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Potential Application of Blockchain Technology for Embodied Carbon Estimating in Construction Supply Chains

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Abstract: Carbon emissions are categorised as Embodied Carbon (EC) occurring in the production phase and Operational Carbon (OC) occurring in the operational phase of buildings. The current focus on producing zero-carbon buildings, emphasises reducing OC and ignores the importance of reducing EC emissions. This study focuses on EC. Methods available in EC estimating currently produce estimates that often do not complement each other. This makes it important to develop a robust and accurate methodology for estimating EC. Blockchain is an emerging technology that has significant potential for transaction processing in supply chains. The construction industry being the second least digitalised industry, the adoption of innovative technologies is predominantly important. This paper explores the potential application of blockchain for accurate estimation of EC in construction supply chains. A detailed literature review and expert interviews revealed that, compared to traditional information systems, blockchain systems could eliminate issues in EC estimating highlighting its potential credible application for EC estimating. Scalability was identified as a feature that was lacking in a blockchain system, however, for EC estimating, its impact was identified as minimal. It will be difficult to generalise the findings of the study due to interview based qualitative methodology adopted in this study along with the fact that blockchain is an emerging and fairly new technology. However, a similar process could be followed by other studies to compare blockchain with traditional information systems, to evaluate the suitability of blockchain technology to develop prototype systems.

Keywords: blockchain; construction supply chains; embodied carbon; embodied carbon estimating; traditional information system

1. Introduction

Blockchain, being an emerging technology that resulted through Industry 4.0, has drawn considerable interest from various start-ups, technology developers, enterprises, national governments, and the academic community [1]. Manglekar and Dinesha [2] identified blockchain as a distributed, decentralised ledger that stores all transactions. In addition, it provides a distributed shared database and a computational infrastructure, which prevents the tampering and revision of data [3]. Before approving a transaction, blockchain performs an autonomous verification through the consensus algorithms to ensure security, prevent false transactions being recorded, and avoid double spending [4]. It was originally designed as a decentralised network for exchanging digital money. Blockchain technology is not only used for the transfer of digital money, but lately it has been adopted for various other applications. According to Walport [5], blockchain as a technology has the capacity to deliver a new kind of trust to a wide range of services while revolutionising the industries to reform financial markets, supply chains, consumer and business-to-business services, and publicly-held registers.

Blockchain technology can be applied to many areas of the construction industry including Construction Supply Chains (CSCs), building information modelling, design management, sustainability and waste management, property and land titles, asset management, and maintenance among others [6–10]. However, construction industry is having difficulties embracing digitalisation due to various reasons such as fragmentation, lack of replication, transience, and decentralisation among others [11]. According to Perera, et al. [10] and Agarwal, et al. [12], the construction industry is the second least digitalised industry, which had just managed to surpass the lowest digitalised industry, agriculture. It is predominantly important to adapt innovative technologies to improve productivity and performance in construction. Embodied Carbon (EC) estimating in CSCs using blockchain has been identified as a credible application of blockchain [13]. This study explores the importance of using a blockchain system compared to a traditional system to estimate EC in CSCs. Initially, the paper discusses fundamental principles on blockchain highlighting layers of blockchain architecture, followed by discussing the importance of carbon estimating and current issues in carbon estimating. Subsequently, an elaborated analysis was carried out to explore the suitability of using a blockchain system to estimate EC rather than using a traditional information system, by considering the salient features of blockchain such as decentralisation, anonymity, security, immutability, and so forth. A traditional information system is "a system in which human participants and/or machines carry out processes using information, technology, and other resources to produce informational products and/or services for internal or external customers" [14] (p. 451). For example, different databases and IT-based tools used for estimating EC are classified as traditional information systems in this research. Blockchain is a new technology that has added features and, therefore, is distinguished from the traditional information systems.

