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USE OF BLOCKCHAIN FOR ENABLING CONSTRUCTION 4.0

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20.1 Aims

- To describe the basis and evolution of blockchain in the context of built environment activities and processes.
- To evaluate the implications and impact of blockchain technology upon the construction and property industries.
- To reflect upon the linkages between blockchain and Construction 4.0.

20.2 Introduction

The construction industry is a high impact sector and a key driver for all national economies, be it through employment of people, development and return on investment for the advancement of civilization or as a fundamental stimulator for any economic activity. Yet, the complexity of construction, in particular with regards to design, legal and financial aspects, causes recurrent and chronical inefficiencies. Emerging technologies related to the Fourth Industrial Revolution and specifically blockchain technology bring opportunities of overcoming these inefficiencies.

The Industry 4.0 emerged in the 2010s and is currently being defined as the merge of the 'physical and digital', the era where the 'bits' connect with 'atoms' and objects and environments become smart. There is a shift to almost instantaneous global distribution with popular YouTube videos being seen by billions of people and E-Scouters appearing simultaneously in many cities around the world.

The scope and magnitude of transformation is deep and wide, with, for example, software being distributed and update online and in real-time. This is an immense change and impacting billions of people. Never before we had to contemplate this scale of change.

The decomposition of the Industrial 4.0 can be describe in waves of changes (Case, 2017), with the first wave (1985–1999) charactering the development of *the building blocks of hardware and software* and the start of the broadcasting static information.

The second wave (2000–2015) was marked by the *software as a service* and the ability to search the world wide web, social networks and e-commerce. The second wave also introduced the use of mobile phones and the invention of the smartphone and the app economy. This increased the number of internet users to 3.2 billion by 2015 (BBC, 2015).

We are currently experiencing the third wave of the Industry 4.0 (2016–Now). Internet access is ubiquitous and new business models are 'born online'. This acceleration and degree of interconnectivity create the conditions for further development, bringing to us the rapid advances in the many different sciences in a similar fashion to the 1600's Renaissance. It might have an assimilation period of similar dimension (of about 200 years) or instead, it might match the accelerating times.

By 2025, it is expected that the world will have 75 billion things exchanging information in the IoT (Statista, 2019a). This information flow is becoming a detailed account of all and each one of us and how we interact with our environment. To prepare and respond to this new age of ubiquitous and embedded information, we have to consider technologies like blockchain.

Blockchain, also known as the '*Trust Protocol*' (Milutinovic et al., 2016; Tapscott, 2016; p. 4), can be described as the amalgamation of a few technologies for secure decentralized data management and value transaction. The interest in blockchain has been increasing since the idea of a decentralized cryptocurrency was developed in 2008 (Nakamoto, 2008) and Bitcoin was launched in 2009 (Wattles, 2017).

Blockchain has characteristics in its architecture that provide security, anonymity, provenance, immutability and purpose of data without any third-party organization in control of data transactions. Because of this automation, blockchain creates novel opportunities in the many digital applications and ecosystems out there. It becomes particularly disruptive in cyber-physical systems, the Internet of Things, cloud computing, cognitive computing and other automation and data exchange processes relevant for the manufacturing technologies and the Fourth Industrial Revolution (Hermann et al., 2016; Kagermann et al., 2013; Schwab, 2017).

The general field of Distributed Ledgers Technologies (DLT), with and without the blockchain component, is also highly relevant in application for Virtual Environments (VE), including Building Information Modelling (BIM) and digital construction management.

In this work we investigate the consequences of blockchain in relation to technologies associated with the construction sector, examining current case studies and discussing the prospects of the evolving technology itself.

We also discuss some known limitations and challenges in implementing the technology and how this reflects in prospective applications in the construction sectors.

20.3 Construction challenges in the era of BIM

Construction is manifested as a highly project-based sector, with tasks typically considered as non-repetitive activities where various professionals organized in firms come together to deliver housing, infrastructure of other construction projects. This delivery of projects is a complex undertaking, typically over-budget and over-schedule. The construction process is fragmented and coordination between the various stakeholders is often suboptimal, resulting in lost productivity, rework, delayed progress and consequentially, increased fees.

The complexity of construction projects starts from its onset, as these temporary endeavours are financed from multiple sources; from governmental backing of large infrastructure or public works, to private funding of commercial real estate. The driver for such financing is, generally, stimulus of economic activities. Additional interests that stimulate investment may include improvement of delivery of services, environmental resilience, transportation connectivity, efficient utilization of capital and for-profit activities.

In the UK, construction contributes more than £163 billion per annum and contributes 6.5% of GDP to the UK's Gross Domestic Product (GDP) between 2015 and 2020 (ONS, 2018, 2017). The importance and also the complexity of the construction sector can be outlined by a national macro-level that contributes 6% to UK GDP, or approximately £113 billion in 2017 by value. In total, 2.4 million jobs in Q3 2018 (Rhodes, 2018) are employed by the UK sector and 10.7 million jobs by the USA construction (Statista, 2019c).

On the other hand, at a sectorial micro-level, construction projects vary significantly by size and economic value. By market segment, housing accounts for 25% value of construction sector orders, infrastructure for 12%, repairs and maintenance for 34%, other private orders 22% and other public 7% (Rhodes, 2018).

In a typical construction project there are numerous stakeholders' organizations involved throughout the supply chain. This includes sponsors (client, funders), the design team, building contractors, the supply chain (manufacturers and product suppliers), the operation team, and the users, including tenants, residents, customers.

All parties have invested interests that are impacted by adverse project events often initiated by poor information and communication.

Construction is also a highly fragmented industry. This fragmentation can be described as informational and organizational, with over 99% of businesses being comprised of disperse Small-Medium Enterprises (SMEs) (White, 2015). This is consistent with the European average of construction industry structure (White, 2015).

The fragmentation of information in construction projects are a persistent problem characterized by a disconnect between design and construction (Bryde et al., 2013). This takes place mainly because of the lack of open and trustworthy distribution of coherent, cohesive information across all stakeholders. Blockchain technology has the potential to subvert some of these effects through open, transparent transactions, particularly if associated with BIM processes.

For a *Construction 4.0* in line with current emergent technologies, managerial supervision from all stakeholders on every aspect of a project has to crosslink all design, procurement, statutory compliance and operations in a framework that creates information symmetry in a project's structures, roles and responsibilities.

