ASSOCIATION OF RESEARCHERS IN CONSTRUCTION MANAGEMENT

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Workshop Proceedings

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

This workshop was scheduled to take place on 25th March 2020 in Newcastle-Upon-Tyne, United Kingdom, but was cancelled as a result of Covid-19 lockdown measures. While the workshop did not take place, the papers have been published to allow the researchers to share their contributions to the field.

Workshop Conveners and Proceedings Editors:
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Preface

The architecture, engineering, construction and operations (AECO) industry is going through a period of digital transformation with many new technologies, processes and practices improving day-to-day operations at pace. Distributed ledger technology (DLT), (e.g. Blockchain, the underpinning technology for cryptocurrency Bitcoin) is suggested as a key technology to support this digital transformation due to its inherent characteristics to redefine the trust relationship between parties leading to better collaboration and information sharing. DLT offers decentralisation, privacy, anonymity, immutability, traceability and transparency among others. When coupled with smart contracts, it offers a powerful tool to support solutions to the industry's many challenges such as low productivity, poor procurement models, fragmentation, and the need for payment and regulatory reform.

DLT is still at a nascent stage in its development. This workshop was proposed to support doctoral researchers in broadening their knowledge and understanding of the application of DLT in AECO through sharing their research and networking with their peers.

The papers contained within these proceedings underwent full peer-review by the editorial committee.

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Professor Mohamad Kassem
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ARCOM Doctoral Workshop

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

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Crypto-Economic Incentives in the Construction Industry

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1 Problem

Construction is one of the largest industry sectors in the world both from an economic and society perspective. With current challenges of population growth, migrations into cities, and climate change, it is likely to grow in importance. Nevertheless, it faces problems related to productivity, sustainability, and transparency. Many of these problems can be related to fragmentation of a very complex industry with numerous actors involved. This structure was described with three dimensions of fragmentation: horizontal, vertical and longitudinal fragmentation as depicted in Figure 1 [1,2]. Vertical fragmentation occurs between project phases [3]. Each phase has a different set of stakeholders, decision-makers, and values. This creates displaced agency – also called 'broken agency' - where involved parties will engage in self-interested behavior and pass costs off to others in the supply chain in a subsequent phase [4]. Horizontal fragmentation occurs in the trade-by-trade competitive bidding environment of traditional project deliveries. Because it is difficult to cross-subsidize changes across trades, globally-optimal innovations cannot compete with traditional solutions that are more cost-effective from the perspective of a particular building element or phase [5]. Longitudinal fragmentation occurs when project teams disband at the end of projects and are selected on future projects by competitive bidding. They are thus unlikely to work with the same set of partner firms on future projects. Consequently, team members lose tacit knowledge about how to work together effectively [6] and organizations are unable to build long-term trusting relationships across firm boundaries.

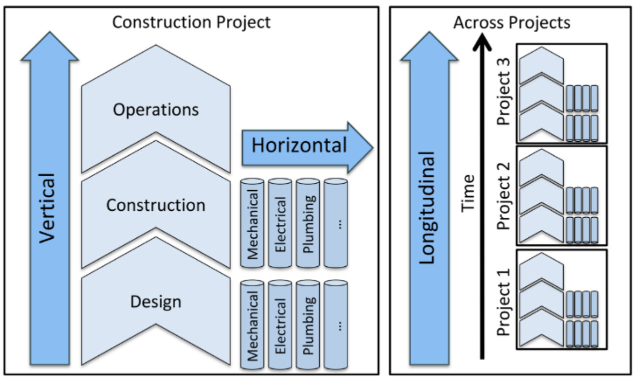

Figure 1. Three degrees of fragmentation in the construction industry (Source: [2], adapted from [1,3]).

Overcoming these different levels of fragmentation through more integration of the construction process seems to be one of the main hurdles in becoming a better and more efficient industry. For that, of course various approaches are possible. Next to managerial concepts that try to achieve more integration through new multi-party construction arrangements, LEAN or agile methods, also technology is seen by many as very promising to achieve more integration. Especially Building Information Modelling (BIM) promises potential for more collaboration across stakeholders and is currently perceived as the baseline for information technology and industry 4.0 awareness in construction. Having said that, the integration of BIM as a systemic innovation poses again major challenges in the adoption due to the prevailing industry structure [7,8]. Next to the general difficulties with innovation diffusion, it was found that the adoption of BIM has lagged as project teams struggle with trust and liability concerns associated with sharing information on the project [9]. It seems that the industry structure and technology cannot be treated in isolation and digital technologies must be integrated with adaptions in management, contracts and collaboration forms [10]. In other words, technology implementation should be treated as means to an end to address the fundamental problems of the construction industry, and not the other way round [11]. Interestingly, one recent technology potentially enables better integration between these two worlds: distributed ledger technology (DLT), with blockchain as the best-known sub-type of DLT.

2 The Promise of Crypto-Economic Design

DLT offers an opportunity to increase trust and collaboration within the construction industry by integrating digital information with management and contracts. It can help making the construction process more efficient, transparent, and accountable between all involved participants [12]. Various use cases for blockchain in construction have already been proposed [13]. The main idea of blockchain is to track transactions over time and store them in a trustworthy, distributed manner. The users in the peer-to-peer network can trust the system to ensure valid transactions, instead of trusting intermediaries or other network users. One of the most promising features built on these distributed networks are *smart contracts*, which are code protocols running on top of the protocol layer. They allow for distributed workflow automation and the creation of so-called *tokens* as containers for different kinds of value, such as utilities, securities, currencies, or other [14]. With these tokens, incentive systems can be built to influence the human behavior when interacting with blockchain based digital processes.

> *"Blockchain gives us programmable money. When you can program money, you can program incentives, and when you can program incentives you can program people"* - Mike Goldin

In fact, the use of smart contracts and tokens for crypto-economic incentives could be one of the major applications for the very fragmented construction industry. Such incentive systems can be targeted towards various goals in different contexts. In the example of Finance4.0, Dapp [14] describes a crypto-economic system based on the proposal of Kleineberg and Helbing [15] to incentivize sustainable behaviour through the use of cryptoeconomics by focusing on a multidimensional payment systems, instead of the one dimensional monetary system we have nowadays. Summarized, DLT offers opportunities to combine various dimensions of our socio-economic system nowadays, using financial or non-financial incentives to improve (business) processes by steering people's behaviour in a bottom-up, decentralized way. This particular application of DLT might help to create a new economic paradigm, potentially reducing fragmentation in construction by fostering more trust and collaboration across the life cycle. Having said that, designing incentive systems is not an easy task and could lead to many unforeseen and unwelcome secondary effects. There is emerging research fields of "crypto-economic system design" and "token engineering" [16] investigating possibilities to guide humans through smart contract based incentives.

3 Motivation in Construction

Despite of the increasing digitalization, technology was so far not been able to achieve the targeted productivity, transparency, and sustainability in construction that would be needed in the context of current challenges like climate change, resource shortages, or mass migrations into cities. One possible explanation is that part of the industry problems are linked to organizational and people related issues, rather than process and technology issues. New and innovative ways need to be explored to tackle the challenge of integrating technology and processes with the construction-industry, -organizations, and -workforce. DLT offers an opportunity to achieve this through new, decentralized incentive systems, building on the availability of data with increasing level of digitalization. An opportunity that should be also explored in the context of construction.

4 Research Objective

Therefore, the goal of this Ph.D. research is to investigate the potential of DLT and crypto-economic incentive design to overcome various problems related to the fragmented and complex context of construction. The hypothesis is that existing incentive structures in construction could be refined and adjusted through newly introduced incentives structures enabled by DLT. Acknowledging that there is a large number of potential application areas, the selected use cases for now are 1) incentives for data collection during design and construction, and 2) incentives to enhance collaboration in contractual arrangements. Both cases face issues regarding misaligned incentives, resulting in selfish behavior of individual participants instead of collaboration towards the overall project success.

5 Expected Outcome

The research is expected to give first insights to what extend the hypothesis on the potential alignment of fragmentation in construction, with the decentralized and bottom-up approach towards more collaboration through crypto-economic incentive design, holds true. Given the complexity in designing such incentive systems and the size of the construction industry, more and interdisciplinary research e.g. with social science and system engineering will be needed in the future to fully understand the underlying dynamics. Nevertheless, the theoretical assessment of the use cases together with some initial prototypes should demonstrate to researchers and practitioners the potential future opportunities of crypto-economic incentives as an additional possibility towards better integration in the currently fragmented construction industry.

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The potential of Distributed Ledger Technologies to improve product traceability assurance in the construction industry.

