain could work hand-in-hand to achieve this.

Research on blockchain will assist in understanding the effects of the salient properties and in identifying suitable societal fields of application [11]. Initially, blockchain was used for cryptocurrencies, which was identified as Blockchain 1.0 [12]. Subsequently, Blockchain 2.0 was introduced for economic, market and financial applications and Blockchain 3.0 for applications beyond currency, finance and markets [13]. Many world recognised companies such as Linux Foundation, Microsoft, IBM, Ubiquiti and the like are currently investing in blockchain technology to be used in various platforms [14]. Li et al. (2019) opined that Blockchain is regarded as having the potential to transform many global industries including construction.

The paper discussed the background of blockchain technology, building up the research question whether it is pure hype or real in construction followed by the second section, which discusses the research methodology of the study. The third section reviews the fundamental concepts of blockchain technology; hashing algorithm, peer-to-peer network, public-key cryptography, and consensus algorithms. The fourth section elaborates the blockchain architecture discussing prominently on private/permissioned blockchain, public/permissionless blockchain, and consortium blockchain. Subsequently, Section 5 explores the salient features of blockchain in general as well as considering its suitability to the construction industry. Apart from the various drivers that lead to the implementation of blockchain in construction and other industries, there are various barriers and risks inherent with blockchain technology as identified in Section 6. Section 7 highlights recognised use case applications of blockchain for various sectors which is followed by the exploration of the potential for application in the construction industry.

2. Research methodology

The research methodology of this study comprised of five steps, as illustrated in Fig. 1. Following a systematic literature review, search rules were used to filter the research papers related to blockchain from the Scopus and Web of Science databases. Afterwards, a screening process was carried out to identify the research papers that are thoroughly focused on blockchain, technological aspects and applications. The literature review was carried out on 64 journal papers, 25 conference papers, 9 books, 2 theses, 8 technical whitepapers, 17 reports and 50 other sources including web pages and blogs among others given the nature of the rapidly evolving topic. Afterwards, the identified literature was critically reviewed. Pomponi and Moncaster [15] have carried out a similar study to evaluate the existing literature on embodied carbon using systematic review and have identified the potential research gap.

As illustrated in Fig. 1, the conceptualisation process took place where literature was classified into different categories. Afterwards, the blockchain architecture comprising of different layers and blockchain technology were identified. This lead to interpreting of features, drivers, barriers, and risks. This was followed by carrying out a thorough use case analysis to identify the potential applications of blockchain. Finally, as the way forward, the potential credible applications for the construction industry were recognised.

3. Technologies behind blockchain

A ledger (often public) is maintained in blockchain, where all committed transactions are stored in a list of blocks, and the chain grows as new blocks are appended continuously [16]. Blockchain uses a decentralised network of nodes to protect the stored lists of records against tampering or modification [17]. The participants on the blockchain network are allowed to view the digital ledger, which is shared over a distributed network of computers in a secure way [18].

Blockchain technology is a combination of concepts, including peer-to-peer protocols, hashing algorithm, cryptographic primitives such as public-key cryptography and distributed consensus algorithms [2]. Fig. 2 illustrates key technologies behind blockchain and each mechanism is discussed in the next section.

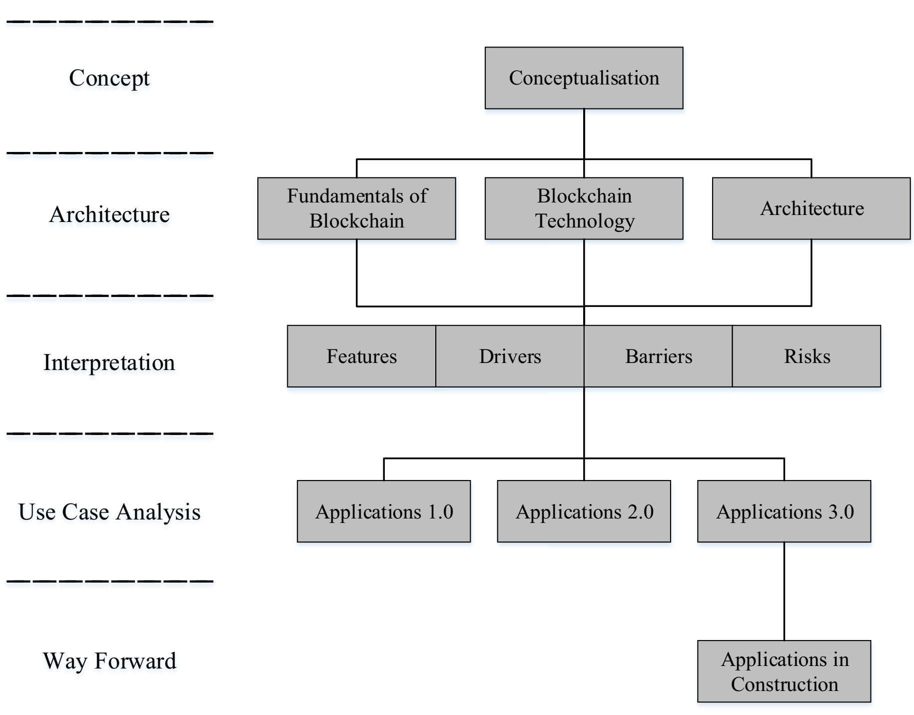

Fig. 1. Research Methodology.

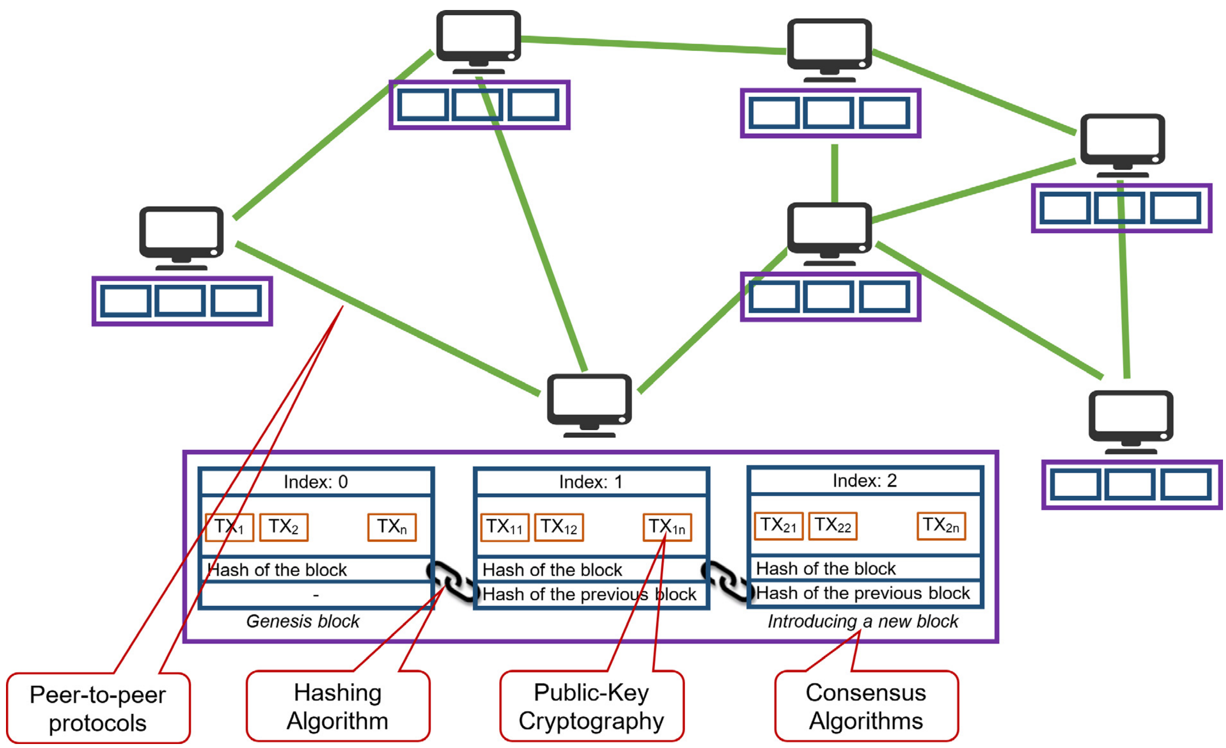

Fig. 2. Overview of technologies behind blockchain.

3.1. Peer-to-peer network

Blockchain is identified as a decentralised consensus network in which peer-to-peer network has contributed to achieving such a network [19] as illustrated in Fig. 2. In a peer-to-peer network, a peer is also identified as a node. In a peer-to-peer network, no peer is superior to others, and all nodes share the burden of providing the required network services [20]. All the nodes are connected on a flat topology without a hierarchy, central authority or main server, making the peer-to-peer network purely decentralised. In a peer-to-peer network, a consensus mechanism is used to ensure that the block is valid before it is recorded on the ledger [21]. Once the block is recorded on the ledger, the entire network will have a copy of the updated ledger. All nodes in the peer-to-peer network have access to data and create an autonomous network, to provide and share data among these nodes [22]. The consequent blockchain then becomes the single source of truth.

3.2. Hashing algorithm

The blocks in the blockchain are linked to each other, forming a chain of blocks, signifying the term ‘blockchain’ as illustrated in Fig. 3. The first block is called the ‘genesis’ block. As shown in Fig. 3, each block comprises of multiple transactions, i.e. TX_1 to TX_n, the block index, the hash value of the previous block (also identified as the parent block), timestamp, the hash value of the block and a nonce, which is a random number to verify the hash considering the network rules. Apart from the transactions, each block contains a respective hash derived by the data stored on the block and the hash of the previously accepted block in the blockchain [23]. Nofer et al. [24] highlighted that the hash values are unique, and if any change is made to a block in the chain, the respective hash value would be changed immediately.

It is important to understand how cryptographic hashing works in order to understand digital identities [20]. If an attacker attempts intentional misuse by tampering with data of a block, then the respective hash of that block needs to be changed. Therefore, if an attacker attempts to change one hash, the hashes in the entire chain between the tampered block and the latest block need to be changed [24]. However, a successful attack will not be completed by only changing a single blockchain or a ledger in one node, unless the majority of ledgers have been replicated in the network. It is extremely difficult to replicate more than 50% of the nodes within a short period. Hence, it is believed that tampering with the data in a blockchain is almost impossible. This hash is the key element in a blockchain that provides security to prevent tampering with the data stored in a block.