Currently, in construction procurement, the parties involved have to go to great lengths to have certainty regarding identity, reputability and a price guarantee. In a very near future, once the Internet of Things (IoT) has gathered and compiled enough data, blockchain is likely the mechanism that will govern how it is distributed. An immutable ledger of transactions offers great potential to manage and benchmark infrastructure and construction assets efficiently.

As the systems around us, including transportation, infrastructure, energy, waste and water, become more interconnected, a trusted system such as blockchain can offer a greater value yield. The technology has the potential to efficiently manage the ever increasing demand for infrastructure nodes and energy supply (Arup, 2019). BIM platforms and protocols are the natural choice to accelerate this digital transformation. BIM brings together architecture, engineering and construction professionals under a Computer Supported Collaborative Work (CSCW) process to produce a federated digital design model and therefore create a coherent dataset for the construction and management of a new asset.

20.3.1 Delivering projects in BIM

BIM projects start with the development of an Employer's Information Requirements (EIR) for a new asset. This is often developed with the assistance of the architect and design team and is later translated into the BIM Execution Plan (BEP or BXP) (BSI, 2014).

The BEP aims to define roles and responsibilities, activities and level of development of the digital model for each stage of the project. There are a number of cross-mapping references between BEPs and project contractual protocols, including the RIBA Plan of Work (Sinclair, 2012) and more recently, construction contracts (JCT, 2019).

EIRs and BEPs are often ignored, misunderstood or underestimated. This might happen because of general lack of understanding on the benefits of adopting the BIM process. There is still little education and training available on what is necessary as a BIM requirement. On the other hand, it is hard to justify the extra overheads to deliver a useful BIM ‘layer’ with the project. The processes to validate the model according to the EIRs and BEPs are also very labour intensive and prone to errors.

The delivery of a BIM is also very front-loaded process, with a consultant having to develop a great deal of work that will not immediately benefit their contribution to the project. Surely BIM is very useful for the design of the building, but the extra labour in delivering a high *Level of development* is considered currently to be excessive. For models with a high Level of Detail (LOD) and Level of Information (LOI), the latency and performance of the system is also a problem.

One of the main strategies for BIM platform interoperability is the Industry Foundation Class (IFC) open file format (OpenBIM, 2017). However, for complex geometries, other file formats are used, and extensive geometry and data scripting often the only viable way to avoid geometrical distortion and data loss in the interoperability and agile of federated models (Autodesk, 2019; Davidson, 2019). Nevertheless, BIM has an immense impact on the construction industry and has created noticeable efficiencies in the sector.

20.3.2 Procurement and integrated teams

As BIM is positioned by governments and construction professionals as a key solution to persistent problems in the construction industry, more research is needed to measure the benefits of BIM and how these benefits might be augmented with blockchain.

The effectiveness of BIM as a medium for communicating information within a construction team can indeed promote considerably more accurate, on-time and appropriate exchange of information. In that sense, it is possible to quantify some of its benefits in relation to information management in construction (Demian and Walters, 2014).

BIM solutions helps to foster earlier creation of critical information relating to design detailing, programming, logistics and coordination that help to generate significant value during the later production phases. These underlying trends highlight the core potential of BIM to foster better collaboration between project participants, thus placing considerable emphasis on its role in ‘a human activity that ultimately involves broad process changes in construction’ (Eastman and Rafael, 2008; Eastman et al., 2011).

There is some evidence to suggest that these benefits are observed not only on large scale projects but also projects of a relatively small scale (Aranda-Mena et al., 2009; Eastman and Rafael, 2008).

The application of BIM has resulted in a fast-changing landscape for construction contracts. Lawyers struggle to keep up with the pace of innovation and the need to provide legal solutions and accommodate new approaches. Intelligent contracts appear as a logical extension to BIM whereby the contractual performance itself becomes automated.

Smart contracts, as proposed today, are of short-term execution or of instantaneous effect. This is at odds with the complex and long-running nature of construction projects. Storage constraints, compatibility and reliability issues together with confidentiality and the long-term nature of distributed ledgers pose additional problems (Mason, 2016).

As new legal applications emerge, 'LawTech' or 'LegalTech' technologies are becoming part of the practices of law, including processes in courts. LawTech refers to the use of technology and software leveraging blockchain to provide legal services where advice is given both before the transaction commences and after disputes break out. This refers to the application of technology and software to help law firms with practice management, documentation, storage, billing, accounting and electronic discovery.

In relation to cash flow in construction, the Construction Act 2009 amended the Construction Act 1996 by incorporation of detailed notice requirements (LDEDCA, 2009, Part 8, SCCR, 1998, Part 2, s.2). The parties to a construction contract were no longer free to agree notice periods not otherwise in accordance with those specified in the legislation, or on failure to agree such notice periods under the contract those prescribed by the Scheme (as amended). This progress in legislation resolution and the advent of smart contracts could jointly promote unforeseen levels of development the construction sectors.

Blockchain in procurement can be used to effect if the parties agree to abide and produce an outcome within days rather than years in the most complex of disputes. They can be more easily incorporated in anticipatory disputes, such as in construction contracts.

The concept of 'algorithmic regulation', modelled on 'algorithmic trading systems' (Treleaven et al., 2013), is to stream compliance, social networks data, and other kinds of information from different sources to a platform where compliance reports are encoded using DLT and regulations are 'codifiable' and 'executable' as Decentralized Applications (DApps) in the blockchain.

Generally, five areas of impact have been highlighted and include 'intelligent regulatory advisor' as a front-end to the regulatory handbook; 'automated monitoring' of online and social media to detect consumer and market abuse; 'automated reporting' using online compliance communication and big data analytics; 'regulatory policy modelling' using smart contract technology to codify regulations and assess impact before deployment; and 'automated regulation' employing blockchain technology to automate monitoring and compliance (Treleaven and Batrinca, 2017).

