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Blockchain in the built environment: analysing current applications and developing an emergent framework

Jennifer Li[a,*], David Greenwood[a], Mohamad Kassem[a,*]

[a]*Northumbria University, Newcastle, NE1 8ST, United Kingdom*

Abstract

Distributed ledger technology (DLT), commonly referred to as 'blockchain' and originally invented to create a peer-to-peer digital currency, is rapidly attracting interest in other sectors. The aim in this paper is (1) to investigate the applications of DLT within the built environment, and the challenges and opportunities facing its adoption; and (2) develop a multi-dimensional emergent framework for DLT adoption within the construction sector.

Key areas of DLT applications were found in: smart energy; smart cities and the sharing economy; smart government; smart homes; intelligent transport; Building Information Modelling (BIM) and construction management; and business models and organisational structures. The results showed a significant concentration of DLT research on the operation phase of assets. This is expected given the significant resources and lifespan associated with the operation phase of assets and their social, environmental and economic impact. However, more attention is required to address the current gap at the design and construction phases to ensure that these phases are not treated in isolation from the operational phase.

An emergent framework combining the political, social and technical dimensions was developed. The framework was overlaid with an extensive set of challenges and opportunities. The structured and inter-connected dimensions provided by the framework can be used by field researchers as a point of departure to investigate a range of research questions from political, social or technical perspectives.

Keywords: blockchain; distributed ledger technology, construction industry; built environment; smart contracts.

1. Introduction

Technological advancements and their adoption in the construction industry have been less effective to date than in other industries such as automotive, manufacturing and logistics [1]–[5]. £600bn will be spent on construction in the UK over the next 10 years to improve infrastructure; the efficiency and productivity of the sector are now strategic priorities of the UK Government's construction and innovation policies [6]. Building Information Modelling (BIM) is currently the expression of digital innovation within the construction sector [7]–[9]. If BIM is the main enabler for promoting collaboration, information sharing and data management, Blockchain is a possible solution to eliminating the trust element that often hinders these practices [8]. Blockchain is "*an emerging technology that enables new forms of distributed software architectures, where components can find agreements on their shared states for decentralized and transactional data sharing across a large network of untrusted participants without relying on a central integration point that should be trusted by every component within the system*" [10, p. 182].

Corresponding author: Authors emails: Jennifer.Li@northumbria.ac.uk; mohamad.kassem@northumbria.ac.uk

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The Blockchain, the first DLT, was introduced in 2008 with Satoshi Nakamoto's white paper on Bitcoin (the world's first cryptocurrency) [11] which was released in 2009 as a verification tool for cryptocurrencies but that also has the power to be applied to other applications [12]. blockchain has the potential to benefit the economic, political, humanitarian, and legal sectors by reconfiguring the workings of society and operations [13].

Blockchain is being explored for a number of different industries including, but not limited to health care [13], information sharing [14], information management, insurance, automated dispute resolution, real estate, [15], crowdfunding [16], big data analytics [17], and education [18].

The aims of this paper are to explore the current level of research on blockchain applications in the built environment and to develop a framework for its implementation within the construction sector. First, the paper explains the key concepts underpinning DLT and smart contracts. Second, it briefly explains the adopted systematic literature review approach and summarises the findings. Third, the paper discusses the challenges and opportunities facing the application of DLT within the built environment. Fourth, the paper presents an emergent multi-dimensional framework for DLT implementation in construction that considers the political, social and technical aspects.

2. Background

2.1 Distributed Ledger Technology

A distributed ledger is a simple database of transactions. Unlike a bank, where all transactions are processed and stored by one organisation (i.e. centralised), transactions on DLT are processed and stored across many different computers, known as nodes (i.e. decentralised) replacing trust with proof [19]. Trust is built into the technology through its decentralised nature and basis of consensus representing a paradigm shift from trust to a "trustless" society in which third parties become redundant [20]. Decentralisation, or decentralised trust, is a key feature of public DLTs transferring trust from people or intermediaries to computational code [21]. Centralised trust is the 'as is' situation where trust is put in one person, organisation or authority based on their knowledge, expertise or power in a certain subject area. Werbach suggests trust in centralised systems is waning with DLTs offering "a compelling alternative" [22, p. 58]. While it is not yet know at this stage whether DLT has the ability to revolutionise markets, it proposes to offer something new and, therefore, warrants further investigations [23].