Kaushik et al. [20] and Selmanovic [25] revealed that a good hashing algorithm needs to fulfil the following requirements and SHA256 is the most common hashing algorithm in blockchain platforms;

- The hashing algorithm must have a fixed output length (256 bytes is a good value)
- The smallest change in input data must produce a notable difference in output
- The same input will always produce the same output
- There must be no way to reverse the output value to calculate the input
- Calculating the hash value should not be compute-intensive and should be fast

3.3. Public-key cryptography

Traditionally private-key cryptography was used to communicate messages securely by using a single secret key shared by two parties while maintaining its anonymity and providing security. Asymmetric public-key cryptography refers to a cryptographic method, where different keys are used for encryption and decryption rather than the shared secret single key [22].

There are two common applications of public-key cryptography; a) message encryption and b) the digital signature. In the process of message encryption, the sender can use the receiver's public key to encrypt the data and send through a public channel without compromising security. Only the corresponding receiver can decrypt the data

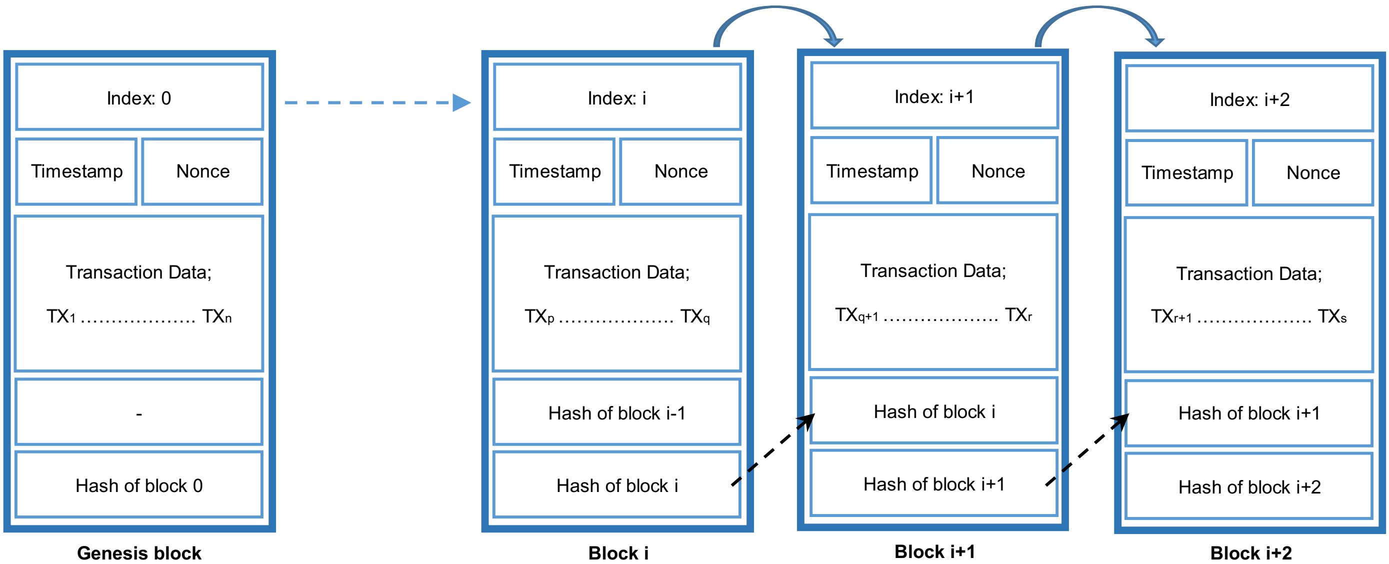

Fig. 3. An example of a blockchain.

by using their private key [19]. In the process of digital signing, the sender can sign the message by using his private key and send or broadcast message to one or more recipients. The receiver or receivers can use the sender's public key to verify the digital signature is legitimate or not [26]. The digital certificate is a fundamental concept behind blockchain technology to verify the ownership of broadcasting or messages through public ensure networks enhance trust.

3.4. Consensus algorithm

Lamport et al. [27] proposed a fault tolerance mechanism to solve dependability issues of a fault-tolerant system by adopting the Byzantine Generals' problem. A transformation of the Byzantine Generals' problem aided to ensure consensus among the untrustworthy nodes in the blockchain network [16]. In the blockchain, consensus refers to a series of procedures related to approving and confirming a transaction or set of transactions by using the consensus algorithms [22]. Most of the public blockchains use Proof of Work (PoW) or its derivative consensus algorithms to ensure that transactions cannot be tampered with. PoW is a better security mechanism as long as no single miner controls more than 50% of the network's hash power [23]. However, a PoW mechanism needs high computing power for countless calculations, resulting in high energy consumption [28]. Bitcoin network uses PoW consensus mechanism, and as a result of the bitcoin mining operations and increasing competition for the most hash power, it consumes around 0.33% of world electricity consumption [29]. Once a transaction or set of transactions are added as a block to the ledger, as all nodes share a copy of the ledger, all ledgers reflect this change. Consensus mechanism allows for the near-instantaneous update of every copy of the ledger [30].

There are dozens of consensus algorithms other than PoW, which are aiming to solve mainly three issues: scalability, security, and decentralisation as illustrated in Fig. 4 [31]. A good consensus algorithm should address all three factors. However, based on the requirement, consensus algorithms can be more specialised in one or two factors, as indicated in Fig. 4. Most commonly used consensus algorithms are Proof of Work (PoW), Proof of Stake (PoS), Practical Byzantine Fault Tolerance (PBFT), Delegated Proof of Stake (DPoS), Proof of Importance (PoI), Ripple Protocol Consensus Algorithm (RPCA), Stellar Consensus Protocol, and Byzantine algorithm based Tendermint [16, 32]. These are discussed below in detail. Few other known consensus algorithms are Proof of Authority, Proof of Burn, Proof of Activity,

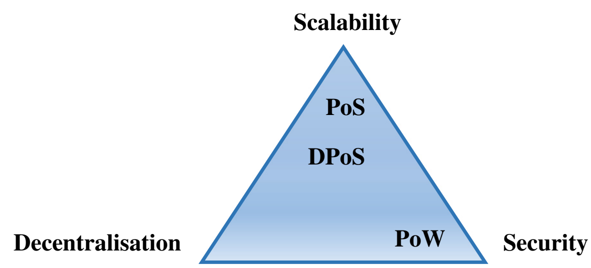

Fig. 4. Trilemma triangle of blockchains.

Proof of Capacity, Simplified Byzantine Fault Tolerance, Federated Byzantine Agreement, Zero-Knowledge Proof and so on [16, 32–34]. Most common consensus algorithms are discussed below.

- **PoW** is the most common consensus algorithm, and more than 75% of cryptocurrency market capital is controlled by it. PoW is an open consensus algorithm [16]. Simply PoW refers to calculating the hash value of a block with the required number of leading zeros by changing nonce (a random number). This process is identified as mining, and it is a highly energy consuming process. Once a miner has found a valid nonce, it can be broadcasted to other nodes for verification purposes [32].
- **PoS** was introduced as an energy-saving alternative for PoW, and it is a moderately energy-consuming mechanism. PoS is an open consensus algorithm [16]. The philosophy behind the PoS is, there is a low risk of attack to the network from the people with more stake. PoS is mainly based on the calculation of the coin's age. Simply, the system calculates coin days by multiplying holding coins and held days, followed by calculating the stake size to decide which node to make the next block. Cardano cryptocurrency uses PoS consensus algorithm [16, 32].
- **DPoS** has representatives, and it also uses the coin's age-based stakes. DPoS is an open consensus algorithm [16]. The major difference between PoS and DPoS is that DPoS uses representative democratic. In DPoS, stakeholders elect their delegates to generate and validate blocks. The fact that fewer nodes are involved in the block production process enhances the performance of the network. DPoS is a consensus mechanism with low to moderate energy consumption [16].
- **RPCA** uses a specific voting mechanism with single or multiple

rounds, until all transactions that meet a minimum of 80% acceptance rate. When all nodes receive 80% or more yes votes, it will be written into the public ledger [32]. RPCA is an open consensus algorithm, and also it is a low energy consumption mechanism [16].

- **PBFT** is a permissioned network's consensus protocol, which Hyperledger Fabric utilises. PBFT has a three-step process, such as pre-prepared, prepared and commit. At each step, there is a voting process, and it is necessary to get 2/3 votes from all nodes before proceeding to the next step. After the completion of three steps with more than 2/3 votes, the system will allow adding next block to the ledger. PBFT is a permissioned consensus algorithm, and it is one of the lowest energy consumption mechanisms [16].

PoW, PoS, DPoS and RCPA use open identity management, and PBFT uses permissioned identity management. PBFT and RCPA have better energy saving while PoS and DPoS have moderate energy saving, and PoW has the highest energy consumption among consensus algorithms. Consensus algorithms' tolerated power of adversaries depends on different factors such as computing power of network, stakes, number of validators, number of faulty nodes and others. PoW can tolerate up to 50% computing power, PoS can tolerate up to 50% stake, DPoS can tolerate up to 33.3% validators, RCPA can tolerate up to 20% faulty votes, and PBFT can tolerate up to 33.3% faulty replicas [16, 35].

4. Blockchain architecture

Blockchain architecture is illustrated in Fig. 5 as five layers, namely Network layer, Data layer, Consensus layer, Execution layer and Application layer [36, 37]. Decentralised communication model and distributing data in the blockchain network are handled by the Network layer, and it is fully responsible for inter-node communications. Consensus layer manages agreement between each node regarding the contents in the blockchain network. Consensus algorithms such as PoW, PoS, PoA and PBFT run in this layer [38].

Data layer handles the total structure of the blockchain contents [37] by using chain structure, timestamp, Merkle tree, hash function, data books and public-key encryption. Execution layer handles runtime environment of the blockchain, including managing programming and scripting languages and compiler, decoder, smart contract, virtual machine and other elements related to the execution of system [36]. All use-cases of blockchain such as cryptocurrencies, supply chain management, smart grids, smart voting systems are classed as the Application layer [37].

Blockchain network may consist of few to millions of nodes throughout the globe. Based on the Network layer arrangement including privileges of nodes to access, check and add transactions to the ledger, and arrangement of a network, it can be identified as three types of blockchain networks commonly named as public, private, and consortium, which will be discussed below.

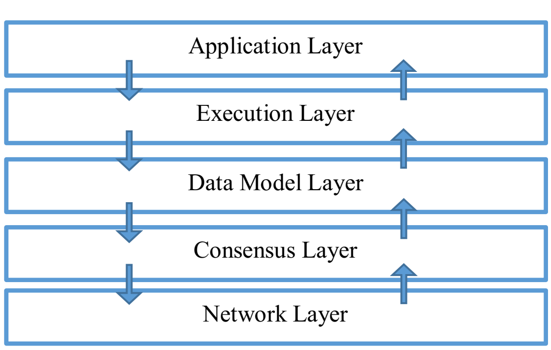

Fig. 5. Blockchain abstract layers
Adapted: Mosakheil [37] and Dinh, et al. [36].