20.3.3 Supply chains and circular economy

The structure of resource consumption in the built environment is shifting from a fragmented and untraceable workflow. Where once consumption took a linear form, from sourcing to use to disposal – sometimes termed the *take-make-use-dispose* model – we are now on the crossover of a different culture. The circular economy in the built environment is becoming a priority for developers looking to curb the consumption of natural resources, prevent waste and increase efficiency through the recycling and responsible sourcing of building resources (Accenture, 2014; Arup, 2016). This model aims to save on negative externalities such as carbon emission, unsustainable landfill and water extraction and widespread ecosystem pollution. In addition, it aims to create opportunities for the industry across the supply chain.

Better Supply Chain Management (SCM) software is in high demand (van der Meulen, 2018) and the effect of blockchain in circular economies should not be underestimated. It is very likely that blockchain will enable the effective and reliable tracking of materials, components and whole products throughout the supply and reuse chain, although the exact nexus between the physical and the digital record is still problematic. If this is resolved, there is great potential to create a perpetual cycle of use of units, elements and products, opening the industry to new economic models of construction processes where manufacturer, recycler and consumer can confidently assess the circularity of their products.

Some rudimentary application platform has been developed for open-source distributed communications protocol for a circular economy (Circularise, 2018). This allows information to be exchanged throughout the value chain, creating transparency around product histories and destinations of materials.

20.3.4 Health and safety

Since the fire of London's Grenfell Tower in 2018, there has been perplexity and intense debate in relation to the UK's statutory and compliance frameworks. How can such an accident like this happen in our time? There are a number of reports showing a mismatch of information, roles and responsibilities (Marrs, 2018). The Grenfell Tower accident was characterized by multiple and systemic failure point including professional services, design specification, component manufacturing, material performance, statutory compliance checks and tests, facilities management processes, etc.

Traceability of design and construction, from early EIR for BIM to unified operations and statutory compliance framework can now be envisioned with the advent of blockchain.

The immutability of blockchain has the potential to create a fully traceable and trusted *accountability chain*, also capturing decisions and interactions of all agents on the creation and maintenance of built assets. The very existence of such a record can not only have a persistent effect on the industry's behaviours but also provide the level of granularity necessary to derive accurate '*macro-behavioural economic models*' to better management risk in the industry and prevent incidents such as Grenfell Tower's. Currently, macro-behavioural economic modelling is a very difficult challenge to say the least (Baddeley, 2017).

20.4 Context and aspects of blockchain

Blockchain technology can improve the quality, traceability and security of live data collection in the construction sector. A digital immutable ledger allows a project to be mapped and tracked at every stage. During the design phase, this is useful for establishing ownership of models and tracking project progress reliably, benefiting stakeholders by reducing the opportunity for corruption, inefficiencies and contractual disputes.

Blockchain is central to cyber-physical systems and from its beginning, complexity beyond currency and payments was envisioned. the possibilities for programmable money and computational contracts were considered into the protocol of the earliest cryptocurrencies like Bitcoin (Nakamoto, 2008). This '*tokenized economy*' offers a large variety of possible transaction and applications yet to be discovered and exploited.

The technology has evolved from decentralization of money and payments into the decentralization of markets and contemplates the transfer of many other kinds of assets beyond cryptocurrency: from the creation of a unit of value through every time it is transferred or divided (Swan, 2015; Tapscott, 2016).

New developments in blockchain since 2014 are leveraging novel categories, distinctions, and understandings of value allocation, and new standard classifications and definitions are still emerging. Some of the terminology that broadly refers to the blockchain 2.0 space can include Smart Contracts, Smart Property, Decentralized Applications and Decentralized Autonomous Organizations (DAOs) (Choi, 2017; Dino et al., 2016; Swan, 2015).

It is also important to note that not all processes need an economy or a payments system, or peer-to-peer exchange, or decentralization, or robust public record keeping. The scale of operations is a relevant factor, because it might not make sense to have every tiny microtransaction recorded on a public blockchain and every node of the ledger to contain all data. Transactions could be batched into *sidechains* (Back et al., 2014) in which one overall daily transaction is recorded and nodes can be *sharded* to speed up ledgers synchronization (Kelly, 2014).

There is ample opportunity to explore more expansively the idea of the blockchain as an information technology converging the design and construction activities and the built environment, including what a consensus models might it mean and enable in the design process (Maciel, 2014). A key question is what is consensus-derived information; that is, what are its properties and benefits vis-à-vis other kinds of information?

Blockchain technology helps to distinguish at least three different levels of information. The first level being plain, unmodulated data. A second level can be described as data elements enriched by social network peer recommendation. The quality of the information is denser because of this social recommendation layer. On the newly proposed level three, blockchain consensus-validated data, peer recommendations are further formalized using a consensus mechanism about the quality and accuracy of the data (Swan, 2015). Blockchain technology thus is thought to produce a third tier of information modulated with quality attributes.

20.4.1 Basic principles

Blockchain is a growing list of records, called blocks. These blocks are linked using cryptography and each block contains a cryptographic hash of the previous block, a timestamp and transaction data.

A cryptographic hash is generated by a function that has certain properties which make it suitable for use in cryptography of blockchains. It is a mathematical algorithm that maps data of arbitrary size to a bit string of a fixed size (a hash) and is designed to be a one-way function, that is, a function which is infeasible to invert (Halevi and Krawczyk, 2006). The Bitcoin blockchain uses the SHA-256 (Secure Hash Algorithm) standard typically looking like the following in Table 20.1:

Table 20.1 SHA-256 example

'hash': '0000000082b5015589a3fdf2d4baff403e6f0be035a5d9742c1cae6295464449',

In Figure 20.1, we can find a basic diagram of the composition of a block in a Bitcoin blockchain. As blocks are created, each block has a header containing a number of key data.

A *timestamp* is added, registering when blocks are found. The block also contains a hash referring to parent block. This *Prev_Hash* of the previous block header ties each block to its parent, and therefore by induction to all previous blocks. This chain of references is the eponymic concept for the blockchain.

The Merkle Root or *Tx_Root*, is a reduced representation of the set of transactions that is confirmed with the block. The transactions themselves are provided independently, forming the body of the block. In the case of Bitcoin, there must be at least one transaction, called the *Coinbase*. This is a special transaction coining a program that may create new Bitcoins and collect the transactions fees. Other transactions are optional. An arbitrarily picked number or a *Nonce* is used to add entropy to a block header without rebuilding the Merkle tree.