In a public network, anyone can access the ledger; in a private network, people need to be granted access to participate [24]. Blockchain technology operates across a decentralised P2P network; it is immutable once chained; it has an algorithm ensuring all nodes have the same version of the blockchain; it is a public ledger of transactions; it uses a Proof-of-Work mechanism to validate transactions; in the case of Bitcoin, there is a mathematical and deterministic currency issuance mechanism [15], [25]. Each user has a unique public key made up of an alphanumeric string of 27 to 32 characters that makes it almost impossible to identify the individual it belongs to so, while it is not anonymous it is pseudonymous [26]. By design, it is secure and uses cryptography and a distributed consensus mechanism to offer 'anonymity', persistence, auditability, resilience and fault-tolerance [24].

Upon creation of a new transaction, the details are broadcast to the network for validation and verification, that is, to "run predefined checks about the structure and the actions in the transaction" [27, p. 763]. If a consensus is reached (i.e. agreement from more than 50% of nodes) that the transactions in the block are valid, the block is appended to the blockchain and each node's copy of the blockchain is updated accordingly [28]; it will remain there forever and is considered immutable. In a public blockchain, it is not impossible to change an existing block but it is very difficult because all blocks thereafter must also be changed as each block contains a hash of the block before it and this will be visible to the entire network [29]. Moreover, this must be done in the time it takes to mine one block to the blockchain by the network [30]. As all nodes have a complete copy of the ledger, it is very easy to see by comparison if any block has been tampered with. For changes to a private blockchain, all nodes on the network need to agree by consensus (typically off-line) and then modify the data. All blocks are linked all the way back to the genesis block ensuring the blockchain's integrity [31]. Data privacy is stronger in a private blockchain due to access rights [24]. The blockchain architecture is constructed such that malicious attacks are difficult to achieve. They require significant computational power and simultaneous access to each node to be successful [1].

2.2 Smart Contracts

The concept of smart contracts, conceived in 1994 [29], is a computerized transaction protocol that executes the terms of a contract [32]. The general objectives of smart contract design are to satisfy common contractual conditions (such as payment terms, liens, confidentiality, and even enforcement), minimize exceptions both malicious and accidental, and minimize the need for trusted intermediaries. Related economic goals include lowering fraud loss, arbitration and enforcement costs, and other transaction costs [32]. Smart contracts are considered a key influential development that will support Britain's achievement to becoming a digital economy as set out in the government report - Digital Built Britain (HM Government, 2015) [3]. Late and missed payments is a top issue within the construction sector resulting in cash flow problems, businesses failing and/or major disputes [2], [33]. A smart contract has the ability to embed funds into the contract to protect contractors, subcontractors and other supply chain actors from insolvency [33]. Combining smart contracts with cryptocurrencies has the potential to ensure guaranteed payments to an extent never before seen in the construction industry [2]. These developments are expected to have impact in areas where finances are involved and where there are time lags with regards "processes, speed of settlement, risk of fraud, back-office costs or operational risks" [34, pp. 180–181].

Due to the resources required to set up a smart contract (i.e. time and cost), Boucher *et al* [35] suggest that they are best used for repetitive agreements and not one-off complex agreements, particularly where the contract is susceptible to change throughout the life of the contract. Once a smart contract has been coded and embedded into the blockchain, it becomes permanent, unchangeable and irrevocable [16]. In the event mistakes or vulnerabilities are written into the code due to lack of legal knowledge of the coder or simply human error, once the contract is uploaded to the blockchain it becomes unchangeable and will be executed exactly as it is coded [35]. However, smart contracts can be cancelled and replaced with new ones once they have been uploaded to the blockchain [36] demonstrating some flexibility, but this would require consensus to be actioned.