1.1. Blockchain

A blockchain is a shared and distributed database that contains a continuously expanding log of transactions that is stored according to a chronological order [1]. Blockchain is a decentralised transaction ledger that acts as part of a large computing architecture, which includes many other functions related to storage, communication, file serving, and archives [15]. According to Li [16] (p. 278), "blockchain is an integrated technology, which includes Hash, asymmetric encryption, workload proof, Merkel tree, timestamp, and peer-to-peer network are not new technologies, but with new ideas to combine them cleverly". The security and accuracy of the data stored in the ledger are maintained cryptographically through the use of public and private keys, and signatures to control "who can do what" within the shared ledger [5].

Blockchain architecture consists of four main layers: the application layer, contract layer, consensus layer, and network layer as illustrated in Figure 1. The network layer is the lowest level, which generates, validates, and stores the data and information in the blockchain [17]. The peer-to-peer network consists of multiple nodes that could act as public (permission-less), private (permissioned), or a consortium, based on the arrangement and limitations of access to data. The consensus and contract layers act as the intermediary level between lower and upper levels. The consensus layer contains protocols that contribute to appending a block to the blockchain [18]. There are several consensus mechanisms available, such as proof of work, proof of stake, delegated proof of stake, and proof of importance among others, which have been used in various blockchain platforms considering the requirements of the platform and characteristics of the consensus mechanism. Though the consensus mechanism, proof of work consumes massive amount of energy, other consensus mechanisms such as proof of stake, delegated proof of stake among others are comparatively energy efficient. Therefore, it is recommended that energy efficiency be considered for selecting the blockchain platform. The contract layer includes smart contracts and incentive mechanism that enables flexible programming and operational data functions for the blockchain system [17]. The application layer contains classes of the blockchain applications [18] related to various sectors, for example, finance (cryptocurrencies and FinTechs), supply chain management [19], energy trading, and asset management among others.

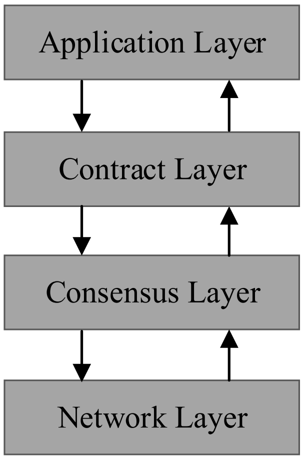

Figure 1. Layers of blockchain architecture. Adapted from Dinh, et al. [18] and Lu [17].

Initially Blockchain 1.0 was introduced to securely validate and store information of transactions, which was populated as cryptocurrencies [20]. Subsequently Swan [15] identified the usage of Blockchain 2.0 for economic, market and financial applications such as stocks, bonds, smart property, and smart contracts, whereas Blockchain 3.0 was used for applications beyond currency, finance, and markets, particularly related to the government, health, science, and art among others. Blockchain has the potential to be considered for various energy related applications such as energy trading [1], energy management, carbon trading [13], and carbon offsets among others. Similarly, a decentralised accounting process used in blockchains, can be applied for the purpose of accounting EC in CSCs of projects.

1.2. Embodied Carbon Estimating

Carbon emissions can occur as Operational Carbon (OC) and EC emissions. OC refers to carbon emissions that occur during the operational phase of a building [21], while EC emissions occur during the production process of a product/service [22]. The novel trend of reducing OC in typical projects to deliver more energy efficient buildings known as zero-carbon projects, has led to the remaining EC component to becoming almost 100%. As a result, estimating and reducing EC emissions of buildings has become an increasingly vital topic internationally and domestically. EC estimating can be carried out using various tools such as the CapIT estimator, Building Research Establishment (BRE) calculator, Carbon Footprint Calculator for Construction Projects (CFCCP), French Development Agency (AFD) tool, GaBi software, SimaPro, eToolLCD, Embodied Carbon Explorer (ECE) tool, The Footprint Calculator and databases such as Inventory of Carbon and Energy (ICE), Blackbook, Waste Reduction Action Plan (WRAP), Ecoinvent, Australian Life Cycle Inventory (AusLCI), Environmental Performance in Construction (EPiC), and The GreenBook 2010 among others [23], whereas a summary of these EC estimating tools and databases has been illustrated in Table 1.

