Digital Construction Management Series

Distributed information & BIM total lifecycle

Edited by Abel Maciel

About the Construction Blockchain Consortium

The Construction Blockchain Consortium (CBC) was established to develop knowledge transfer, arrange commercial and academic presentations, assess and test commercial services and technology, conduct research, and drive policy, regulation and understanding of the consequences of Distributed Ledger Technologies (DLT) such as Blockchain, and other emerging technologies in the Built Environment. We also establish open-source projects and encourage application developers to build proprietary technology and services for sustainable construction solutions.

In this second document of a series of white papers, we elaborate on the impact of Blockchain in the production of the Digital Twin (DT) and how this unfolds in Virtual Design and Construction (VDC) and Building Information Modelling (BIM) processes and technologies. We review the current impact of Blockchain, as well as emerging DLT such as BlockDAG and TDAG technologies in relation to digitally-enabled Pre-Construction and Construction processes throughout the whole lifecycle of built assets.

This document presents evidence for shaping future policy and regulation in collaboration with the British Parliament. We review current developments of Blockchain technology that are relevant for the construction sector in line with ISO 19650:2020. We also consider issues of cyber security, e.g. the NIST (IoT supplement) IST, ISO/IEC 27001:2017 and ISO8887-1:2017 and assess their impact.

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How to use this document

This document is directed to business strategists and policy makers. It aims to map current complexities, disruptions and contradictions of Building Information Modelling (BIM) within the construction total lifecycle. We then present opportunities for future policy and compliance by reviewing developments in BIM and construction automation and examining how DLT and Blockchain may play a role in the advancement of BIM and the digital transformation of construction generally. It also takes into consideration the growing concerns of cybersecurity in digital transformation.

For ease of reading, technological details and their clarification are reserved for the appendices or footnotes, with the intention of offering entry points to the key concepts of technologies discussed. The authors have also made an effort to select and use high-quality references that readers can use to expand their knowledge in the domain.

Executive Summary

1 *Digital transformation in the construction sector is accelerating. This is true not only for large and complex projects but also smaller, simpler projects involving Micro, Small and Medium Enterprises (SMEs). Production of digitally native design data and 'reality capture' in the sector is expanding exponentially. This heterogeneous data is envisioned to play a significant role in the performance required to meet targets in the industry.*

2 *While the adoption of Building Information Modelling (BIM) is increasing, there remain challenges to its full exploitation. Distributed Ledger Technology (DLT) applications, typified by Blockchain, can offer solutions to many of these challenges.*

3 *However, such advancement will not be possible without disruption to some of the traditional business models and processes that the industry has used over the last 200 years. The sector stands on the threshold of a disruptive but beneficial digital transformation.*

4 *Disruption in the industry highlights the impact of entrepreneurs and startups. It points to the potential of Small and Medium Enterprises (SME's) wider participation. Blockchain is likely to lead to redundancies in BIM library management. However, the scope for implementing Blockchain solutions in BIM systems must take detailed account of the challenges of current legislation and context. The industry has to take coordinated action to maximise the benefits of BIM in the context of Industry 4.0.*

5 *We review the industry's maturity in BIM and related technologies, to indicate how much progress needs to be made to educate users, integrate technologies and implement project standard methods and procedures. This also considers opportunities for Design for Manufacturing and Assembly (DfMA) and Modern Methods of Construction (MMC).*

6 *Future opportunities include the upgrading of cyberphysical architectures, automated management and automated contractual arrangements and mechanisms. This has to be conceived via a wider definition of BIM encompassing procurement processes and diverse financial models for construction.*

7 *Data and information bridging between 'pre' and 'post' construction processes will become critically important. Digital Twin (DT) will enable better knowledge management over the whole asset lifecycle and assets' second life. New opportunities will arise to leverage BIM data for business intelligence and foresight.*

8 *Potential disruption caused from cybersecurity threats and attacks are increasingly significant, with an impact on systems, teams and organisations. The hash encryption that makes Blockchain inherently secure may help to overcome such mounting cybersecurity threats. Current BlockDAG architecture can overcome Quantum decryption.*

Foreword

The construction industry is largely characterised by fragmentation in processes, services and firms. One of the most persistent problems is the disconnect between the design, construction, and eventual operation of its products. This is mainly due to the lack of open and trustworthy information across the supply chain. Distributed Ledger Technology (DLT) such as Blockchain has the potential to overcome these effects through the use of open and transparent transactions.

