Blockchain and the ‘Internet of Things' for the construction industry: research trends and opportunities

Elghaish, F., Hosseini, M. R., Matarneh, S., Talebi, S., Wu, S., Martek, I., Poshdar, M., & Ghodrati, N. (2021). Blockchain and the ‘Internet of Things' for the construction industry: research trends and opportunities. *Automation in Construction*, *132*, Article 103942. https://doi.org/10.1016/j.autcon.2021.103942

Published in:
Automation in Construction

Document Version:
Peer reviewed version

The application of Blockchain and the 'Internet of Things (IoT)' in the construction industry: Research trends and opportunities

Abstract

Various applications integrating Blockchain with the Internet of Things (IoT) have emerged in recent years. While industries such as automotive have embraced this integration, application in other areas such as construction remains limited. The scientometric analysis is applied to 648 papers, identifying the use of IoT and Blockchain in engineering, as well as evaluating the progress of research in the construction industry. The qualitative critical review is applied to 88 papers and analyses successful IoT and Blockchain application cases in construction while also highlighting challenges and limitations. Blockchain of Things (BCoT) as a new concept is introduced to exploit the advantages of IoT and Blockchain, and this paper presents potential uses of BCoT in the construction industry. This paper provides researchers with a comprehensive view of related literature and research gaps that offer opportunities for future research.

Keywords:

Blockchain of Things; BCoT; Industrial Internet; Distributed Ledger Technology (DLT); Industry 4.0; Digitalisation.

1. Introduction

Industry 4.0 is a technology-rich platform to automate traditional manufacturing and industrial processes and practices. It can also be seen as an extension to existing mechanisation, electrification and computerisation processes (Kagermann, Helbig, Hellinger, & Wahlster, 2013). Moreover, Newman et al. (2020)the concept and the process of industry 4.0 has received attention in the construction industry in recent years (Ghosh, Edwards, & Hosseini, 2020). Newman et al. (2020) argue that a significant amount of research exists for Industry 4.0, business analytics and IoT. Blockchain is still in its infancy, and specific aspects of Blockchain such as decentralisation, transparency, publicly available transactions have been investigated, but other aspects of Blockchain such as scalability and network require further research. Industry 4.0 applications in construction (which is sometimes referred to as construction 4.0) broadly consist of industrialised production (e.g., prefabrication, additive manufacturing, modularisation), cyber-physical systems (e.g., Internet of Things (IoT), sensors, drones), and digitalisation (e.g., Building Information Modelling (BIM), laser scanning, cloud computing, etc.) (M. Reza Hosseini et al., 2020; Newman et al., 2020). However, the transformative application of industry 4.0 in the construction industry has been slow due to the fragmentation of activities along the construction supply chain, with construction project delivery compartmentalised across many independent, discrete processes (Arayici & Coates, 2012), the lack of awareness and the culture of organisations (Reinhardt, Oliveira, & Ring, 2020). Therefore, advanced Information and Communication Technologies (ICTs) should be increasingly adopted to automate construction tasks and reduce the inherent process fragmentation (Elghaish, Matarneh, et al., 2020; Newman et al., 2020).

Evidence shows that the transformation of the construction industry towards Industry 4.0 relies on integrating advanced technologies like Blockchain and Internet of Things (IoT) as a necessary prerequisite to automating value-added tasks and data-acquisition systems (M. Reza Hosseini et al., 2020; Mohamed & Al-Jaroodi, 2019; Wollschlaeger, Sauter, & Jasperneite, 2017). Blockchain is defined as a distributed ledger technology characterised by decentralised operations across a consensus mechanism network (i.e., peer to peer) (Zheng, Xie, Dai, Chen, & Wang, 2018), where all data is stored as blocks that are immutable once joined and authenticated in a chain (Kinnaird, Geipel, & Bew, 2018; Turk & Klinc, 2017). During the last few years, workable solutions based on Blockchain in construction were developed, such as (1) automating financial transactions and securing interim payment (Das, Luo, & Cheng, 2020; Elghaish, Abrishami, & Hosseini, 2020), (2) minimising fragmentation in supply chain, tracking resources and efficient shipment management (Hamledari & Fischer, 2021; Hasan, AlHadhrami, AlDhaheri, Salah, & Jayaraman, 2019; Z. Wang et al., 2020), (3) Enhancing the quality information management based on hyperledger-fabric as a decentralised system (Sheng et al., 2020). The IoT is an evolution of the internet with integrating billions of smart objects (Iqbal, Butt, Afzaal, & Salah, 2019). It is also a process of interrelating several computing devices and digital machines through unique identifiers (UIDs) in order to exchange data among devices without requiring human interactions (Tan & Wang, 2010). Value-added services are introduced to internet devices through integrating IoT sensors, such as securing the privacy of shared data among network users (Butt, Iqbal, Salah, Aloqaily, & Jararweh, 2019). By reviewing the literature review, there are different applications of IoT in construction industry such as operational and assets management, project progress evaluation, facilitating the delivery of prefabricated industry. These three main applications are critically discussed in this paper.

The integration of IoT and Blockchain has been discussed in previous studies in terms of the technological potential and challenges (Alladi, Chamola, Parizi, & Choo, 2019; Banafa, 2017; Panarello, Tapas, Merlino, Longo, & Puliafito, 2018; Reyna, Martín, Chen, Soler, & Díaz, 2018). Studies have also discussed different use cases of integration for different industries like food and automobiles, among others such as Ourad, Belgacem, and Salah (2018) proposed blockchain-based solution, using Ethereum smart contracts, that provides authentication and secure communication to IoT devices. However, no available study has yet considered the potential use of integrating these two within the construction domain (Ghosh et al., 2020). Researchers like Jennifer Li, Greenwood, and Kassem (2019a) and Perera, Nanayakkara, Rodrigo, Senaratne, and Weinand (2020) provided a holistic view of the potential uses of Blockchain in the construction industry and concluded that Blockchain has significant potential in construction. This is mainly due to the transformation in the industry with regards to procurement combining the change of onsite to offsite construction. As for IoT, extant literature is for the most part comprised of conceptual frameworks or is focused on creating point solutions for technical challenges (Ding et al., 2018; C. Z. Li, Xue, Li, Hong, & Shen, 2018; Wan & Bai, 2020)(Ding et al., 2018; C. Z. Li et al., 2018; Wan & Bai, 2020).

Given that there is ample opportunity for the integration of IoT and Blockchain (Alladi et al., 2019; Q. Wang, Zhu, Ni, Gu, & Zhu, 2020), such as automated tracking of project resources, managing supply chain process, solving the disconnectivity issues in complex projects, managing equipment remotely and supporting the transformation to smart cities, together with a conspicuous gap in the literature on this point, gaining a full understanding of various aspects of integrating these two technologies within the construction industry is much needed. This paper is an attempt to address this gap.

To this end, a combined scientometric and critical review of the literature is carried out to analyse existing attempts at coupling Blockchain and IoT for automating construction activities, with reference to lessons and similar attempts undertaken in leading industries such as automotive, healthcare and transportation industries.

The findings of this paper will help researchers develop a variety of solutions applicable to construction engineering in integrating IoT and Blockchain. Moreover, it provides an updated picture of the latest developments of each technology (IoT and Blockchain) individually. Accordingly, significant limitations and existing gaps are highlighted, providing springboards for future research into these fields. The section that follows gives a brief review of similar major studies and review studies in the field to corroborate the necessity and significance of conducting the present study in light of the gap identified in the literature.

2. Previous review papers, summary and gap

There are several review studies on these two technologies. Table 1 tabulates a summary of related review papers and the limitation of each one.