4.1. Public blockchain

The public blockchain is also known as the permissionless blockchain, and it is open to anyone who wishes to participate as a member of the network. All the members of the network are allowed to access and read any transactions on the blockchain [30] as illustrated in Fig. 6. There is no authentication required for reading and writing in the blockchain. However, it is compulsory to follow the network governing rules [39]. Consensus mechanisms assist to the accuracy of the ledger and ensure the security of the distributed ledger [30]. The reliability and consistency of the data and transactions have been ensured by the consensus mechanism in blockchain technology [28].

In a public blockchain, the miners (block validator/ block producer) use a variety of algorithms to validate the transactions and finally publish the confirmed transactions to other nodes [30]. Only when most of the nodes confirm by reaching a consensus, the transaction or set of transactions are recorded within a block into the public ledger. Most of the public blockchains have performance and scalability concerns compared to private blockchains. Famous permissionless blockchains such as Bitcoin and Ethereum use proof of work (PoW) consensus algorithms and however, Ethereum is planning to move to a proof of stake (PoS) consensus algorithm [11, 40]. Fig. 6 illustrates the skeleton of a public blockchain.

One of the best public blockchain applications in the construction industry will be government procurement systems. They should maintain good governance criteria such as transparency, schedule, and accountability, for which public blockchain is one of the best solutions [41].

4.1.1. Sharding

Scalability is one of the most critical issues in public blockchain networks. Specifically, where blockchain focuses on decentralisation and security; scalability is a challenge. Ethereum blockchain network is trying to adopt the sharding data partitioning concept, without compromising decentralisation and security of the network. Sharding is a mechanism used in databases for horizontally partitioning data within a database into several smaller sections called "shards". Each individual shard can execute, mine and verify the transaction in parallel. There are some 'supernodes' that communicate with all the shards and put the newly introduced blocks into the root chain as shown in Fig. 7. This parallel transaction process will significantly increase the throughput of the blockchain network [42].

4.2. Private blockchain

The private blockchain is also known as the permissioned blockchain, and only authorised participants can join the network [39]. According to Boucher [43], a limited group of nodes retain the power to access, check and add transactions to the ledger and it is a small nodes group when compared with public blockchain networks as illustrated in Fig. 8. In a permissioned blockchain, participants can be limited to those who are pre-approved and further it is possible to limit the participants regarding the different access levels to the information in the ledger [30]. As an example, some users will be allowed to view all the data in the ledger but not allowed to add any transaction. Depending on the level and area of access of each user, the transactions in the ledger will be visible and will be allowed to add transactions to the ledger. In a permissioned blockchain, the users' access levels, roles and other permissions have been pre-decided and granted in the initiation participation phase. However, some information access levels are managed by the rules in the network. Once the transaction is submitted by the two parties involved, it would be validated by a permissioned member of the blockchain [30].

Building a consensus in a private blockchain is quite easy compared to public blockchain environments [22]. There are several options for a private permissioned blockchain, and the most common platforms are

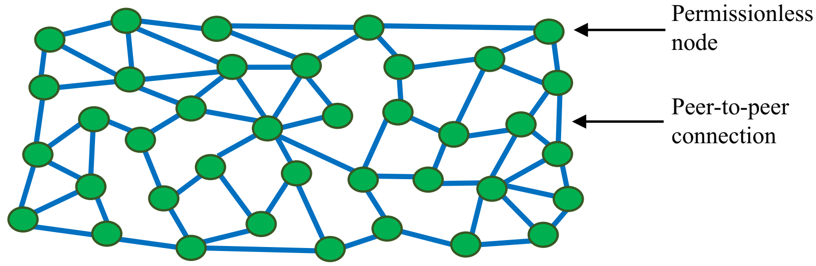

Fig. 6. Skeleton of a public blockchain network.

Hyperledger Fabric, HydraChain and Sawtooth [44]. Private blockchain platform provides high privacy and security, enterprise permissioned, high performance, better scalability, compliance support and provide more efficient consensus mechanisms [11, 17]. However, they deviate from the egalitarian concepts as identified before to a controlled environment.

The construction industry has a significant amount of sensitive data, such as pricing, legal agreements, financial data, and many others. Private blockchain network has a high capability to maintain security aspects such as confidentiality and integrity. Therefore, private blockchain networks can provide trustworthy business software solutions to the construction industry.

4.3. Consortium blockchain

A consortium blockchain is a partly private blockchain solution without a single owner organisation and usually called a federated blockchain [45]. Consortium blockchain has privileged permissioned nodes across the network as illustrated in Fig. 9. Consortium blockchain platforms have many of the same advantages such as privacy, efficiency, scalability, performance and the like, which a private blockchain has, but operate under the governance of a group [11, 17]. Therefore, governance is essential for consortium blockchains. Similar to a private blockchain, a consortium blockchain can limit the participants regarding the different access levels to the information in the ledger and also a different set of information. Subsets of organisations can have their own channels to communicate and can have isolated data only for respective associations. As an example, some users will be allowed to view all the transactions, or even part of the transactions in the ledger and nodes on the network that are pre-approved [11, 17, 46]. Proof of Authority (PoA) is one common consensus algorithm in consortium blockchains. Consensus participants of a consortium blockchain are likely to be a group of pre-approved nodes on the network. Corda R3, EWF, B3i and Quorum are common consortium blockchains [11, 17, 47, 48]. Microsoft Azure Confidential Consortium Blockchain Framework (CoCo) is an integration solution to the consortium blockchain platforms [17, 48].

Today's businesses tend to utilise more networks than in the past. Corda R3 is one of the most popular consortium blockchain networks developed and implemented by the financing sector [49]. The construction industry has many consortia or partnering arrangements. Enhancing the partnering trust and transparency with high collaboration will be offered by consortium blockchain solutions.

4.4. Comparison of blockchain architectures

Table 1 compares 30 characteristics among popular private, public and consortium blockchain platforms by referring to many sources as listed below the table.

Among presently available popular blockchain platforms, EOS.IO and Hyperledger Fabric have significantly better features as shown in Table 1. Both employ DPoS and PBFT high-performance consensus algorithms. Therefore, out of the presently available blockchain platforms, EOS.IO is one of the most suitable open blockchain platforms, while Hyperledger Fabric is one of the most suitable permissioned blockchain platforms for complex construction industry transactions and business requirements.

5. Salient features of blockchain

Blockchain technology is one of the latest approaches that have the potential to enhance decentralisation, transparency, equality and accountability on the internet [78]. It is a product of the egalitarian society aiming to bring a decentralised approach to peer to peer transactions building trust and avoiding the middleman. Blockchain consists of a secure and transparent technology to store and transmit data between users without a central point of control [17]. Similarly, Rodrigues, et al. [79] opined that blockchain moves the control of the centralised entities, redistributing it among users in a decentralised and transparent manner. Risius and Spohrer [11] stated, “Blockchain technology refers to a fully distributed system for cryptographically capturing and storing a consistent, immutable, linear event log of transactions between networked actors”. According to Miraz and Ali [80], blockchain comprises of two main components; (1) transactions, the action triggered by the participant; and (2) block, a collection of data related to a number of transactions.

Blockchain consists of unique features that enhance the uses and applications of blockchain within various industries. The salient

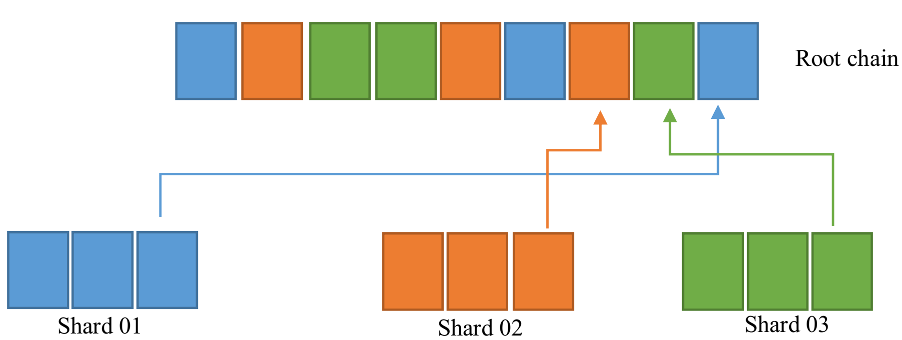

Fig. 7. Blockchain network with Shards.

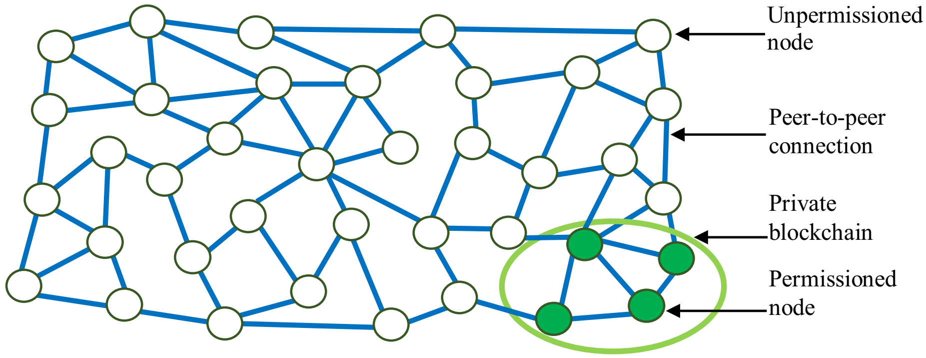

Fig. 8. Skeleton of a private blockchain network.

features of blockchain, which are identified by various researchers have been summarised in Table 2.

