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Exploring the mutual role of BIM, Blockchain and IoT in changing the design, construction and operation of built assets

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Archival Study of Blockchain Applications in the Construction Industry From Literature Published in 2019 and 2020

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ABSTRACT

Purpose: This paper aims to investigate proposed blockchain applications in the construction industry from contemporary literature.

Methodology: Archival studies will be used to obtain academic content from secondary sources. An explorative strategy will be adopted with no preconception or biases on the preferred route of execution. Blockchain is a fast-evolving technology with a high rate of yearly progression; therefore, this paper refines the search to recently published material in 2019 and 2020. Data is collected in two stages, firstly, categories of research are extrapolated from secondary literature and recorded into a table, and afterwards, the corresponding proposed application of blockchain is documented and reviewed.

Findings: An adequate breadth and variety of categories are substantiated from archival literature, which effectively contributes to the extraction of proposed blockchain applications for construction. The data collection extracts 19 categories from the explorative study, in which 19 proposed solutions (one per category) is presented. All of the advisory content for the proposed solutions were obtained from a deliberated selection of 21 academic study papers.

Limitations: The study is limited to one proposed application per category, totalling 19 proposed solutions; however, assessing various approaches per category could not be researched comparatively due to voluminous information. Thus, recommendations incorporate a holistic case study of one subject category which incorporates a multitude of various proposed applications.

Originality: This paper contributes to new knowledge through extrapolating proposed blockchain applications from academic literature in 2019 and 2020.

Keywords:

Blockchain, smart contract, distributed ledger technology, decentralisation, construction

1 Introduction

Blockchain first came into existence in 2008 through a whitepaper called ‘Bitcoin: A Peer-to-Peer Electronic Cash System’ authored by a pseudonymous user Satoshi Nakamoto [1]. The term pseudonymous refers to a person whose identity has not been revealed and is known by a fictitious username [2]. The first proof of concept and successful deployment of the Bitcoin blockchain network was in January 2009 by Satoshi Nakomoto [3].

The term ‘block + chain’ is broken down into two parts. The ‘block’ part is an accumulated list of transactions sent by users sending and receiving cryptographic currency over a decentralised network, where algorithms, cryptography, and coding handle the accounting and recordation of new transactions [4]. The ‘chain’ part is derived by each block containing two hashes (unique identifiers), the hash of itself and the hash of the previous block in the chain [5]. Blockchain is underpinned by several key functions, which is distributed, consensus, and decentralised [6]. Blockchain is a ledger that is shared across many computer nodes (distributed), all the computers must agree probabilistically that the data written into the blockchain is correct (consensus), and the platform must not have a central power of authority (decentralised) [7]. Block hashes (their unique identifier) are sensitive to the data stored within it, thereby, changing the data within an existing block will cause the hash to change [8]. Because of consensus and cryptography, if a block hash is changed because of tampering, then it is autonomously omitted from the chain and replaced with the most concurrent ledger state of the network [9].

Blockchain allows transactions to execute with smart contracts. The emergence of smart contracts is dated back to 1994, and was invented by computer scientist Nick Szabo, with the ideology of using computer code to execute contract agreements autonomously without input from an administrator [10]. Usage of the term smart contract may be misleading, as the term 'smart' represents inherent intelligence with logical processing; however, contemporary smart contracts can only perform basic linear functions [11]. Nevertheless, commands executed repetitively and at high volume are the rudimentary mechanics of modern computerised systems [12].The term 'smart contract' was created with the emergence of the Ethereum Foundation in 2015, which brought the evolution into blockchain 2.0 [13]. First-generation blockchain (Bitcoin) allowed users to transact without a trusted third party and created a self-sustaining algorithmic system for accounting transactions; however, second-generation blockchain (Ethereum) enabled users to program self-executing agreements into computer code (smart contract) and permitted programmers to build and deploy blockchain applications on the Ethereum network [14].

Motivation to conduct research is to amass proposed applications for blockchain in construction from contemporary literature, with data is collected from Archival studies. Blockchain is a fast-evolving sector with a healthy and dynamic ecosystem that has expanded to the construction sector [15]. Blockchain potentially integrates fragmented parties of the supply chain, automates transactions, reduces intermediareis, and may incorporate Internet of Things (IoT) into digital contracts [16]. Due to the rapid pace of innovation, data collection is filtered to suit content published in 2019 and 2020.

2 Methodology

Methodology classification selected for this paper is quantitative since numerical data is collected [17]. The method is archival and secondary in nature since existing literature is used throughout the entirety of the data collection [18]. The data collection includes amassing research categories within the construction industry, and documenting one proposed application per category. A total of 21 papers were selected following a three stage process as shown in Figure 1.

Scopus was selected as the database of choice for obtaining papers due to the reputation to deliver high quality content, as it includes the largest multidisciplinary bibliographic database with approximately 71 million papers spread across a variety of sectors including blockchain, and built environment [19]. The secondary scientific database options include Web of Science, IEEE Xplore, and Science Direct. Decision to choose Scopus was reinforced by a journal publication in 2018 which reviewed the aptitude of the Scopus database, outlining the multi-criteria benchmarks, affluent rating system for content, coverage within variety of sectors, international accreditation, technical tools for managing content, and strong affiliations with reputable journals and publishers [20]. Extending the queries to suit "DLT", "distributed ledger technology", "distributed ledger", and "block chain" did not return additional content after the Figure 1 filtration process was applied.