Longevity is another potential issue of smart contracts. Coding smart contracts today to be executed in many years (i.e. wills or futures) is a challenge, particularly when external information sources may no longer exist [16]. In addition, cryptocurrencies are currently extremely volatile with respect to value and exchange rates against fiat currencies [26]. Ethereum, running on the Bitcoin Blockchain, is the most widely used smart contracts platform [37]. Like the Bitcoin Blockchain, Ethereum works on a Proof-of-Work protocol. Execution fees (called 'gas' and paid in Ether by the user) give incentives to miners for participating in the network. Users set the price they are willing to pay for their code to be executed and miners accept to execute the code based on that price. Execution fees deter adversaries from bombarding the network with time-consuming computations resulting in denial-of-service. While it is not impossible to do this, it is not economically viable because the gas associated with such an act would make it uneconomical [37]. One of the newest smart contracts platforms in development is NEO that proposes to provide solutions to throughput and latency, interoperability and be resistant to quantum attacks [38].

3. Findings from the systematic literature review

Three research questions were devised for this research: (1) Where is the research currently focused on application of distributed ledger technology in the built environment?; (2) To what extent is the socio-technical system of distributed ledger technology considered in the current body of research?; and (3): What are the biggest challenges the built environment is facing in implementation of distributed ledger technology? These questions were answered using a systematic literature review while adopting a socio-technical system design (STSD) approach. STSD is an approach to design that considers human, social and organisational factors, as well as technical factors in the design of organisational systems" [39, p. 4]. In addition to identifying the application of blockchain in the built environment, an emergent framework summarising the challenges and opportunities from multiple dimensions (social, technical and political) was developed.

From the initial searches in three databases (Scopus, ScienceDirect and Web of Science), 534 papers were returned. After removal of duplicates and application of inclusion and exclusion criteria within the databases, 131 papers remained. Abstracts for these papers were reviewed and 32 selected for review. In addition, further searches were conducted in Google Scholar following a more traditional route and an additional 21 papers were added resulting in 53 papers being reviewed.

Seven categories of blockchain applications in the built environment were identified: smart energy; smart cities and the sharing economy; smart government; smart homes; intelligent transport; Building Information Modelling (BIM) and construction management; and business models and organisational structures. The distribution of applications within the papers reviewed (Table. 1) demonstrates how quickly the energy industry has embraced distributed ledger technologies. Most of the papers in this category provide some element of prototyping or proof-of-concept demonstrating that the research community is developing cutting-edge technologies to exploit it.

Blockchain discussions in conjunction to BIM and construction management were found in 9 papers. However, these papers mainly provide a number of hypothetical use cases for DLT in construction but are lacking in empirical research to support those hypotheses.

Table 1. Categories of blockchain applications in the built environment

Category	No. of papers	References
Smart Energy	19	[12], [40], [49]–[57], [41]–[48]
Smart Cities & the Sharing Economy	6	[28], [58]–[62]
Smart Government	7	[21], [35], [63]–[66]
Smart Home	4	[67]–[70]
Intelligent Transport	5	[71]–[75]
Building Information Modelling (BIM) & Construction Management	9	[1], [3], [7], [8], [15], [16], [33], [76], [77]
Business Models & Organisational Structures	5	[25], [34], [35], [78], [79]

DLT in smart energy is changing the energy market by opening it up to allow individual homeowners who produce their own renewable energy the opportunity to trade with Major Power Producers (MPPs) through the smart grid and/or directly with their neighbours through the use of DLTs and microgrids. These prosumers generate competition in the energy market by offering alternative energy choices, which, as a side effect, is encouraging proliferation of renewable energies. Moreover, they are supporting demand response management through offering additional sources of energy that were not available previously. Different models and architectures have been proposed for the implementation of blockchain depending on the aims and objectives of the research for smart energy ranging from implementation of new cryptocurrencies and tokenisation models as incentives to trade or as currency for energy (i.e. NRGCoin) [48], through resource management using serious gaming [55], to development of end-user mobile applications integrated with DLT to make the technology more user-friendly for the general public [53].