The salient features identified in Table 2 have been further elaborated below;

- **Decentralisation -** Blockchain consists of a decentralised peer-to-peer network. Accordingly, the main property of the blockchain distributed ledger system is that there is no central administrator or centralised data storage mechanism [102]. Decentralisation provides robustness while eliminating many-to-one traffic flows to avoid delays and single point of failure [83].
- **Anonymity -** In blockchain transactions, as public and private keys are used, people can choose to remain anonymous to protect their privacy while enabling third parties to verify their identity [84]. This enables the ability to maintain and preserve privacy on transactions.
- **Security -** Blockchain uses encryption mechanisms involving asymmetric public-key cryptography (Tapscott & Tapscott 2017) to secure the validity of the stored information and to prevent fraud [21]. Encryption allows maintaining the privacy of private data while digital signatures ensure authenticity, data integrity and non-repudiation [103].
- **Immutability -** Data stored on a blockchain is considered immutable as it is secured by the peer-to-peer network of participants [83]. Transactions cannot be undone after the records have been added to the blockchain [95], resulting the ledger to be an immutable record of all previous transactions [30]. Blockchain allows create and read (CR) operations only [30].
- **Auditability -** The transactions are validated and recorded on the blockchain with a timestamp, which enables the users to easily trace the previous records by accessing any node in the distributed network [88].
- **Veracity -** Blockchain provides veracity to the stored records as the same copy of the historical records of the ledger is replicated and stored in the network of nodes. Further, each record is verified by consensus improving veracity at a higher level. If bogus entries are created, they will be identified and eliminated due to failure to reach consensus [104].
- **Transparency -** In a public blockchain, all the transactions are transparent and announced to the public [86]. The records of activity can be made public so that it is visible to all market participants [104, 105] or else the level of transparency can be controlled as required.
- **Disintermediation -** Blockchain technology negates the involvement of third parties, avoiding the need to trust the intermediaries [103]. Thereby operational costs can be lowered while increasing the efficiency of the sharing service [84]. When the third party and its associated fees are removed, it will enable better value to be shared between the buyer and the seller [2].
- **Trust -** Blockchain provides greater trust among its users [106]. When adding data, a majority of the participants in the blockchain need to agree for it to become a part of the definitive blockchain [103, 107]. Due to the trust built up, intermediation can be avoided.
- **Turing-complete -** Most of the modern blockchain networks support smart contracts where developers can build and run the various applications on top of blockchain networks [11, 28, 40]. Turing-complete is the key factor for creating a distributed application by using all the rich functions available in such programming languages [28, 40]. Other than Bitcoin, most of the blockchain networks such as Ethereum, EOS and Hyperledger Fabric comply with Turing-complete and support stateful contracts [40, 108].
- **Performance -** Not only for blockchain but for any system, performance is one of the key non-functional requirements (NFR). Usually, performance is defined by using speed, efficiency, resource consumption, throughput and response time. System performance is how many transactions or operations can be handled per second

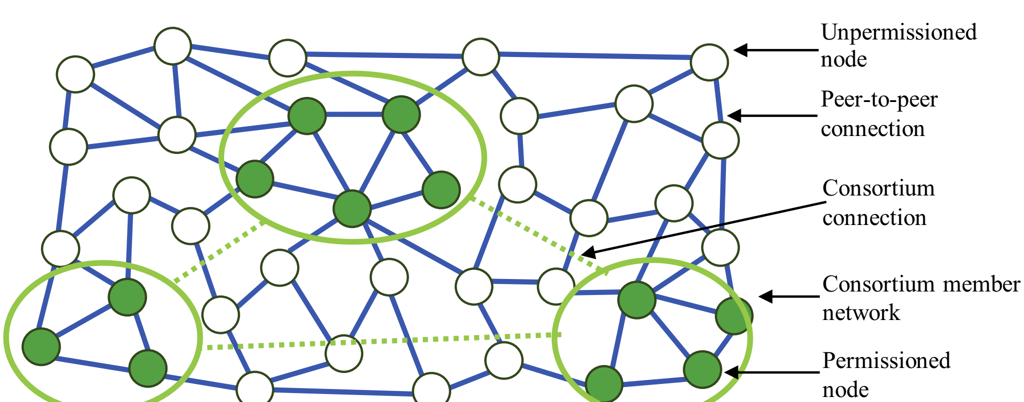

Fig. 9. Skeleton of a consortium blockchain network.

Table 1
Key characteristics of popular blockchain platforms.
Sources:.

Characteristics	Bitcoin network	Ethereum	EOS.IO	Hyperledger Fabric	R3 Corda
Year of implementation	2009[c]	2015[ab]	2018[q]	2016[r]	2016[ac]
Source model	Open source[y]	Open source[v]	Open source[q]	Open source[v]	Commercial and Open source[s]
Governing	Community[z]	Community[v]	Block producers[i,v]	Linux Foundation[g,v]	R3[a]
Primary type	Public[o]	Public[v]	Public[q]	Private[v]	Consortium[v]
Focus domain	Cryptocurrency[y]	Cryptocurrency + Generic blockchain platform[v]	Cryptocurrency + Generic blockchain platform[q]	Generic modular platform for any industry[v]	Specialised for the finance industry[a]
Permissioned networks	No[y]	No[v]	No	Yes[t]	Yes[f]
Supporting for APIs	Yes[y]	Yes[c]	Yes[k]	Yes	Yes[w]
Primary scripting language	Bitcoin Scripting[y]	Solidity[v]	Web Assembly[u]	Javascript & Chaincode[v]	Kotlin[v]
Turing complete	No[c]	Yes	Yes	Yes	Yes[w]
Smart Contracts	No[c]	Yes[v]	Yes[v]	Yes[v]	Yes[v]
Smart Legal Contracts	No	No	No	No	Yes[b]
Implementing data protection laws	No	No	No	Can	Can[b]
Modular architecture	No	No	No	Yes[t]	No
Confidentiality	Medium	Medium	Medium	High[v]	High[a]
Network	Flat	Flat	Flat	Role-based[v]	Role-based[v]
Isolation	Not available	EVM[n]	–	Docker[g]	JVM sandbox[s]
Throughput (transactions per second)	3–7[h]	10–20[h]	More than thousand[j]	More than ten thousand	More than Hundred[x]
Performance	Low	Low	Medium	High	Medium
Block-size	1MB[aa]	Varies[c]	Varies (limited to available bandwidth)[e]	Configurable[r]	On-demand[b]
Block-time	10 min[o,n]	12–15 s[h,n]	0.5 s[e]	Configurable[r]	Real-time[p]
Scalability	Poor[q]	Poor[v]	Moderate[m]	Better[v]	Better[v]
Consensus Mechanism	Proof of Work[l]	Proof of Work[c]	Delegated Proof of Stake[l]	Byzantine Fault Tolerance, Proof of Elapsed Time[v]	Notary node[b]
Anonymity Implementations	–	–	–	Channels, Private Transactions, Zero-Knowledge Technology[g]	Party, Anonymous Party, Zero-Knowledge Technology[b]
Identity Implementations	Public key[o]	Public key[c]	Public key[e]	X.509[r]	X.509[b]
Power consumption	Very high[l]	High[v]	Medium[l]	Low[v]	Low[v]
Data partitioning	No	No[v]	No	Yes[t]	Yes[v]
Private and group channels	No	No	No	Yes[t]	Yes[v]
Data-rich queries	No	No	No	Yes[t]	Yes[w]
Cryptocurrency	Available (Bitcoin)[o]	Available (Ethereum)[c]	Available (EOS)[q]	Can be developed by using Chaincode[v]	Not Available[v]
Cryptocurrency Market Position	1[f]	3[f]	5[f]	Not in cryptocurrency market[v]	Not in cryptocurrency market[v]

[a] Brown [50].
[b] Brown, et al. [46].
[c] Buterin [51]; dCachin [52].
[e] Cox [53].
[f] Coin Market Cap [54].
[g] Cuomo [55].
[h] Melvin [56].
[i] Town [57].
[j] Trustnodes [58].
[k] Block Matrix Limited [59].
[l] Ian [60].
[m] Boulianne [61].
[n] Lewis [62].
[o] Nakamoto [63].
[p] Gendal [64, 65].
[q] Risberg [66].
[r] The Linux Foundation [67].

s [68].
t Cocco and Singh [69].
u Dantheman [70].
v Valenta and Sandner [71].
w R3 Limited [72].
x Ward [73].
y Korsakov [74].
z Rochard [75].
aa Canellis [76].
ab Gerring [77].
ac Chernykh [49].

with a defined resource level [109]. Performance is one of the key drawbacks of public blockchain networks with security enhancements, and this issue has been solved by some consensus algorithms such as DPoS and PBFT [28].

- **Scalability -** It is the ability to accommodate the workload and provide storage for the situation with increasing the number of tasks or objects [110]. A significant number of researchers highlighted that one of the key challenges to the blockchain technology is scalability [11, 85, 108, 111].

These salient features can be identified in different types of blockchain at the high, low or medium level of significance according to its inherent qualities. Therefore, depending on the various needs and demand in the construction industry, these salient features will result in adopting blockchain for potential applications. For example, creating a land registry in a public blockchain provides greater transparency to the general public who will be immensely benefited [43]. Yli-Huumo et al. [86] declared that "the goal of Blockchain technology is to create a decentralised environment where no third party is in control of the transactions and data". Similarly, in construction, the involvement of intermediaries such as banks and financial institutions can be minimised resulting in reducing transaction costs and opportunity costs. This section focused on the salient features inherent in blockchain while the next section explores the drivers, barriers and risks associated with the adoption of blockchain.

6. Drivers, barriers and risks in blockchain

In a similar manner to other innovative technologies, blockchain adoption in the industry faces drivers that encourage adoption of technology, barriers that hinder adoption and use of blockchain, and risks that organisations may need to consider. These are discussed in detail in this section.

6.1. Drivers for blockchain adoption

There are several drivers that lead to adopting of blockchain in business computing applications in different industries. Security, anonymity, no single point of trust, fraud resistance, non-physicality, and financial incentives are a few of the drivers that have been identified and discussed in this section.

- **Security -** For a transaction to occur the sender needs to use their private key to access their cryptocurrency or tokens [112], and for the sender to make a transaction to any receiver, the sender needs to use the receiver's public key. For a transaction to be recorded on a block, member nodes should create and validate a new block according to the consensus algorithm of the network. Blockchain also provides repudiation of fraud ulent digital signatures, the impossibility of double spending and creates immutable transactions [112], which will be immensely beneficial for the construction industry. Moreover, construction is a dynamic project-based industry where there are numerous approval processes involving multiple organisations. In such a scenario, one can argue that public-key cryptography based blockchain is more applicable to the construction sector.
- **Anonymity -** To create an account on a blockchain, personal details are generally not required. Only the private key and public key need to be generated, and one can use their public key as the account number for all transactions without exposing the information related to identity [113]. In the construction industry, anonymity will be advantageous in many occasions. For example, in a construction e-tendering process the bids can be submitted anonymously until it is necessary to disclose the bidder.
- **No Single Point of Trust -** Blockchain consists of a decentralised distributed ledger technology where issues due to centralisation

Table 2
Publications identifying Salient Features of Blockchain.