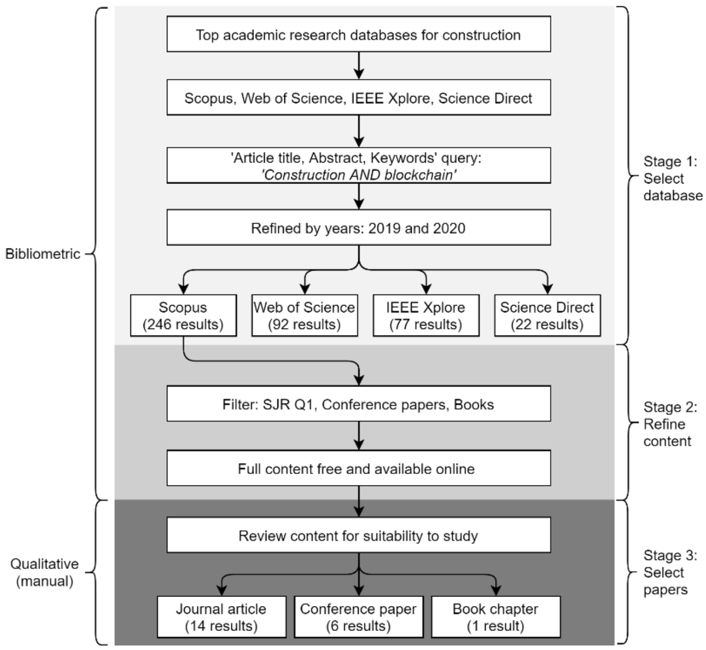

Figure 1. Review method for selecting study papers.

3 Blockchain in Construction Applications

Table 1 includes a list of 15 categories and 4 technology components (technology components are supportive systems which allow the categories to function efficiently). A popularity rating is given to each category/component exemplifying (in percentage) the number of times it was discussed by the study papers. BIM was discussed 11 times within the study papers, therefore: 11 / 21 (study papers) X 100 = 52% (popularity rating).

Table 1. Categories & technology components for blockchain in construction obtained from selected study papers.

Literature key:
Q1 Journal publication
Conference paper
Book

Categories	(Das, Luo, & Cheng, 2020) [27]	(Yang et al., 2020) [22]	(Wang et al., 2020) [34]	(Li, Kassem, & Watson, 2020) [23]	(Kabra et al., 2020) [30]	(Elghaish, Abrishami, & Hosseini, 2020) [21]	(Perera et al., 2020) [14]	(Di Giuda et al., 2020) [35]	(Wan, Huang, & Holtskog, 2020) [41]	(Sun & Zhang, 2020) [24]	(McNamara & Sepasgozar, 2020) [12]	(Li, Greenwood, & Kassem, 2019a) [23]	(Shojaei, 2019) [36]	(Nanayakkara et al., 2019) [40]	(Hunhevicz & Hall, 2019) [44]	(Hargaden et al ., 2019) [42]	(Dakhli, Lafhaj, & Mossman, 2019) [33]	(Xiong, Xiao, Ren, Zheng, & Jiang, 2019) [32]	(Zheng et al., 2019) [39]	(Bai, Hu, Liu, & Wang, 2019) [38]	(Nawari & Ravindran, 2019) [25]	= Popularity rating
1) Integrated Asset Delivery																						
1.1) Building Information Management (BIM)				✓		✓	✓	✓	✓			✓	✓	✓		✓			✓		✓	52%
1.2) Data management and storage	✓	✓	✓	✓		✓	✓			✓				✓	✓				✓			48%
1.3) Integrated Project Delivery (IPD)						✓															✓	10%
2) Automated Systems																						
2.1) Facilities management				✓									✓									10%
2.2) Smart cities									✓	✓		✓										14%
2.3) Regulation & compliance		✓		✓								✓									✓	19%
3) Decentralised Public Services																						
3.1) Payments and FinTech	✓	✓		✓	✓	✓	✓				✓	✓			✓	✓						48%
3.2) Banking solutions					✓		✓		✓													14%
3.3) Decentralised energy and water							✓					✓		✓								14%
3.4) Account security	✓				✓		✓											✓	✓		✓	29%
4) Supply Chain and Life Cycle																						
4.1) Supply chain management	✓	✓	✓			✓			✓		✓		✓	✓			✓	✓				48%
4.2) Workshare / shared intelligence			✓	✓						✓												14%
4.3) Procurement		✓		✓							✓											14%
4.4) Circular economy & life cycle								✓					✓									10%
4.5) Identity management	✓	✓					✓											✓		✓		24%
Technology Components (Providing services to the above categories)																						
Internet of Things (IoT) sensors				✓											✓					✓		14%
Token incentivisation/reward system							✓								✓					✓		14%
Application Program Interface (API)	✓	✓	✓			✓																19%
Decentralised Autonomous Organisations				✓											✓							10%