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ABSTRACT: Product traceability in the Architecture, Engineering, Construction and Operations sector (AECO) is a complex challenge that remains largely unsolved. Even in advanced economies it is frequently not known which specific construction products are installed in a given built asset. This leads to downstream operational, financial and safety issues throughout the asset lifecycle. Nevertheless, the fragmented and commonly adversarial nature of the AECO supply chain conspires to inhibit product traceability despite mounting external pressures to improve it. Following a critical review and synthesis of the traceability literature, one area of technology that is widely believed to have the potential to improve traceability outcomes is Distributed Ledger Technology (DLT), yet some critical questions of its ability to improve product-level traceability remain unanswered. One such question is if it has the ability to help determine the overall accuracy and reliability of traceability information or whether it can improve the link between digital information about a product and the physical product itself.

1 Introduction

Supply chains in the Architecture, Engineering, Construction and Operations sector (AECO) and others, are striving to be more responsive and resilient in pursuit of higher gains. Simultaneously pressure is mounting for them to act transparently and tackle a raft of contentious issues such as counterfeiting and unethical sourcing [1]. This trend, along with growing safety, quality and regulatory concerns, is inducing the development of traceability practice across the board [2,3]. Although an apparent dearth of sufficiently potent drivers to catalyse the wholesale adoption of traceability in AECO renders it far behind comparators. Simultaneously, the notion of *Industry 4.0* is sweeping through the manufacturing industries of advanced economies proliferating innovative technologies and business models in the quest for global relevancy and competitive advantage. The development of *traceability*, a practice within the broader area of Information Management, is foundational to the success of many Industry 4.0 innovations due to the increasingly inherent dependence on the creation and flow of information in these complex sociotechnical systems. One nascent area of technology in the emerging AECO, Industry 4.0 and Computer Science literature, Distributed Ledger Technology (DLT), is widely believed to hold the potential for radical advances in traceability in the context of supply chains. However, solutions to two fundamental problems are unresolved, undermining the potential efficacy of DLT in traceability applications above existing alternatives.

This paper examines the concept of traceability through the lens of stakeholder and information management theory before contrasting current traceability practice in AECO with that of comparatively mature sectors. Thirdly the emerging DLT literature is explored with respect to traceability, in order to identify key propositions made in support of its potential utility in construction product traceability solutions. The current challenges are highlighted leading to the synthesis of several research problems for future work.

2 The Concept and Theoretical Underpinnings of Traceability

Despite a broad use of the term 'traceability' in the business lexicon, Olsen and Borit postulated that the literature lacked a non-recursive, universally applicable definition. They posit that it is: *"the ability to access any or all information relating to that which is under consideration, throughout its entire life cycle, by means of recorded identifications."* [4, p.148] The traceability literature spans computer science, quality management, supply chain management and several others. In this paper, traceability is considered in the context of supply chain management and quality management. From this broadly accepted definition, it is evident that traceability concerns the flow of information about a defined artefact between stakeholders. These stakeholders exist in varying arrangements, both within organisational boundaries and across them.

Broadly speaking, a Traceability System (TS) must contain four mechanisms. The following are synthesised from [3–6]:

- A mechanism for *identifying entities* – the most common term for this is a Traceable Resource Unit.
- A mechanism for *documenting transformations* – inputs consumed, outputs generated and the process in between.

- A mechanism for *recording attributes of entities* – facts about an entity that are not observable, e.g. its custody at any point or its data of manufacture.
- A mechanism for *retrieving trace information* – the ability to access the information.

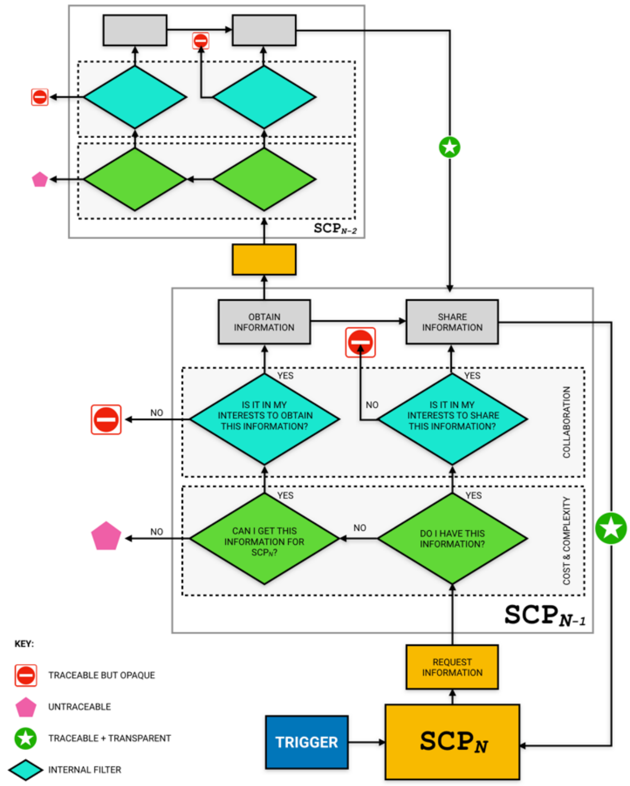
The literature abounds with barriers to traceability in the areas of *cost* and *complexity*, but a third area, *collaboration*, in particular stands out. This refers to the lack of motivation to participate in TSs. Even in contexts where a TS is forced upon Supply Chain Participants (SCPs) (as is typical in the agriculture and automotive industries), control over information input ultimately resides with the individual SCPs [7]. Even Walmart's lauded pilot traceability system *"depends on cooperative partners agreeing on what information to contribute"* [8]. The reasons for this are several, but in particular three dynamics should be considered: first, the SCP responsible for creating / sharing traceability data may not derive any direct benefit from it. Secondly, some SCPs see the types of information they need to provide to others as commercially sensitive and therefore a potential benefit to their competitors. Thirdly, in some instances information provided by an SCP to another stakeholder may expose its creator to risk in the form of liability insofar as the provision of traceability information may be construed as a liability-transfer mechanism (if an SCP can show that the fault for an given error exists with an upstream supplier, they can transfer the liability to that supplier) [6]. In all models of TS, the quality of traceability information falls upon the shoulders of individual stakeholders, as previously noted: "*traceability is based on systematic recordings and record–keeping, there is no guarantee that the recordings are true. Both error and fraud may lead to untrue claims"* [4, p.148].

2.1 *A Theoretical Framework and Exposition of the Concept of Traceability*

These dynamics are modelled in figure 1 showing a hypothetical Trace Initiative (TIN) scenario in which one Supply Chain Participant (SCP_N) requires access to information from another (SCP_{N-1}) who, in turn, may request information from additional upstream SCPs (e.g. suppliers) if they do not possess it internally. The analysis of traceability is aptly informed by two bodies of theory: Stakeholder Theory, concerning stakeholder actions and agency; and Information Theory, concerning the nature of traceability information itself (with particular reference to information assurance).

Figure 1 shows that at a micro-level, SCPs may not be incentivised toward discretionary, spirited and honest participation in TINs. They may in fact arguably possess sufficient incentive to actively disrupt TINs that potentially expose them to risk. At a macro-level, if the SCP does not know which information may expose them to increased risk or disadvantage in the future – they may abandon meaningful TS participation altogether, undermining the entire TS in the process. This behaviour aligns with the self-serving motives portrayed in agency theory [9].

Figure 1. A simple trace scenario demonstrating the stakeholder dynamics



To delve further into the dynamics at play in a TIN, from the aforementioned bodies of theory, the generally accepted definition of traceability is dissected into segments in order to identify the logical requirements to achieve traceability in the context of the hypothetical TIN proposed in Figure 1. An overview of these components and requirements are shown in Table 1.

Table 1. Further logical requirements to achieve traceability

Component of Definition	Logical Requirement	ID
"the ability to access"	Ability to access and interpret information	T1
"any or all information relating to"	Defined information requirements	T2
"that which is under consideration,"	Rationale for query	T3
	A trace target (focal object)	T4
"throughout its entire life cycle,"	Scope-breadth: Internal/external	T5
	Scope-direction: Back / forward / through	T6
	Scope-timeframe: Past / present lifecycle stages	T7
"by means of recorded"	Preserved or shared information	T8e
	Captured information	T8d
"identifications"	Codified observations (data)	T8c
	Observable phenomena (events)	T8b
	Judgement of potential utility of captured information	T8a

2.2 *A logical exposition of the traceability process*

The following is an explanation of the sequence of events within the trace initiative demonstrated in Figure 1 from the perspective of a focal SCP, the trace initiator. This exposition uses the components of traceability from [4] to provide a detailed understanding of the informational and behavioural requirements to achieve traceability in a supply chain. This understanding provides the context within which emerging AECO and DLT traceability literature is examined to identify gaps in the knowledge and research opportunities.