The *target* corresponds to the difficulty of finding a new block. In the Bitcoin blockchain, the target is updated every 2016 blocks when the difficulty reset occurs.

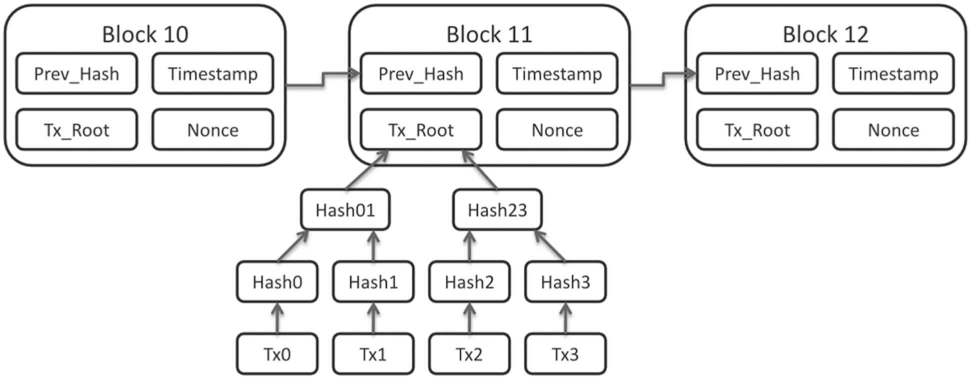

Figure 20.1 Bitcoin block data (Wander, 2015)

All of the above header items (i.e. all except the transaction data) get hashed into the block hash, which for one is proof that the other parts of the header have not been changed, and then is used as a reference by the succeeding block.

20.4.1.1 Synchronizing ledgers

As many miners compete to find the next block, often there will be more than one valid next block discovered. This is resolved as soon as one of the two forks progresses to a greater length, at which any client that receives the newest block knows to discard the shorter fork. These discarded blocks are referred to as *extinct blocks*.

This and other consensus mechanisms are necessary to create tolerance to failure in the given distributed system resilience. This is normally refed to as Byzantine Fault Tolerance (Lamport et al., 1982) and it can be summarized as any fault presenting different symptoms to different observers, or any loss of service due to a Byzantine consensus fault (Driscoll et al., 2004). The development of new consensus mechanisms is one of the main avenues to improve performance in blockchains.

20.4.2 Disruptive aspects of blockchain

Blockchain represents a significant leap in the way we digitally manipulate value, identity and automation of processes. There are numerous blockchain applications and use cases, and they have been previously structured into six categories (Strategic Registry, Identity, Smart Contracts, Dynamic Registries, Payment Infrastructures, and Others) across its two fundamental functions – record keeping and transacting (Carson et al., 2018).

20.4.2.1 A network of value

One of the primary concerns of a digital value network is the issue of double-spending. This refers to the incidence of an agent spending the same balance of a unit of value more than once, effectively creating a disparity between the spending record and the amount of that unit available. The issue of double-spending is a problem that cash does not have. A transaction using a digital currency like Bitcoin, however, occurs entirely digitally.

Bitcoins and other blockchains solve this double-spending problem with no central authority by using one or more consensus mechanisms. In the Bitcoin case, the waiting for confirmations when receiving payments leads to the transactions becoming more irreversible as the number of confirmations rises (BitcoinWiki, 2019; Hoepman, 2008; Osipkov et al., 2007). This reliable digital network of value with no central authority opens up a number of opportunities in a wide range of fields.

20.4.2.2 Data ownership and control

Decentralized Identifiers (DIDs) are a type of identifier for verifiable, 'self-sovereign' digital identity on a blockchain. DIDs are fully under the control of the DID owner, independent from any centralized registry, identity provider, or certificate authority. DIDs are URLs that relate a DID owner to means for trustable interactions with that owner. DIDs resolve to DID Documents, which are simple documents with instructions for the specific DID. Each DID Document may contain at least three things: proof purposes, verification methods, and service endpoints. For example, a DID Document can specify that a particular verification method, such as a cryptographic public key or pseudonymous biometric protocol, can be used to verify a proof that was created for the purpose of authentication. Service endpoints enable trusted interactions with the DID controller (W3C, 2019a; Windley, 2019).

Opensource blockchain projects like Hyperledger Indy (Hyperledger, 2018) enable purpose-built decentralized identity. It provides a toolkit for creating and using independent digital identities rooted on blockchains or other DLTs so that they are interoperable across administrative domains, applications, and any other 'silo'.

Generally speaking, because blockchains cannot be altered after the fact, it is essential that use cases for ledger-based identity are carefully consider in relation to its foundational components, including performance, scale, trust model, and privacy. In particular, 'privacy by design' and 'privacy-preserving' technologies are critically important for a public identity ledger where correlation can take place on a global scale.

For all these reasons, open source initiatives emerged to developed specifications, terminology, and design patterns for decentralized identity along with an implementation of these concepts that can be leveraged and consumed universally (Hyperledger, 2019). Other Hyperledger projects are infrastructure and tools to enable the exchange of blockchain-based data, support peer-to-peer messaging in various scenarios, and facilitates interoperable interaction between different blockchains and other DLTs (George et al., 2019).

20.4.3 Technical challenges and limitations

Blockchain limitations include those related to technical issues with the underlying technology as well as ongoing industry thefts and scandals, government regulation, and the mainstream adoption of the technology.

The issues are in clear sight of developers, with different answers and solutions suggested. Many are building different and new blockchains to circumvent limitations. One central challenge with the underlying blockchain technology is scaling up from the current maximum limit of transactions per second, especially if there were to be mainstream adoption of blockchains like Bitcoin (Lee, 2013). Some of the other issues include increasing the block size, addressing blockchain bloat, countering vulnerability to 51% mining attacks, and implementing hard forks (changes that are not backward compatible) to the code, as summarized here (Spaven, 2014).

20.4.3.1 Throughput and latency

The Bitcoin network has a potential issue with throughput in that it is processing only one transaction per second (tps), with a theoretical current maximum of 7 tps. The Ethereum blockchain supports 15 tps (Etherscan, 2019; Hertig, 2018).