In addition to coordinating the interfaces between design, construction, and operation, Blockchain technology can contribute to improving each of them individually. First, Blockchain can facilitate Computer Supported Collaborative Work (CSCW) and Computational Design in general by enabling transparent information flows. Second, Blockchain technology can enhance information and change management in Building Information Modelling (BIM) (both authoring and managing tools). Third, Blockchain can offer a secure, immutable and auditable electronic record of built assets and the transactions, actions and decisions that occur over their lifetime.

By building upon the solid data foundation that Blockchain offers, and automating this data using smart contracts, projects can operate in a trusting environment. Distributed Ledgers and Blockchain can improve supply chain management and logistics control to an unprecedented level of efficiency and reliability.

The Internet of Things (IoT) is changing the way built assets and their contents and systems are serviced. Through the use of sensors and connected/smart appliances, buildings can benefit from true life-cycle thinking. Blockchain can facilitate the feasibility, scalability, privacy, and reliability of IoT applications in construction. With the advent of connected devices pertinent to Building Management Systems (BMS), Blockchain can rationalise and regulate information flows to and from building systems reliably and securely.

The CBC started to investigate what DLT means for BIM and IoT in 2018. We are converging technologies to forge a ‘responsibility’ chain for the manufacturing and construction sectors. We are exploring how BIM capabilities can be expanded by integrating and inter-operating BIM and Blockchain/DLT technologies.

As an open platform for industry and academic collaboration, the CBC investigates transferability of solutions, generic enablers, and use case translations of technology applications, for example, from aviation to construction. Throughout this paper, we present references and examples to highlight and demonstrate the potential of the integration of BIM and Blockchain.

Prof. David Greenwood,

Construction Blockchain Consortium

1.0 Advances in BIM and Construction Automation

Summary

- *This Introduction chapter outlines the main processes and areas in the construction industry expected to be disrupted by the conciliations of BIM and Blockchain frameworks.*
- *It explains BIM foundational technologies and how they are currently implemented in project delivery.*

1.1 Exploring Reconciliations

Building Information Modelling (BIM) is now largely perceived by the construction sector and policy makers as a combination of technologies and processes that can change the way built assets are designed, constructed, maintained and operated. Proper implementation of BIM can unlock benefits that extend across the whole lifecycle of built assets: these include improved predictability and quality of design, increased confidence in project programmes and budgets, reduced overall project risk, and enhanced sustainability of physical assets (Sacks et al., 2018).

Since its introduction, BIM connotations have been broadening, from early interpretation focusing on its technological aspects to current views depicting BIM as the expression of digital innovation in construction. The benefits of BIM and its expanding connotations have had important consequences for the sector and we expect that these will increase. For example, the benefits of BIM have attracted many policy makers to either encourage or mandate Information Technology Systems (ITS) adoption within their respective construction sectors. The UK Government has positioned BIM at the centre of its strategy for the future of construction, and mandated BIM requirements on all centrally-procured projects since 2016 following their intention to do so in 2011 (Cabinet Office, 2011). In the UK, as advocated by the UK BIM Framework (comprising the UK BIM Alliance, the British Standards Institution and the Centre for Digital Built Britain), BIM now refers to an information management methodology that has at its core the adoption of a standards-based approach to managing information across the whole lifecycle of built assets (i.e. encompassing design, build, operate and integrate) (UK BIM Framework, 2021). In an information-intensive industry such as construction, the adoption of such a holistic and standardised approach to information management and the innovative digital ways of working are deemed necessary to achieve improvements in delivery and performance efficiencies critical for the industry.