	Decentralisation	Anonymity	Security	Immutability	Auditability	Veracity	Transparency	Disintermediation	Trust	Turing-complete	Performance	Scalability
Abeyratne and Monfared [81]	✓		✓	✓	✓		✓		✓		✓	
Christidis and Devetsikiotis [82]	✓								✓		✓	
Dorri, et al. [83]	✓	✓	✓	✓					✓		✓	✓
Sun, et al. [84]	✓	✓	✓				✓	✓	✓			
Underwood [1]			✓	✓	✓		✓	✓	✓			
Wang, et al. [85]									✓		✓	✓
Yli-Huumo, et al. [86]	✓	✓	✓			✓		✓				
Zhao, et al. [87]	✓		✓	✓					✓			
Zheng, et al. [88]	✓	✓	✓	✓	✓				✓		✓	✓
Al-Saqaf and Seidler [78]	✓	✓					✓		✓			✓
Guegan [17]			✓						✓	✓		✓
Kewell, et al. [89]			✓	✓			✓	✓	✓			
Kuo, et al. [90]	✓	✓	✓		✓		✓					✓
Li, et al. [28]			✓			✓			✓	✓	✓	
Lu and Xu [91]			✓				✓		✓		✓	
Nofer, et al. [24]	✓	✓							✓			✓
Notheisen, et al. [92]	✓		✓	✓		✓	✓	✓	✓		✓	✓
Otte, et al. [93]			✓						✓		✓	✓
Risius and Spohrer [11]	✓	✓	✓	✓	✓		✓		✓			✓
Vranken [23]	✓		✓								✓	
Wang, et al. [94]	✓				✓		✓		✓		✓	
Atlam, et al. [95]	✓	✓	✓	✓	✓		✓					✓
Chen, et al. [96]	✓		✓	✓		✓			✓		✓	
Coyne and Onabolu [97]	✓		✓						✓			
Jesus, et al. [19]	✓	✓	✓	✓	✓				✓			✓
Kim and Laskowski [98]	✓									✓		
Miraz and Ali [80]	✓		✓						✓			
Nguyen and Kim [34]	✓		✓						✓			
Rodrigo, et al. [99]	✓	✓	✓	✓	✓	✓	✓	✓	✓			
Savelyev [100]	✓		✓	✓		✓	✓	✓	✓			
Viriyasitavat and Hoonsopon [101]	✓	✓		✓	✓		✓				✓	✓

have been avoided [112]. Therefore, no single authority has control over the blockchain, and it is a collective effort in validating transactions and creating blocks. It enables a trustworthy platform for the construction stakeholders to carry out secure payments and maintain good supply chains eliminating payment risks and compliance issues.

- **Fraud Resistance -** Blockchain transactions are non-reversible and immutable [112]. Therefore, once a transaction is recorded in a block and attached to the blockchain, it is extremely difficult for an attacker to change the data in a blockchain. In the case of PoW blockchains, this requires a vast amount of processing power, i.e. more than 50% of the hash power of the network. Moreover, smart contracts execute contract agreements without human interference [91]. Construction projects involve large amounts of money transfers carried out through intermediaries such as banks to ensure a trustworthy platform. However, blockchain that provides fraud-resistant platform can eliminate the intermediaries and enable direct payments between stakeholders without any delays or issues of non-payment and cash flow.
- **Non-physicality -** In blockchain transactions, a digital currency or tokens are exchanged between parties. Therefore, it does not require any physical instrument such as bank bills and bank vaults to store cash, reducing the cost of printing bills and the cost of providing security [112]. The construction industry has a great challenge in estimating contractors' or subcontractors' capacity and credibility history. There is a great possibility to create construction crypto tokens to maintain credibility history and consider construction crypto token capacity before the contract offer.
- **Financial Incentives -** Bitcoin has been designed to financially reward users that take part in validating transactions by mining [112], and at the same time, miners also get to collect optional transaction fees for their effort in mining [114]. Due to these financial incentives, people are interested in carrying out mining as a way of earning bitcoins while generating blocks. Even in other forms of consensus mechanisms such as PoS or DPoS, block creators/producers are incentivised by way of tokens or greater capacity to make decisions. In a construction supply chain, the supply of imported materials involves the transfer of money across borders and continents, requiring the assistance of third parties such as banks and other financial institutions that charge a transfer fee and various taxes due to regulatory requirements. Introduction of blockchain would reduce such transaction fees, the client would be liable to pay in a traditional method of transaction. The miner would receive an additional reward, which is a motivation factor to transfer faster and achieve more rewards.

6.2. Barriers for adoption of blockchain

Barriers to adopting blockchain create a negative impact in initiating and implementing blockchain in industries. A few barriers such as data privacy, data storage, limitations in scalability, and need for high computation power have been discussed in this section.

- **Data Privacy –** Public blockchains are lacking of data privacy [91]. As there are no privileged users, every node in the blockchain can access all the information on the blockchain, and anyone can join and participate in the public blockchain network without any permission. Therefore, data privacy is a major issue in public blockchains. Such users, who are concerned about data privacy would prefer private blockchains. Private blockchain, data encryptions, membership management, channels and many other solutions have been proposed and implemented to solve data privacy issues in public blockchains. On the other hand, even in a public blockchain, sensitive or confidential information can be stored off-chain to ensure that all nodes do not have access to those [105], which will be beneficial for the construction industry as confidential information can be stored off-chain to avoid issues of data privacy.
- **Data Storage -** According to Lo et al. [105], blockchain is not considered suitable for storing Big Data, due to the large volumes of data and low velocity of data taken for processing. Public blockchains have limits on the amount of data that can be stored on a blockchain [91]. On the other hand, for a transaction to be recorded, it has to be validated and accepted by the majority of the nodes. When a large amount of data is stored, it will delay the mining/block producing process as well. As a solution to this issue, only the most important data, which need to be on the blockchain will be on-chain, all other data will remain off-chain. A construction project comprises of a massive amount of data. However, only the required data to be processed on the blockchain can be stored in the blockchain ledger.
- **Scalability -** Public blockchains have limits on transaction processing rate and data transmission latency [91]. For a transaction to be recorded in a blockchain, the block should be validated by more than 50% of the nodes, which takes considerable time. As a result, currently, a public blockchain will be able to handle on average 3–20 transactions per second [115], whereas, mainstream payment services like VISA, currently handles 24,000 transactions per second [116]. Compared to the finance sector, the construction industry has a very limited number of transactions. However, other consensus algorithms such as PoS, DPoS, PBFT address scalability issue, which will be beneficial for the construction industry to adopt many business applications without any issues of scalability.
- **Need**for**High Computation Power** - The mining work related to PoW requires much computational power that uses a great amount of electricity, which is a waste of energy [91] and unsustainable. Therefore, other consensus mechanisms such as PoS, DPoS and many others have been introduced to address this issue and these require computation power, which is significantly lower than PoW networks. (Refer to a detailed discussion on consensus algorithms in Section 3.4).

6.3. Risk in blockchain

Though blockchain consists of many salient features that promote adopting blockchain in various industries, there exist several risks inherent with blockchain technology. Most of the risks are mainly applicable to PoW and PoS algorithms while most of the other consensus algorithms are trying to overcome those risks. This section discusses a few risks such as vulnerability, private key security, criminal activity, exposing identity and the like.

- **50% Vulnerability -** In PoW consensus mechanism based blockchains, if a single miner gains more than 50% of the total hashing power of the entire blockchain, then the 51% attack may be launched [28]. Hashing power means the attempts or guessing made per second by miners for creating a new block [117]. Similarly, in blockchains that use PoS consensus mechanism, 51% attack may occur if a single block producer or a colluding group of miners has more than 50% of the total stakes owned by the blockchain. Li et al. [28] identified the following possible attacks that could occur as a result of 51% vulnerability:
- Reverse transactions and initiate double-spending attack
- Exclude and modify the ordering of transactions
- Hamper normal mining operations of other miners
- Impede the confirmation operation of normal transactions
- **Code vulnerability** - Anyone can write a distributed application and run it in a smart contract enabled public blockchain. In such a situation, the consequences of code vulnerability are significant [11, 108].
- **Private Key Security -** In the blockchain, the user's private key is considered as the identity and security credential. If the private key is stolen by a criminal, as the blockchain is not controlled by a single

authority, it is difficult to track the criminal's behaviours and recover the modified blockchain information [28]. Newer blockchain technologies such as EOSIO provide several means to deal with situations such as compromised or lost keys and have innovative concepts to improve account security, i.e. it is possible to define an Active key for daily activities, and an Owner key which is stored in cold storage and which is only used to change the Active key in case it got compromised [118]. Even though private key security is a significant risk factor, it can be minimized by using security best practices.

- **Criminal Activity -** The exchange of cryptocurrencies or tokens occurs pseudonymously. Therefore, cryptocurrencies or tokens can be used for any illegal activities, and no one would know the parties who are involved in it, and it is difficult to track user behaviours as well. Li et al. [28] declared examples for criminal activities related to the cryptocurrency, bitcoin, as (1) generating ransomware, i.e. CTB-Locker, where an attacker sends an email comprising of virus, which will run in the users system encrypting files and to recover the files the user has to pay the attacker in bitcoins within a limited time, [119]; (2) using in an underground market; and (3) money laundering. Cryptocurrencies based criminal activities are less relevant to enterprise blockchain solutions.
- **Exposing of Identity -** Though blockchain is identified as a technology that maintains anonymity, the attackers could trace the IP addresses used in the transactions and the transaction processor [112]. Afterwards, the location of the user can be traced, which can ultimately expose the identity of the user. Similarly, if one buys a product online and pays for it using cryptocurrencies, to receive the product one has to enter a physical address of a location, which also ultimately exposes the location and user's identity. Therefore, though the blockchain is considered to have preserved anonymity, it can be exposed in certain ways and according to different circumstances.

The identified drivers and barriers associated with blockchain can be mapped with the previously identified salient features. Fig. 10 illustrates the connectivity between features and drivers and between features and barriers.

As demonstrated in Fig. 10, the feature of decentralisation enables the drivers, security; no single point of trust; and fraud resistance while creating the barrier, data privacy. Similarly, each feature leads to different drivers and results in creating barriers, as well. However, the drivers outweigh the barriers and most barriers could be overcome. Therefore, it reverts back to the research question whether the potential applications of blockchain in the construction industry is real or hype?

7. Applications of blockchain

Blockchain is seen as a highly disruptive technology with applications in many fields while evolving into three generations of blockchain, namely Blockchain 1.0 for digital currency, Blockchain 2.0 for digital finance and Blockchain 3.0 for digital society [13, 87]. Adoption of blockchain creates opportunities not only to change the established businesses and business processes but also to innovate new businesses [11]. These three generations of blockchain applications are evaluated in the following subsections. Greater emphasis has been given to Blockchain 3.0 as the focus of the paper lies in this sector.

7.1. Blockchain 1.0 - Cryptocurrencies

Initially, Blockchain 1.0 was introduced, which was used for cryptocurrencies as a mode of securely validating and storing information of transactions [12]. Cryptocurrencies or tokens rely on encryption techniques to generate, transact and validate their values in a blockchain [30]. As explained in the study of Li et al. [28], cryptocurrencies compared with traditional currency, provides many advantages; irreversible; traceable; decentralised; anonymous; secure; fast; and global transactions.