For reference, metrics in other transaction processing networks are VISA (2,000 tps typical; 10,000 tps peak), Twitter (5,000 tps typical; 15,000 tps peak), and advertising networks (>100,000 tps typical) (Swan, 2015). A higher performance would be necessary and core Bitcoin and Ethereum developers are working to raise limits for when it becomes necessary (GitHub, 2019). One way that Bitcoin could handle higher throughput is if each block were bigger, though right now that leads to other issues with regard to size and blockchain bloat (Swan, 2015).

Average confirmation time of Bitcoin transactions from in 2019 was about 10 minutes (Statista, 2019b). For sufficient security, it is advised to wait longer for larger transfer amounts as the confirmation number must outweigh the cost of a double spend attack.

20.4.3.2 Size and bandwidth

The Bitcoin blockchain already takes a long time to download. If throughput were to increase by a factor of 2,000 to VISA standards, for example, that would be 1.42 PB/year or 3.9 GB/day. At 150,000 tps, the blockchain would grow by 214 PB/year. The Bitcoin community calls the size problem 'bloat'. Scaling to mainstream use may not require necessarily more nodes, but a more efficient access. This might motivate centralization, as more resources are needed to run a full node, and about 50% of all nodes are in only three countries (Bitnodes, 2019). It is an ongoing discussion whether location discrimination for running full nodes should be a factor for automated rewards by the network.

Innovation to address blockchain bloat and make the data more accessible are APIs that facilitate automated calls to the full Bitcoin blockchain. Some of the operations are to obtain address of balances and balances changes and notify user applications when new transactions or blocks are created on the network. There are also web-based block explorers (Blockchain, 2019), middleware applications allowing partial queries of blockchain data, and frontend customer-facing mobile e-wallets with greatly streamlined blockchain data.

20.4.3.3 Security

From the potential security issues with blockchain, the most troublesome is the possibility of a 51% attack, in which one mining entity could take control of the blockchain and double-spend previously transacted coins into his own account (Valkenburgh, 2018). The issue is the centralization tendency in mining where the competition to record new transaction blocks in the blockchain has meant that only a few large mining pools control the majority of the transaction recording. At present, the incentive is for them to be good players, and some have stated that they would not take over the network in a 51% attack, but the network is insecure (Rizzo, 2014). Double-spending might also still be possible in other ways – for example, spoofing users to resend transactions, allowing malicious coders to double-spend coins.

Another security issue is that the current cryptography standard that Bitcoin uses, Elliptic Curve Cryptography, might be crackable. Financial cryptography experts have proposed potential upgrades to address this weakness (Wang et al., 2019).

20.4.3.4 Resources

Some consensus mechanisms and mining draw an enormous amount of energy, all of it wasted. The earlier estimate cited was US$15 million per day, and other estimates are higher (O'Dwyer and Malone, 2014). Bitcoin's annual electricity consumption adds up to 45.8 TWh. The corresponding annual carbon emissions range from 22.0 to 22.9 MtCO2. This level sits between the levels produced by the nations of Jordan and Sri Lanka (Stoll et al., 2019). The wastefulness proof of work (PoW) and mining is what makes blockchains like Bitcoin trustable, but such a huge waste indicates the consensus mechanism needs to be improved and become sustainable.

20.4.3.5 Infrastructure and usability

Many technical issues in blockchain have to do with their infrastructure. One issue is the proliferation of blockchains, and that with so many different blockchains in existence, it is becoming easy to deploy the resources to launch a 51% attack on smaller chains as happened with the Ethereum Classic (ETC) in January 2019 (Nesbitt, 2019).

Another issue is that when chains are split for administrative or versioning purposes, there is no easy way to merge or cross-transact on forked chains.

From a different perspective, APIs for working with blockchains like Bitcoin, Ethereum and Hyperledger projects are far less user-friendly than the current standards of other easy-to-use modern APIs, such as widely used RESTful APIs (RESTfulAPI, 2019; W3C, 2019b).

20.4.3.6 Ecosystem

Another critical technical challenge and requirement is the creation of a complete ecosystem of solutions, particularly in service delivery. There are needs for secure decentralized storage (MaidSafe, 2019; Storj, 2019) messaging, transport, communications protocols, namespace and address management, network administration, and archival to name a few.

The blockchain industry may develop similarly to the cloud-computing industry, for which standard infrastructure components were defined and implemented at the beginning to allow for the development of value-added services instead of the core infrastructure. This is important in the blockchain economy due to the cryptographic engineering aspects of decentralized networks.

20.4.3.7 Innovations

Many of the innovations to the technical issues include *Offline Storage* for storing the bulk of consumer cryptocurrencies (Bonneau et al., 2015).

The proposition of *Dark Pools* envisions a more granular value chain such that big crypto-exchanges operate their own internal databases of transactions, and then periodically synchronize a summary of the transactions with the blockchain – an idea borrowed from the banking industry (Peters and Vishnia, 2016).

Hashing Algorithms like the one proposed for Litecoin and other cryptocurrencies are at least slightly faster than Bitcoin (Christidis and Devetsikiotis, 2016). As new, faster hashing algorithms are being developed, the prospect of new applications of blockchain become feasible.

There are many novel *Consensus Models* being proposed with lower latency, requiring less computational power, wasting fewer resources, and improving security for smaller chains (Zheng et al., 2017). Methods for consensus without mining or proof of work are also appearing and evolving. One example is the Practical Byzantine Fault Tolerance algorithm (Hyperledger, 2018).

To coordinate transactions between blockchains and create blockchain interoperability using several *Sidechains* is also being investigated and developed (Hwang et al., 2018).

20.5 Application considerations

Blockchain can play a significant role in facilitating new business models and the new transactional requirements in the construction industry. It makes possible for BIM platforms to be operated via smart contracts, signalling the team when to initiate a particular transaction and further automating construction procurement processes from the outset.

Here we discuss a few considerations on blockchain application development.

20.5.1 Levels of distribution and access

Over the past few years, blockchains have evolved in different builds and configurations. The content stored on the blocks of the blockchain and the activities performed by the various participants on the blockchain networks can be controlled depending upon how the blockchain is configured, and how it is expected to fulfil the desired business purpose.

Public and private blockchains are the two most common types used in various cryptocurrency networks and the private enterprises. A third category, permissioned blockchains, has also gained traction in recent times.