The UK is now an international leader in the adoption of BIM and the development of related standards. Central to the UK's success with its BIM journey was this holistic interpretation of BIM. With this shift in focus towards holistic information management across the whole lifecycle of built assets, in which BIM is only one of the main technological and procedural means, it is of paramount importance for the UK, to consider potential integration of BIM with other technologies such as Blockchain and the Internet of Things (IoT). Indeed, emerging studies show several potential applications where the two technologies (BIM and Blockchain) form part of wider technological systems that can transform existing processes in a radical way and enable new ones. Examples include CognitiveBIM that uses real-time data collection and response to ensure the comfort and safety of building occupants (Tagliabue, 2021); intelligent contracts such as the iContract - a self-executing contract containing electronically drafted provisions with the ability to automate a variety of processes in accordance with its terms (McNamara and Sepasgozar, 2020); improving liability for design input through record-keeping of legally critical information exchange transactions on a Blockchain (Erri Pradeep et al., 2021); the use of IoT devices for real-time monitoring on a construction site to support better site management practices and efficiency increases (Shojaei, 2019); and supporting the building of trustworthy 'Digital Twins' as virtual representations of physical assets (Lee et al., 2021) that can facilitate the use of new performance contracting models (Hunhevicz et al., 2022).

The UK's approach to construction is set out in The Construction Playbook (Cabinet Office, 2022), which captures commercial best practices and specific sector reforms while outlining the government's expectations of how contracting authorities should engage with suppliers and their supply chains. BIM forms a central part of the Playbook throughout its 14 key policies[1] that set out how the government should assess, procure and deliver public works projects and programmes, which all central government departments and their arms length bodies are expected to follow, on a 'comply or explain' basis.

1.2 The Evolving Nature of Construction Data

The perception of data in the AECO[2] industries has changed since the early days of CAD/CAM geometrical manipulation to include a huge range of information relevant to construction processes and built asset operation. There is an increasing coupling of the fundamental geometrical representation with material specification and performance, costing, maintenance instructions and operation (NBS, 2021; RIBA, 2014). This is leading to a surge in the amount of digital data being generated through the whole lifecycle of built assets. Advances in BIM allow for high quality and very detailed project documentation to be developed and shared dynamically. Digital models exploiting Design for Manufacturing and Assembly (DfMA) can enable offsite fabrication methods and building systems improvements. This is opening up significant opportunities for automating the design and engineering processes and is increasingly being exploited for integrating supply chains.

IoT sensors providing live data and analytics derived from this data, processed in the cloud or at the edge (by the sensor itself), can be used to monitor the safety of resources on site and their productivity. Such developments

[1] *These 14 policies include: commercial pipelines; market health and capability assessments; portfolios and longer term contracting; harmonise, digitise and rationalise demand; further embed digital technologies; early supply chain involvement; outcome-based approach; benchmarking and should cost models; delivery model assessments; effective contracting; risk allocation; payment mechanism and pricing approach; assessing the economic and financial standing of suppliers; and resolution planning.*

[2] *Architecture, Engineering, Construction and Operations*

are leveraging the increased capacity to capture and process data to establish a 'data-driven' construction sector that harnesses value from BIM data and information. However, one of the key challenges is the very nature of data and processes within the AECO industries, which influence our ability to exploit and derive value from this surge in data volume. Our response, whether in the development of new technologies or new standards, can lower some of the barriers but it may also introduce new ones. For example, competition in BIM authoring software has created new technologies and tools that contribute to the production of additional data but at the same time created issues of interoperability of proprietary data formats.

Therefore, there is a growing need (and opportunity) to improve digital workflows involving BIM, IoT network fabrics[3] and all the data of external systems that can enhance the built environment. However, harnessing such data through improved digital workflows must address the challenge that valuable data is heterogeneous, with both structured and unstructured content, and is supplied by verified and unverified sources. Prospective solutions need to consider transparent management, network scalability, security, and transaction costs.

While transparency is a main attribute of Blockchain, its scalability has been questioned, especially when the number of participating entities in a given process grows. Recent Blockchain-based technological innovations are addressing these challenges, for example, solutions like IOTA (2020), NANO (2021), Byteball (Obyte, 2021) are DAG-structured[4] Blockchains. These are lightweight chain-structured Blockchains like LSB (Dorri et al., 2019) and PoET[5] (Imes et al., 2015). Alternative structures like Tree-Chain are also addressing the scalability issue. Additionally, Peer-to-Peer file sharing protocols like IPFS[6] (Protocol Labs, 2021) and data formats are scalable and can constitute part of the solution when applied in conjunction with Blockchains and/or BlockDAGs.