T1 – To complete a trace, the trace initiator (SCP_N) must be able to access the required information (T2) which satisfies their query (T3) about a given subject of concern (T4) and interpret it as satisfactory (therefore consider it 'traceable'). The information must be preserved (T8b) internally or externally. If external, it is subject to the internal 'self–interest' filter of SCP_{N-1}.

T2 – The types of information concerning the Trace Target (T4) could include transactions / transformations / movements / custody or contextual attributes and can span across three potential 'dimensions' (T5 T7). This must have been captured and preserved (T8e–T8f) by the $SCPs_{[N-N]}$).

T3 – A trace objective is the goal of retrieving specific information (T2) from the relevant SCP (T5–T7) concerning a subject of concern (T4). This is normally in response to an internal or external 'trigger', e.g. a request from an external agency to SCP_N. Whilst SCP_N may have a specific objective, it may not be able to control the effectiveness of the trace, since it is subject to the control that other SCPs have over access (T1) and all SCPs are limited by the fulfilment of requirements T4 – T8b. The likely agreed objectives within a given system must be agreed before, since they dictate the potentially valuable data (T8a) to be captured throughout the supply chain (T5 – T7) and the lifecycle (T2) of the Trace Target (T4).

T4 – The Trace Target is the item about which information (T2) is sought, i.e. a focal product. The Trace Target and the Information Requirements (T2) are dictated by the objective of the Trace Initiator and nature of the trigger. It requires that SCPs have an understanding of what the target is, e.g. a TRU [10].

T5, T6, T7 – The information requirements (T2) about the trace target (T4) may lead the Trace Initiator to consult information sources in their own organization or that of external participants, upstream (towards the ultimate source) or downstream (towards the ultimate customer) in the supply chain. The Trace Initiative could also concern current events or historical events. In both instances, the information must: exist (T8d–T8e), be understandable (T8c) and be made accessible to the Trace Initiator (T1).

T8e – The crux of traceability is the recorded identifications which means capturing valuable and useful data (T8a – T8d) and preserving / sharing it as required (T8e and T1) between SCPs.

T8d – The paradigm of the SCPs and likely objectives of potential trace initiatives will affect the amount of 'recorded identifications' made, due to the cost implication of gathering and storing more voluminous amounts of traceability (granularity).

T8c, T8b – Before information is captured and preserved, it must first be observed (T8b – by an observer or sensor). Observability of a datum point stipulates that it should be explicit (something which can be easily expressed), as opposed to tacit (something which is not easily expressed) and which cannot be stored in information systems [11]. If it is explicit (defined as *'highly detailed, formal and systematic'* [12]), it is codifiable as a datum point (T8d) and can therefore be captured (T8e).

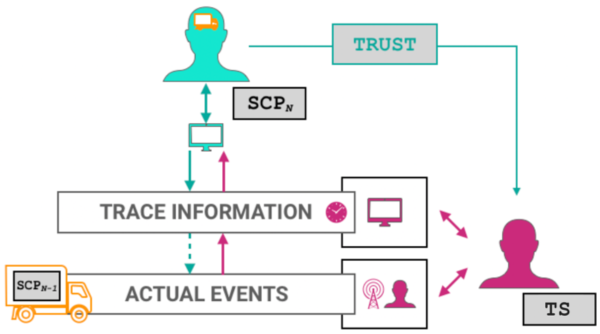
T8a – Given the variety of potentially key information that is created on a continual basis in almost any scenario, a value judgement must be made on what information is pertinent to potential traceability objectives (T3), considering the potential Trace Target (T4). For example, a clear brief to a site manager to 'monitor the weather for the concrete pour' in a construction site improves the site manager's ability to notice the weather and take note, since it is inferred that weather conditions are of potential consequence. An alternative to pure human observation, would be to deploy sensors for the purpose of capturing meteorological data on site, and cross-reference this with other records to ensure the timeframes aligned.

2.3 *Information Assurance Considerations*

It has been noted that traceability information does not inherently equate to accurate or reliable information [3,4]. This is of critical importance and is overlooked by many authors – who infer precisely the opposite. Borit and Santos [13, p.15] summarise: *"there is no guarantee that the recordings are true or complete, as both error and fraud can lead to false claims […] There is a clear need to verify these claims, and in this area, analytical methods and instruments play a crucial role."*

The trust in information is depicted below in Figure 2, where SCP_N wants to find out where his purchased product is from (SCP_{N-1}). SCP_N queries his TS and receives trace information back. As he did not physically observe the lorry, he has no way of verifying that the information is an accurate depiction of events. His trusts in the TS, which normally constitutes humans (shown earlier to be vulnerable to error or fraud) and machines, to provide an accurate depiction of the real events. Thus the accuracy and security of the information retrieved from a TS is crucial to reliable traceability [14] and supply chain and quality management in general [15]. This link between a physical item and its informational representation in a TS may be referred to as the Cyber Physical Bond (CPB). Examples of the potential weakness of the CPB link from the literature abound: Forged product certification paperwork [16]; tampered IoT sensors [17]; cloned RFID tags [18].

Figure 2: Trust in Traceability Information and the Cyber Physical Bond



3 Contrasting current AECO traceability practice with other sectors

The automotive, agriculture and pharmaceuticals sectors are seen to have developed a comparatively mature traceability practice [3,19]. Its development in the AECO sector, as with many areas of innovation [20,21], lags behind these industries [22,23]. Whilst some low–tech voluntary initiatives exist to encourage the responsible sourcing of raw materials such as timber [24–26], there is no industry–wide scheme to facilitate the traceability of construction products through their entire lifecycle [23]. The general state-of-the-art of product traceability in the sector is summarised by an industry spokesperson *"From government, down to small sub–contractors, we suffer from a shocking lack of data. Traceability technology exists, but we understand little about our supply chains below tier 1"* [27, p.6].

The very nature of the sector introduces barriers to being more proactive in this area; its significant degree of fragmentation, project–basis, separation of activities, poor information management and adversarial relationships [28–31]. These all conspire to further entrench information in silos that stifle traceability [4].

4 Traceability Drivers and Incentives

Despite the apparent inertia, several factors point to the increasing importance of improved product traceability in construction:

- $4.8 billion is spent each year by US building owners verifying operations and maintenance data for buildings. A further $613 million is spent to rekey the information into a different format or system [32].
- The incidence of counterfeit and fraudulent products in general is increasing globally (over $1 trillion annually in 2003 [33]); and a high proportion of construction projects become victims (almost a third, according to [19]).
- Significant issues in the transfer of product information in construction projects can directly and severely affect occupant safety [34].

Despite evidence of the growing need for improved traceability in AECO, its currently established initiatives (e.g. CARES, FSC) tend to entail a narrow focus on responsible sourcing, ostensibly concerning the extractive industries [26]. The comparator industries, however, demonstrate a plethora of drivers beyond this in three broad areas (legal, economic and social drivers) with application areas of traceability spanning the extremities of the supply chain. These include: regulatory compliance, product recall facilitation, fraud/security, quality and safety management, counterfeit prevention, business efficiency, inventory control, financial analytics, waste prevention, transparency, and the supporting of origin claims; to say nothing of emerging business models which are penetrating the psyche of these industries (discussed in section 4.2). The aforementioned application areas convey a sense of being a *push* or *pull* incentive, or both [1–3,13,35–45]. This is to say that businesses in comparator industries willingly engage in some application areas (pull), whilst in others they are forced (push) to do so by external agency, such as governmental bodies or pressure groups [2].

Whilst the majority of application areas seem to be driven by the self–interests of businesses (pull), Borit and Santos [13] note that, in general, regulatory compliance mechanisms tend to induce the initial application of traceability in a sector (push). Though these levers are yet to fully materialise in AECO, recent events may mean that the sector is forced to develop traceability systems by future regulation [23,34]. This external agency may catalyse progress in the industry, but the burden it places on a sector known for its backward relationship with technology could place substantial strain on existing sub-optimal information systems [46] with consequences for the resultant information assurance.

4.1 A Paradigm Shift in Traceability Objectives

Sterling *et al.* propose that traceability 'best–practice' delivers business benefits in the four areas of compliance, risk mitigation, market access, and operational efficiencies [47]. Charlebois *et al.* [45] along with [47] and [3] concur that a more proactive stance to traceability is beneficial, with the latter stating that *"adopting traceability for strictly compliance reasons can markedly limit the value that businesses derive from implementing traceability systems."* [3, p.396].