For instance, Bitcoin, the most popular cryptocurrency blockchain, allows anyone to participate in the network in the capacity of a full node, or a contributing miner. Anyone can take a read-only role or make legit changes to the blockchain like adding a new block or maintaining a full copy of the entire blockchain. Such blockchains, which allow equal and open rights to all participants, are called open, public, or un-permissioned blockchains. Recently, Bitcoin, Ethereum and EOS (2019) have been ranked as the most popular public blockchains and a number of performance indicators for public blockchains have been proposed (Tang et al., 2019).

If one needs to run a blockchain that allows only a selected entry of verified participants, like those for a private business, an internal private blockchain can be implemented. A participant can join such a private network only through an authentic and verified invitation, and a validation is necessary either by the network operator(s) or by a clearly defined set protocol implemented by the network (Seth, 2019). An incentive strategy, like a payment for mining for blocks, mainly aims to promote resource sharing, to stimulate group intelligence, and to promote collaborative communication. Private blockchain platforms are set to a specific group, rather than to everyone. Thus, incentive mechanisms or mining activities are not mandatory (Lu, 2019).

Permissioned blockchains can be nested in public blockchains and maintain an access control layer to allow certain actions to be performed only by certain identifiable participants. These blockchains differ from public as well as private blockchains.

The intrinsic configuration of such blockchains controls the participants' transactions and defines their roles in which each participant can access and contribute to predetermined parts in the blockchain. It may also include maintaining the identity of each blockchain participant on the network. An example of such blockchains include Ripple (2019), which determines roles for a select number of participants who can act as transaction validators on their network (Frankenfield, 2018).

The versatility of permissioned blockchains are popular in industry-level enterprises and businesses, for which security, identity and role definition are important. However, the transactions that occur on such a blockchain may also involve logistics partners, financing banks, and other vendors involved in the supply and financing process. These external parties, though part of the whole network, don't have to know the price at which the manufacturer supplies the products to various clients. Use of permissioned blockchains allows such role-limited implementations.

Some of the features of public, private and permissioned blockchains can be combined in hybrid, more exotic blockchain architectures (Foley, 2018).

20.5.2 Tokenized economies and alternatives

As previously mentioned, the *tokenization* of assets refers to the process of issuing blockchain tokens (specifically, a security token) that digitally represents a real tradable asset. This is in many ways similar to the traditional process of securitization (Laurent et al., 2018).

This new *token economy* offers some efficiencies by reducing friction associated with the creation and treading of securities. Some of the key advantages are greater liquidity, faster and cheaper transaction, more transparency and more accessibility (Laurent et al., 2018).

Some obstacles are the regulatory framework around the decentralized nature of the blockchain infrastructure. Security regulations are typically technology agnostic, and security tokens, depending on their exact features, can be implicated by the full scope of relevant security regulations and variations from different jurisdictions (HMT, 2018).

Tokenization represents a novel and powerful way to coordinate assets and value distribution in all verticals, including real estate, finance and naturally, in the construction sector.

20.5.3 Energy, speed and resilience

A *consensus mechanism* is a fault-tolerant device used in distributed computation systems to achieve the necessary agreement on a single data value or a single state of the network among distributed processes or multi-agent systems, such as with blockchains. It is useful in record-keeping, among other things (Frankenfield, 2019).

Bitcoin was originally described as a purely peer-to-peer version of electronic cash allowing online payments to be sent directly from one party to another without going through a financial institution (Nakamoto, 2008). It is one of the original blockchains and probably one of the most power-hungry platforms because of its proof of work (PoW) system to compile blocks in the ledger.

Ethereum describes itself as a decentralized platform that runs smart contracts (Ethereum Foundation, 2018) as Decentralized Applications (DApps). The Ethereum platform uses a Proof-of-Stake (PoS) involving the allocation of responsibility in maintaining the public ledger to a participant node in proportion to the number of virtual currency tokens held by it. This is a low-energy, low-cost methods to create consensus in the ledger. However, this method has been criticized for promoting cryptocoin saving, instead of spending.

R3 Corda is a blockchain and smart contract platform initially developed for financial applications but now being used in various domains (R3, 2019a). Corda can handle complex agreements. This capability has broad applications across industries including finance, supply chain and health care. The consensus mechanism in Corda is has two combined ties aiming to determining whether a proposed transaction is a valid ledger. They are *Validity* consensus – this is checked by each required signer before they sign the transaction, and *Uniqueness* consensus – this is only checked by a notary service (R3, 2019b).

Hyperledger is an open source collaborative effort created to advance cross-industry blockchain technologies. It is a global collaboration, hosted by Linux Foundation, developing enterprise grade blockchain technology (private and beyond) in finance, banking, Internet of Things, supply chains, and manufacturing (Hyperledger, 2018). Hyperledger architectures of the consensus layer in their many projects use a number of algorithms, including *Proof of Elapsed Time* (PoET), *Proof of Work* (PoW) and the use of voting-based methods including *Redundant Byzantine Fault Tolerance* (RBFT) and *Paxo* (Hyperledger, 2019). This creates flexibility to customize blockchains for particular applications and sectors.

Many new blockchains are appearing and some have creative propositions for their consensus mechanism. It is important to take into consideration the properties of the blockchain when selecting one for deploying a new application.

20.6 Blockchain and the construction sector

Construction brings together large teams to design and shape the built environment. Technologies and workflows like BIM create openness to collaboration across the industry. This momentum could be leveraged to bring the use of blockchain technology to the fore (Hughes, 2017).

Reports published since 2017 indicate that there is much progress to be made with the education, implementation and deployment of services based on blockchain technology. They point to a number of prospects and opportunities posed by using the technology in the sector, including efficiency (payments and transactions), cost savings, transparency and the augmentation and enhancements of IoT, AI and BIM (Arup, 2019; ICE, 2018; Reuters, 2018).

The fact that many surveys have all shared a number of the above points is encouraging as it suggests a willingness to critique and thereby improve understanding of the technology, not solely to appear ‘ahead of the curve’ with industry trends.