Table 1. Summary of the embodied carbon estimating databases and tools After [23].

Type	EC Estimating Tool	Type of Software	Details	Last Updated	System Boundary	Location	Publicly Available	Free	Reference
Databases	ICE	Excel Sheet	EC	2019	cradle-to-gate	UK	Yes	Yes	[24,25]
	Blackbook	Book	EC	2010	cradle-to-gate	UK	Yes	No	[26,27]
	WRAP	Web Application	EC			UK	For registered users	Yes	[28,29]
	Ecoinvent	Web Application	LCA	2017	cradle-to-gate	Switzerland	Yes	No	[30]
	AusLCI	Excel Sheets/XML Format	EPD	2016	cradle-to-gate	Australia	Yes	Yes	[31,32]
	EPiC	Book	EE and EC	2019	cradle-to-gate	Australia	Yes	Yes	[33]
	The GreenBook 2020	Book	EC	Nov 2019	cradle-to-end of construction	Australia	Yes	No	[34]
Tools	CapIT Estimator	Published as Hutchins UK Blackbook	EC	2011	cradle-to-gate	UK	Yes	No	[35]
	BRE Green Guide Calculator	Web Application	EC	2015		UK	For licensed BREEAM/EcoHomes users	No	[36,37]
	CFCCP	Excel Sheet	EC		cradle-to-end of construction		Yes	Yes	[38]
	AFD Carbon Estimating Tool		EC and OC	2017	site-grave	France			[39]
	GaBi Education Software	Software Application	LCA	2017	cradle-to-grave	Germany	Yes	Yes	[40]
	SimaPro	Software Application	LCA	2017	cradle-to-grave	Netherlands	Yes	No	[41]
	eToolLCD	Web Application	LCA	2010	cradle-to-grave	Australia	Yes	No	[42]
	ECE Tool	Web Application	EC	2019	cradle-to-gate	Australia	Yes	No	[43]
	The Footprint Calculator	Web Application	LCA	2019	cradle-to-grave	Australia	Yes	No	[44]

Carbon accounting is currently being considered in the tender selection process in the UK and internationally, due to the evident identification on the importance of reducing the EC component in the construction industry [45,46]. However, Sinha, et al. [47] found that when estimating carbon using the tools, GaBi and SimaPro, even after using same materials, similar origins and similar technology, the models had produced different results as the considered assumptions, boundaries among others, vary dependent on the estimator. Similarly, Elhag [45] declared that in carbon accounting and measurement many inaccuracies exist due to the issues associated with scope, data representativeness, tendency to use generic data and so forth. In addition to that, Rodrigo, et al. [23] identified many other issues in the current EC estimating databases and tools, for example, usage of different system boundaries, different geographical locations, lack of standardisation, lack of data on new products, incomplete data, assumptions, and lack of transparency. Subsequently, the authors introduced a new methodology for estimating EC in CSCs using the value chain concept and blockchain technology that could eliminate these identified issues. As the next step, this paper investigates the importance of using a blockchain system to estimate EC instead of a traditional information system.

2. Research Methodology

The aim of this study was to explore the potential application of using a blockchain system in estimating EC in CSCs by comparing and contrasting the salient features of blockchain technology against a traditional information system. Initially a traditional literature review was carried out to identify the fundamentals and salient features of blockchain, followed by three expert interviews to obtain experts' opinions and validate the literature findings while investigating the possibility of using blockchain for estimating EC. All experts were senior consultants who had more than 13 years of experience in Information Technology (IT) and more than 4 years of experience in distributed systems and blockchain technology, especially on smart contract development and deployment. Due to the limited number of expert interviews that were carried out, the findings of the study cannot be generalised. However, as blockchain is an emerging technology that was introduced only in 2008 and further due to limitations of the study, especially related to time constraints, knowledge and experience of experts in blockchain among others, these experts were selected through convenience sampling and data was collected through semi-structured interviews. In order to reduce biasness in these interviews, interviewees were given the freedom to respond on traditional information systems vs. blockchain systems based on its features without discussing the literature findings in advance. Subsequently, the literature findings were provided and verified whether their responses would change. The findings of the literature review and expert interviews have been discussed in the following section.