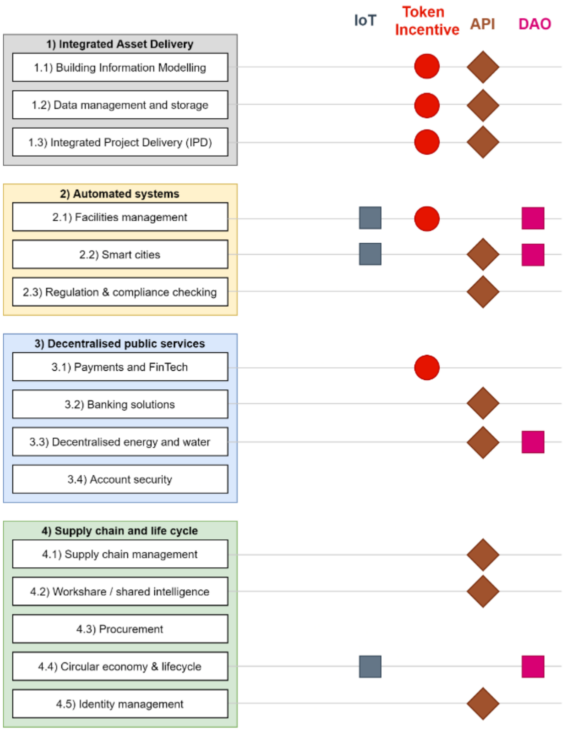

Figure 2. Mapping of categories to technology components.

The technology components allows users and systems to interact directly with blockchain applications, and facilitates incentive mechanism for decentralised technologies to sustain autonomy (e.g., reward tokens for miners to participate in proof of work, and APIs which allow users and sensors to interact with smart contracts).

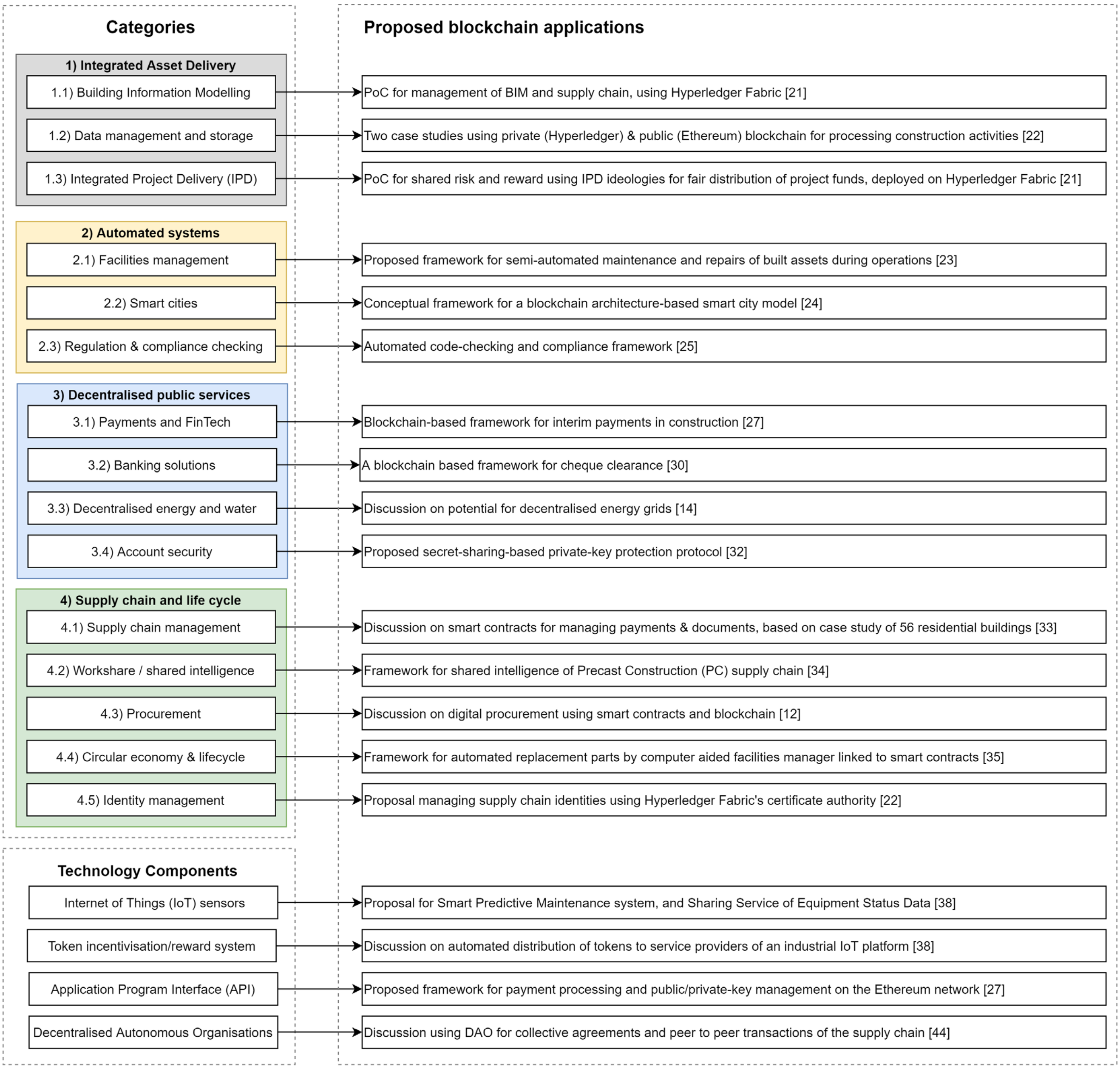

Figure 3. Proposed blockchain applications extracted from 21 study papers.