The first cryptocurrency, 'Bitcoin' was introduced by Satoshi Nakamoto in 2008, and the first block was created in 2009 [22] a decade ago. Bitcoin was the first blockchain application that was introduced to the financial industry [33]. In addition to Bitcoin, there are many other cryptocurrencies, such as Litecoin, Dogecoin, Ethereum amongst others and some of which are currently available in the financial market [28]. Presently there are over 1600 types of cryptocurrencies, and their total market capitalisations are over USD 217 billion [120].

Crowdfunding is another popular method for raising capital as a type of investment, where many startup organisations sell their Initial Coin Offering (ICO) before the network being publicly launched. Bitshares is one of such well-known coin networks that used this method to get started while EOS, Tron and VeChain Thor are few other examples. Block.one has raised more than USD 4 billion for ICO of EOS.IO in 2017 as the largest ICO in history [121].

Though Blockchain was born with Bitcoin, its applications have gone far beyond Bitcoin and other digital currencies [87]. As a result, novel perceptions have been identified generating new markets and opportunities. Blockchain 1.0 was initially used for decentralisation of money and payments, while Blockchain 2.0 is recognised for decentralisation of financial markets [13].

7.2. Blockchain 2.0 – smart contract and financial applications

Swan [13] identified usage of Blockchain 2.0 for economic, market and financial applications such as stocks, bonds, smart property and smart contracts. Further, Turing-complete or universally computational programming languages have enabled the users to develop smart contracts running on the blockchains, which initiated the era of Blockchain 2.0 as discussed in this section [5, 28].

A smart contract has been defined as a computerised transaction protocol that executes the terms of a contract [122]. Smart contracts are capable of expressing triggers, conditions and business logic in order to enable more complex programmable transactions [91] while strengthening the mutual trust mechanism among users becoming the core technology of Blockchain 2.0 [38]. Smart contracts enable digitisation and automation of executing business workflows; i.e. self-executing contracts, in which the execution is enforced by the consensus mechanism [2, 82]. Smart contracts are written as computer codes and get deployed to and executed in blockchains such as Ethereum, EOS and others.

Li et al. [28] defines a smart contract as a lightweight Decentralised Application (DApp), which provides the following benefits to its users;

- DApps can run autonomously without the assistance of a third party
- Failure of a few nodes will not affect the execution of the smart contract code on the other nodes. Therefore, DApps are considered stable
- As the DApp runs on a blockchain, the outcome is easily traceable and has a greater level of transparency.

Zhang, et al. [123] stated that "smart contracts can store data objects and define operations on the data, enabling the development of DApps to interact with blockchains and provide seamless services to the application users" as illustrated in Fig. 11. Smart contracts are stored in the ledger, which means it is immutable but can be called up at any point to be executed as and when required in any future transaction. A smart contract can be recorded only on a blockchain [124], which signifies the fact that the qualities and advantages applicable to the blockchain are complemented by a smart contract. The advantages of a smart contract could be identified as automated transactions, high accuracy, trustless (as there is no intermediation, it is not needed to trust an individual or organisation) and lower costs. Due to such benefits of

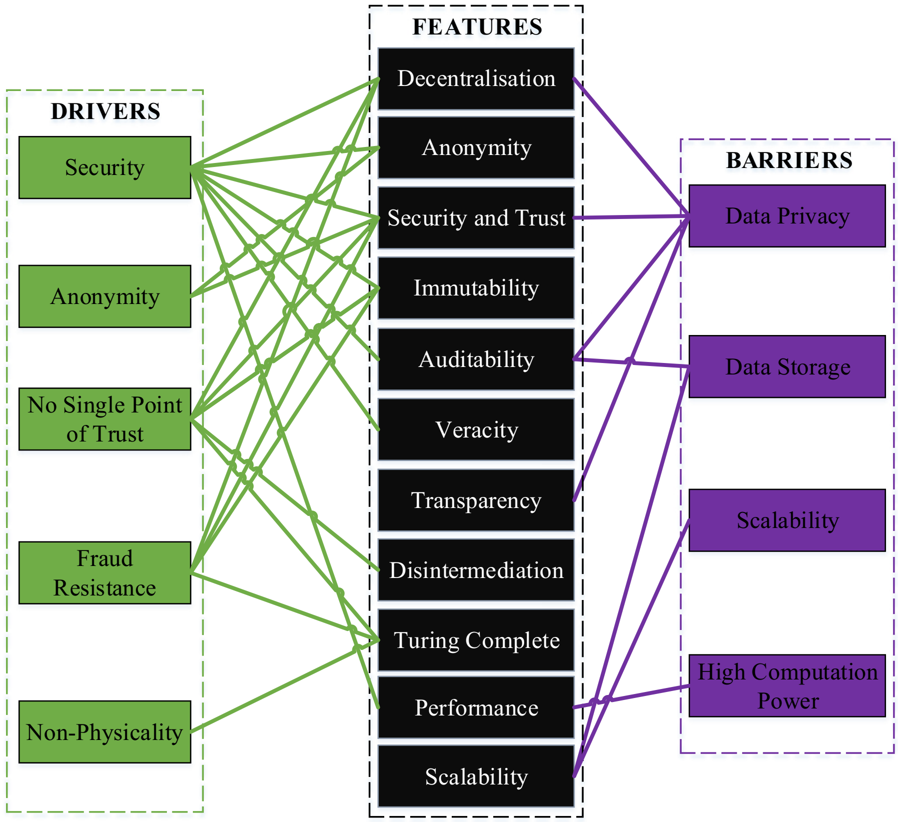

Fig. 10. Relationship mapping between features and drivers and features and barriers.

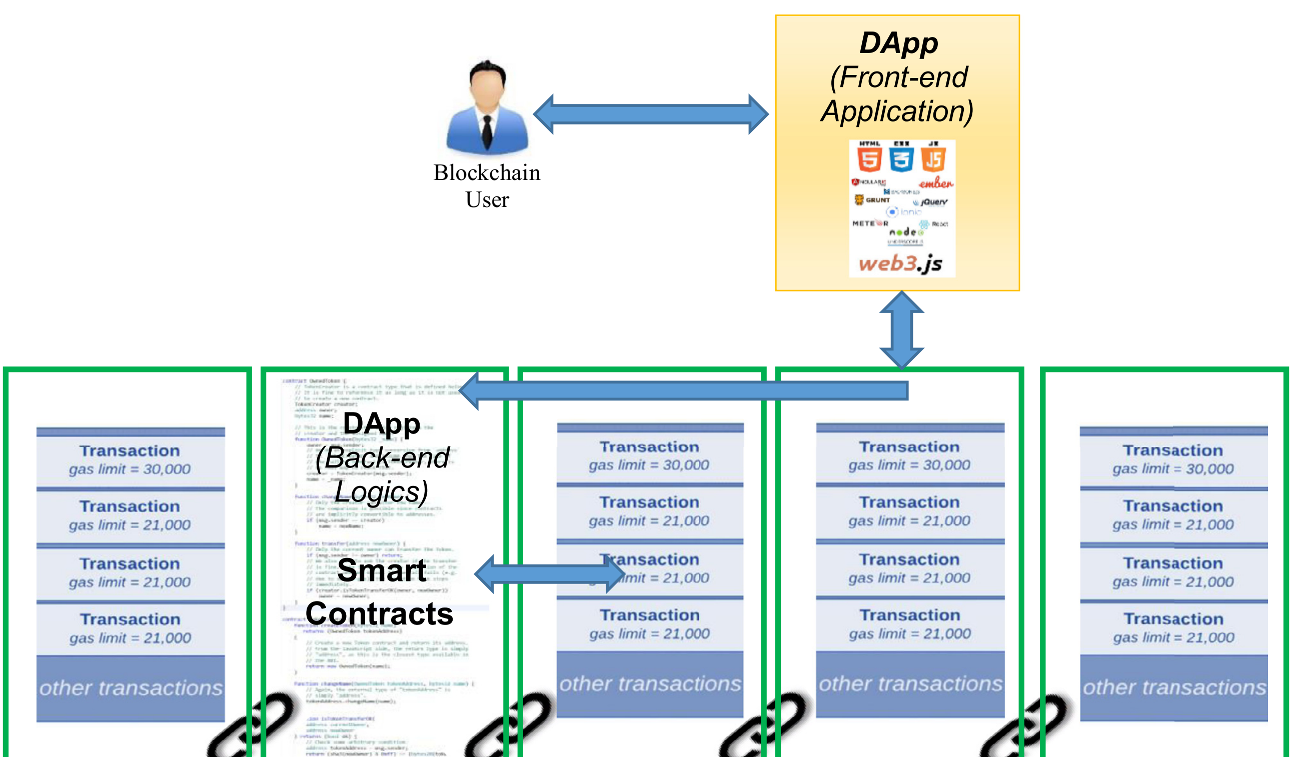

Fig. 11. DApp and smart contracts in the blockchain network.

blockchain, innovators started to envision how the concepts might be applied to other fields. As a result, Blockchain 3.0 originated [13].

7.3. Blockchain 3.0 - Industry applications

Usage of Blockchain 3.0 is recognised for applications beyond currency, finance and markets, particularly related to government, health, science, art, culture and others [13, 94]. Kuo, et al. [90] mentioned that Blockchain 3.0 has been introduced for non-financial applications of the distributed ledger technology. In Blockchain 2.0 and Blockchain 3.0 applications, a combination of other activities related to government, education and finance can make these non-financial activities express the property of currency [96]. Many use cases have been conceptualised and implemented in various industries, and several examples have been discussed in this section.

7.3.1. Finance

Mingxiao et al. [33] declared that all major banks in the world have commenced exploring the application of blockchain technology in the banking sector to align with the rapidly changing technological advancements. Six of the world's largest banks (Barclays, Credit Suisse, Canadian Imperial Bank of Commerce, HSBC, MUFG and State Street) have collaborated to work on the cryptocurrency, utility settlement coin, which was introduced by Switzerland's UBS, to make improvements in the financial markets [125]. This cryptocurrency allows financial groups to pay each other or buy securities such as bonds, equities and the like, without waiting for the traditional money transactions to occur, reducing the time, cost and capital required in the post-trade settlement.

Santander being the first UK bank to introduce blockchain technology for international payments, predicted that blockchain technology could reduce banks' infrastructure costs related to cross-border payments, securities trading and regulatory compliance by between USD 15–20 billion per annum by 2022 [126]. In the banking sector, usage of blockchain technology would avoid the issue related to double spending as the transactions need to be verified by a majority of the nodes, for a valid transaction to be recorded [33]. Hassani [127] opined that in order to survive in a highly competitive and volatile market, banks will have to innovate with blockchain based big data and ensure not to lose the competitive edge in a rapidly progressing technological environment. The Australian Securities Exchange (ASX), a blockchain-enabled stock exchange system will be launched by Australian Stock Exchange in 2020.