Closely linked to smart energy are smart cities, smart homes and smart government. These concepts are not new per se but they are constantly under development as technologies evolve and understanding and acceptance of these technologies proliferates throughout society. A key concern across these areas is the security and privacy of data; something that DLT addresses in some respects but not entirely. Any data uploaded to a blockchain is considered to be immutable (unchangeable and everlasting) which removes people's right to be forgotten [80] but alternative approaches to address this concern are being considered, particularly in smart government. For example, government records can be stored off the blockchain but pointers that they exist and where to find them are put onto the blockchain. Key issues raised with regards smart government are interoperability, longevity, accessibility and balance of power [21], [63]. Interoperability is important as records produced today should be accessible and in the right format for many years into the future. While internet connectivity, both high-speed broadband and mobile networks, has advanced significantly in recent years, there still remains a large portion of the population without reasonable connectivity – only one in seven people has access to the internet in the world's least developed countries [81]. Central governance is inherent in society and blockchain technology aims to disrupt that entirely whether it be through revolutionising the finance industry by removing the need for banks or through changing the role of governments [21], [82]. Organisations and roles within them will change with the introduction of wholly automated and semi-automated organisations [16]. Corporate hierarchies will become much flatter and many roles will disappear entirely with new ones coming into being.

Also residing under the umbrella of smart cities is intelligent transport. This is already in operation in many major cities and arterial roads throughout countries, for example, through traffic calming and route variations to avoid congestion and improve air quality. Like in smart energy, blockchain technology and innovative technology companies (e.g. La'zooz) are opening up markets in the transport industry where vehicle owners now have a platform on which to monetise their idle vehicles or offer ride sharing to people travelling in the same direction [75]. This crosses over into the sharing economy where communities are able to devise and utilise proprietary value systems for sharing information, products and services resulting in a more user-led and user-empowered society [47]. The challenges and the opportunities facing the identified blockchain applications specific to the built environment are summarised and discussed in the next section. More generic challenges and opportunities have not been discussed here.

4. Challenges facing adoption of blockchain technology in the built environment

Ensuring the legitimacy of data uploaded to the blockchain about a good or service is important. Means and rules for ***authentication of data*** need to be developed to ensure predefined conditions are met to reduce the probability of fraudulent activity throughout the supply chain [34].

Sufficient ***bandwidth and capacity*** are required for stability of the system [80], [83]. Reliable internet connectivity is required, or means of storing data offline until connectivity can be achieved to ensure data can be uploaded to the blockchain in a timely manner. For example, elements of the supply chain delivery system could cause problems for instance when a warehouse lacks internet connectivity [83].

Coding of smart contracts is key, where a badly programmed contract could be disastrous [51]. Human error could also pose problems with creating smart contracts in construction given that the code is only as good as the person writing it [36].

There is a negative stigma surrounding Bitcoin and, therefore, blockchain technology with regards ***criminal activity and the Dark Net*** [26], [80]. Cryptocurrencies could be used in construction projects to finance criminal activity through money laundering and corruption [1].

One of the biggest social and environmental concerns regarding blockchain technology is its ***energy consumption*** required to satisfy the Proof-of-Work protocol resulting in excessive requirements of computational and electrical power [51], [80]. Excessive energy usage has massive impacts on the built environment with regards CO_2 levels, current grid capacities, and peak demand management [51]. Any application in the construction industry where cryptocurrencies and tokenisation are proposed is likely to have a long lead time given the extreme ***exchange rate volatility*** seen with cryptocurrencies today [84]. For example, in 2017, Bitcoin fluctuated between $1,000 on New Year's Day to almost $20,000 on 17th December only to drop by 30% in the days following [85].

Interoperability, currently considered a key challenge in construction [33], will also be a key issue for blockchain where requirements differ from one application to another. A blockchain access layer is proposed to integrate different blockchains and offer application-specific functions [28], [80]. With lack of regulation surrounding blockchain technology, it is important that risks and responsibilities be set out in a written contract.