4 Review of Blockchain Applications

4.1 Integrated Asset Delivery

4.1.1 *Building* Information Management (BIM)

With a popularity rating of 52% (11 of 21) of the study papers. Elghaish, created a Proof of Concept (PoC) for the integration of BIM, IPD, & blockchain on the Hyperledger Fabric blockchain platform [21]. The BIM dimensions such as 3D BIM (model), 4D (schedule), and 5D (cost) feed data into the hyperledger smart contracts, which controls the execution of payment to the supply chain [21]. Hyperledger was selected due to the ability to use a single platform for managing identities through a certificate authority, allow automated payments, and account transaction whilst upholding privacy that is suitable for enterprises [21]. The PoC is based on a conceptual case project, where a property developer builds 100 identical houses using seven supply chain participants, such as owner, architect, main contractor, and subcontracts, using 'IBM Blockchain Cloud 2 Platform' as the user interface and Hyperledger Fabric as the blockchain platform [21]. Project participants are logged into the Hyperledger Fabric platform and a payment channel is assigned based on the works package, milestone agreement, and work value [21]. Purpose of the PoC was to test the capacity for blockchain to integrate with BIM & IPD for shared risk and reward with project delivery, whilst also benefiting from the timestamped evidentiary trail [21].

4.1.2 Data management and storage

Discussed by 48% (10 of 21) of the papers from Table1. Yang et al., provides a framework on the public and private blockchain spectrum, instantiated from data collected from two case studies, developed using the native tools of each platform, and a diagrammatic elaboration of the fundamental workflow differences of each platform [22]. Case study one used private blockchain Hyperledger to provide data management for the design of a cladding system for an apartment block, with a demonstration of the activities simulated on the Hyperledger network, and built using programming language Java [22]. Case study two utilised public blockchain Ethereum, for the procurement process of equipment delivery for an international mega project, with scheduled deliverables programmed into the Ethereum network using native programming language Solidity [22].

4.1.3 Integrated Project Delivery (IPD)

Standing at 10% (2 of 21) study papers. Elghaish et al., produced an IPD Proof Of Concept application deployed on Hyperledger Fabric [21]. The paper followed a decision criteria for selecting the appropriate blockchain platform, followed by selection of the design tools for development of the PoC, and a framework which exemplifies the integration of Hyperledger functions into the IPD process, which includes smart contracts [21]. The process includes the integration of BIM tools, followed by the management of the project budget through smart contracts, such as profit, cost, saving, and risk pool, and discusses the operations of the smart contracts to distribute funds according to the shared risk & reward methodology of IPD [21]. Screenshots of the API & evidence of the written code are documented within the publication.

4.2 Automated Systems

4.2.1 Facilities management

Accounting for 10% (2 of 21) of the study papers. Li et al., published 'A Proposed Framework For Semi-Automated Maintenance and Repairs of Built Assets During Operations', incorporating the integration of BIM, IoT, blockchain, and smart contracts, for the operation and maintenance of a built asset [23]. The adopted methodology uses a conceptual framework exemplifying how physical assets fitted with IoT sensors can feeds data into a Computer Aided Facilities Manager (CAFM), which integrates with a DAO, e-marketplace, and blockchain [23]. Connected to the CAFM and DAO is a National Product Database, which holds data about the built asset, such as product name, classification, manufacturer, compliance certifications, market data, and unique identifier [23]. Connected to the DAO is a Construction Certification Organisation that maintains a record of the user identities, qualifications, and certifications, for the autonomous inspection of personnel [23]. The paper expands further the operations involved with triggering building maintenance repairs, through sensors interacting with the CAFM, NPD, DAO, and e-marketplace, which instantiates the Invitation To Tender, and allows contractors to bid for work, additionally, the DAO manages the awarding of work, and the suitability of project participants [23].

4.2.2 Smart cities

Attributing to 14% (3 of 21) of the study papers. Sun & Zhang, proposes a 'Block architecture-based smart city overall architecture model', which includes data producers and consumers, such as government, health organisation, education, finance, civil affairs, security, institutions, and businesses [24]. The various sectors each utilise a multi-blockchain model to incorporate the handling of various functions, with data generated by ordinary citizens, enterprises, and government agencies [24]. Sun & Zhang explains that a smart city blockchain model is broken down into three layers, such as network layer, blockchain infrastructure, and business applications, furthermore, the three layers are supported by five systems, such as peer to peer network, blockchain name system, shared directory, shared intelligence, and authenticator service [24]. Furthermore, Sun & Zhang conducts a smart city case study on Hefei City, which focuses on smart networks, smart transportation, and smart government, and the results show that "the relative closeness of the level of smart city planning and the trend of the smart city planning level" increased in "relative development" at a weighting of 0.14278 (2012) to 0.85536 (2017), the increase in correlation over the five year period indicates that the government's policy makers have realised the importance of having a strategic position in smart city construction [24]. Frameworks, diagrams, and tables are displayed in their paper.