Significant progress is needed in the development of standards before adoption is achieved. There have not been many concrete indications of a future timeline for this, however it is expected that cities, energy and transport use cases will likely see adoption from 2025 (Arup, 2019, p. 18). Earlier reports such as by Thomson Reuters (2017, p. 12), Digital Catapult (2018) and the CDBB (Lamb, 2018) suggest that there is still a high degree of uncertainty about the future of blockchain. Indeed, it has been asserted that, by 2023, 90% of blockchain-based supply chain initiatives will suffer ‘blockchain fatigue’ due to a lack of strong use cases, according to Gartner (Omale, 2019). This conclusion was reached from data gathered between November 2017 and February 2018, including the finding that only 19% of respondents ranked blockchain as a very important technology for their business, and only 9% have invested in it (Omale, 2019).

Now more than a year later, it could be that these attitudes have improved following the further industry analysis and education that has taken place through these reports and continuing investment in piloting the technology. There has also been a doubling of tech investment in construction in the past decade (ENR, 2018) and there are a number of well-established firms providing blockchain solutions. A further detailed study to confirm or refute any changes in attitudes would be welcome.

In order to accelerate the understanding and development of blockchain technologies, more investment and collaboration is necessary. The University College London based Construction Blockchain Consortium (CBC, 2019) exists as a neutral platform to further these objectives through its series of white papers, providing knowledge transfer and assisting the development of use cases.

20.6.1 Blockchain and building information modelling

Blockchain technology is ideal for total life cycle management of an asset, from design to delivery to operation and reuse. The technology can act as a bridge between all stakeholders, allowing each party to track progress with the option to set up automatic payments, address responsibilities quickly and protect intellectual property.

Blockchain can help to better manage the construction progress monitoring stage, as well as solve the cash flow problem often experienced by companies.

As BIM evolve and further the 3D Design description model, adding extra dimensions of Time, CapEx, carbon cost and life cycle costing, and eventually include more complex dimensions of risk, financing and change control performance, asset management and project control performance, blockchain seems to embody the data architecture necessary to enable the deployment of these new dimensions. This evolution leading to highly integrated workflows and closer collaboration will demand for more and better professional transdisciplinary in order deal with future challenges and to future-proof design and construction (Brown et al., 2010).

Virtual Environments, including VR, AR and XR are key coadjutants on the process of capturing and 'blockchaining' data at source, also visualizing this back to integrated teams. Open source real-time graphics engines (Unity, 2019; Unreal, 2018) are opportunities to further develop Construction 4.0 and enable some of the interface ergonomics necessary for blockchain adoption.

From the many types of AI and ML, novel methods like *Big Generative Adversarial Networks* (BigGAN) are proving to be far more effective in yielding complex automation by unsupervised learning (Zhang et al., 2019). In an age of 'Fake News' and uncertainty of facts in an ever-increasing digitalized world, immutability and provenance of data it's not only timely, it is also absolutely paramount. This data forms the basis for realistic AI/ML applications on predictions, operations and benchmarking of the built environment.

20.6.2 Construction supply chains

Another area in which blockchain is predicted to feature heavily in the next decade is the transactions and security mechanisms associated with the IoT. Blockchain can also pride 'trustless' interactions between users and machines and add value to the supply chains in a similar way it can add value to BIM.

In the context of the property sector, IoT is the method of collection and exchange of data processed by smart contracts. This has potential to disrupt supply chains, leading to live tracking of goods and materials, allowing the circular economy to flourish, dramatically automating the 'metabolic' systems in the built environment and conserving energy (Arup, 2016).

20.6.3 Computational legal contracts and procurement

Currently, most construction projects work towards BIM Level 2 (BSI, 2014; 2013, 2007). Blockchain could accelerate the development and application of BIM Level 3 and realize the end-to-end transparent collaboration.

Computational contracts or smart contracts are currently described as applications that run exactly as programmed without any possibility of downtime, censorship, fraud or third-party interference (Ethereum Foundation, 2018). Smart contracts have the potential to become fully developed computational legal contracts and improve dramatically all aspects of construction project administration and payment systems in the sector. Computational legal contracts can become the engine for smart infrastructure and the combine circular economy.

The use of collaborative BIM has created a necessity for the use of single project insurance. Smart contracts operating with BIM processes offer a far more proactive method for delivering projects. The interoperability of smart contracts and BIM can leverage efficiencies in the allocation of accountability in seconds instead of days or weeks. Blockchain can address project complexity and in doing so reduce late payments, remediations and disputes that place companies under cash flow risk (ICE, 2018).

At the same time, collaborative procurement is a decisive enabler of digital transformation and are under intensive study. All the chronical issues identified in the sector, like frequent change requests, cost overruns and late delivery, failure to administer contracts correctly and/or effectively, failure to manage projects, mishandling of delay can bring cash flow restrictions, such as late payments and other cash flow issues. To address these, enhanced project management and control, transparency and availability of accurate information in project governance are needed. A sector-generic and project-bespoke blockchain-enabled solution can alleviate these repercussions and optimize cash flow restrictions (ICE, 2018).

20.7 Challenges in the adoption of blockchain

Recent reports published in the period 2016 to 2019 BIM (Arup, 2019; Digital Catapult, 2018; ICE, 2018; Reuters, 2018) note that the full-scale adoption of blockchain could take years because the majority of use cases are in test phases and concerns about profits and the vested interests underpinning these may hinder adoption.

In general, there is still a lack of understanding and trust in the technology, which is slowing investment in, and adoption of, the technology.

The assumption that blockchain technology is inherently secure is wrong. Security vulnerabilities have been uncovered, with potentially more arising in future, and need to be addressed rapidly on an ongoing basis. Failure of firms to ensure that blockchain is appropriately integrated into their processes and business model – and with necessary interoperability – could result in any potential cost savings being nulled or reversed.

A system of globally compatible governance needs to be created in order for blockchain adoption to effectively address global challenges and work seamlessly across regions and borders.

It is expected the blockchain will become an invisible layer and will not represent a great deal of difference for the user but there are energy, scalability and flexibility issues. Consensus mechanisms have to be studied carefully and become more sustainable, faster and scalable.

Ergonomics and Users eXperience (UX) on the application of blockchain is also a factor. As BIM become more complex and map/represent wider phenomena in the built environment, this new knowledge has to be presented eloquently. Effective UX will have to be implemented to handle this new knowledge and some evidence supports that integrated team favour graphic and immersive UX systems (Demian and Walters, 2014).