Table 1. Relevant literature review research

<table>
<tr><th>Author/year</th><th>Methodology</th><th>Focus of study</th><th>Limitation</th></tr>
<tr><td>Panarello et al. (2018)</td><td>Systematic literature review</td><td>• Discuss the potentials of integrating IoT and Blockchain for different industries.</td><td>• The paper was published in 2018, and significant development in both technologies has taken place last three years.</td></tr>
<tr><td>Reyna et al. (2018)</td><td>Manual literature review</td><td>• Evaluate the capabilities of Blockchain to enhance the performance of employing IoT technology.</td><td rowspan="2">• Focusing only on the technical advantages of integrating Blockchain and IoT without mentioning potential use cases for different industries/sectors.</td></tr>
<tr><td>Lo et al. (2019)</td><td>Systematic literature review</td><td>• Discuss the technical characteristics of integrating IoT and Blockchain, as well as the existing challenges.</td></tr>
<tr><td>Alladi et al. (2019)</td><td>Manual literature review</td><td>• Explore the utilisation of Blockchain and IoT to move towards industry 4.0.</td><td>• This paper discussed several industries; however, the construction industry was not sufficiently covered.</td></tr>
<tr><td>Alamri, Jhanjhi, and Humayun (2019)</td><td>Manual literature review</td><td>• List the existing challenges of integrating IoT into Blockchain.</td><td>• There are no listed use cases beyond the proposed integration.</td></tr>
<tr><td>Mistry, Tanwar, Tyagi, and Kumar (2020)</td><td>Manual literature review</td><td>• Present a comprehensive review on blockchain-based 5G-enabled IoT.</td><td>• Even though use cases of the proposed integrations were discussed for smart homes, however, the potentials utilizations in the built</td></tr>
</table>

	environment sector were not critically and sufficiently analyzed.

Given the limitations as illustrated in Table 1, future research is needed to address certain gaps: (1) evaluate the status quo of research in IoT and Blockchain in construction through conducting a scientometric analysis, (2) critically review the existing research in IoT and Blockchain in construction to draw a map for future researchers to deal with the identified limitations, and (3) discuss possible combined arrangements of IoT and Blockchain, subsequently, reflecting the use cases and potential applications of integrating them within the construction industry. As such, this paper is needed in order to bridge the mentioned three gaps in the existing review papers.

3. Research method

McGowan and Sampson (2005) state that the mixed methods systematic review is the most effective method when the objective of the research is to define gaps in the body of knowledge and identify future research trends. Employing a mixed methods systematic review enables researchers to form an objective presentation of the field. Mixed methods systematic review studies are superior to mono-method manual review studies in which researchers might be biased and their judgment and interpretation subjective (He et al., 2017). Besides, relying on a mixed methods systematic review enhances the depth and breadth of literature review studies (Heyvaert, Hannes, & Onghena, 2016).

The scientometric analysis in this study consists of consecutive steps, as illustrated in Figure 1. A keyword search in the Web of Science database was conducted using different keywords: (1) 'Blockchain/Distributed Ledger Technology (DLT)', (2) 'Smart Contract Applications in Construction', (3) 'Internet of Things applications in Construction', (4) 'BIM and Blockchain' and (5) 'BIM and IoT'. Then, prominent journals and conferences, which were classified as Q1 and Q2 were maintained. Eventually, the two lists (n=415 for Blockchain) and (n=188 for IoT) were downloaded. The scientometric analysis were carried out for IoT and Blockchain individually as well as combining both lists together to identify the interrelationships points between them.

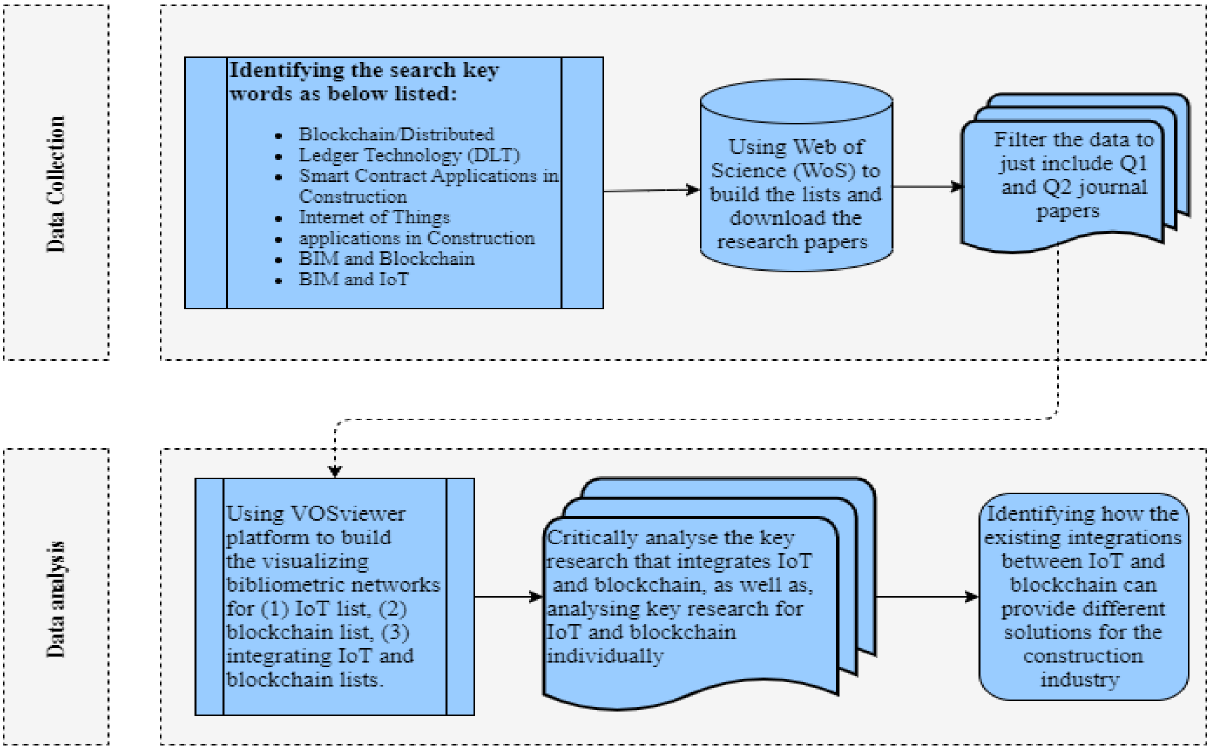

Figure 1. Flow diagram of selection of articles for Scientometric analysis on IoT and Blockchain in construction.

The main aim of the scientometric analysis was to create a map of a specific scientific knowledge area. This enabled conducting a critical review of the area (B. Zhong et al., 2019). Critical analysis of the content in this study was adopted to derive qualitative data analysis of the selected articles based on the technical aspect of each article to derive patterns and propose future research directions.

Figure 2 shows a taxonomy of construction topics that Blockchain and IoT can provide workable solutions for existing challenges. There are main seven topics that Blockchain and IoT can be integrated to enhance the entire construction process, including supply chain management, collaboration, operational and assets management, project progress evaluation, leveraging BIM implementation and enhancing the delivery of prefabricated buildings. This taxonomy provides an overview of the research context.