4.2.3 Regulatory and compliance

Explored by 19% (4 of 21) of the study papers. Nawari & Ravindran, proposed an 'Automated Code-Checking and Compliance (ACCC) framework, highlighting the importance for tools that can link formal language into built assets for automated compliance checking [25]. Current trends on the development of ACCC consist of regulatory text mining, semantic web approaches, rule based text extraction through AI, and natural language processing [25]. Nawari & Ravindran states that, the goal for automated code checking is the ability to transfer project data it into coding syntax for smart contract processing, which is exemplified through their proposed ACCC framework using the Hyperledger Fabric software development kit [25]. On another note, Li, Greenwood, & Kassem, produced a decision tree analysis titled 'do you need a distributed ledger?', with 'regulation and compliance' as the topic, and the key takes included the need for regulatory reform within the industry before blockchain can be adopted, and the potential for blockchain to assist in delivering regulation support [26]. Support from the World Economic Forum suggest that the industry would benefit from blockchain if regulators were part of the delivery team, rather than a third party [26].

4.3 Decentralised Public Services

4.3.1 Payments and FinTech

Accounting for 48% coverage (10 out of 21) of the study papers. Das et al., proposes a 'blockchain-based framework for interim payments in construction projects', which includes signed agreements for project deliverables, generation of a shared private-key for the encryption of data transfer, and the programming of smart contracts to be responsive to interface applications [27]. Das et al., states that the fundamental requirements for the framework consists of "(1) to incorporate transparency in interim payments by making payment records public to all project participants, (2) to restrict the access to sensitive payment-related information to the respective contracting parties only, and (3) to support the execution of interim payment cycles in an automated manner". Payments follow the process of: signed agreements from the supply chain, validation by site inspection, awarding of payment certificates, and execution of payments to the supply chain by smart contract [27]. Das et al., further discusses in technical detail the workings of: transparency models, logic automation for smart contract functions, integration of banks that include manual processing of payment proofs, security considerations, and cost and speed of execution based of varying security measures [27]. On another note, cryptocurrency is known for high volatility, and as a response, stablecoins which peg fiat currencies at one to one, such as $USD & £GBP were developed to stabilise value exchange and encourage commercial adoption [28]. Furthermore, decentralised finance (DeFi) which emerged in 2019 is a blockchain innovation that imitates the function of banks, where users can borrow/lend currency and earn interest, which removes delays caused by credit checks, and allows cheaper interest rates for users [29].

4.3.2 Banking solutions

With a coverage of 14% (3 of 21) of the study papers. A blockchain based framework for cheque clearance with banks was proposed by Kabra et al., using a QR (quick response) based authentication algorithm, allowing the digital signing of cheques with a user's blockchain private key, whereby, users sign into their blockchain banking wallet application to sign the cheque, followed by authentication from the bank, and validation that the QR credentials are successfully stored on the blockchain [30]. Kabra et al., states that the benefits include the removal of fraud as cheques can only be signed once, with evidence of the signature stored on the blockchain without risk of personal identity exposure [30]. Another practical integration with banks is the ability convert fiat currency (GBP, USD, EUR etc.) into cryptocurrency to exploit blockchain services, followed by the withdrawal back into a standard bank account without having to pass through a cryptocurrency exchange [31].

4.3.3 Decentralised energy & water

Engaging a total of 14% (3 of 21) of the study papers. Perera et al., conducted an evaluation of multiple use cases assimilated with a comprehensive literature review, with topics such as energy and water trading [14]. Perera et al., investigated the potential to create decentralised energy grids, where collective producers of renewable energy can sell excess energy at fair market price using blockchain to automate the processing of trade, the same principle is applied with water, where certified treatment plants can be provided by members of the community to allow decentralised trade [14].

4.3.4 Account security

Investigated by 29% (6 of 21) of the study papers. Protection against loss or stolen private keys is a serious problem that is addressed by Xiong, Xiao, Ren, Zheng, & Jiang, through the proposed 'secret-sharing-based private-key protection protocol' designed to provide a backup recovery system for lost or stolen keys, furthermore, the proposal has been proven feasible from a theoretical and experimental perspective, with evidence substantiated from detailed analysis [32]. Xiong et al., states that existing approaches to protect against loss or theft include 'biometric-based signature schemes', which currently conflicts with the anonymity aspect of blockchain and is superfluous in cost; 'index-hidden private key design' only partially solves the loss problem; and 'post-quantum blockchain schemes', which mitigates the theft from a quantum perspective, however, requires significantly upgrading to existing digital architecture to support quantum compatibility [32]. Xiong et al., tests their framework through a conceptual simulation with the construction supply chain, involving suppliers, enterprises, and dealers, while the analysis involves a comprehensive series of technical evaluations, regarding protocols, algorithms, encryption, security stress tests, and performance analysis [32].