7.3.2. Identity protection

Identity theft is a major crime occurring globally. In the year 2017 alone, there have been 16.7 million victims in the United States, whose identities were misused [128]. Blockchain is identified as the ideal solution to prevent identity theft. As data stored in a blockchain is considered to be immutable, it is impossible for a fraudster to alter data without the assistance of 50% of the nodes. Therefore, identity protection can be enabled through blockchain.

As the initial step one needs to store Decentralised Identifiers (DiDs) in a blockchain by including personal details such as name, birth date and social security number, for which you will receive a QR code that can be saved in the digital wallet. Whenever one signs up for an application, the QR code can be scanned rather than inputting all the details over and over again. SelfKey is such an identity wallet that has been created to allow individuals and companies to truly own, control and manage their digital identity [129]. ShoBadge developed by ShoCard is another secure enterprise identification authentication built on the blockchain, in which one can select an identity recognition form out of forms such as QR code, fingerprint, iris scan, face recognition among others to prove one's identity when using the digital wallet [130].

7.3.3. Foreign aid

There exist several issues and inefficiencies in the current systems that offer aid to refugees and displaced persons. Paynter [131] found that 3.5% of most international relief aid is spent as transaction fees or other related costs while an estimated 30% of all development funds do not reach the intended persons due to third-party costs, theft or mismanagement. To avoid this issue, a blockchain can be introduced to connect the donors with the final recipient avoiding third-party involvement. Usizo is a crowdfunding platform in South Africa, that has been planned to be launched where a Bankymoon meter that is blockchain-aware will be installed in rural schools and donors around the world can make payments directly to the meter using tokens and fund energy or water the school needs [132, 133]. This would enable the donors to witness exactly where their contributions were spent.

Another project was implemented by the United Nations to provide aid to the refugees in Jordan, who moved from conflict zones in Iran and Syria. In here, rather than providing aid to the refugees directly, through an Ethereum blockchain, aid is provided to a few shops (merchants) in the neighbourhood of the refugee camps. The refugee can go to a selected shop and receive the funds allocated to them by proving his/her identity through Iris Scan, where the refugee's identity details are already stored in the blockchain network.

7.3.4. Voting

Low voter turnout and voter frauds are two major issues faced by the community and politicians of many countries. Online voting could be a better alternative to paper ballots as it can boost the number of active voters while addressing the security and integrity issues in elections [134]. Horizon State is an organisation that offers powerful and reliable digital ballot box systems for shareholder voting to official government elections of all scales [135]. Jamie Skella of Horizon State opined that if a digital ballot box could be run on a blockchain, the provided votes cannot be reversed or changed, making it a trustworthy process based on a system, which is not owned by any single entity [136].

7.3.5. Transportation - ridesharing

Blockchain can be used as a ridesharing platform. Arcade City is such a blockchain-based ridesharing platform, which matches passengers and drivers without the involvement of a third party like Uber. Arcade City improves sharing economies while using the power of blockchain to facilitate trustless peer-to-peer models [137]. Arcade City introduced 'Arcade City Token' as the cryptocurrency to be used in transactions. Arcade City, identified as Hamida et al. [2] suggested introducing a "decentralised transportation ecosystem, where people can use the same token to ride on a bus, rent a bike or carpool, without any central authority to organise its operation".

7.3.6. Food and agriculture

Food and agriculture industry includes products such as meat, fruits, vegetables and many more. The quality of food produced in the agriculture industry greatly depends on how well the supply chain is managed. However, the main disadvantage of the present supply chain is that the consumer has no way of verifying the source and origin of the food or agriproducts they use. In food and agriculture blockchains, data will be stored in a decentralised manner, and each stakeholder can read or trace important data for its operations from origin to sale and subsequent recycling [138, 139]. A blockchain-based e-agriculture system is being developed to manage data on pesticide use, production costs, local weather, energy use, soil quality, and others in Taiwan. As an initiative, National Taiwan University developed a GCOIN blockchain-based decentralised system to manage irrigation data collected by remote sensors [140].

Walmart retail corporation partnered with IBM and initiated to develop a blockchain-based food tracking solution [138]. In the first pilots, Walmart planned to digitally track both domestic and international movements of pork from small Chinese farms [139]. Estimated food fraud costs are over USD 40 billion each year globally. Australia's beef has a high demand, especially in Asia. However, there is a significant amount of counterfeit Australian beef in the market. To solve this issue, CSIRO's Data61 is working to adopt blockchain and reduce the costs of food fraud in Australia [141]. However, most of the present blockchain-based supply chain innovations are trying to enhance clients' necessities such as product quality and compliance, rather than payment and other concerns of suppliers [138].

7.3.7. Healthcare

Implementation of IT systems is crucial to improve the health sector in any country and systems should support data store, process, and exchange between consumers, providers, government and quality entities, and insurers [142]. Patients' medical records are scattered across various organisations. It is a challenging process to get all health data stored in a central place or moving data from place to place, as and when required [123]. MIT Media Lab Consortium initiated to develop a blockchain-based electronic medical records (EMRs) system called MedRec to solve interoperability issues among different systems. The full functional MedRec system should be implanted on the Ethereum blockchain network. However, a prototype was implemented on the PyEthereum and the PyEthApp client [143]. OmniPHR is a personal health record (PHR) management system based on blockchain technologies to provide the structuring of semantic interoperability and integration of different health standards. However, privacy is the main challenge in handling the sensitive personal health record in a decentralised manner [144].

7.3.8. Logistics management

As a use case for Blockchain 3.0, supply chain management is one of the key sectors where blockchain applications have been experimented, especially in the area of logistics. The recent adoption of blockchain technology promises better supply chain provenance [98]. The potential tracking of supply chains via blockchain provides greater traceability [91], transparency [94] and simpler processes for the businesses to deal with [104]. Blockchain used in supply chain management will provide certification and documentation, including the lifecycle data of the product accessible to all parties but impossible to falsify [145].

OriginChain is a private blockchain introduced for the supply chain management of products, mainly for traceability of products between suppliers and retailers. In the OriginChain, when the product supplier or retailer requires the service of the traceability from the service provider, the two parties sign a legal agreement agreeing on the traceability services provided, for which a smart contract will be generated [91]. Because of limitation of blockchain data storage, OriginChain stores two types of data on-chain as variables of smart contracts; (1) the hash of traceability certificates or photos; and (2) the small amount of traceability information required by the traceability regulation, i.e. the batch number, traceability results, place of origin and inspection date. All the other data will be stored off-chain.

Many blockchain applications have been recognised in various industries, whereas some of them are only at the conceptual stage while some are at the implementation stage. Apart from these blockchain applications, there is considerable potential in introducing blockchain in the construction industry, which is explored in the following section.

7.4. Applications for construction and built environment

The construction industry is ranked as the second lowest sector to have adopted information technology [7], and it had remained so for the past three decades [146]. The global construction industry is one of the least productive sectors with productivity increases standing at 2% [147]. However, the rate of investment in construction is increasing significantly, with USD 8 trillion global construction market growth predicted to be achieved by 2030 [148]. With the advent of Industry 4.0, forces of globalisation and digitalisation are impelling the construction industry to advance the digitalisation processes to make the industry more effective and efficient. Blockchain, as discussed before, provides a ripe environment for the impending digital disruption in the construction industry. Technologies such as BIM were expected to provide the step change for the construction industry in the last decade but its penetration is yet to be seen [149, 150]. The main reason being that it is more of a technological change with marginal impact on construction procurement [151]. However, blockchain is a technology that has enormous potential to change the construction procurement process. Therefore, it is predominantly important to explore possible applications of blockchain for the construction and built environment.

7.4.1. Property management

The property sector is one of the most significant sectors in the built environment that has the potential to create global economic impact. Blockchain can be used as an immutable distributed ledger where transactions are timestamped into a block, which enables asset tracking, ownership transfer certification and maintains accurate, immutable history records [2]. Similarly, blockchain technology is considered ideal for maintaining a land registry on a blockchain as there are many occasions reported regarding tampering of data in land ownership related aspects. In Ghana, 78% of the land is unregistered [152]; as a result, there are many land-disputes reported. Hence, Bitland is looking at resolving this issue by introducing a blockchain-based land registry. Similarly, Bitcoin mining company, BitFury and the Georgian government have collaborated to develop a land registry using blockchain [153]. The platform will be developed as a permissioned blockchain tied to the Bitcoin blockchain providing transparency and reduction of fraud. In 2017, two states in India, Telangana and Andhra Pradesh have announced to use blockchain for the land registry, and Telangana has already started a pilot project.

7.4.2. File sharing for document management

Complexities involved in construction means that there are many different types of documents generated on a daily basis for each project. A construction project consists of large amounts of data and construction organisations face many difficulties in data storing and managing masses of documentation it produces as it requires a large amount of storage space. Similarly, storing data of past projects is another major issue faced by organisations as the data of completed projects need to be stored for future purposes as a good practice, which requires massive storage space. Therefore, file storage sharing is a good solution for construction practitioners to store data and manage documentation in a Blockchain. As there is a massive amount of unused data storage in data centres and hard drives around the world, there is a possibility to sell these unused data storage spaces for any users who are in need of it. Hence, Filecoin was introduced as a digital storage and retrieval system that rents their disk space for data storing purposes [154] where cloud storage is converted into an algorithmic market [155]. Filecoin is the cryptocurrency that will be used by the users of the data storage, to pay the data storage providers in the decentralised network. In order to store data of construction projects, organisations can use a blockchain-based digital storage and data retrieval system such as Filecoin.

7.4.3. Construction supply chain management

The construction industry makes a significant impact to the global economy and global construction industry output whereas in 2017, it was worth more than USD 10 trillion [156, 157], and it is approximately 13% of the global gross domestic product [157]. The construction industry produces complex and largest objects, and it has arduous, lengthy supply chains with a large number of internal and external suppliers [146, 150]. Therefore, it is challenging to implement an information and communication technology solution in project-based industries when compared with process-based industries [158]. Although Information Technology (IT) applications can improve the efficiency of information flow, they cannot completely eliminate uncertainty in construction supply chains [159]. The complexity of the construction supply chain and low transparency are weakening the level of trust and security of payments, especially creating an adverse impact on the suppliers or sub-subcontractors in the top of the supply chain. Similar to the method of tracing products in supply chain management, in a construction project, each item could be tracked from the extraction/ production stage until it is delivered to the site and incorporated in a building or structure [124]. Blockchain-based supply chain management can improve the authenticity and compliance of products and ultimately it would lead to greater quality assurance of the final product [94]. In this manner, throughout the entire life cycle of the project, an immutable record of data can be stored and maintained. Further, such data stored can even be retrieved during the post-construction stage [124]. Blockchain-based supply chain management provides greater payment security, ensures product compliance and authenticity, efficient payment handling and reduces the cost of finance, induces trust among suppliers and clients, and provides transparency for auditing purposes as well [160].