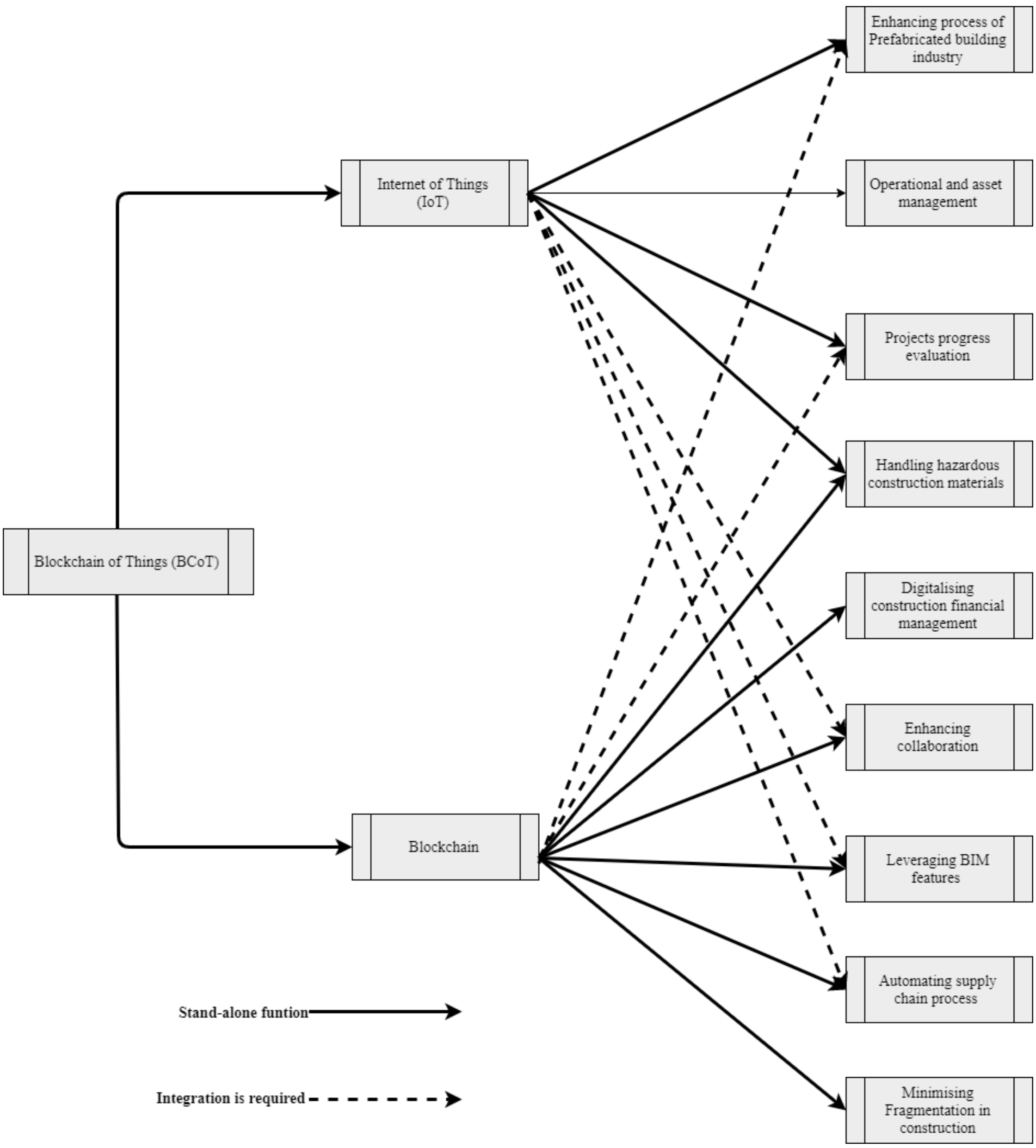

Figure 2. Taxonomy of construction topics for which Blockchain and IoT can offer solutions

4. Findings from the Data

A scientometric analysis of both topics is carried out in order to analyse the co-occurrence of keywords and undertaking document co-citation analysis, citation burst analysis, direct citation, analysis of outlets, and co-authorship analysis for both topics separately.

4.1. Trend of publications

The scientometric analysis results reveal that over the last decade, there has been a noticeable increase in publications on IoT in construction, which was initiated in 2013, with a constant increase until 2018 (Figure 3). Interestingly, 89% of publications were published during the last five years, which means that IoT in construction is a new domain with increasing interest, especially in 2018 when 42% (30 articles) of publications were published this year. However, during 2019 and 2020, the number of publications dropped to only 16 papers in 2019 and 4 papers in 2020. Therefore, there is a need for research to provide different use cases to motivate researchers to publish more in this area.

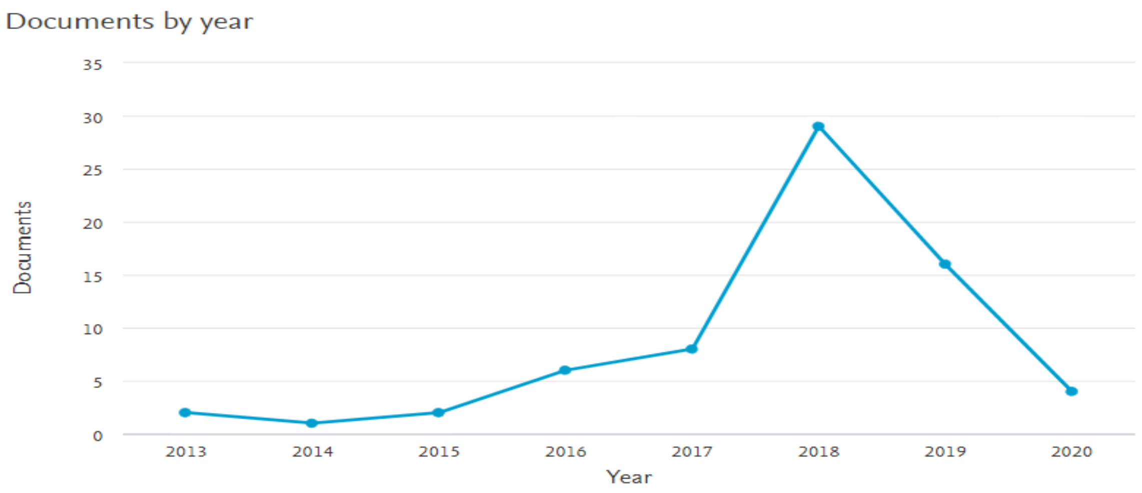

Figure 3. Published papers on IoT in construction (by year)

Figure 4 shows the number of publications of Blockchain per year. It can be seen that the peak point of publications is 2020 by 30 journal papers. This reflects the significant attention that Blockchain in construction is receiving.

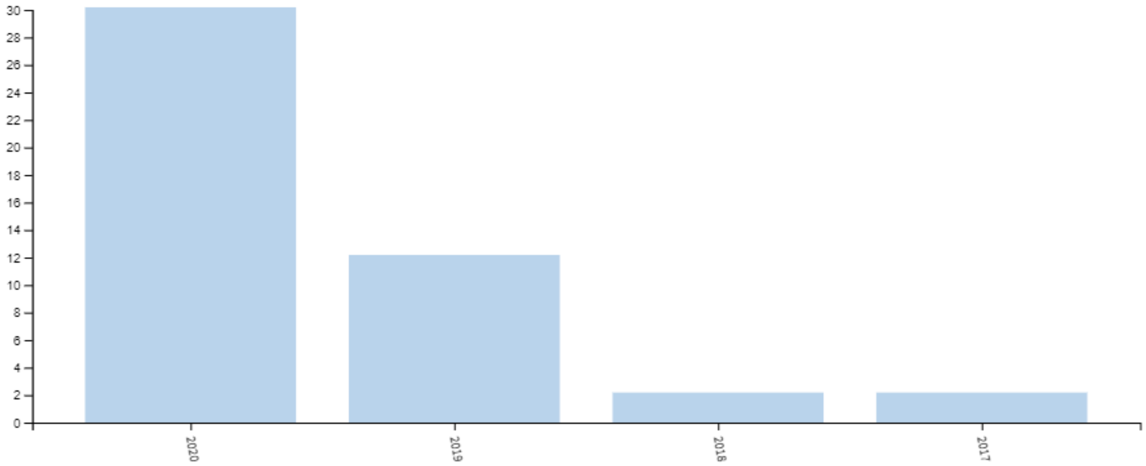

Figure 4. Number of blockchain publications in the construction industry

4.2.Key research areas

Keywords selected by authors reveal major focus areas of studies; they reflect the content of papers (Hosseini, Maghrebi, Akbarnezhad, Martek, & Arashpour, 2018). The most frequent keywords after removing (Internet of Things and IoT) from the keywords analysis are (1) maintenance, (2) real time tracking, (3) asset management, (4) stakeholders management, as shown in Figure 5. The short distances between all presented nodes in Figure 5 refer that there is a significant correlation between all these themes, as discussed next.

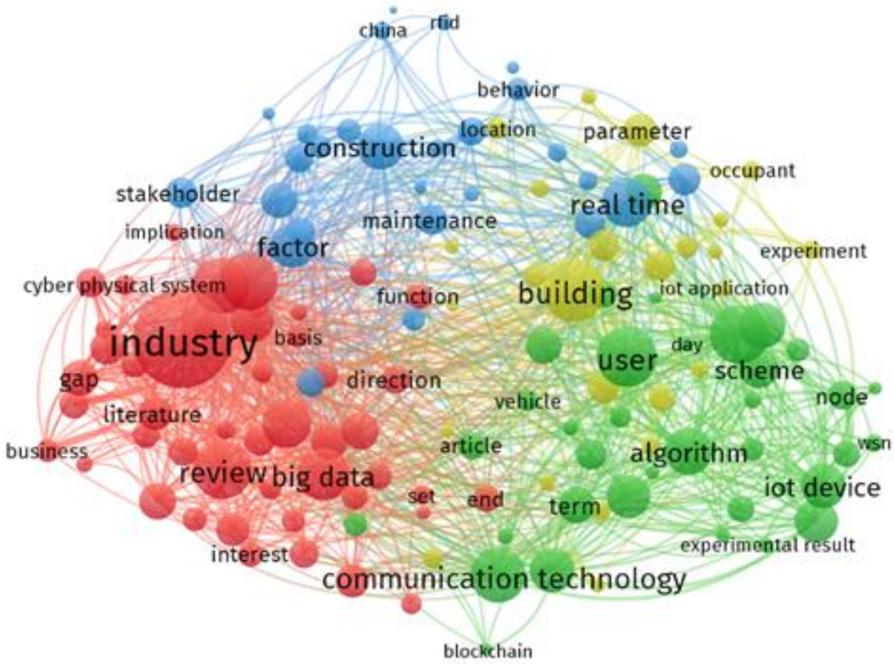

Figure 5. Main research areas in IoT in construction.