4.4 Supply Chain and Life Cycle

4.4.1 Supply chain management

Accumulating 48% (10 of 21) of the study papers. Dakhli, Lafhaj, & Mossman, utilise a real estate developer case study on 56 residential buildings which specialises in acquisition, development, and management of properties, and has calculated an estimated cost saving of 8.3% from building costs using blockchain [33]. Dakhli et al., explains that the cost savings were incorporated through using smart contracts to manage transactions, integrate fragmented documents, timestamp actions, and certifications to ensure compliance to building standards [33]. McNamara & Sepasgozar, substantiates the claim by expressing that blockchain can amalgamate supply chain responsibilities, through the assimilation of user integrated applications, which link fragmented construction documents together [12].

4.4.2 Workshare / shared intelligence

Discussed by 14% (3 of 21) of the study papers. Wang et al., uses a blockchain framework for shared intelligence of a Precast Construction (PC) supply chain, where a PC model is used by the owner, contractor, plant, and logistics company, whereby, a multitude of operations take place using a single blockchain ledger, such as ordering of PC by contractor, scheduling of delivery, organisation of plant, and transport [34]. McNamara et al, proposes a similar theoretical framework for intelligent contracting [12].

4.4.3 Procurement

Accounting for 14% (3 of 21) of the study papers. A qualitative investigation on the perceptions, challenges, and opportunities of digitising the construction process through intelligent contracting was investigated by McNamara & Sepasgozar, through interviewing seven industry practitioners using an unstructured and open-ended question format [12]. The respondents agreed that current contracting methods are inadequate, and the requirements for asset delivery are commonly misunderstood due to unclear contract terms, reluctance to innovate, and the lack of investment [12]. The respondents also believed that automating contracts and removing the human decision making process can streamline delivery, reduce manual processing, and integrate the sector to encourage better procurement practices [12]. The discussions and study was based on four themes, such as optimism, innovation, comfort, & security, and the key takes for these include: the desire to optimise the construction process, streamline contract delivery, innovate through intelligent contracts, automate decision making, transparency of risk, and payment stability [12].

4.4.4 Circular economy & lifecycle

Discussed by 10% (2 of 21) of the study papers. Di Giuda, discusses in literature how asset lifecycle can be improved through blockchain and Building Information Management (BIM) [35]. The BIM model maintains an as-built record of all the building components and the associated macro data such as supplier information, additionally, blockchain can be used to process the ordering of replacement parts during operational phase, with potential for the BIM/digital twin to be used as the component database [35]. Similarly, Li et al, proposes a facilities management framework which links machine sensors to a computer aided facility manager, and is linked to the blockchain for the automated ordering of replacements parts, with transactions executed by smart contracts [23]. Shojaei, discusses how blockchain enables the construction industry to be equipped with a transparent evidentiary trail of material sourcing, allowing the provenance of materials to be tracked from building to contractor, vendor, factory, and raw source, which provides reworks contractors greater insight on the material lifecycle and reuse potential [36].

4.4.5 Identity management

Analysed by 24% (5 of 21) of the study papers. Identity management is crucial for even the most basic of enterprise operations, as business is conducted with known identities, Yang et al., discusses the potential to manage supply chain identities effectively using Hyperledger Fabric, for the identification of users and activities instantaneously for traceability, as Hyperledger uses a Certificate Authority (CA) for the management of trusted identities[22]. The CA is responsible for adding new identities to a project and can reuse identities from a historic record, and all identities within the Hyperledger network are stored in digital wallets, which can be stored on a databases or file system[22]. Each wallet can interact with multiple membership service providers, which gives permission to replicate the same identity for various projects, however, due to the modular nature of Hyperledger Fabric, organisations have full rights to customise the identity and access policies, which may cause storage restrictions [22]. Conversely, the emergence of zero knowledge proofs in 2019/2020, by auditing firm Ernst & Young, allows private transactions to occur on a public blockchain, at a current marginal price of $0.05 USD per transaction, which bypasses the expensive fees incurred from being on a private blockchain network [37].

4.5 Other categories worth accreditation

Other categories that deserve accreditation that were not included into Table 1 include insurance [26]; AI & Big data [38] [24] [39]; dispute resolution [12] [40] [41]; real time tracking [34] [42]; Bid & tender [35], carbon credits [14], transport [14], Ownership certificate [14], and logistics [14]. Reasoning behind excluding the aforementioned proposed blockchain uses is due to a lack of content substantiation from the study papers or active discussion.

4.6 Technology Components

Technology components are not standalone categories; however, they are compulsory in allowing blockchain applications to operate, such as when users interact with an Application Programming Interface (API) to transact on blockchain [27].

4.6.1 Internet of Things (IoT) sensors

Analysed by 14% (3 of 21) of the study papers. Bai,Hu, Liu, & Wang, presents a proposal for a blockchain-based industrial IoT platform, which utilises on-chain and off-chain functionalities, presented by two application uses [38]. Application one is a Smart Predictive Maintenance system, which records and manages equipment data, maintenance processes, production dates, status data, maintenance records, and inventory. [38]. Application two is a Sharing Service of Equipment Status Data, aimed at tackling the fragmentation of system data owned by various service providers, which allows manufacturing companies greater insight into increasing value and longevity of their assets, through registering manufacturing equipment on the Ethereum blockchain [38]. AI & big data is formatted off-chain, with on-chain connectivity when required, and privacy is achieved through consensus and encryption [38]. Both applications are presented with explanatory frameworks.