These and other more recent work denote a paradigmatic shift from an historic reactively orientated approach that has not sought out or exploited business opportunities beyond regulatory compliance towards a faster, more reliable and cost–effective approach to traceability designed to *"capture data proactively for use to commercial advantage"* [47]. This shift, from push to pull, can be analogised as a transition from a compliance centric 'must do' activity to an opportunistic 'can do' activity with incentives sufficiently attractive that SCPs voluntarily overcome the profusion of cost, complexity and collaboration barriers which bedevil TS adoption [2,6,48–50]. The new approach seeks to unlock new value streams and business benefits – as in the case of Amazon, a company labelled by many business commentators as predominantly a data company (as opposed to retail, its inaugural classification) due to the value it extracts from the collection and exploitation of data in new value propositions and data driven business enhancements [51,52]. This shift is in the spirit of observations made by Teece *et al.* over 20 years ago, who argued that *"knowledge, competence and related intangibles have emerged as the key drivers of competitive advantage in developed nations. This is not just because of the importance of knowledge itself, but because of the rapid expansion of goods and factor markets, leaving intangible assets as the main basis of competitive differentiation in many sectors"* [53, p.76]. Accordingly, Hartmann *et al.* [54] defined six types of data-driven business models which are anchored to the principle of the exploitation of information, alluding to the clear proliferation and maturation of the new paradigm.

4.2 Potential Development of Traceability in AECO

To envisage what such a shift in traceability in AECO could look like, one can examine the transformation underway in the manufacturing industries of developed economies; these are undergoing rapid digitalisation and innovation in a quest to remain competitive and relevant in the global marketplace [55–57]; rallying under the colloquial term of *Industry 4.0* [56,58]. The espoused benefits of the Industry 4.0 movement include more responsive and resilient supply chains, improved operational efficiency, enhanced customer value propositions, and reduced waste [58–60]. In some cases technology is enhancing the facilitation of existing approaches, in others it is catalysing the genesis of entirely new ones [61]. Far from being the mere overlaying of novel technologies on existing practices, entirely new business models are emerging based on the innovations. Three such innovations include: servitisation, cyber physical systems, and digital twinning [56,62–69]. These concepts are also discussed in the emerging AECO literature, with a major underlying driver of improved productivity in a sector commonly lambasted for its poor performance in this area. Product traceability, spanning each stage of the supply chain and throughout the full lifecycle of a product, is a key enabler of these innovations. It would also directly lead to financial and social benefits by solving the three problems identified in section 4 whilst contributing to improvements in counterfeit elimination and environmental credentials. Finally, the flow of in-use construction product data could lead to a panoply of other valuable benefits for stakeholders: manufacturers could optimise designs based on real usage data, orders of magnitude richer than laboratory-based test results; whilst facilities managers could receive predictive maintenance and product-recall alerts, driven by fresh data.

5 The Potential Role of DLT in Traceability

A central tenet to many such innovations is their wholesale reliance upon the flow of information throughout supply chains in complex sociotechnical systems. Alongside the development of technologies in areas such as robotics, sensors, internet of things, geolocation, space, and materials; the soaring dependence on information flow has arguably catalysed the accelerated development of an entirely new area within the information management field, blockchain, and a broader category termed Distributed Ledger Technology. Widely popularised by Bitcoin (its first major application), blockchain has rapidly become a poignant topic of conversation across a spectrum of academic and business literature. It is arguably one of the most novel technological and sociological developments in recent times.

There are two types of blockchain: *permissionless* (like Bitcoin or Ethereum) which is fully decentralised with no central authority, and fully accessible to anyone to participate; or *permissioned* where a central actor must grant access and permissions for someone to participate [70,71] (like Corda). In general, a blockchain can be conceptualised as a distributed append–only database [72] made up of interlinked blocks of data which contain records of the transactions made in the system between nodes (participants) since the last block was added. The blocks of transactions are confirmed and added to the existing chain by mutually mistrusting [73] 'writers' called validators [74], leading to the descriptor 'trustless' [75], since no trusted centralised third-party is needed to facilitate the effective functioning of the system.

The writers come to an agreement on the validity of the transactions communicated in the system via a self–propagating consensus algorithm [71]. Each new block that is appended to the chain references the previous block via a one–way cryptographic hash function [71], essentially a fingerprint ID of the previous block, which prevents data from validated blocks from being tampered with. Furthermore, the information within a blockchain system may hide in plain sight, sitting securely behind the protection of "very big numbers" [76] and within a small space, due to optimising Merkle Tree hashing–functions [77] whilst indefinitely preserving the integrity of historic transaction data. These features mean that blockchain systems are generally accepted to possess five key attributes, as noted in Table 2 below.

Table 2. Purported Attributes of DLT Systems

Attribute	Comment
Auditable	Provides an unbreakable audit trail of all transactions all the way back to the first (genesis) block, which can also be conceived as transaction traceability [78].
Disintermediative	There is no reliance on a third 'trusted' party to execute transactions, it is peer to peer (and information is also directly accessible) [70].

Transparent (with/without pseudonymity)	The information within blockchains is viewable by all participants [...] Users can choose to remain anonymous or provide proof of their identity to others [71]
Secure	Expensive computational algorithms create disincentives to 'hack' the system [72], and blockchains' distributed and encrypted nature makes them difficult to hack. [70,71]
Immutable	Existing data in public systems is extremely hard (and economically unfeasible) to change [77,79].

There is growing consensus in the literature that blockchain can lead to enhanced traceability in supply chains due to its novel approach to information management. An extensive body of literature asserts a degree of support for the notion that blockchains are especially well placed for the enhancement of traceability of physical artefacts in supply chains. Cole *et al.* [80, p.471] provides a succinct synthesis of the emerging consensus: *"immutability of the data means that agreed transactions are recorded and not altered. This provides provenance of assets, which means that for any asset it is possible to tell where it is, where it has been and what has happened throughout its lifetime."* Outwith the academic literature, prominent industry bodies such as IBM, Deloitte, and Oracle tend to sympathise with this stance [81].

6 Open research problems

6.1 Distributed Ledger Technology

There is no notable opposition to claims that blockchain can prove the provenance of data created within a blockchain system due to its advances over older technologies (namely. immutability). That being said, two erroneous propositions pervade the nascent argument that blockchain by itself will enhance traceability of non-informational artefacts. These are as follows:

- The conflation of the guarantee of the provenance of traceability information received with the validation of the claims made within the traceability information received.
- The conflation of the provision of traceability information with the utility of the traceability information provided – e.g. asserting that the presence of traceability information is tantamount to achieving traceability of a physical artefact.

For example:

> *"With improved visibility, each participant in the supply chain will be able to see the progress of goods as they move through the supply chain."* [82, p.72]

> *"This improved visibility provides an auditable trace of the footprint of a product, which is particularly attractive to industries where the provenance of a product is crucial."* [71, p.223]

> *AI augmented verification technology can help determine material provenance, while blockchain can provide real–time provenance visibility to reduce tampering and counterfeiting."* [81, p.5]

Viewed through the lens of the information assurance considerations (section 2.3), the issue of the potential weaknesses of the Cyber Physical Bond must be accounted for in the development of a balanced view of the potential utility of blockchain in traceability applications. Considering a case where the RFID tag of a physical artefact is tampered with, thus sending erroneous signals to a receiving TS, shows clearly that blockchain alone cannot guarantee the truth of information pertaining to that item.

Whilst it is plausible that blockchain could safeguard information in a TS, the safeguarding of the creation of the information is not accounted for by the current literature. Two open information assurance phenomena face blockchain-based traceability applications:

- Garbage In Garbage Out (GIGO) – the quality of the informational output of a system can only be as good as the quality of the input, which is subject to fraud and error.
- The Oracle Problem (TOP) – an oracle is the interface between real–world events and the blockchain ecosystem. For example, a reporting observer, RFID tag or third-party data feed could be oracles because they create the information that blockchains process.

An established approach to overcoming the traceability information creation dilemma could be to appoint a third-party authority over the TS. Although firstly this would place a potentially unsustainable financial burden on the supply chain. Secondly, it does not necessarily eliminate SCP animosity towards the TS. Thirdly, the introduction of a central authority with ultimate control over information creation and management in the TS may undermine of the practical or philosophical arguments for the inclusion of blockchain in the TS. The resultant research challenge is thus to seek out a solution to the assurance of the information creation process; without reliance on a single authoritative actor and whilst maximising utility of the information, solving for the stakeholder incentive dilemma elucidated by agency theory.