The key ***legal concerns*** include: allocation of risk, scope of obligations, scope for variations in the contract, grounds for termination of a contract, standardisation of processes and terminology, ownership/intellectual property rights, confidentiality/data protection, corruption/bribery, appointment of a legally-recognised entity to bear responsibility of automated actions [86]. Consideration should also be given to the "parties' rights to claim additional costs, time and, in the case of NEC contracts, compensation events" along with "[w]ho bears the risk should they result in delays or increased costs to the project?" Finally, what happens to the blockchain in the event of insolvency and/or termination? [87]. Dorri *et al* [67] highlight seven types of ***malicious attacks*** as follows: 1) accessibility threats; 2) anonymity threats; 3) authentication and access control threats; 4) Denial-of-Service (DoS) attacks; 5) modification attacks; 6) dropping attacks; and 7) appending attacks. Eyal [88] discusses block withholding attacks in mining pools. A 51% attack is where a miner tries to take control of the system by controlling more than half of the network and revising transaction history or preventing new transactions from being validated [28], [56], [67], [89]. Other types of attacks exist where a miner or a pool of miners attempt to control and compromise the system (see for example, [37]). Personally identifiable data or the potential to gain financially (i.e. theft of cryptocurrency) from a smart city is attractive to a potential attacker [68].

There is agreement with regards ***readiness for adoption*** of DLT in the construction industry particularly with it not being ready for the level of collaboration and information exchange required for it to be successful [1], [76]. The construction industry is typically slow at adopting new technologies [1] and historically ***resistant to change*** which could result in less benefits being realised by the implementation of DLT [84]. There is a current lack of ***sufficiently skilled people*** trained in blockchain technology [80]. Even organisations looking to embrace BIM struggle to recruit suitably skilled personnel [76]. The ***technological state of the construction industry*** is not sufficiently digitised to take full advantage of DLT and implementation of this new technology is likely to be costly [84].

5. Opportunities from adoption of blockchain technology in the built environment

Lack of trust and limited collaboration between parties is one of the frequent issues cited in the construction sector that is also affecting BIM adoption [90]. Due to data becoming more transparent, ***increased collaboration and trust*** between parties is likely and data will be shared more freely [87]. Tokenisation through cryptocurrencies (i.e. ConstructCoin) could encourage data sharing where contributors are rewarded for information they generate and could gain more if/when that data is bought by a client [84]. Reputation ratings on DLT is a potential booster for increasing collaboration throughout the supply chain, for example, promoting strategic partnerships [76]. Particularly where cryptocurrencies are involved, ***cross-border trade*** can be made easier without the need for international exchange rates and border controls. However, this has the potential to interfere with the current international economic order [65]. Where [sub-]contractors are based in countries other than where the client/project is based, blockchain with suitable cryptocurrencies can mitigate exchange rates and fluctuations in currencies [1].

DLT can be used for ***digital twinning*** of built assets providing valuable detailed information throughout the lifecycle of an asset where all information related to that asset from inception to decommissioning is recorded and available for facilities management, buyers/sellers, surveyors, demolition teams etc. [36]. This is in line with other technological advancements such as IoT, drone and real-time data capture technologies that support digital twinning and improving ***building operation*** [84]. The distributed nature of blockchain technology removes the requirement for intermediaries and provides a guarantee of execution of transactions [47]. Smart contracts can be used to automate payments upon successful inspection of a completed task by a subcontractor through if/then commands and payments can be made in cryptocurrency further speeding up the process [84].

Disintermediation means clients will have more control over their projects with regards costs, time and scope [91]. Blockchain can also promote ***efficiency*** in international business-to-business trade and increases access to trade and supply chain finance [80]. In addition, automation of activities within construction leads to reallocation of resources reducing administration activities as well as transferring risk and reducing time and costs [76]. ***Faster processes*** through streamlining verification will reduce the need for multiple verifications by different participants where the relevant information is stored on the blockchain, particularly in functions such as planning and design of construction projects [36]. Costs for intermediaries is eliminated ***lowering transaction costs*** [47], [80]. Efficiency is increased in international payment systems; friction and costs of property registration is reduced [80] resulting in lower costs for the client [1].