These emerging solutions involving distributed data technologies are likely to play an important role in achieving more resilient, transparent and secure information management within the AECO sector in the near future.

1.3 The Collaborative Dimension of BIM

Cloud-based Common Data Environments (CDEs) servicing BIM processes are now widely used in medium to large construction projects where distributed teams are a necessity to run projects effectively. The BIM data, including its geometry, can be developed, reviewed and validated in a browser or in a virtualized application. There is a constant flow of data from stakeholders' models to the federated BIM in the CDE.

[3] *The IoT Network fabric is the interconnected, woven systems of gathering and transmitting data for the Internet of Things. The network fabric carries data from the hardware-defined product to the software-defined product. It functions as a distributed computing system and facilitates networking through various digital communications layers.*

[4] *Emerging blockchain technology with Directed Acyclic Graph (DAG), also known as BlockDAG, is deemed an alternative technical idea to solve some of the bottleneck issues of blockchains throughputs capability and the scalability.*

[5] Proof of elapsed time (PoET) is a consensus algorithm developed by Intel Corporation that enables permissioned blockchain networks to determine block winners and mining rights. It follows a lottery system that spreads the chances of winning equally across network participants, giving every single node the same chance of winning.

[6] *The IPFS (InterPlanetary File System), is a peer-to-peer protocol for storing and sharing large amounts of data in a distributed manner. It It is both highly scalable and resistant to hacking, and can also help protect data ownership when integrated with Blockchain.*

This capability has been vital during the COVID-19 pandemic as it brings new project coordination opportunities but also a new set of challenges, from Intellectual Property (IP) issues to data licensing and cybersecurity points of failure that may, for example, result in system attacks when a Digital Twin is applied to a built asset.

Although the project federation of collaborative BIM content creation is a critical step in eradicating data silos that obstruct project delivery, the AECO design processes lag behind other industries in change notification and model versioning (Watson et al., 2019).

The development and application of CSCW[7] tools in other industries and social media platforms are moving at a far greater pace than we currently experience in the construction sector. However, current solutions like the Construction Cloud Suite (Autodesk, 2021), iTwin (Bentley, 2021) and more generic 'reality mesh modelling', have constant synchronisation of built asset data that can be accessed from various interfaces, from Mixed Reality displays to building management data driven dashboards. This incorporates other systems like geographic information systems (GIS), Artificial Intelligence (AI) and an array of cloud based microservices, complex virtual environments infrastructure being developed in frameworks and computational languages (Microsoft, 2021).

1.4 Interoperability and ToolChains

Interoperability is the "ability of two or more systems to exchange information and to use the information that has been exchanged" (IEEE, 1991). Toolchains are sets of distinct development tools that are linked (or chained) together by specific stages (Fitzgerald et al., 2015). Both toolchains and interoperability features are desirables outcomes A Systems Approach to Infrastructure Delivery (ICE, 2020).

In creating a new built asset, architects, engineers and specialists use many tools chained in different fashion to design, specify and manage the data and collaboration in a construction project. The change of a tool in a toolchain may yield different results in the data generated by that toolchain set. This represents an interoperability challenge in terms of data consistency for the current and future teams involved with a building asset.

To guarantee consistent data and ontologies in a given data-driven construction project, common structures for describing things in the world: geometry, materials, assemblies, phasing, etc., must be formulated and agreed upon. The functional challenges of providing dependable interfaces for software capabilities (given input x, output y) depend upon this.

In relation to simulation and analysis, cloud services to BIM help to accelerate project delivery, completing computation-intensive tasks in minutes instead of days. Extending BIM management to the entire team to improve quality, safety, and commissioning processes in the field. However, cloud services and cloud storage are available via subscription or maintenance plans for some software (Autodesk, 2020). Conversely, case studies of decentralised marketplaces for computing power enable CPUs and GPUs[8] to connect in a peer-to-peer network,

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[7] *Computer Supported Collaborative Work*
[8] *Computer Processing Units and Graphic Processing Units.*

enabling both application owners and individual users to rent computational power of their machines on demand and at scale. Nowadays, centralised cloud providers are in control of these services, these platforms are constrained by closed networks, proprietary payment systems, and hard-coded provisioning operations. Alternative frameworks propose an open-source, decentralised and user controlled system (Golem, 2020).