6.2 Traceability in AECO

To date, product-level traceability in AECO has received scant attention from academia, compounded by the fact that existing traceability initiatives predominantly focus on the extractive industries. The rising importance of product-level traceability as established in section 4, in tandem with the opportunistic paradigm of traceability emanating from the Industry 4.0 movement, converge to invite research into entirely new approaches to achieving product traceability in AECO. This invitation is consolidated further by the potential opportunities presented by nascent blockchain technology research, which lays out the possibility for the creation of entirely novel decentralised business models.

The resounding issue of SCP incentives and motivations in TSs remains one of the key issues, however. No research, specifically addressing the issue of SCP incentives in AECO TSs, has been found to date.

6.3 Future Research Direction

The amalgamation of these issues provides several interesting avenues of enquiry which could lead to novel contributions to knowledge.

SCPs' incentives (perceived benefits) and disincentives (perceived risks) to participate in AECO traceability systems will be investigated through interviews with SCPs in the supply chains of selected focal products. A 'lifecycle perspective' will be adopted, taking into account the information created through the full life of a product, as well as the various stakeholders at different lifecycle stages in the AECO process.

Data will be gathered from DLT experts to garner further insight into the problems (GIGO and TOP) facing blockchain in the context of traceability applications; as well as the potential of a specific area of DLT which is not obviously considered in the blockchain-based traceability literature: token-based incentive mechanisms. These might feature cryptocurrencies and smart contracts within a decentralised business model.

The two streams of knowledge will be combined to develop a conceptual design of a TS based on a decentralised business model which features new 'pull' incentives to align the interests of AECO SCPs in order to overcome the incentive dilemma, and achieve enhanced traceability to unlock transformative benefits in AECO. This could explore the commercial exploitation of the potentially valuable data which would be contained in an AECO based TS.

7 Conclusion

The case for product-level traceability in AECO has been firmly established, taking into consideration a diverse set of drivers and mounting industry concerns. Yet the challenging structure and adversarial culture of AECO is known to stifle the proliferation of innovative technologies, and traceability systems universally are known to falter in the absence of participant buy-in. However, a paradigmatic shift in thinking towards data-driven business models and the emergence of DLT with its associated decentralised business models could hold the key to an entirely new approach to traceability in AECO which is much needed to underpin its transformation. Although the apparently unfettered support for DLT is not empirically justifiable and the two key problems of GIGO and TOP remain, it seems that it could have a potential part to play in the assurance of traceability information by facilitating an entirely new approach. The solution to traceability in AECO hinges on the degree to which it can integrate incentives which attract SCPs into willing participation and mutually beneficial alignment, based on the benefits they will receive which must outweigh the perceived risks, rather than forcing participation through external agency. The utility of DLT for product traceability in general has yet to be examined from this perspective. One exciting area for future research is the potential use of token-based incentives in traceability systems.

The achievement of product-level traceability in AECO with wholesale buy-in could release new levels of productivity by solving pertinent operational issues, whilst underpinning radical improvements in many other areas which will benefit society as a whole.

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AN INVESTIGATION ON THE APPLICABILITY OF SMART CONTRACTS IN THE CONSTRUCTION INDUSTRY

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ABSTRACT: Smart contracts and blockchain technology are becoming key parts in advancing the Digital Construction discipline. Although blockchain technology has just started to be used in construction industry, the applicability of smart contracts is being debated. The adaptation of this technology is relatively limited and slow compared to other industries such as finance due to the special characteristics of the construction industry which make it more complicated and fragile. For this purpose, this research investigates the applicability of smart contracts in construction industry, its limitations and possible benefits. First, smart contracts are compared to traditional contracts. Then, the relationship between smart contracts and blockchain technology is discussed, and finally the impact of blockchain technology on the construction process is investigated. In this research, which has utilised a literature review, the following results have been found. In spite of the fact that smart contracts have some limitations for this industry, such as the difficulty of changing transactions and being legally binding, they have potential benefits in many fields, primarily the solution of payment problems and high security. The use of this technology in for example, simple and small-type projects or semi-automation of activities could facilitate their adoption. Furthermore, it is considered that using these technologies together with Building Information Modelling (BIM) in construction projects will contribute more benefit to the project.

Keywords: Smart Contracts, Blockchain, Building Information Modelling (BIM), Digital Construction, Construction Industry

1 Introduction

The use of technology and its applications continue to increase rapidly in the construction industry, across the world. However, due to the nature of the construction industry, its adaptation to technological advances is slower compared to other industries such as finance, automotive [1]. Blockchain technology, and accordingly smart contracts, are seen as the technology of the future, and are envisaged to be used in this industry [2-3]. Using this technology more efficiently requires a smart contract [4]. This contributes to acceleration and automation of the process through the ability of smart contracts to execute themselves.

Smart contracts are a program code that allows transactions to be performed without the need for intermediaries such as banks, lawyers, and notaries [5]. They are based on reducing or eliminating the need for third parties in contracts and automating transactions [6]. The code in the program automates the contract in the blockchain system after the realisation of the variables and principles determined in the project [7]. In this way, it is aimed to prevent loss of time in the projects and to solve the issue of payments, which is one of the major problems in the construction industry, as well as to protect the parties from bankruptcy.

Construction projects are a type of project where multiple professional groups work together. Various problems are encountered due to the lack of coordination and collaboration among these groups. This situation, which is rather extensive in the projects, causes undesirable results in the project [8]. Digital construction aims to increase collaboration among project stakeholders in a project. It gathers projects in an environment and contributes to teamwork. In addition, coordination deficiencies are reduced with the simulation feature. The fact that the transaction approvals in the blockchain system require joint action automatically requires collaboration among the parties. Thus, possible disputes that may occur among the stakeholders in the project can also be reduced.

This study investigates the applicability, possible benefits, limitations of smart contracts in the construction industry. Smart contracts are first compared to traditional contracts. Next, the relationship between smart contracts and blockchain is revealed. Finally, the impact of blockchain technology on the construction process is investigated.

2 The Relationship between Smart Contracts and Blockchain Technology

Smart contracts are defined as computer codes that execute a contract partially or fully automatically and stored on the blockchain platform. Programming languages are used in the formation of smart contracts. The codes contribute to the execution of agreement among stakeholders and the realisation of payments. They are replicated and archived at nodes in the blockchain system and these codes cannot be changed. Each node added to the blockchain network means that the activity determined in the project has taken place. This is accomplished by initiating a transaction on the blockchain network by project stakeholders and requires consensus among them. If the activity determined in the project has not taken place, the code will not progress [9].

Bitcoin and Ethereum are two common samples of the blockchain system known as distributed ledgers. While Bitcoin has distributed ledgers and cryptography capability, Ethereum may also include codes capable of executing transactions. The Bitcoin blockchain system uses Bitcoin as its digital currency, while the Ethereum blockchain system uses Ether [4]. A transaction fee is required for a smart contract to be executed in blockchain system. In these transaction fees, digital currencies Bitcoin and Ether are used. The payment made in the Ethereum blockchain system is called 'gas'. As the figure of nodes in a blockchain network increases, the amount of gas spent increases accordingly [9]. The size and complexity of a project affect the amount of gas needed. Therefore, the amount of gas to be spent on a large and complex project will be much higher than for a small and simple project.

Today, smart contracts generally carry out the transfer of money among stakeholders through cryptocurrencies in the blockchain system once the set criteria are complete. Figure 1 demonstrates the general working principle of smart contracts in the blockchain system.

Figure 1. Working Principle of Smart Contracts in Blockchain System [14]

First, an account is created in the blockchain system, the smart contract depending on the events determined in the project is written as a code to the blockchain system and all project parties are included in this account. In the second step, in consequence of the realisation of an event determined, the conditions coded in smart contracts are triggered. In the third step, the payments are transferred to the related parties in the blockchain system. Finally, the project parties have an immutable example of all the activities that have taken place and they can be accessed at any time. Their functions are expected to increase with their use and adoption over time. In addition, it may take much longer to add criteria such as performance evaluations of the parties and compensation [9]. These limitations would delay the adoption of smart contracts in the construction industry.

3 Applicability of Smart Contracts in the Construction Industry

Smart contracts and blockchain technology have become key parts in the advancement of the finance discipline nowadays [1]. Therefore, this technology is closely related to all sectors based on finance. This situation is reasonable considering the payment method and security for industries with minor transaction complexity such as banking, real estate, insurance, healthcare and retail. Some countries, including Ghana, Georgia and Honduras, have switched to smart contracts to avoid land disputes and problems in the land transfer [10]. The adoption of smart contracts, which are also considered to be used in the construction industry, is debated due to the nature of this industry.