4.6.2 Token incentivisation/reward system

With a popularity of 14% (3 of 21) of the study papers. Bai, Hu, Liu, & Wang, discusses incentive mechanism for blockchain, through the automated distribution of tokens to service providers and trusted third parties, whereby, the service providers of a blockchain industrial IoT platform are rewarded with tokens for participation, through uploading, storing, and validating data, furthermore, the IoT sensor records equipment data, such as pressure, vibration frequency, and temperature [38]. Each measurable is set with a maximum performance threshold, and when the threshold is breached the IoT sends a service request to the maintenance system and a spare part is sent for ordering, furthermore, a token is provided to the maintenance system node for participation in the network [38]. On another note, financial institutions are incentivised to use security tokens, which are cryptographic representatives of real world assets, such as financial securities and bonds, allowing users to trade in an open blockchain marketplace [43]. The result is less administrative burden and capital requirements, with the benefit of immutability, speed, and cheaper trading fees [29].

4.6.3 Application Programming Interface (API)

Occupying 19% (4 of 21) coverage by the study papers. Das, Luo, & Cheng, provide a framework for payment processing and public/private-key management linked to the Ethereum Rinkby test network, and demonstrates how the supply chain interacts with the Ethereum API [27]. Das et al., also covers technical elements regarding shared key management, validation procedures, and the process of mapping interim payments with blockchain [27]. An API is crucial for commercial and enterprise adoption, as many of the coding elements for basic blockchain functions are programmatically technical [22]

4.6.4 Decentralised Autonomous Organisations (DAOs)

Totalling 10% (2 of 21) of the selected papers. A use case review of blockchain in construction was conducted by Hunhevicz & Hall, with papers ranging from 2017-2018, which identified 22 blockchain categories from 9 papers, including DAO [44]. DAO is the complete reformation of delivered assets by the diminishing of third parties, through the collective agreements of the supply chain transcribed in computer code, promoting the ideology that technology has the potential to alleviate processing responsibilities of the contractor, which allows the supply chain to transact in a peer to peer manner, enabling IOT to directly interacting with BIM tools and smart contracts [44]. DAO has potential to deliver assets economically with reduced corruption and processing delays, however, full governance with the DAO will require uptake in many gradations, due to complexities and integration requirements of legacy operations [45].

5 Discussion

Table 1 provides an adequate breadth and variety of categories for blockchain in construction, with content substantiated from multiple academic sources. The research methods from the study papers consists of seven frameworks [23] [27] [35] [34] [30] [25] [24], two literature reviews/discussions [33] [30], three proposed applications [38] [22] [32], one case study [22], one proof of concept (used in two categories – BIM & IPD) [21], one qualitative interview [12], and protocol update for private-key management [32]. Figure 2 links the connections between categories and technology components, such as how Elghaish et al., uses an Application Programming Interface (API) supplied by 'IBM Blockchain Cloud 2 platform' for the development of their proof of concept [21]. While, Figure 3 extracts the blockchain applications from the Table 1 categories.

Mapping of technology component 'Internet of Things (IoT)' to the blockchain categories, as shown in Figure 2, occurred in three occasions, such as facilities management [23], smart cities [24], and circular economy and lifecycle [35]. Mapping of tech-component 'token incentives' also occurred in three occasions, such as data management and storage [22], facilities management [23], and payments and FinTech [27]. Mapping of tech-component 'Decentralised Autonomous Organisations (DAO)' occurred in four occasions, such as facilities management [23], smart cities [24], decentralised energy and water [14], and circular economy and lifecycle [35]. While Application Programming Interface (API) was mapped to ten categories, as listed in Figure 2. Elghaish et al., utilises an API to produce a proof of concept that amalgamates BIM, IPD, payments, supply chain, and identity, using the 'IBM Blockchain Cloud 2' API [21]. Similarly, Wang et al, addresses API integration through a conceptual framework for increasing traceability in precast construction, incorporating supply chain, BIM, payment automation, and data storage, with transaction executions recorded on the Hyperledger explorer API [34].

Amalgamation of multiple technology components within a single category is exemplified by Li et al., who incorporates three technology components (IoT, DAO, & Token incentives) into one category (facilities management) through a conceptual framework for 'Semi-Automated Maintenance and Repairs of Built Assets During Operations', which utilises IoT sensors linked to a Computer Aided Facilities Manager (CAFM), which interacts with an e-marketplace for the ordering of new parts, while DAO organises the bidding of work with supply chains and checking of standards, and a National Product Database (NPD) is used for the registration of verified products [23]. The DAO, CAFM, e-marketplace, & NPD are incentivised through token rewards for providing services to the ecosystem. Another example where three technology components (IoT, API, & DAO) was incorporated into one category (smart cities) was a proposal by Sun & Zhang, with a 'Block architecture-based smart city overall architecture model' where IoT is used on smart transportation and infrastructure, DAO is applied to the decentralised management of multiple organisations that makeup city functions, such as education, government, health, and security, while an API allows the various city organisations to integrate and transact through a smart city model [24].