Through analysing around 450 papers in the construction and relevant engineering fields, Figure 6 shows the overlay visualisation of the Blockchain publications. The main areas of publications are security, supply chain management, innovation, integration into IoT, transportation and deep learning. Given the distances between network nodes and also the size of nodes represent the strength of the relationship between knowledge (Perianes-Rodriguez, Waltman, & Van Eck, 2016), the major areas of applications are supply chain, contracts, sustainability and IoT applications. Moreover, other smaller nodes such as energy, real time monitoring, smart cities and access control are substantially related to the IoT. Accordingly, the interrelationship between the use cases of Blockchain and IoT is very high, and this will be explored individually in the ensuing section.

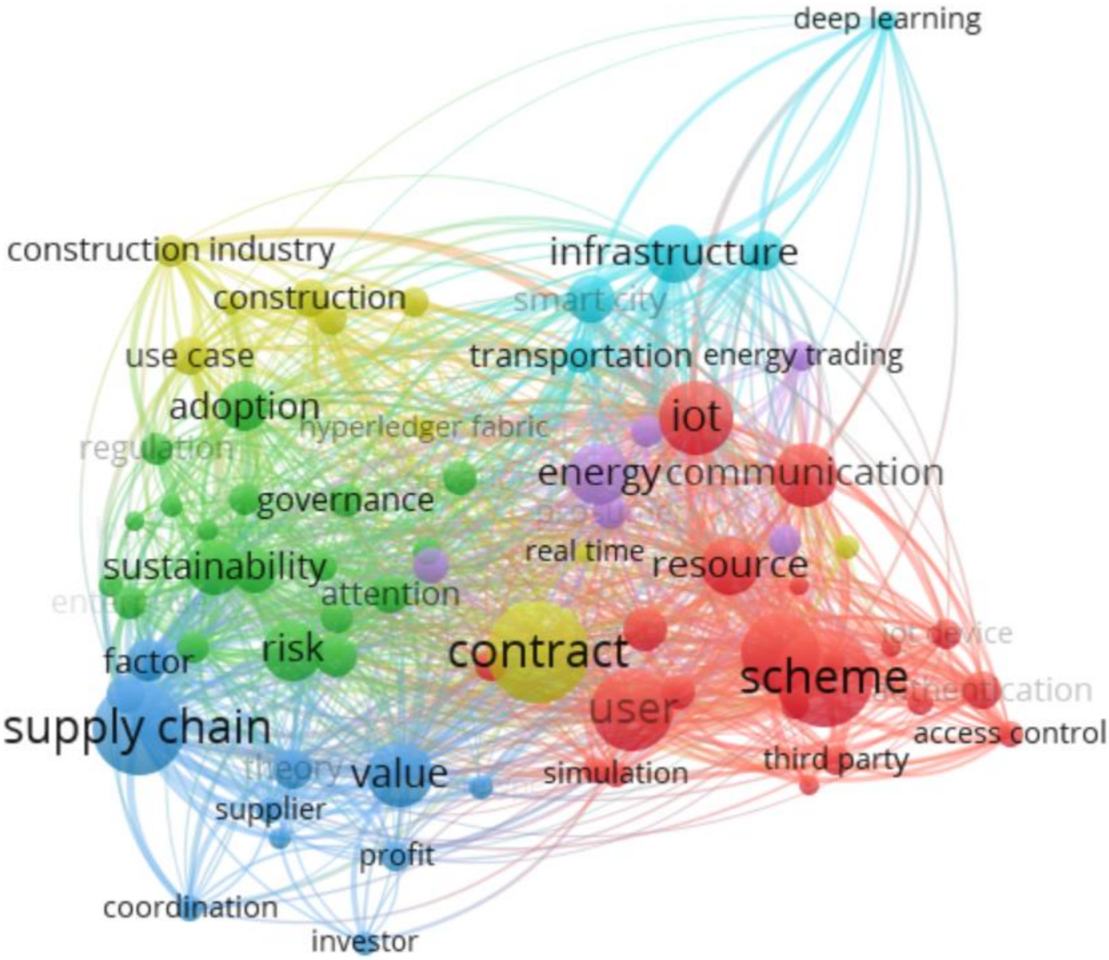

Figure 6. Main research areas in Blockchain in construction and relevant engineering fields

4.3. IoT and blockchain integration network visualisation

Figure 7 depicts the network visualisation of analysing (n=648) papers that are published in the fields of IoT and blockchain integration. It can be seen that the publications in the Blockchain are relatively new compared to the IoT, as most of the studies were published in 2019. The network proves that there are good interrelationships between both topics, particularly for nodes that are located close to both of the main nodes (IoT and Blockchain), which are BIM, big data, security, productivity and sustainability.

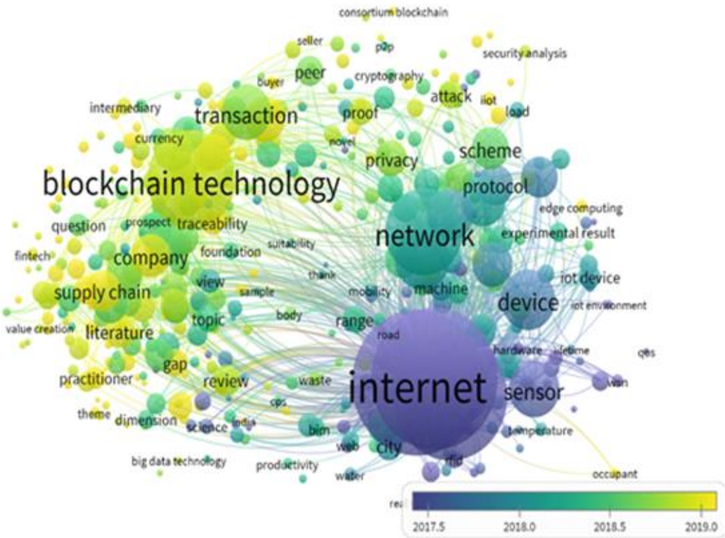

Figure 7. The network overlay visualisation of IoT and blockchain research

5. Internet of Things (IoT) for the construction industry

In this section, all published research on IoT in construction are critically discussed to highlight successful solutions and limitations to enable future researchers to explore different solutions, namely, IoT for Prefabricated Building Industry, IoT in operational and asset management and the implications of IoT for measuring project progress parameters.

5.1. IoT for prefabricated building industry

Many contributions have been made to utilize IoT for prefabricated buildings. Zhong et al. (2017) developed an integrated model to link collected data from a BIM model and Radio Frequency Identification (RFID), using IoT. The purpose behind developing this model was to enable real-time visibility and traceability in prefabricated construction. Moreover, Lu (2017) proposed a new utilization of IoT for the prefabricated industry through the Autonomous Assembly Approach. The author presented a conceptual approach to automate the process between the manufacturer and assemblers; however, no practical model was presented. Later, practical applications of IoT were developed to foster the implementations of prefabricated buildings, such as the IoT-enabled platform developed by (Li et al., 2018). This IoT-enabled platform provides a tool for prefabricated stakeholders to help track their daily operations and in decision-making, collaboration and supervision during the assembly process for prefabricated buildings. However, the developed tool was only designed to collect cost and schedule data. Meanwhile, health and safety, quality and construction environment data were not considered. IoT was utilized and applied on a small scale to measure its validity and manage the performance of pre-assembled beams (Zhuo, 2018). This system was built by employing different hardware, such as RFID, cloud technology and big data in a single integrated system to retrieve data and send it automatically to a visualisation platform. This system proved its capability in terms of automation, visualization and remote control of the entire process of the pre-stressed structural element. However, more research is needed to scale IoT applications to measure holistic structural performance in different scenarios.