While not technically ***immutable***, blockchain technology is considered as such due to the difficulties involved in changing transactions and/or blocks already uploaded to the blockchain [47]. In construction, a historical record is essential for activities such as "timestamping acts or transactions, Multisignature Transactions, Smart contracts…and Smart Oracles which are real work depositories of information to be used in conjunction with smart contracts" [15, p. 642]. ***Proof of ownership and rights*** issues can be addressed using blockchain technology due to the advantages of cost, speed and double-entry bookkeeping in terms of providing proof-of-ownership for many different assets from real estate to vehicles to art and stocks and bonds [30]. In construction, where ownership and rights are a legal issue [15], and in the event of a single [shared-access] BIM model, ownership and rights (i.e. responsibilities, liabilities, intellectual property rights) can be made explicit in the blockchain leading to better trust between parties [77].

Proof-of-Provenance will be much easier to obtain through DLT [92]. DLT has the potential to provide better record keeping through a traceable, seemingly immutable ledger allowing investigators to immediately pinpoint where problems occurred in the supply chain and possibly prevent problems such as Grenfell Tower from taking place as people are held more accountable for their actions through increased transparency. DLT will allow tracking of goods and services throughout the supply chain offering near real-time data as well as provenance history [93].

A ***reduction in human error*** will be seen through the automation of tasks, the use of sensors and/or artificial intelligence and smart contracts. Certification and/or verification of coding through DLT would provide quality assurance for construction projects [36].

Through ***smart contracts,*** many tasks can be automated and entire legal contracts can be written into code changing how organisations operate, speeding up payment of funds embedded into smart contracts, help to reduce disputes etc. [2], [32], [33], [35]. Construction is notorious for its number of disputes, particularly regarding payments. Blockchain could operate as a "trustworthy contract administrator by introducing an error-free process based on which the contracts would be both built and monitored" [84].

Its nascent nature means the technology will advance significantly in coming years and it is likely that it will evolve into a solution that puts ***societal benefits*** at the centre rather than the technology [82]. Smart buildings and smart contracts in conjunction can add benefit to society through extending asset lives and ensuring timely repairs are scheduled based on performance, occupant behaviour, energy requirements though quantitative data analysis ensuring continued learning and improvement [76].

Blockchains provide ***traceability and auditability*** through an "immutable" historic record [21]. Koutsogiannis and Berntsen [84] believe it can "add more transparency to every type of agreement and transaction in a construction project". Supply chains become more visible and allow real-time tracking of materials to a construction site providing a history from origin [94]. Finally, blockchain indirectly contributes to ***improved workflow*** through contributing to creation of more open project environments**.** This opportunity is linked to the role blockchain can play in increasing collaboration and transparency and improving accountability and project control. BIM technology uptake may increase as the need for peer-to-peer information sharing increases [84]. If these peer-to-peer exchanges are within workflows supported with smart contracts, the waiting time for 'sign-off' would be eliminated as *input* for the completed task would be followed by an automatic *forward* to continue to work [95]. This will positively impact on the schedule performance of construction projects.

4.3 Emergent Framework

The emergent framework for blockchain implementation within the built environment is depicted in Fig. 1a. It combines three interconnected dimensions, namely the political, social and technical dimensions. The framework is overlaid with the challenges and opportunities (Fig. 1b,c). Challenges and opportunities will reside within one dimension, across two, or at the overlap of all three in the centre. The extensive list of challenges and opportunities identified within this review were all embedded within the framework according to their classification (technical, social and political). The framework's dimensions are also used to identify the agents pertinent to each challenge and opportunity who may play a role in either facilitating or impeding the adoption of DLT in the built environment.

The ***technical*** dimension is concerned with the implementation of the technical architecture of DLT. Many of the challenges highlighted at this stage in the technology's development (e.g. throughput, latency and interoperability) are likely to be addressed over time with updates and as new products become available. For example, NEO is an example of a DLT that is already attempting to address many of the technical challenges. Agents involved in this dimension include but are not limited to developers, system architects and nodes (computers running on the P2P Network).