By its nature, the construction industry is exposed to many variables and unknowns. Transaction load and complexity are higher compared to the industries mentioned above. For this reason, while some of the industry members favour the adoption of smart contracts, some oppose it. For example, in the study conducted by Mason, some of the participants argued that the potential benefits of smart contracts, mainly in eliminating payment problems, outweigh the limitations. On the other hand, some participants specified that adoption is much more difficult than it seems, particularly because of the complexity in the construction works, each identified event cannot be reduced to "yes" or "no" in smart contract transactions [6].

Smart contracts currently make payments automatically based on sensors or devices. However, there is no flexibility in any changes or mistakes during the project. Due to the immutability of the blockchain, a change in the smart contract is fairly complicated [9]. For this reason, it is more reasonable to use and develop these contracts primarily in simple and small-type projects. Thus, while solutions to existing limitations are being developed, both possible losses can be reduced, and their adoption can be facilitated.

Although the main factor in contracts is money, contracts do not consist of just payments. It also includes many key factors such as time, quality and responsibilities. These critical factors are not involved in enabling of smart contracts. This restricts the use of smart contracts in the construction industry. On the other hand, digital construction supports the collaborative approach to tackle the problems encountered [11]. The inclusion of the smart contracts and blockchain technology in the Building Information Modelling (BIM) process increases collaboration in the project and enables more precise data to be obtained [2]. According to Perera et al. BIM has made various contributions to construction projects, but it has been ineffective on supply of goods and services [12]. The potential of blockchain and smart contracts on supply encourages the combined use of these technologies and enables more contribution to the project. In addition, this process contributes to the automation of the contract [6]. Liu et al. investigated the potential benefits of using blockchain and BIM technologies together in sustainable building design information management [13]. As a result of this research, they have demonstrated that smart contracts could be used effectively in this process, the possibility of sustainable design being realised, and proposed a framework for this.

Blockchain and BIM can be used together in many fields such as pre-construction, procurement, and construction process, similar to the design process in construction projects. As can be seen from these mentioned studies, the combination of these technologies has the potential to reduce the main problems in the construction industry as well as facilitate their adoption.

4 Comparison of Smart Contracts and Traditional Contracts

This comparison was made to determine the potential advantages and limitations of smart contracts for the construction industry over traditional contracts, and it uses a number of measures such as payments, collaboration and trust, cost and time, possibility of mistake, archiving-backup and safety, prevention of bankruptcy; difficulty changing transactions, long-term trade relations, execution options, hacking and fund security, and legally binding and responsibilities.

4.1 Possible Benefits of Smart Contracts to the Construction Industry

It is anticipated that smart contracts will be able to solve or reduce some important problems and make a significant contribution to the project if their adaptation to the construction industry is provided. These possible main benefits are outlined below:

⁎ **Payments:** Payments are one of the main problems in the construction industry. It is thought that the most significant advantage of smart contracts will be in solving payment problems. The activities and milestones in the project compose smart contracts in the form of codes. Completion of these determined activities and milestones allows smart contracts activated by sensors to make payments instantly in the blockchain system [15]. This provides construction projects the opportunity to minimise payment-related disputes, one of the main problems encountered in traditional contracts.

⁎ **Collaboration and Trust:** On the basis of blockchain, transactions on the network require consensus. Therefore, project funds are not allowed to be managed by a single person or organisation as in traditional contracts [16]. This increases collaboration and trust among stakeholders while at the same time ensuring the protection of the rights of the parties.

⁎ **Cost and Time:** Since the execution of transactions is automatic in smart contracts, monitoring and execution process does not require human intervention. Thus, the need for monitoring and execution costs in the contract is eliminated [9]. In addition, the amount paid for transaction fees in smart contracts is much less than the transaction fee paid to the bank in traditional contracts [16]. They also prevent any friction that may arise between the parties accordingly. As a result, they contribute to shortening the project duration while reducing the project cost.

⁎ **Possibility of Mistake:** The formation of smart contracts from codes and automating the process of these codes eliminates possible errors during the preparation of contracts in traditional contracts. They also prevent a contract from being perceived differently by different people [1]. Thus, they provide the potential to reduce human errors as well as not requiring human intervention.

⁎ **Archiving, Backup and Safety:** While the parties archive and backup the data themselves in traditional contracts, smart contracts utilise features such as digital archiving, backup and cryptography which are at the core of blockchain. Whole stakeholders in the blockchain network can instantly access the project data and keep it in their archive. Also, the data is encrypted on each block through cryptography [17]. Thus, the project is rather protected against possible attacks.

⁎ **Prevention of Bankruptcy:** In traditional contracts, one of the main reasons for the bankruptcies of the construction companies is the lack of timely payments to the project parties, and the consequent deterioration of the cash flows of the companies. It is expected from smart contracts to guarantee the project funds, to ensure that the payments of project stakeholders and suppliers other than the client are made on time, and to protect the project stakeholders from bankruptcy. In addition, the instant realisation of payments will reduce companies' cash flow problems [18].

4.2 Limitations of Smart Contracts in the Construction Industry

The adoption of a new technology will induce with it some risks and limitations. These main risks and limitations are summarised below:

⁎ **Difficulty Changing Transactions:** Smart contracts do not offer the opportunity to change transactions in their current form. Considering that the blockchain is immutable, a change in contract is much more complex than standard contracts. The change in the contract will increase the transaction cost of the smart contracts which are normally more economical, and the margin of error resulting from the change [9]. Despite this disadvantage, as the use of smart contracts becomes widespread, such deficiencies could be expected to be resolved or reduced over time.

⁎ **Long-term Trade Relations:** The ability to conduct transactions automatically, seen as a key feature of smart contracts, restricts the flexibility in traditional contracts. For example, in a traditional contract, a short-term delay of payment can be tolerated when long-term trade relations among stakeholders are considered. The absence of such options available in a project that uses a smart contract is one of the main obstacles to their adoption [9].

⁎ **Execution Options:** Another limitation of smart contracts is execution options. Transactions in smart contracts are conducted on the consensus in the blockchain network. The fact that the command system is based on the "yes" or "no" principle ("maybe" as a third option can be added in the future) restricts their use [1-7]. For example, "yes" or "no" options are offered to the parties as a payment option by smart contracts in the blockchain system for an identified expired job. If 95% of this job was completed within this time period, the option "no" is selected and no payment is made to the parties.

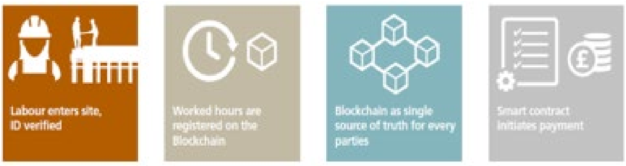
⁎ **Hacking and Fund Security:** Smart Contracts are much more resistant to tampering and hacking than other applications thanks to the cryptography feature of the blockchain. However, there are still gaps in the system and accordingly some cases of hacking have been encountered in some industries [10]. The fact that the entire project fund is in the system makes the issue even more critical.

⁎ **Legally Binding and Responsibility:** There is currently no legal binding available for smart contracts. In this case, in a project where smart contract is used, if the parties cannot agree on the contract, it causes the problem of which path to follow. It is an issue to be considered who will be responsible for the mistake that may occur in the project. It also includes legal and operational constraints such as what can be done in case of possible problems of sensors that will activate smart contracts and how this affects project stakeholders [19].

5 The Impact of Blockchain Technology on the Construction Process

The construction industry allows many professions to work together. Therefore, the performance data, identity and reliability of the contractors involved in the project must be verified [20]. This is very important for the project to continue as planned, especially in a special and complex project. Stakeholders involved in a project must verify their identity in order to access the blockchain system, otherwise they cannot access the project data. All transactions made in the blockchain system are recorded on the network in the form of chains. The tracking and performance analysis of the project can be done more easily by this feature. In addition, data such as working hours, breaks and wages of labourers can be calculated, and payments can be made automatically accordingly (Figure 2).

Figure 2. An example for the Use of Blockchain in Construction Site [21]



Working hours, breaks and wages of labourers can be kept under legal control and used as evidence in possible labourer-employer disputes. Furthermore, the transactions completed in the project require majority approval of the stakeholders in the system [7]. This allows for increased collaborative work among the stakeholders while contributing to the reduction of possible disputes.