In addition to the research providing technical solutions using IoT for large prefabrication contractors, there is also research exploring how IoT can help enable Small and Medium Size Enterprises (SMEs) to execute the prefabrication operations. An example of such research is (Xu, Li, Chen, & Wei, 2018), which presented an economical and flexible IoT system-based cloud asset that supports the application of Information and Communications Technologies (ICT) to prefabrication operations. However, this research was validated using data from Hong Kong, and further research is needed to measure the model validity for different construction contexts/environments.

IoT was also utilized to measure gas emissions during the construction stage by installing a laser system on the production line to perform measurement readings (Tao, Mao, Xie, Liu, & Xu, 2018). Accordingly, the manufacturer and builder can avoid high emission periods; however, this study was conducted only in China, which limited the generalizability of the findings. Subsequent research assessed the feasibility of IoT for fault diagnosis and providing an early warning system during the manufacturing stage; a construction case study was conducted, and the results proved the feasibility of utilizing IoT for quality control during the manufacturing process. Additionally, IoT has been used to support the supply chain process for prefabrication in the construction industry, (Meng Wang, Altaf, Al-Hussein, & Ma, 2018) developed an automated management system using IoT to automate the supply chain of a floor-material management system for panelized homebuilding. Even though the proposed automated supply chain system was validated using a single case study, the scalability of this system was an issue. Therefore, more validations could be conducted to measure its scalability in different scenarios.

5.2. IoT in operational and asset management

Lilis and Kayal (2018) proposed a smart message-oriented middleware-based (MoM) IoT. This system allowed the digital and physical assets of a smart building to interact efficiently. It was also decentralized, and therefore, any single deficiency would not affect the entire system. However, this system was only tested in a small case study, and the authors recommended extending the system through a larger "library" of such protocol abstraction modules.

The utilization of IoT technologies has improved the performance of smart cities, particularly in terms of infrastructure, such as road planning (Bermudez-Edo, Barnaghi, & Moessner, 2018).

The researcher developed a set of algorithms to analyze the movements of IoT stream data based on spatio-temporal correlations. However, more work is needed to find enhanced methods and solutions to analyze correlation-versus-causation for multiple causations, considering the two-way interrelationships (Bermudez-Edo et al., 2018).

The utilization of IoT sensors for managing smart buildings showed a significant success, according to (Silverio-Fernandez, Renukappa, & Suresh, 2019). The researchers stated that IoT sensors enhanced the efficient management of timesheets, employees, customers and documentation. However, more case studies should be applied to raise the technology awareness between contractors and operators. These findings were confirmed in another study by (Love & Matthews, 2019) by providing a generic benefits dependency network for System Information Modelling (SIM). This system shows the role of different technologies and how they will add value to the business process. However, this system was only tested and required further validations, as recommended by the authors: "Future research is required to examine how this can be integrated and coupled with an assets wider ecosystem, within which ECIS exists" (Love & Matthews, 2019).

Costin and Eastman (2019) articulated an ontological framework to list the challenges and potential of IoT in providing Seamless Information Exchanges in Smart and Sustainable Urban Systems. The main findings indicate that the technical challenges are: (1) lack of practical interoperability between interdisciplinary domains, (2) lack of automation, and (3) lack of IoT methods in the architecture, engineering, construction and owner industry.

5.3. The implications of IoT for measuring project progress parameters

The IoT concept was earlier utilized in measuring project progress by employing RFID technologies (readers and sensors), particularly for "health and safety" and for evacuation planning during the construction stage (Kiani, Salman, & Riaz, 2014). This research proposed valuable extensions for the developed system to enhance and support the visualization and reliable data acquisition for construction health and safety management tasks. Subsequently, much research has been conducted to cover a wide range of IoT applications for measuring construction project progress. Zhou and Ding (2017) utilized IoT to provide automated warning systems, as well as safety-barrier strategies for underground sites to avoid accidents. However, even though the system was tested using a case study, the Yangtze River-Crossing Metro Tunnel, the health and safety regulations are different from one country to another. Therefore, more applications and extensions to this system are still needed to maximize the benefits.

Kochovski and Stankovski (2018) explored how edge computing applications, such as video communications and construction process documentation, can support the movement to smart construction with high Quality of Service (QoS). However, the security of the data was an issue, which is why the researchers recommended the integration of the presented applications and blockchain technology. Further case studies have been conducted to measure the significance of IoT in managing smart buildings. Cheng Zhou, Luo, Fang, Wei, and Ding (2019) developed a cyber-physical-system-based safety monitoring system for metro and underground construction, particularly for blind hosting. A real-life complex case study was conducted to measure the validity of the system in a complex site environment, and the findings show that the integration of BIM models and physical activities can provide real-time feedback information for all movements of equipment onsite, enabling risks to be identified automatically. However, the authors recommended that studying and optimizing the relationships between safety issues and construction conditions could enable building future simulations to predict similar issues. More utilizations of the IoT in health and safety have been presented, such as using IoT-based architecture to automate non-hard-hat-use (NHU) testing (Zhang, Yan, Li, Jin, & Fu, 2019). The researchers proposed a system that relied on an infrared beam detector and a thermal infrared sensor for non-intrusive NHU detection to deal with the problems of employing traditional sensors, which were not efficient enough to detect human movements.

Construction mobility for industry 4.0 requires an ecosystem to utilize the IoT in the entire construction operation rather than utilizing it in a single operation (Woodhead, Stephenson, & Morrey, 2018). This research revealed that there was a contradiction between acquiring a highly secure IoT environment and sharing data, and a set of new processes. That is, systems should be developed to enable utilization of the IoT in the construction industry, such as new information workflow and new business models. In other words, if the construction company received the long-term maintenance costs and was paid a periodic service charge, subsequently, industry parties would receive reimbursed profit

6. Blockchain and smart contracts

In this section, critical analysis of blockchain applications in the construction industry is conducted through (1) providing an overview of Blockchain and smart contracts, (2) critical analysis of published blockchain papers that directly articulated for the construction industry,(3) highlighting the challenges that face fostering Blockchain implementation in construction, and (4) exploring Blockchain and BIM integration.

Blockchain/Distributed Ledger Technology (DLT)

There are two categories of blockchain networks (BCNs), namely: *public Blockchain network (BCN)* which can be accessed publicly under the generic consensus mechanism (Li, Barenji, & Huang, 2018), but remains secure because of its cryptography power mechanisms such as Bitcoins (Andoni et al., 2019); and *private Blockchain network* (BCN) which is characterized by having pre-identified users, for which the mechanism for their consensus should also be identified clearly (Zhetao Li et al., 2018). The private Blockchain network (BCN) represents a single platform for a specific organisation where the data is secured in the blockchain network, and only pre-identified users can see stored information in the network (Andoni et al., 2019; Butt et al., 2019).

Kumar and Mallick (2018) define BCN as a tamper-proof technology that is suitable for a range of applications. As such, it is a promising technology for avoiding a wide range of bad practices across various industries. Similarly, BCNs provide a high level of security since the block recorder can check all the recorded data in terms of the sequence and the interrelationship of data in the network (Banafa, 2017). This reduces the likelihood of data being tampered within BCNs (Kumar & Mallick, 2018). As such, BCNs are efficient in supporting computing solutions (Lamb, 2018; Penzes, 2018; Turk & Klinc, 2017). Moreover, there are opportunities for Blockchain in banking include transparency, smart contracts, security, transaction speeds. However, challenges include legislation and regulations, operating costs, and standardisation requirements work as an obstacle towards achieving this aim (Hassani, Huang, & Silva, 2018).