3. Research Findings and Discussion

The detailed literature review carried out assisted in identifying the salient features of blockchain; decentralisation, anonymity, security, immutability, auditability, veracity, transparency, disintermediation, trust, and scalability (See Table 2). There was lack of research work that had carried out a comprehensive comparison between the salient features of a blockchain system against a traditional information system. Therefore, the researcher carried out a comparison between a traditional information system and a blockchain system over the pros and cons to decide on the suitability of blockchain to be used for EC estimating as depicted in the last two columns in Table 2. The comparison was carried out as a qualitative study based on available literature sources; as a result, the terminology, no, low, medium, and high were used to compare the salient features. These findings were validated through expert interviews as discussed in the latter part of this section.

The overall summary of Table 2 reveals that though blockchain supports most of the features listed, traditional information systems would either not accommodate most of them or else would be accommodating in a comparatively lesser portion. An EC estimating system requires one to produce an accurate EC estimate (accuracy), secure EC data ensuring that data is not tampered with (security), a transparent EC estimating method which shows the EC contributors and the supply chains without revealing confidential data (transparency), remove the involvement of a third party to estimate EC (disintermediation), and so forth. Hence, at a glance, a blockchain system is ideal for EC estimating. In addition, all experts agreed with the findings of Table 2 and highlighted that compared to a traditional system, a blockchain system is more suitable to estimate EC in CSCs. However, for further clarification, each feature was considered, and experts' opinions were obtained to understand which system is most suitable for carbon estimating in CSCs.

Table 2. Comparison of features between a traditional information system and a blockchain system.

No	Feature	Reference	Traditional Information System	Blockchain System
1	Decentralisation	Atlam, et al. [48], Risius and Spohrer [49]	Low	High
2	Anonymity and Pseudonymity	Atlam, et al. [48], Rodrigo, et al. [50]	Medium	High
3	Security	Risius and Spohrer [49], Underwood [51]	Medium	High
4	Immutability	Risius and Spohrer [49], Underwood [51]	No	High
5	Auditability	Risius and Spohrer [49], Underwood [51]	Medium	High
6	Veracity	Perera, et al. [10], Rodrigo, et al. [50]	Low	High
7	Transparency	Risius and Spohrer [49], Underwood [51]	Low	High
8	Disintermediation	Underwood [51], Sun, et al. [52]	No	High
9	Trust (without a third-party)	Underwood [51], Sun, et al. [52]	No	High
10	Scalability	[10,53]	High	Low

1. Decentralisation—A traditional information system consists of a centralised approach where everything is controlled by a single point along with a central database that stores the data [54]. According to Tan, et al. [55], single point of contact provides effective management of services. However, interviewees B and C opined that a traditional information system being centralised, arises few disadvantages, such as increased dependence, open to vulnerability, low auditability, trust issues, etc. In order to mitigate such issues while providing the same benefits of a centralised system, decentralised blockchain technology has been introduced [56]. In an EC estimating blockchain system, a distributed ledger that contains all the EC transaction records are shared among all the nodes in a peer-to-peer network. In order to record a new EC transaction or supersede an existing EC transaction record stored in a distributed ledger to make a change, generally the consent/validation by majority of the nodes is required. Hence, the peer-to-peer network makes it extremely difficult to tamper with data stored in a blockchain. The decentralisation feature of blockchain provides a tamper-proof data storage mechanism fulfilling one of the utmost essential features that is required to use blockchain for EC estimating in CSCs.
2. Anonymity—A centralised system as well as a blockchain system can maintain anonymity; however, the anonymity level in a blockchain is quite high. A blockchain system protects the identity of the user by maintaining anonymity or pseudonymity. In order to carry out transactions in a blockchain based EC estimating system, each user will have a public key and a private key, which comprise of large integer numbers, but since these numbers are so large, they are usually represented using a separate Wallet Import Format (WIF) consisting of letters and numbers [57]. Neither the private key nor the public key discloses the identity of the user by any means. The user of an EC estimating blockchain system can use his public key to prove his identity, thus, blockchain enables pseudonymity effectively. Moreover, interviewee A added, "unlike a traditional information system that could be hacked to reveal the encrypted information where anonymity can be at stake, a blockchain system is considered as almost impossible to hack as the public key is too complicated for a hacker to decrypt and recover the user details". In EC estimating, it is quite important to maintain anonymity of the EC contributors as well as other confidential information. Hence, a blockchain system is more suitable for recording EC transactions.