One of the most important features of the blockchain system is that it features cryptography. It is one-way encryption which adds to the security and privacy of the system. The blockchain system encrypts all transactions made in the system [4]. Thus, it is almost impossible to change or manipulate the data contained in the chain [22]. Each transaction performed is added linearly to this network in real-time and this network continuously expands depending on project progress.

Cost, duration and quality are the basic elements in the construction industry. The aim is to achieve maximum quality with minimum cost and duration. The fact that blockchain makes the project traceable and transparent contributes to the increase in quality. It also provides for more efficient material procurement [20]. Blockchain technology offers the opportunity to eliminate intermediaries by smart contracts while eliminating paperwork such as paper, invoices, documents [23]. As a result, it has a positive impact on project cost and duration [19].

6 Conclusion and Recommendation

Smart contracts are expected to offer benefits to construction projects on key issues such as timely payments; increasing collaboration and trust among stakeholders; optimizing project cost and duration; reducing error rates; archiving, backing up and security of data; and preventing bankruptcy of stakeholders involved in the project. On the other hand, since this technology is quite novel, it needs improvements to overcome the difficulty of changing transactions, to be adoptable to all payment conditions of traditional contracts (e.g. timing of payment, deduction of payment), to improve the security of the system, to formalise legal binding and responsibility in the project.

Smart contracts and blockchain have complementary features. Generally, blockchain facilitates collaboration and trust among the stakeholders while smart contracts execute the blockchain system. With the principle of working together, payments are made instantaneously and automatically.

The fact that Blockchain makes the project traceable, enables collaborative work and contributes to project security makes a significant contribution to the project in terms of cost, quality and duration.

Finally, the use of semi-automatic contracts in the beginning will contribute to the adoption of these systems, as it is quite difficult to change to smart contracts and the blockchain system in one stage. Furthermore, the implementation of these technologies primarily in small and simple-scale projects can ensure that possible limitations are seen more clearly and that the losses that can be experienced in the project remain at a low level. The fact that smart contracts are based on sensors and blockchain consensus can make these technologies easier to use with BIM. Thus, this process will contribute more to the project efficiency in the construction industry.

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ARCOM Doctoral Workshop

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

25 March 2020, Newcastle, UK

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

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ABSTRACT

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

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

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

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

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

Keywords:

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

1 Introduction

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

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

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

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

2 Methodology

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

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

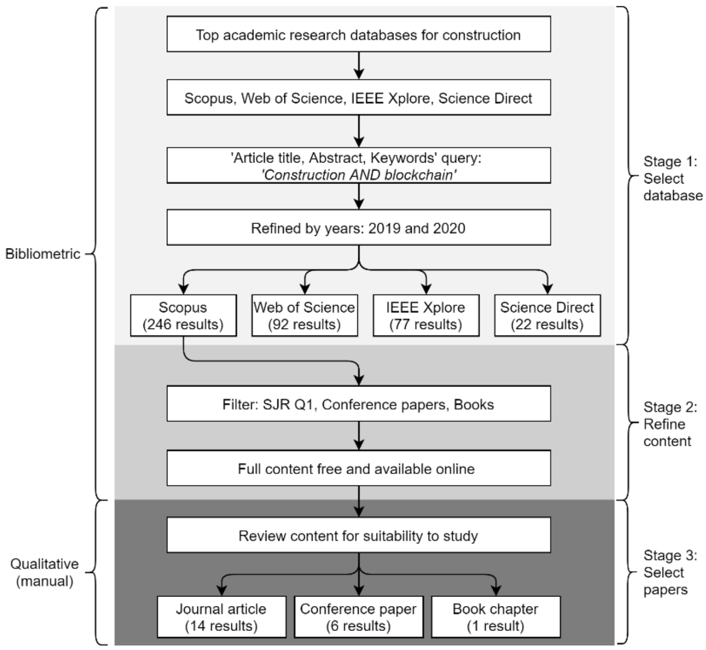

Figure 1. Review method for selecting study papers.

3 Blockchain in Construction Applications

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

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

Literature key:
Q1 Journal publication
Conference paper
Book

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

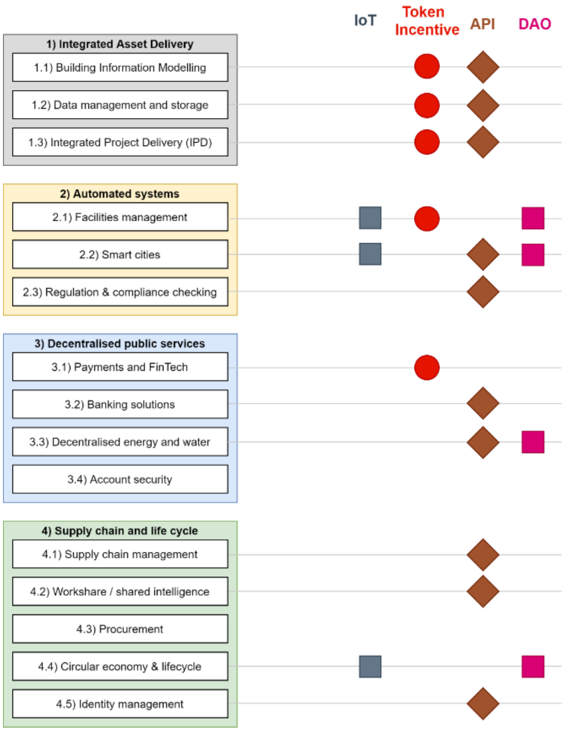

Figure 2. Mapping of categories to technology components.

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

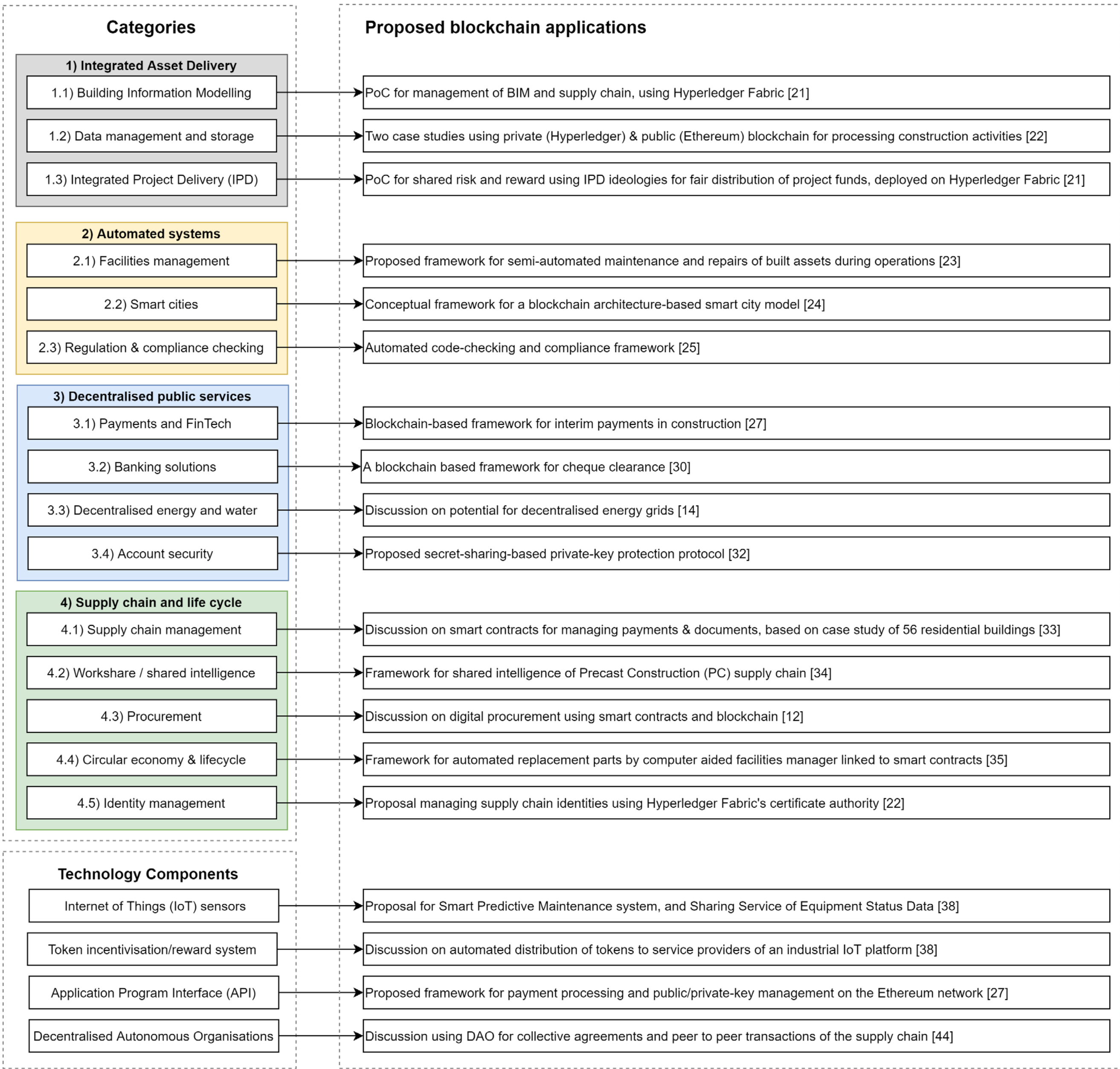

Figure 3. Proposed blockchain applications extracted from 21 study papers.