The ***social*** dimension is associated with the impact DLT will have on the society and is broad reaching in terms of the agents associated, which include, but are not limited to individual users, social groups and organisations operating within the built environment generally and construction projects particularly. This dimension addresses how the technology will integrate into the real work and represent the social system where benefits of DLT adoption will occur and the agents who will benefit from its adoption. At this early stage of the development of the framework, an 'holistic social' dimension is adopted as the focus is on exploring the opportunities and challenges for the whole built environment. For the future development of the framework and to improve its applicability to project level, a consideration will be made to add a 'process' dimension that is now inherently embedded within the social dimension.

The ***political*** dimension represents the environment in which DLT will be established and the interactions /influences that agents from the political field exert on DLT adoption. This includes establishing robust regulations, laws and compliance for implementation of DLT in the built environment and the construction industry. Agents for this dimension include, but are not limited to governments, authorities, DLT councils (i.e. those with the power over how DLTs function) and other organisations/individuals in governance positions.

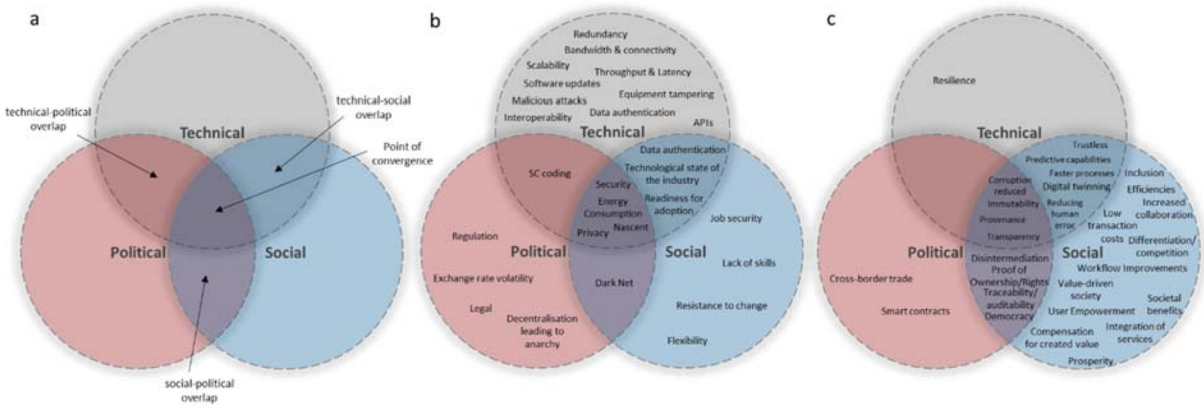

Fig. 1: (a) emergent framework for blockchain applications in the construction industry; (b) framework overlaid with challenges; (c) framework overlaid with opportunities

6. Conclusions

This paper aimed to (1) capture the current state-of-the-art of DLT research for built environment applications; (2) understand the challenges and opportunities associated with the adoption of DLT in the built environment; (3) to develop an emergent framework for DLT adoption in the built environment. A systematic literature review driven by a socio-technical system design (STSD) approach was used to address the first two aims. An inductive research approach underpinned the inquiry process and culminated with the development of the emergent multi-dimensional framework.

DLT applications were found in several areas including: smart energy; smart cities and the sharing economy; smart government; smart homes; intelligent transport; Building Information Modelling (BIM) and construction management; and business models and organizational structures. Within the built environment, most applications are focused on the operation phase of assets. DLT empirical evidence and technological developments exist across most of these areas with the exception of BIM and construction management where research is either limited to proposing hypothetical case studies or focused on smart contracts. An extensive set of challenges and opportunities facing the adoption of DLT in the built environment were identified and explained.

An emergent multidimensional framework for blockchain adoption within the built environment was developed. The framework combined three interconnected dimensions consisting of the political, social and technical dimensions. The framework was overlaid with an extensive set of the challenges and opportunities facing the implementation of DLT in the built environment. This framework represents an important baseline for DLT adoption in the built environment. Field researchers can utilize it as a point of departure for a wide range of investigations from political, social, and technical perspectives.

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