Authors from the study papers who have conducted similar research to this paper and displayed their data in a table format include Li et al., 'Categories of DLT applications in the built environment' [26]; and Hunhevicz & Hall, [44]. However, blockchain is a fast evolving sector, and the papers reviewed by Li et al., and Hunhevicz & Hall., are delimited to publications up to the year 2018, thus an investigation into the trends of 2019-2020 were explored in this paper.

Several topics were excluded from Table 1 even though they appeared often throughout the study papers, this was because the content was not actively discussed and lacked academic substantiation. E.g., a proposed use for logistics was not listed on the Table 1 as it was passively discussed in other categories such as ‘shared data’ by Das et al., [27]; ‘supply chain management’ by Yang et al., [22], and ‘information management’ by Wang et al., [34]. Many Crossovers exist within the categories in Table 1, such as ‘BIM’ & ‘workshare solutions’, however, they are not synonymous with definition. E.g., Sun et al., published an in depth journal article on workshare solutions for construction industry, however, does not mention BIM anywhere in the entire paper [24]. The segregation of overlapping topics was carefully considered to ensure the correct amount of division was applied. Furthermore, defining BIM as a subcategory of workshare solutions would be taxonomically unfitting for this paper, as BIM was categorised in Table 1 under ‘integrated asset delivery’, while workshare solutions was listed under ‘supply chain and life cycle’ due to how terminologies was discussed by the study papers.

Two blockchain protocols are dominant in the study papers, these are Ethereum (public) and Hyperledger (private). Private blockchains such as Hyperledger are popular for several reasons, they have the ability to execute higher volume of transaction per second, protocol infrastructure is modular (customisable), and includes greater privacy controls [22]. Public blockchains (Ethereum) are completely decentralised, includes greater security, does not require an identity management authority, and the benefits from free protocol architecture [22]. Enterprise blockchain solutions are reliant on the ability to integrate with existing enterprise systems, which favours the modular capabilities of private blockchains [46]. However, private blockchains suffer from expensive on-boarding and monthly fees charged by service providers such Hyperledger by Linux Foundation, while public blockchains are free to join and charges a smaller fee per transaction, solely for sustaining the network of miners who update the ledger [47]. Despite the competition between public & private blockchains, both protocols support cross platform deployment of smart contracts [48]. The privacy functions of Hyperledger’s certificate authority can be maintained while executing Ethereum smart contracts on Hyperledger [22]. Software company ConsenSys created Decentralised Public Key Infrastructure for maintaining enterprise grade privacy for cross-platform use, and provides on-boarding services for enterprise clients [49].

A notable discovery from the Figure 3 review of blockchain applications is the ability to retrieve access to lost and stolen private keys [32]. Blockchain cryptography provides cybersecurity that is stronger than standard internet centralised user systems, however, it can also backfire, as there are countless occasions recorded in blockchain history where users have forgotten or lost their private-keys and are unable to retrieve their funds [25]. Xiong et al., addresses this problem through proposed ‘secret-sharing-based private-key protection protocol’ which enables users to retrieve access to lost/stolen private-keys from accounts that were considered inaccessible [32].

The construction industry has been plagued by poor procurement practices for many generations [50]. In an interview regarding the state of procurement conducted by McNamara & Sepasgozar, misunderstanding of contract terms by project participants was stated as the primary problem, which leads to disputes, project delays, and a lack of trust, resulting in the interviewees supporting the use of automated contracts to reduce manual processing [12]. Automated procurement is discussed by Li et al., through a framework integrating an e-marketplace for the ordering of new machine components, using IoT sensors that interact with a facility management system [23]. Yang et al., also discusses procurement in a case study regarding the capability to streamline processing of delivered assets, exemplified through an application demonstration where an Ethereum smart contracts was used to process contractual agreements and transactions [22].

6 Conclusion

This paper contributes to further knowledge through providing a review of 19 proposed applications for blockchain in construction from archival literature published in 2019 and 2020. Content was extracted from 21 study papers following a bibliometric and qualitative filtration process. Data was collected in two stages:

1. An explorative study was conducted from a deliberated list of 21 study papers, and categories for blockchain in construction were extracted and recorded into Table 1. Several of the categories were listed as technology components and Figure 2 maps the relationship between these.

2. 19 Proposed blockchain applications were extracted from the study papers and recorded into Figure 3; afterwards, a review is documented which discusses the methodology, approach, and motive behind each application.

Limitations include the restriction of reviewing one proposed blockchain application per category, due to superfluous content, which totals 19 proposed applications altogether. Conversely, recommendations suggest a comparative investigation of multiple applications for one specific category, potentially through a holistic case study. Furthermore, conceptual frameworks was abundant within the proposed applications, accumulating 37% of the research methods; therefore, hypothesis testing on the feasibility of these frameworks into the enterprise environment would be informative inclusion to research.

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