This is a key aspect in facilitating BIM adoption and accelerating maturity of both technologies in the construction sectors.

20.8 The fourth wave: what might happen next

The Decentralized Autonomous Organization (DAO) represents an innovation in the design of organizations, in its emphasis on computerized rules and contracts, but the DAO's structures and functions also raise issues of governance (Chohan, 2017).

One of the first incarnations of a DAO was 'The DAO' (stylized Đ). This was form of investor-directed venture capital fund (Waters, 2016).

The DAO had an objective to provide a new decentralized business model for organizing both commercial and non-profit enterprises (Allison, 2016; Rennie, 2016). It was instantiated on the Ethereum blockchain (Ethereum Foundation, 2018), and had no conventional management structure or board of directors (Allison, 2016). The code of the DAO is open-source (Brady Dale, 2016).

The DAO was stateless, and not tied to any particular nation state. As a result, many questions of how government regulators would deal with a stateless fund were yet to be dealt with (The Economist, 2016). It was crowdfunded via a token sale in May 2016. It set the record for the largest crowdfunding campaign in history (Waters, 2016).

In June 2016, users exploited a vulnerability in The DAO code to enable them to siphon off one-third of The DAO's funds to a subsidiary account. In July 2016 the Ethereum community decided to hard-fork the Ethereum blockchain to restore virtually all funds to the original contract (Buterin, 2016).This was controversial, and led to a fork in Ethereum, where the original unforked blockchain was maintained as Ethereum Classic. The DAO was delisted from trading on major exchanges in late 2016.

Despite this incident, the concept of a global automated legal persona is very attractive. If we consider superhuman computational processes yielding better outcomes, as in algorithm trading, can a DAO eventually fix national health systems? Can they strategically invest globally to remediate global challenges? Perhaps this is far-fetched, but let's consider for a moment the interoperability issues in the construction sector: Could a DAO help to deliver BIM Level 4 or 5 – fully coordinate and interoperate BIM models, leveraging IFCs and CoBie ontologies to deliver better projects and protect IP in the industry?

The possibilities are many and fundamentally disruptive. They bring a new set of problematics that need to be investigated thoroughly.

20.9 Conclusion

Data and information asymmetry represent one of the major challenges for all agents in the construction sector. Supervising every aspect of a construction project is currently an opaque, fragmented and inefficient process.

Blockchain is a way of organizing transactions or information so that they can be viewed independently by relevant parties and cannot be changed after the fact.

To fully grasp the potential impact of blockchain in the built environment, it is worth taking a holistic view of Industry 4.0. Previous industrial revolutions were erratically distributed across the world, with change often taking significant time before affecting communities.

In today's industrial revolution we have almost instantaneous knowledge-driven dissemination. This is a new socio-technological phenomenon with effects yet to be understood and, needless to say, controlled. It is expected that the Fourth Industrial Revolution will transform the world with a far higher speed, scope and impact than any previous technological revolutions we have experienced.

In this new context of ubiquitous and embedded computing, we can still duplicate and tamper with data. We can fake news, manipulate imagery in real time and double-spend money. How can construction projects' participants prove their identity, stakes and actions? How can different communities have an effect on how their cities are developed and how can they interact with the new emerging intelligent environments they live in?

Blockchain offers much more than a secure, immutable and resilient DLT. It offers the means and opportunity to rethink financial, social and political relationships informing the built environment. It does so by providing digital assets with some of the properties and behaviours of physical objects. This represents one of the key technologies enabling the cyber-physical convergence in the Fourth Industrial Revolution.

The 2018 'Gartner Hype Cycle' displays a decline in the hype of blockchain (Gartner, 2018). Blockchain has now entered the 'implementation phase' and will probably become an invisible but important layer in an interconnected world.

DLT and blockchain also provides a new foundation for machines and humans to interact and exchange information. As a consequence, we may see disruption in infrastructure management, energy and real estate to autonomous transport and water management.

Blockchain can be used as an ID for asset for a circular economy, from design to delivery to operation and reuse. For its resilience, it is the favoured technology to connect people, assets and environments over long periods of time. It can create an '*automation of trust*' with parties having certainty regarding identity, reputability and a price guarantee.

Decentralized Smart Legal Contracts are emerging as the LegalTech to automate contract administration, avoiding chronic industry problems and optimizing construction cash flow. This represents an immense opportunity for the industry and can further improvements on areas such as IP protection, accountability, building management systems, operations and energy conservation.

Blockchain is only one piece of the puzzle in the Construction 4.0. It will very likely be the common thread connecting many technologies. It will require careful consideration on its design and implementation when creating the new global digital trust ecosystem in order to fulfil its promises.

20.10 Summary

- Construction projects rely on effective use of complex data and information, which often exist in different forms.
- Lack of consistency and symmetry of data can result in an opaque, fragmented and inefficient process.
- Blockchain allows organization of transactions or information so that they can be viewed independently and cannot be changed after the fact.
- Unlike previous industrial revolutions, which developed erratically across the world with a time-lag before affecting communities Industrial Revolution 4.0 features almost instantaneous knowledge-driven dissemination.
- The Fourth Industrial Revolution is likely to impact the world with higher speed, scope and impact than any previous technological revolution.
- This carries with it opportunities and risks with ubiquitous, embedded computing that can still allow data to be duplicated and tampered with.
- Construction project participants need a way to prove their identity, inputs and actions, whilst communities and stakeholders seek to have an effect on how their cities and emerging intelligent environments are developed.
- Blockchain offers a secure, immutable and resilient DLT, but also the means and opportunity to rethink financial, social and political relationships informing the built environment by providing digital assets with some of the properties and behaviours of physical objects.
- Blockchain is one of the key technologies enabling the cyber-physical convergence in the Fourth Industrial Revolution.

- Blockchain will probably become an invisible but important layer in an interconnected world, providing a foundation for machines and humans to interact and exchange information.
- As a core technology of IR4.0, it will cause disruption in infrastructure management, energy and real estate to autonomous transport and water management.
- Blockchain can create an '*automation of trust*' with parties having certainty regarding identity, reputability and a price guarantee.
- Smart Legal Contracts are emerging as the LegalTech to automate contract administration, avoiding chronic industry problems and optimizing construction cash flow.
- Blockchain is very likely be the common thread connecting many technologies.

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