7.4.4. Asset management

A government of any country is responsible over a diversified set of public constructed facilities and infrastructure including complex buildings, roads, railways, tunnels and many others. Majority of large complex buildings are often owned by the private sector. Most of the organisations are now recognising the importance of proper asset management in their organisation [161]. British Standards Institution [162] defined asset management in PAS 55–1 as the systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organisational strategic plan.".

According to PAS-55 asset management definition, all the necessary data and information related to the built asset needs to be tracked in every stage of the asset life cycle. However, construction projects are scattered across different geographical locations, supply chain processes are complex, and there is a significantly large number of temporary firms involved in the process [163]. Therefore properly managing asset data in each stage is a significant challenge in the construction industry [164]. Blockchain is considered immutable as the peer-to-peer network of members secures it. No record will be lost, and all the data originated from different organisations will be in a single blockchain network [83]. Blockchain-based construction asset management system allows to access all the necessary data throughout the asset life cycle and will provide better asset life cycle while minimising challenges.

7.4.5. Construction management

Construction projects involve a number of stakeholders and organisations whereas the complexity of the project leads to fragmentation issues among the professionals and organisations [165]. On the other hand, current construction management processes suffer numerous challenges related to trust, information sharing and process management [166]. However, blockchain technology enables trust, immutability, accuracy, security and transparency among others, providing the possibility to resolve management related issues. As an example, construction drawings can be issued at various stages and all stakeholders need to be notified of this. However, as the stakeholders are working in separate entities several issues can arise such as identification of the latest set of drawings, who issued the latest drawing, was it incorporated with the architectural/structural/services drawings and the like. All of these issues can be resolved by introducing a smart contract enabled blockchain system as the latest information can be updated and made available for the respective parties [183].

7.4.6. Payment management

Late payments and cash flow related issues are a few of the key issues identified in most construction projects. The construction industry has a chained payment settlement culture, and default settlement durations, which are much higher than the other industries [167]. Over and above the long settlement period, there is a substantial amount of payment delays in the construction industry [168]. There is a considerable number of partial payments and non-payments in the construction industry [167]. These result in additional costs to cover delays in payment, causing the contract price to be inflated to cover the cost of finance. In general, Small and Medium sized Enterprises (SMEs) are unable to tolerate the upfront costs without continuous payment and healthy cash flows [169]. Due to issues of cash flow management, many large construction companies such as Strongbuild, Cooper and Oxley, Carillion, Interserve, Dawnus among others have gone into administration. Therefore, it is acutely important to manage cash flows in construction projects and organisations. Smart contract enabled blockchain applications with automated payments can effectively be used to resolve these issues.

On the other hand, due to trust issues, clients have concerns in buying materials directly from the suppliers resulting in involvement of a third party such as a bank or a financial institution which leads to additional costs related to transaction costs, taxes among others. Implementation of a smart contract enabled blockchain payment application can provide more trust in the transaction as automation allows greater enforceability of the contract. The client can directly buy products from the supplier, making an initial payment at the ordering stage and once the products are delivered to site, the full payment can be released to the supplier in an automated process, which is initiated and controlled through a smart contract.

7.4.7. Integration with building information modelling as a procurement solution

Building Information Modelling (BIM) is a process used by construction stakeholders to simulate a construction project in a multi-dimensional digital model and provide multitudes of project benefits from project inception to its occupancy [150, 170]. The construction supply chain is treated separately from the BIM, and that affects the final construction product quality. Thus, the integration of the construction supply chain with BIM is required to improve the construction process activities and the data for facilities management during the design, operation and post-construction stages [171, 172]. The construction supply chain stakeholders typically come together temporarily to deliver one-off projects. Therefore, the construction supply chain operating in a blockchain will overcome the transparency issue and better integration throughout the lifecycle of the construction project [124].

BIMCHAIN, a tech start-up business, is involved in designing bridges in France, incorporating BIM and blockchain. BIMCHAIN assists in creating a shared document handling platform through validation using digital signatures by the project stakeholders. Furthermore, the smart contract enabled platform validates models, initiates automatic payments enhancing blockchain-enabled proof of consistency, publication and approval [173].

7.4.8. Building maintenance system

During the operational phase of a building, preventive maintenance and planned maintenance plays a key role in safety aspects as well as occupant satisfaction. An automated blockchain-enabled system has the ability to assist in monitoring the maintenance procedures of a building. Maintenance requests, procurement process, delivery of products, payments and the like can be easily and accurately managed through smart contracts. The occupant and all other parties are aware of the status of the maintenance request from the beginning to the completion of the work due to the transparency provided through blockchain. It enables maintenance managers to identify who supplied and installed any building component at what cost at any given time [182].

7.4.9. Energy management

Distributed ledger technology can be used to trade energy at the local grid level, between individual producers and consumers [2]. As the usage of solar panels and other green energy sources is the latest trend in generating energy, blockchain can be used to allow energy producers and consumers to pool and exchange energy on a blockchain for transparency, traceability and other benefits. Power Ledger provides cutting-edge blockchain energy-based solutions to the worldwide community [174]. Currently, Power Ledger, together with BCPG, one of the leading companies carrying out renewable energy business in Thailand, is carrying out the world-first peer-to-peer renewable energy trading trial at the T77 urban precinct in Bangkok, Thailand [175]. Power Ledger is providing its world-leading blockchain technology across 18 m points to monitor energy transactions between participants while enabling peer-to-peer trading and ultimately evaluate the trading position of individual participants.

Similarly, blockchain can be used for smart grid and smart power generation to create a smart and energy-efficient platform in electricity generation and distribution. This is another applicable use case for the construction industry.

7.4.10. Embodied carbon management

Blockchain can be used for estimating embodied carbon in buildings due to its inherent features such as decentralisation, transparency, veracity, auditability and the like. According to the current context, though there are several embodied carbon estimating techniques identified by the practitioners and academia, the accuracy of such estimates is questionable. Therefore, an accurate methodology of estimating embodied carbon has become intricately important. The decentralised accounting process used in blockchains can be applied for the purpose of accounting embodied carbon in construction supply chains in an accurate way [176,181].

7.4.11. Water trading

Water trading allows users to buy and sell the water resources depending on the supply and demand, which is generally governed and managed by government agencies who have set its own processes and rules creating transparency issues [173]. Introducing blockchain technology to water trading will eliminate these issues while eliminating intermediaries, providing a transparent platform, connecting the water sources and the buyers and providing smart contract enabled transactions. OriginClear, a US-based water treatment technology provider, is developing the blueprint for a blockchain protocol called WaterChain aiming to create transparency and efficiency in the water treatment with the usage of smart contracts and cryptocurrency [177].

7.4.12. Waste management

Waste generated by the construction industry is recognised as a global issue, which has a direct adverse impact on the environment [178]. Therefore, proper waste management has become critical, whereas an accurate estimating of construction and demolition waste is one of the critical factors for the implementation of a successful waste management system [179]. Construction and demolition waste currently is treated as a necessary evil, but in essence, it is a by-product of the construction process. As such, waste can often be traded and recycled. A uniform waste management system that treats waste as a resource may be developed with the use of blockchain technology to provide solutions for construction waste management. Furthermore, utilisation of smart technologies for monitoring and tracking would provide a holistic solution to improve the accurate waste estimation and management practices towards achieving sustainability in construction projects [180].

In summary, there are numerous blockchain applications conceptualised or implemented in various industries. Apart from them, there are many other potential applications of blockchain related to construction or built environment, out of which several were discussed in this section.

8. Conclusions

This paper critically reviewed a substantial amount of existing knowledge on blockchain technology and its applications. Blockchain being a decentralised distributed ledger provides several advantages; creating immutability, transparency, trust, security, auditability, single source of truth among others, has started to disrupt a number of industries such as finance, insurance, logistics, energy and transportation by its promising advantages and various applications. The literature findings revealed the various drivers for blockchain implementation while a few other research demonstrated the barriers and risks inherent in the blockchain.

Several blockchain applications have been introduced after Blockchain 1.0 for cryptocurrencies. Blockchain 2.0 was recognised for economic, market and financial applications and Blockchain 3.0 was identified as applications beyond currency, finance and markets. Introduction of Blockchain 3.0 established a trend that attracts different industries to use blockchain due to its potential benefits. As a result, researchers are investigating possible avenues in adopting blockchain in their respective fields.

Presently, there are over 1600 types of cryptocurrencies, and their total market capitalisations are over USD 217 billion. Crowdfunding is another popular method for raising capital as a type of investment, where many start-up organisations sell their ICO prior to the network being publicly launched. Bitshares™ is one of such well-known coin network that used this method to get started. Block.one™ has raised more than USD 4 billion for ICO of EOS.IO in 2017 which is the largest ICO in history. Apart from investment in cryptocurrencies many world recognised companies such as Microsoft, IBM, Ubiquiti and the like are currently investing in blockchain technology to be used in various platforms. Australian Stock Exchange will be launching a blockchain-enabled stock exchange system: The Australian Securities Exchange (ASX) by 2020. One of the most significant impacts of blockchain is that it is becoming a middle layer for different technologies to interoperate efficiently. This technological convergence enabled intercommunication with novel technologies such as Internet of Things, Artificial Intelligence, among others [151]. Even individually, these technologies have enormous potential. As a technological convergence, blockchain can incorporate these technologies together, and remove some of the drawbacks with those technologies. Combined outcome is explosive multiplied potential to modern applications as discussed in Section 7. These demonstrate that the blockchain is not just hype, but it is real, and it has been well conversed among the practitioners from many industries.

The potential of Blockchain in construction is significant. The examples of use cases discussed in Section 7.4 indicate a vast array of applications. The forces of globalisation, industrialisation and digitalisation are inevitable as industries move deeper into Industry 4.0 where the integration of cyber-physical environments are coming to fruition. Blockchain, for the first time, is extending the procurement revolution that was brought about by the advent of the internet and the subsequent processes of e-procurement [150]. It is bound to take the construction industry through to a full-scale change in the way construction is procured combining and supplementing the change of onsite to offsite construction that is happening at present. The evidence that Blockchain is not just hype but very much real as the next disruptive technology that will propel the construction sector right into the middle of the 4th Industrial Revolution is mounting high [124].

This research paper synthesised the existing knowledge in the literature on blockchain technology and its applications to find out possibilities to create and enable a successful platform to conceptualise and implement blockchain applications in the construction industry to mitigate the existing issues in the current construction systems.

Declaration of Competing Interest

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

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