3. Security—The centralised system as well as a blockchain system maintains security through authentication limitations to control users' access to the systems; however, comparatively, a blockchain system has a higher level of security. According to Heeks [58] (p. 10), "centralised information systems make organisations more dependent and more vulnerable for a number of reasons such as greater numbers of staff relying on single information systems; greater reliance on a few key staff who plan, develop and run those systems; greater technical complexity that makes problems harder to diagnose; and greater potential impact of data security breaches". In a centralised system there is a possibility to be hacked and as the system is centralised, a change in one location is sufficient to affect the entire system. However, in a blockchain, data is stored in cryptographically-linked blocks as a ledger and a copy of the ledger is shared among all the nodes. Therefore, for a hacker to change the data stored in a blockchain system, the respective hash of that block needs to be changed. Subsequently, the hacker has to change the hashes in the entire chain between the tampered block and the latest block [59]. On the other hand, more than 50% of the ledgers need to be replicated within a short period of time for a successful attack to be completed, which is extremely difficult. According to interviewee A's point of view, "security demarcates the combination of confidentiality, integrity, and availability". In a blockchain-based EC estimating system, due to decentralisation, the confidentiality of data is at stake. However, as EC data are not extremely sensitive or confidential, this does not hinder the tendency of using blockchain for EC estimating. Data integrity also plays an important role and it can be achieved easily through blockchain due to immutability and decentralisation. EC data has to be available and accessible to the respective stakeholders involved in a project and data can be easily accessed due to transparency and due to the distributed ledger being shared with all nodes. Depending on the requirements of the system, the access can be controlled through authentication; however, for anyone who has access to the system, the EC data will be available at his/her fingertip. Interviewee B emphasised that "data integrity and availability of information whenever required, is essential for a blockchain-based EC estimating system". In summary, though confidentiality is less in a decentralised distributed ledger platform, data integrity and availability could be achieved well in a blockchain system. Hence, a blockchain system has more security compared to a traditional information system, making it a better option for EC estimating in CSCs.
4. Immutability—A centralised system is quite vulnerable due to its single point of control [58]. Hence, if the centralised database is hacked, data can be tampered quite easily affecting the entire system. Additionally, interviewee A stated that "in a centralised system, data life is totally depending on a single organisation who is mainlining the system. However, in a blockchain system, it is extremely difficult to attack and tamper with its data. Therefore, data recorded in a blockchain is considered as immutable". Immutability can be disadvantageous in certain occasions. If a transaction record is entered in a centralised system, it can be changed quite easily unlike a blockchain system, the transaction record will be superseded by the new transaction record and everything will be recorded in the ledger as data in blockchain is immutable [60]. The existing EC estimating tools such as GaBi, SimaPro, Athena, etc., that are used to estimate EC are controlled by respective organisations. If a certain organisation decides to get rid of the tool, all EC calculations carried out using this tool will be at stake. However, the EC transactions recorded in the blockchain-based EC system will remain eternal throughout the life span of data as a result of immutability.
5. Auditability—A traditional information system and a blockchain system provide auditability. However, auditing related to an information system is conducted by third party personnel to reduce errors and bias [61]. Thus, the auditing process of an information system results in additional costs. In a blockchain system, a node within the blockchain can publicly audit and share transaction records without relying on a trusted third party [62]. According to Zheng, et al. [63], each transaction is validated and recorded with a timestamp in the blockchain; therefore, any user