The development of smart contracts dates back to 1994. They are defined as an automated system to perform contract terms such as payment transactions through an automated/agreed protocol (Christidis & Devetsikiotis, 2016; Tapscott & Tapscott, 2016). Accordingly, the traditional trusted third party is not needed as a result of contract terms being executed based on pre-identified consensus mechanisms (Mason, 2017). Meanwhile, Peters and Panayi (2016) proposed a comprehensive definition for a smart contract: a platform for enforcing and monitoring the data entered by trusted sources to be stored in a BCN, based on pre-identified contract terms. These pre-identified terms should be codified/written using a programming language such as Go (see Donovan and Kernighan (2015) for details). This is one of Blockchain's features and a result of the evolution of BCN throughout the last decade: the ability to transfer cryptocurrency or data over Blockchain (Christidis & Devetsikiotis, 2016). Additionally, smart contracts reduce dependency on lawyers/third parties in terms of executing and monitoring contract terms, such as financial transactions, and therefore the accuracy and transparency of data can be enhanced

(Mason & Escott, 2018). In fact, as Christidis and Devetsikiotis (2016) point out, smart contracts benefit users by giving an automatic audit for the transferred data. Once the data has shown validity, the data can be immutable so as to enhance transparency and security. The smart contract is named as a chaincode in the hyperledger fabric; the chaincode ensures that all transactions are linked and sequenced properly (Hassani et al., 2018).

Throughout the last few years, Blockchain has been used to develop workable solutions. For exampleHasan et al. (2019), Viriyasitavat, Da Xu, Bi, and Pungpapong (2019) developed an architecture made from key technologies such as Practical Byzantine Fault Tolerance (PBFT) with smart contracts to overcome the challenge with time inconsistency and consensus bias to foster the adoption of Blockchain in business processes.

6.1.Blockchain/smart contracts in construction

Blockchain has not been widely adopted across the construction industry. However, there have been several attempts at using it by developing business models (Tozzi, 2018). As an example, Bimchain is a proof of concept of integrating BIM into Blockchain in the form of a plug-in for BIM platforms (Bimchain, 2018; Lamb, 2018). Fox (2019) states that there have been several cases of adopting smart contracts in the construction industry: delivering the agreed contracts automatically with enabling parties to update any variations; enhancing copyright for project documentation; automated payments among project parties; and it can also work as an acclaim submission platform (Lamb, 2018; Tozzi, 2018). As such, smart contracts will be valuable in terms of the automation of some construction processes that traditionally rely on multi-interactions and contributions from project participants in making decisions (Mason, 2017; Mason & Escott, 2018).

Table 2 below shows the contribution of select relevant papers towards raising the awareness of implementing Blockchain and smart contracts in the construction management and built environment and providing different solutions based on Blockchain and smart contract technology (see Table 2). Most developments and research focus on providing theoretical solutions-based Blockchain technology and reviewing the use cases of Blockchain in other leading industries (i.e. automotive industry) and reflect these use cases on similar scenarios in the construction industry. However, a few research provided workable solutions. For example, Elghaish, Abrishami, et al. (2020) developed an automated financial system for Integrated Project Delivery (IPD) using Hyperledger fabric, Z. Wang et al. (2020) proposed a supply chain trackability system based on Blockchain to enhance the collaboration in precast construction, Das et al. (2020) exploited Blockchain as a decentralised environment to secure interim payment in construction projects. The major direct published research in Blockchain for the construction industry have been analysed in terms of contribution, methodology, the final outcome, as shown in table 2. As such, future researchers can directly navigate to define the knowledge gaps in those research and start to provide workable and reliable solutions.

Table 2. The related works of Blockchain in construction management and built environment

Authors/years	Focus of study	Method of research
Turk and Klinc (2017)	• Highlighting the potential of Blockchain in construction management. • Providing a map to direct potential users to select the suitable type of Blockchain based on the nature of the data, as well as the hierarchy of the organization. • Illustrating the blockchain interoperability with other systems (data storage).	Conceptual framework
Mason (2017)	• Asserting the importance of intelligent contracts (smart contracts) for the construction industry by saving the cost of employing a third party and minimising the time needed to perform new transactions. • Highlighting the importance of integrating smart contracts into BIM in order to automate the entire construction process.	Critical review
J. Wang, Wu, Wang, and Shou (2017)	• Presenting an outlook for implementing Blockchain to revolutionize the persistent issues in managing the supply chain, contract management and resource management, particularly the leasing of equipment. • Providing a taxonomy of blockchain implementation challenges in the AEC industry (namely technical) and the construction business (the conflict between blockchain system and other implemented resource-management systems such as ERP, particularly in the case of using permissioned Blockchain) and the human challenges.	Conceptual framework
Mason and Escott (2018)	• Highlighting challenges facing the implementation of smart contracts in the construction industry. • Articulating specific steps that should be considered by industry participants in order to implement smart contracts in the future.	Critical review and conceptual framework
Jennifer Li, Greenwood, and Kassem (2019b); Mason and Escott (2018) and	• Providing an emergent framework that considers multi-dimensions, namely social, political and technical. This is in order to enable potential developers/users of Blockchain in the construction industry to highlight both the potential and the challenges.	Manual review and conceptual framework

Mason and Escott (2018)		
Macrinici, Cartofeanu, and Gao (2018)	• Providing a study map to point out the future research necessary to implement Blockchain and smart contracts. • The authors concluded (n=16) issues in implementing smart contracts. The findings of this paper could be used by researchers and developers to find remedies for the problems mentioned and to make users aware of both the potential and the challenges.	Critical Review
Jennifer Li et al. (2019a)	• Linking the current challenges that face the construction industry to the potential benefits of Blockchain to provide reliable solutions. • Researchers articulated a framework – Presenting the Socio-Technical Dimensions – that could facilitate the implementation of Blockchain in seven areas of the built environment, as categorised by researchers. • Identifying decision making criteria in terms of adopting Blockchain will be either a useful or a redundant technology feature for the organisational structure.	Critical review of case studies
Parn and Edwards (2019)	• Authors recommended utilising blockchain technology with the Common Data Environment (CDE) in order to enable tracking of the recorded data with displaying recorders as the data will be stored as a set of nodes.	Conceptual framework
Shojaei, Flood, Moud, Hatami, and Zhang (2019)	• Integrating BIM and Blockchain to govern construction-project contracts through utilising the hyperledger fabric as a blockchain tool. Authors also noted that "the notion of having to translate all the traditional contract clauses to the computer program is shown to be unnecessary and to some extent not suitable for construction, due to the complexity, fluidity, and high uncertainties involved in each project".	Framework development
Safa, Baeza, and Weeks (2019)	• Providing a strategic plan to integrate Blockchain into the construction process in order to solve existing challenges in the construction-management field. This research is a foundation for further and real applications of Blockchain in construction management.	Conceptual framework
Andoni et al. (2019)	• Highlighting the potential benefits of using Blockchain in the energy sector, such as price discovery, logistics, identification of customers and problem reconciliation and reporting.	Framework development

	• Presenting a MicroGrid-based blockchain to manage and control energy demands among producers, prosumers and end-consumers.	
Elghaish, Abrishami, et al. (2020)	• New methodology manages financial transactions and risk/reward sharing in IPD projects • Novel toolset from BIM/blockchain integration provides an automated financial platform • Create blueprints of blockchain-enabled smart contracts for construction projects • Pioneering hyperledger fabric application for IPD financial management.	Conceptual framework
Yang et al. (2020)	• Measuring the applicability of employing both public Blockchain and private Blockchain in the AEC industry using two real cases. • Developing blockchain architectures for two platforms, namely, Hyperledger Fabric and Ethereum platforms.	Prototype development
Das et al. (2020)	• Providing a secure system to execute interim payment using smart contracts. • Exploring the cost and security of using Blockchain in construction projects.	
Z. Wang et al. (2020)	• Developing a framework to utilise Blockchain and smart contracts to deal with the challenges of supply chain management for precast construction. The solution includes: "(1) information sharing management; (2) real-time control of scheduling; and (3) information traceability".	Framework development
Hamledari and Fischer (2021)	• Enhancing the integration of supply chain processes-based blockchain crypto assets • Minimizing fragmentation between cash and product flow through automating the payment in accordance with progress of production.	Prototype development

6.2.BIM and blockchain integration

Turk and Klinc (2017) stated that blockchain platforms (e.g., Ethereum, hyperledger) could be integrated into BIM to add new features. These features can record all the changes in 3D BIM models throughout the design and construction stages, subsequently enabling stakeholders to track these changes easily (Lohry, 2015). Mason and Escott (2018) asserted that BIM in integration with smart contracts would be attainable by 2020, due to the foreseeable increase in the number of sensors in devices, at a total of almost 25 billion. The promise of BIM level 2 is minimising paper-based communications and exchanges (Gibbs, Emmitt, Lord, & Ruikar, 2015); therefore, a platform that shares information between project parties with high levels of transparency and tracks all possible changes is much needed (Mosey, 2014).