4 Review of Blockchain Applications

4.1 Integrated Asset Delivery

4.1.1 *Building* Information Management (BIM)

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

4.1.2 Data management and storage

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

4.1.3 Integrated Project Delivery (IPD)

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

4.2 Automated Systems

4.2.1 Facilities management

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

4.2.2 Smart cities

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

4.2.3 Regulatory and compliance

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

4.3 Decentralised Public Services

4.3.1 Payments and FinTech

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

4.3.2 Banking solutions

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

4.3.3 Decentralised energy & water

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

4.3.4 Account security

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

4.4 Supply Chain and Life Cycle

4.4.1 Supply chain management

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

4.4.2 Workshare / shared intelligence

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

4.4.3 Procurement

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

4.4.4 Circular economy & lifecycle

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

4.4.5 Identity management

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

4.5 *Other categories worth accreditation*

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

4.6 *Technology Components*

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

4.6.1 Internet of Things (IoT) sensors

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

4.6.2 Token incentivisation/reward system

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

4.6.3 Application Programming Interface (API)

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

4.6.4 Decentralised Autonomous Organisations (DAOs)

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

5 Discussion

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

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

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

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

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

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

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

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

6 Conclusion

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

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

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

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

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ARCOM Doctoral Workshop

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

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The Building as a Lab: Towards the development of a toolbox

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1 Introduction

The construction sector is undergoing significant changes amidst challenging economic conditions, changes in the pace of technology and increasing global narratives around social, personal and environmental health. These narratives are changing the way the construction sector operates, putting an emphasis on projects that can evidence a measurable impact on these performance indicators. Green Building standards (e.g. WELL and LEED) are addressing these challenges by making occupant health and wellbeing a focus of accreditation within building design. This is ushering in a new understanding of value that counterpoints the concept of value engineering"; which can become more of an exercise of cost-cutting than value improvement [1].

The last decade has seen the rise of the living lab research paradigm, placing individuals at the centre of research and development. Living labs are physical environments that act as a laboratory, gathering data and learning from users. By linking building information and Internet-of-Things (IoT) data with occupant feedback, the construction sector can develop buildings as living labs and take an occupant-centric approach to how they innovate the entire building lifecycle.

One area this would benefit is the overall management of building information, which, has come under scrutiny in the wake of the Grenfell Tower disaster. In response to that, A new framework presented [2] legislative and behavioural changes to the construction industry. Authors proposed the idea of a 'Golden Thread of Information', to act as a digital record of data from design through to decommissioning that would include construction and ongoing building-in-use data. Moreover, the framework addressed the lack of knowledge and transparency in building information, which may have served as a catalyst to the events which took place at Grenfell. However, the amount of building data required creates many complex technological challenges that will likely act as barriers to the framework's success.

One aspect of building management which has notable technical challenges is environmental monitoring. Indoor environment is typically measured as the performance of the physical building rather than the experience of the building occupants [3]. To gain a more holistic understanding of the indoor environment, there is a need to capture occupant experiences. Building operation and occupant practices are not static but change over time and in response to one another. New ways to capture occupant experiences would make it possible to better understand the dynamic relationship between occupants, the building and its operation. Hence, buildings are becoming testbeds for more focused research to ensure robust design for improved occupant health and wellbeing. This paper explores some 'building as a lab' methodologies which could form a suite of tools for researchers and practitioners concerned with IoT-based environment management.

2 Background

A recent scoping review [4]. identified the need for low-cost monitoring solutions to better understand indoor environment quality (IEQ). Whilst state-of-the-art sensors can provide a high degree of accuracy, the capital investment required can make it difficult to promote beyond research [5]. This results in either fewer sensors being used, which makes it difficult to measure individuals or solutions being developed that are not pragmatic in construction projects.

The review [4] also identified a need for user-centric research within environmental monitoring studies, aligning with the living lab paradigm. Outlining the prevalent need for user-centric research within building studies, authors explored sensor technologies and environmental factors which are fundamental measuring IEQ. This highlighted a degree of ambiguity around how IEQ is used. It was also noted that future studies should consider supplementing environmental sensor technologies with wearables. This would enable researchers to measure individual patterns of behaviour [6], taking a user-centric approach to study relationships between building and occupant.

Whilst the identified knowledge gaps in IEQ research align with the outcomes of the living lab paradigm, there is no single way to apply this to turn buildings into living labs. Instead, there are several technologies, methodologies and frameworks that can be combined to suit the specific needs of a building or research question.

3 Exploring toolbox development

There are many workflows, methods and technologies, which could be incorporated into a toolbox. However, it is important to initially choose a suitable research methodology to underpin research approaches.

3.1 Methodology

In epidemiological studies, n-of-1, or single-case research, methods are an effective way of exposing how the manner of an individual's health can change over time, with greater accuracy than is seen in group trials [7]. Specifically, n-of-1 methods involve repetition around the measurement of an individual over a longer period of time compared to traditional observational studies [8]. n-of-1 methods can inform many types of research design, but they can also be particularly useful in exploratory research and early-phase trials [9]. Moreover, the versatility of n-of-1 methods is acknowledged across disciplines, enabling measurement of high-resolution data [7]. This makes them ideal for measuring intra-day telemetry data gathered from buildings and occupants, through IoT sensors and wearable devices.

3.2 Holistic Cloud-Based Systems

It is possible to develop prototype monitoring solutions with little to no software development. Web-based services such as IFTTT *(If-This-Then-That)*, enable the creation of services that connect IoT devices via simple logic rules [10]. These services are an effective and affordable way to test the interconnectivity of monitoring solutions with limited capital investment. However, it is likely that, beyond prototyping, holistic cloud-based systems would be required to collect, store and analyse such a complex data stream from multiple sensor sources. It is important that cloud-based systems act as a single source of information right throughout a building's lifecycle and can be legislated both into new buildings and the existing building stock.

3.3 Wearable Technologies and Mobile Devices

Wearable technologies, such as Fitbit personal fitness trackers, present an accessible way to connect individuals with environments. Not only could wearables deliver individualised health measures, but the augmentation of the data with data from environmental sensors will potentially reduce the subjectivity found in occupant studies that focus on health and wellbeing [11]. These devices could also link to mobile devices to allow users to be involved in the research and capture the views of individual occupants, a foundation to the Living Lab paradigm [12]. Furthermore, by augmenting these devices with low-cost sensors, researchers could incorporate more sensors into their studies to ensure solutions have pragmatic real-world applications.

3.4 Digital Ledger Technology

Digital Ledger Technology (DLT) is a transparent and immutable, digital record of transactions that is synchronised across multiple peers on a network of users. When a transaction is transmitted to the network, all users receive an identical record of the transaction and the validity is verified by cross-referencing with all other users [13]. Given the need for transparency and accountability within the Golden Thread of Information, it is likely that DLTs would be needed to underpin and support these workflows. DLTs could also have a place right throughout the building lifecycle. As the data on a building grows over time it will be imperative that contributions and amendments to that data are extremely transparent. By doing this will the ideas that underpin the Golden Thread be greatly reinforced.

4 Discussion and conclusion

This paper explores a conceptual approach to how principles, workflows and technologies could be incorporated into a toolbox that would underpin living lab research in buildings. The principles presented, above all else, highlight the need and value of multi-disciplinary research in this domain. Research siloes have resulted in ambiguity in terminology and research methods, which is forcing current research to sit at the precipice of what is possible. By unifying multidisciplinary approaches, i.e. technologies, workflows and disciplines, to create a suite of tools, it is felt that researchers could provide a deeper understanding of the relationship between building and occupant that is currently seen across the literature base. This would add value to researchers and practitioners and aim to address an industry need for transparency, verbosity and accountability of building information.

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