could trace the previous records, providing higher auditability. Interviewee B mentioned that "in a centralised system, the maintenance audit log exists within the centralised system and the internal team that handles the centralised system has access to change the logs too. This issue is eliminated in a blockchain system due to the feature, immutability, as it guarantees almost 100% auditability". Therefore, a blockchain system has easier ways to fulfil auditing purposes highlighting the suitability of using blockchain for accounting EC transactions.

6. Veracity—In any information system, veracity can be achieved to a greater extent. Unlike manual transactions, where there is a higher possibility for human errors, in an automated information system, possibility for errors is comparatively less. However, if erroneous data are entered, the result will be faulty. The same aspect is applicable for the blockchain system too. However, in a blockchain system, there is a validation process that requires any record to be validated by a majority of the nodes for it to be recorded as a valid transaction. If a faulty record is entered into the blockchain, it will be rejected by the nodes. Thus, veracity in a blockchain system is higher, making it the best option for carbon accounting.
7. Transparency—A traditional information system has no transparency. Interviewee B emphasised that "in a traditional information system, the user has to blindly believe and trust the information system and the data, which are displayed to them. The stakeholders/users have no way of validating or checking on the accuracy of the data that are being displayed or calculated at the back end". As an example, using an EC tool such as GaBi is very risky, as the user is unaware of the method of calculation that has been followed to estimate the EC. The user has to simply enter the materials used and the process carried out while the software calculates and provides the EC estimate. The user is unable to validate the accuracy of the estimate due to non-transparency. However, in a blockchain system, one can easily backtrack and identify the important information as well as the source of the data as a result of transparency. Interviewees A and C agreed that greater transparency provides a higher level of auditability. For an EC estimating platform, this quality of transparency is essential to maintain positive relations with users. Carbon accounting in a transparent blockchain platform provides reliability and trust along with integrity.
8. Disintermediation—Compared to a traditional system, a blockchain system enables disintermediation. Due to the difficulty of trusting an unknown party, a reliable third-party such as banks or financial institutes are involved when carrying out financial transactions. However, in a decentralised blockchain platform, the third-party authorities are removed, and the key transfer processes are verified and authenticated by nodes in the peer-to-peer network [62]. The blockchain provides disintermediation by removing the involvement of a third party. In EC estimating, existing EC databases and tools act as a third-party source that could completely change the estimate depending on various factors and issues as discussed previously. Currently, the EC estimates are prepared by the land developer or very rarely the contractor, who will become the third parties in carbon calculation as they may not be the EC contributors in certain occasions. For example, though it is a manufacturer that contributes to EC emissions, generally the estimate is prepared by the land developer or contractor. In a blockchain-based EC estimating system, EC transactions will be recorded by the EC contributors in CSCs enhancing the accuracy of the EC estimates. Furthermore, the results could be reviewed and analysed by the parties who have access to the distributed ledger. Removal of a third party enables trust and accuracy while reducing any additional costs.
9. Trust—Reliability of data stored in a traditional information system can be questionable due to the possibility of entering erroneous data. Therefore, one can be reluctant to trust a traditional information system. However, in a blockchain system, any transaction entered to the blockchain needs to be validated by a majority of the nodes for the transaction to be recorded in the blockchain. This provides great trust among users of a blockchain system. In order to record EC transactions accurately, a trustworthy platform is required and thus blockchain is the ideal solution. Trust is

the most important feature for the stakeholders in the eco-system to trust the system and use blockchain to estimate EC accurately.