Cousins (2018) argues that BIM processes require a 3D contractual model that includes all the necessary data for the validation and authorisation of all possible tasks. Bimchain is a plug-in for BIM platforms to minimise the existing gap between 3D BIM models and paper-based legal documentation (Bimchain, 2018) and is, in fact, an attempt to manage BIM using smart contracts that enable automated payments, insurance and project information tracking (Bimchain, 2018; Lamb, 2018). As such, smart contracts can be coded for integration into BIM processes and platforms to enable the execution of traditional provisions in an automated way. This will facilitate all stakeholders' access to all the data available in a secure way so as to manage project funds and release the payments owed based on a set of agreed rules (Cardeira, 2015; Fox, 2019). Additionally, Blockchain can provide a secure and collaborative environment for the BIM process (Ahmad, Azhar, & Chowdhury, 2018; Li et al., 2019a), whereby all project parties can get the same benefits in terms of access to all the information. Stakeholders will also have the chance to control project changes as a result of the main principle of Blockchain regarding neutrality (Li et al., 2019a).

Mathews, Robles, and Bowe (2017) contend that IPD requires a high level of trust and a collaboration network between core team members; all IPD members are supposed to be all for one and one for all (Ashcraft, 2012). Blockchain, by its capabilities in terms of transparency, immutability and automated data validation, will be able to create a new proposition (Li et al., 2019a; Vukolić, 2016; Watanabe et al., 2016). Therefore, all sorts of rewards can be extracted, whether tangible or intangible (Elghaish et al., 2019; Pishdad-Bozorgi, Moghaddam, & Karasulu, 2013). Moreover, Blockchain allows several participants to work collaboratively in a single project and also supports a data-driven digital environment for better project delivery (Koutsogiannis & Berntsen, 2019; Li et al., 2019a). Bimchain (2018) and Cousins (2018) assert that the combination of BIM and Blockchain can provide an incorruptible, reliable and transparent system to record, update and maintain the project database. In addition, Blockchain and smart contracts can enhance collaboration in the construction industry, as well as keep all participants informed of the project status and of all the changes related to 3D BIM design, construction site procedures and the flow of supply materials (Mathews et al., 2017).

6.3. Barriers to implementing blockchain/smart contracts for construction project delivery

Given that the construction industry relies on fiat currencies for its payment, Blockchain needs to be changed to transfer fiat currencies instead of cryptocurrencies (Cousins, 2018). In addition, banks currently use a private ledger and therefore, the linking of smart contracts and bank accounts is not attainable (Pisa & Juden, 2017). However, if any commercial/central bank accepted being a part of the distributed ledger, the payment could be sent/received in a fiat currency (Brody). The coding of verbose legal concepts is considered a practical challenge to using smart contracts. Such concepts include "good faith", "negligence", and "reasonableness" in their legal narrative (Sherborne, 2017). In addition, Raskin (2017) contends that smart contracts cannot fully include all legal terms; for instance, legal contracts should include the elements of “offer”, “acceptance” and clear expression to show the intention of parties to enter into a legal agreement. However, the user can articulate a draft contract and subsequently codify all possible terms; thus, the draft contract can work as a recovery for any issues that have not been coded (Clack, 2018).

Intellectual copyrights are sensitive and important for construction companies. However, the shared data in hyperledger is decentralised, and potential copyright issues should be considered and handled accordingly (Cousins, 2018). Arnaud Gueguen, founder and CEO of Bimchain, argues: “We believe a country like the UK, which is more contractual than France, or Scandinavian countries, could deploy our solution more fully.” (Cousins, 2018)

Allison, Ashcraft, Cheng, Klawens, and Pease (2018) stated that the application of Blockchain requires new regulations, laws, and a governance system in order to overcome all possible challenges. In addition, the current set-up costs of Blockchain are prohibitively high. However, the potential benefits of implementing Blockchain can quickly cover the necessary resources (Andoni et al., 2019).

There are several technical issues facing Blockchain implementation in the construction industry, such as the necessary bandwidth and capacity required to ensure that all data will be transferred without any time lag (Kasireddy, 2017). Additionally, the AEC industry is not entirely digitised so as to adopt Blockchain and smart-contract technologies (Mason & Escott, 2018). Andoni et al. (2019) assert that Blockchain must prove its scalability, viability and speed in different cases. In addition, consensus algorithms research is still ongoing to combine all desired characteristics in an integrated consensus protocol (Wang et al., 2018).

ICAEW (2018) mentions different challenges: the fee per transaction ranges from £5 to £8; the period between sequential transactions is around five minutes, and the transaction capacity is low compared with the traditional banking visa. Despite the high reputation of Blockchain in terms of security (Kollewe, 2018), there have been several successful hacking attempts during the last few years, with the most recent theft amounting to around £27 million (Lamb, 2018). As such, each organisation should determine the potential minor and major breaches in each case using cybersecurity. Indeed, Pradhan, Stevens, and Johnson (2017) state: “Full blockchain development could take five to seven years or longer, or may not occur at all. Early adopters who commit to testing Blockchain across the supply chain must be prepared to accept significant levels of risk – and be prepared to fail fast and try again.”

7. IoT and blockchain integration use cases

Integration of IoT and blockchain technology has been discussed since 2016 in many fields in order to collect real-time data and sharing these data through a Blockchain system to ensure privacy, security and scalability (see table 3). Y. Lu (2018) and Y. Lu (2019) confirm that Blockchain has the potential to innovate and significantly improve IoT-related systems through creating a distributed system. Blockchain technology is a promising solution to overcome certain challenges around business process management (BPM). In this context, Blockchain has to be integrated with BPM system components that usually include IoT devices (Viriyasitavat, Anuphaptrirong, & Hoonsopon, 2019; Viriyasitavat, Da Xu, Bi, & Pungpapong, 2019). Moreover, Iqbal et al. (2019) state that key challenges (e.g. context awareness, privacy, dependability, general reputation, architectural choice, ethics) in developing trust models for social Internet of Vehicles. Eventually, the authors present an overview of trending technologies (e.g. Blockchain) that can assist in developing a trust-based social Internet of vehicle models while considering the dynamic nature of the system. Viriyasitavat, Anuphaptrirong, et al. (2019)The importance of analyzing the similar integrations in different fields can help the built environment researchers to apply similar integration architectures in the built environment, such as developing a remote control system of construction sites and developing an automated system to track the performance of assets and keep the collected data in a blockchain system and enhancing the health and safety management for construction projects (See table 3)

Table 3. Major previous works on integrating Blockchain and IoT

Authors/years	Focus of study	Use cases for construction	Method of research
Huckle, Bhattacharya, White, and Beloff (2016)	• Pointing out the benefits of Blockchain and IoT to support a shared economy such as Uber. • Presenting examples of shared-economy applications, such as AutoPay which is used to pay car-parking fees and to record the data using the smart-contract feature.	• This can be used to automate the tracking of resources (O'Connell, 2017) on the construction site through specific sensors (IoT) such as equipment and then processing this data using Blockchain.	Critical review and conceptual framework
Reyna et al. (2018)	• Providing a model to show the possibility of integrating Blockchain into IoT and highlighting the potential of this integration. • Further to the model mentioned, the authors present a detailed list of blockchain usages in different sectors. Moreover, the authors underpin the new concepts of the chain of things and the Blockchain of things as extant attempts to achieve the desired integration.	• The project manager can track the inventory in sites using IoT devices (Jayanth, Poorvi, & Sunil, 2017). • Other technologies are used to manage construction resources such as Radio-frequency identification (RFID) (Ren, Anumba, & Tah, 2011). However, the implementation of IoT and Blockchain to track resources (i.e. equipment) is more workable since the entire process is automated and all observed data will be securely checked and stored without needing human interactions. • The fragmentation in construction supply management in construction due to the miscommunication between parties (Dainty, Millett, & Briscoe, 2001), can be minimized	Framework development
	• The authors articulated a decentralized blockchain-based supply-chain management model to overcome the current challenges of the supply chain. • The proposed supply chain via Blockchain MAS uses smart contracts in Blockchain in order to automate the contractual agreement between the different parties who are part of the MAS model.		Prototype development