10. Scalability—A traditional information system accommodates scalability as it has the possibility in adapting to various changing needs or demands of the users [64]. Interviewee C added that "scalability can be categorised based on storage capacity, transaction time, and new functions". Buterin [65] declared that a public blockchain will be able to handle on average 3–20 transactions per second, whereas, mainstream payment services such as VISA, are currently handling 24,000 transactions per second [66]. However, the Bitcoin blockchain processes a maximum of seven transactions per second and due to the scalability issue in the blockchain design, it is unable to handle large amounts of transactions [53]. Therefore, the blockchain platform initially had this scalability issue to a greater extent. Sharding has been introduced as a solution to this scalability problem. Through sharding, the overheads of processing transactions are split among multiple, smaller groups of nodes [67]. According to Luu, et al. [68], Elastico is a proposed permission-less blockchain where the agreement throughput is scaled up near linear with the computation power of the network and tolerates byzantine adversaries to control up to one-fourth of the computation capacity in a partial synchronous network. Though scalability is one of the greatest disadvantages of the blockchain system, if sharding is introduced, it can be resolved. All experts agreed on introducing sharding to resolve the scalability issue in blockchain. On the other hand, speed or data transaction rate is not an issue for accounting EC transactions as it has a very low rate compared to other financial services. Besides, the logical equations that are used for EC estimating are consistent and on the other hand, they are non-dependent on the features of a project. Therefore, the speed of transactions would not be much of an issue. The storage capacity to store all the EC transactions is the only challenge that will be faced by the researcher. As a solution for this issue most relevant data can be stored on-chain and all other data could be stored off-chain to improve the efficiency of the system.

There are various use cases that have already implemented blockchain in their systems due to the additional benefits provided through its salient features. SelfKey and ShoBadge are two secure enterprise blockchain systems developed related to identification authentication using a digital wallet [69,70]. Arcade City is a blockchain-based ride sharing platform that connects the drivers and passengers without the involvement of a third party [71]. Power Ledger in Thailand provides a peer-to-peer renewable energy trading platform that ultimately evaluates the trading position of individual participants [72]. Filecoin is a digital storage and retrieval system that rents their disk space for data storage [73]. In Ghana, BitFury and the Georgian government have collaborated to develop a land registry using blockchain to resolve the current land disputes [7]. BIMCHAIN integrates Building Information Modelling (BIM) and Blockchain to deliver trusted digital proofs with a clear certification process [74]. These are few of the use cases that have used blockchain to develop various systems due to its salient features. Similarly, blockchain technology could be used to develop an EC estimating system.

4. Conclusions

Blockchain is an emerging technology that has drawn considerable interest from various start-ups, technology developers, enterprises, national governments, and the academic community. Initially, blockchain was used for recording cryptocurrency transactions. However, the trend has shifted to using blockchain technology for various applications related to different industries such as science, property, and construction, among others. The study investigated the potential application of using a blockchain system to estimate EC in CSCs instead of a traditional information system. The extensive literature review and expert interviews revealed that compared to a traditional information system, a blockchain system is more suitable for an application on accurate estimation of EC in CSCs. The results highlighted that most of the salient features of blockchain technology (decentralisation, anonymity and pseudonymity, security, immutability, auditability, veracity, transparency, disintermediation, and trust (without a third-party)) were quite high in a blockchain system compared to a traditional information system, whereas, scalability was comparatively less in a blockchain system. However, the transaction rate in an EC estimating system in the practical context, is quite less and as a result, this being the only disadvantage, could be disregarded. In conclusion, blockchain technology is positively suitable to develop the EC estimating application, compared to a traditional information system. A blockchain-based EC estimating system could eliminate the existing issues in carbon estimating and contribute to knowledge as well as the construction industry. The stakeholders involved in the CSCs could benefit from the EC estimating system that will be developed using blockchain technology. However, the results of this study cannot be generalised as the data were collected through a limited number of interviews due to various limitations of the study, especially related to time constraints, maturity of the technology, and the knowledge level and experience of the experts. A similar process could be followed by other studies to compare blockchain systems with traditional information systems, to decide on the suitability of using blockchain technology for prototype systems.

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