		through involving all parties in a decentralized blockchain network.	
Dwivedi, Srivastava, Dhar, and Singh (2019) and Aceto, Persico, and Pescapé (2020)	• Providing a blockchain system to provide secure management and analysis of healthcare big data. • Collecting real-time data using IoT devices and transfer these data to the blockchain network.	• There are connectivity issues in using complicated big data applications in the construction, particularly, BIM big data (Bilal et al., 2016), Integrating this designed system can deal with these connectivity issues. • Collecting real-time data from construction sites can enable project managers to track project progress proactively (Asadi Boroujeni & Han, 2017). Therefore, the integration of Blockchain and IoT can be used to develop a real-time data collecting system, as well as, processing the collected data to measure the project progress-based blockchain (Elghaish, Abrishami, et al., 2020)	Prototype development
Viriyasitavat, Da Xu, Bi, and Pungpapong (2019)	• Blockchain can ensure the trust by removing trusted intermediaries. This research developed an agent-based approach using Blockchain to support the measurement of Quality of Service (QoS).		
Dorri, Kanhere, Jurdak, and Gauravaram (2019)	• Utilizing Blockchain as an effective technology for providing security and anonymity in IoT and tackling the existing challenges of using IoT such as complexity, bandwidth and latency overheads and scalability.	• Given the utilization of advanced ICT technologies are associated with the complexity in the construction industry (Adriaanse & Voordijk, 2005), therefore, the enhancement of the scalability of IoT devices can support employing it in complex construction projects.	System development
Viriyasitavat, Da Xu, Bi, and	• The authors propose other enabling technologies such as public key infrastructure (PKI) and to be integrated		

Sapsomboon (2019)	with blockchain technology in a new architecture of IoT services.	• Dealing with hazardous materials in buildings is one of the main health and safety issues in construction (Kim & Yu, 2014), IoT with Blockchain enable detecting hazardous materials and warn construction practitioners while handling them.	
Pavithran, Shaalan, Al-Karaki, and Gawanmeh (2020)	• Designing an integrated system to employ both IoT and Blockchain technologies together through comparing their components regarding storages and security levels.		
Rahman et al. (2019)	• Proposed a sharing economy system based Blockchain to store data in immutable ledgers. This system is supported by Artificial Intelligence (AI) infrastructure. It is designed to be used in a future generation smart city that can offer cyber-physical sharing economy services through IoT data.	• Building smart cities requires using advanced IoT devices in order to connect all assets and facilitates together in a centralized system (Tekouabou, Cherif, & Silkan, 2020), when integration AI and Blockchain as proposed in this research, this could enable automating and sorting all problems automatically without any human interactions.	Prototype development
Sultana et al. (2020)	• Developing data sharing system using Blockchain with IoT devices. • The proposed system is efficient regarding the cost of transactions.		Prototype development
Miraz (2020)	• Validating the integration of Blockchain into IoT through the concept of Blockchain of Things (BCoT).	• Secured data sharing system-based IoT and blockchain integration can be integrated with BIM to achieve the objective of developing synchronous production control room to mange complex projects as recommended by (Ezzeddine et al., 2021; Nascimento, Caiado, Tortorella, Ivson, & Meiriño, 2018).	Conceptual framework

Aich, Chakraborty, Sain, Lee, and Kim (2019)	• Developing a conceptual framework to integrate Blockchain and IoT to develop an automated supply chain system that are advantaged by improving the flow of supply chain information.	• This framework can be extended to the construction supply chain in order to enhance the fragmentation in sharing supply data between different parties (Dana Broft, 2020).	Conceptual framework and case study

8. Discussion on findings

IoT is employed in the construction industry in the following areas: the prefabricated building industry, operational and asset management, and the implications of the measurement of a project's progress parameters. Regarding the use of the IoT for prefabricated buildings, it was found that (1) there is a need to develop a platform to enable collaboration between the manufacturer and the assemblers, (2) IoT can track daily operations regarding health and safety, quality and environmental impact, (3) IoT is used to track the tension performance of concrete elements (e.g. beams in bridges), and more research is needed to measure entire structural performances under various scenarios. Even though IoT is currently employed to enhance operational and asset management, more real-life case studies should be conducted to raise technology awareness between constructors and operators, particularly for building new smart cities. There are also technological challenges facing the adoption of IoT in smart cities, such as lack of practical interoperability between interdisciplinary domains, lack of automation and lack of IoT methods in the architecture, engineering, and construction industries.

In terms of measuring a project's progress parameters, IoT is employed in the construction industry for managing health and safety tasks on site. However, more applications and extensions to leverage IoT applications in health and safety measurements are needed to maximize the benefits. Moreover, a set of necessary new processes and systems should be developed to enable the use of the IoT in the construction industry, such as new information workflow and new business models.

Blockchain technology has received significant attention in the construction industry since 2017. However, most of the publications are either conceptual frameworks or review papers. Otherwise, a few papers include workable solutions such as developing an automated financial system for IPD by (Elghaish, Abrishami, et al., 2020), supply chain traceability framework by (Z.

Wang et al., 2020) and securing interim payment approach by (Das et al., 2020). Therefore, this research draws a map for researchers (1) to define research problems and see how these problems were solved in other fields, and also (2) to develop prototypes to validate researchers' proposed themes and conceptual frameworks.

Hyperledger fabric is the most suitable blockchain platform to automate payment through all the construction delivery stages. This is because (1) its consensus mechanism is modular, enabling project parties to build a consistent mechanism according to the project conditions, and (2) the applicability resulting from the integration between hyperledger (Linux), IBM, Oracle and SAP facilitates its implementation.

Although Blockchain was introduced to enhance the construction supply chain management process, real applications are not yet provided. Therefore, the successful attempts in different industries were summarised in this research to enable researchers to exploit the progress in these industries.

Regarding IoT and blockchain integration, several studies have been found; however, this integration is yet to be explored in construction. Such integration can be significantly useful to develop a remote control system of construction sites. The outcome of identified nine papers on this topic were discussed to be a point of departure for researchers in construction, particularly for automated tracking of resources, enhancing the collaboration among suppliers, better connectivity to move the data between different processes and sources and fostering the transformation to the new generation of smart cities.

9. Conclusion

This study explores the current state of research in the field of IoT, Blockchain and the potential integration of both IoT and Blockchain in construction. The area has attracted much interest in the last few years, with a number of studies and literature reviews already undertaken.

Nevertheless, this study presents the first bibliometric study of the IoT and blockchain integration literature in which 603 top-ranked journal articles were systematically examined using 'science mapping' and 'critical analysis' approaches.

The utilisation of both Blockchain and IoT has noticeably increased during the last few years with applications in security, visibility, traceability and automated data collection and processing. All these features can be used to foster the introduction to industry 4.0 in construction. In this paper, the application of these two technologies was critically discussed through analysis of the existing IoT and blockchain research in the construction field and through analysis of most of the indirectly related applications (i.e. engineering, management) to enable identification of research gaps.

The adoption of IoT in the construction industry is relatively higher than in blockchain applications. This is because IoT appeared in the construction industry in 2013, while Blockchain has only been theoretically investigated since 2017. Real-life case studies of IoT exist for different purposes such as progress evaluation, health and safety monitoring in construction sites, and measuring the performance of structural elements such as bridges and facility management. However, all these case studies were conducted for research purposes. Therefore, the recommendations are to extend the application of IoT with larger cases in order to get more reliable results. In contrast, real-life case studies of Blockchain are still limited as only a few prototypes have been presented for various applications such as an automated risk/reward sharing system, secure interim payment platform and quality management system. Further research is needed to transform the presented conceptual proposals into practical solutions.

There have been effective attempts to integrate IoT and Blockchain to provide practical solutions such as tracking resources in construction sites, reducing fragmentation of data in supply chains, and fostering the transformation to smart cities. That's why the terminology of Blockchain of Things (BCoT) was introduced to the engineering field. Moreover, this research presented different cases of BCoT for the construction industry based on analogous applications in relevant fields.

Despite the contributions offered in this study, the findings are to be considered in light of certain limitations. Due to there not being enough direct publications in IoT and Blockchain in construction, the scientometric analysis focused on the field of engineering in order to extrapolate utilisation themes there with construction fields. Therefore, a dedicated construction-only based scientometric research will be needed when a significant volume of research in IoT and Blockchain in construction finally becomes available.

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