BIM processes are also leveraging reality capture to a greater extent. Conventionally, surveys are typically realised in one-shot and stage-based. Current technological advances allow for more frequent updates, challenging established conventions regarding provenance and accountability.

As BIM and Digital Twin progress and digital assets become more sophisticated, verification of output at point of experience/evaluation becomes critical.

1.5 BIM Cybersecurity

Cybersecurity encompasses everything that pertains to our daily lives, from data, and geolocation information, to software and hardware such as smart devices, vehicles, and buildings. With the world moving towards an Internet of Everything (IoE) the risk of a successful cyber attack is increasing. Global connectivity also means integrating services such as cloud technologies for data storage, edge sensors for reporting information, actuators to execute tasks, data in transit for reporting and many other services. These services represent various entry points for an adversary.

In general, adversaries and threats can come from both outside and inside an organisation. They may involve a wide range of skills: from simply launching a software downloaded onto the internet to the ability to disrupt, steal, or ransom an infrastructure (at the level of the nation state).

The importance of cybersecurity in the context of BIM is on the rise with the ever greater integration of disparate data sources such as real-time sensor data, and data continuously shared across organisations. The current cybersecurity measures implemented in BIM have the potential to leave organisations extremely vulnerable to cyber-attacks and data breaches. The impact of such an attack may be devastating to a project or organisation due to the loss of IP, sabotaging the project, or hackers gaining the ability or knowledge to hijack the physical system (Ref). This has a significant cost, with companies in the United Kingdom spending an average of £3.8M in 2019 to recover from a security breach, and taking an average of 280 days to detect an incident and an additional 34 days to stop the breach (Ref). Such an issue will only be exacerbated by the application of Digital Twins, which seek to utilise a multitude of internal and external data sources to create a digital replica of an asset.

The development of BIM for Digital Twin also heralds an ecosystem of connected Digital Twins (CDBB, 2019). Recognition of this in respect of BIM is manifested in the publication of ISO 19650-5 where cybersecure BIM and project information security is discussed (ISO, 2020).

2.0 Why Blockchain? Relevance in the AECO Context

Summary

- *This chapter highlights the principles and processes of Blockchain applications that might be relevant for BIM. It discusses other emerging technologies currently being considered for BIM application.*

2.1 The Distributed Paradigm

To date, the conventional approach to organising digital information in AECO has been to gather it centrally (e.g., a centralised common data environments) despite its highly decentralised and heterogeneous origins. This has resulted in the problems of IP, trust, and security referred to in 1.3, above. A decentralised approach may offer a solution, and represent the resilience we require in the built environment. A decentralised computational method employs several distinct systems processes that consume separate inputs and emit separate outputs in arrays of computers; the outputs collectively constitute a solution to a given problem. Crucially, no computation accesses all of the inputs required to solve the overall problem and in some cases, a change to a single input may change many of the outputs (Kelly, 2020). Computations may, but need not, execute simultaneously and/or in different places; in other words, decentralisation can offer computational resilience.

Software and patterns that support distribution can facilitate decentralisation, but the former do not define the latter. For example, a decentralised design may freely leverage old-fashioned remote procedure calls (Tay and Ananda, 1990), tried-and-true service-oriented architecture (Coatta, 2008) or newfangled[9] microservices. The essence of decentralised computing is not in its infrastructure but in its information asymmetry. No single entity has enough information to solve the problem. Each entity sees a fragment of the overall input and generates a fragment of the output; in the end everything works out as if a single all-knowing solver were at work.

Decentralised computing is a large topic and new architectures like Blockchain and BlockDAG are still emerging. These architectures can protect, perfect and complete information in ways previously unknown.

[9] *Given a topology and one of its MISes, is it always possible to rename nodes so that the TalkDown algorithm computes the given MIS?*

2.2 Data, Information & Synchronising Ledgers

2.2.1 Blockchain Encryption

Central to blockchain immutability is the hash encryption method commonly used in cryptocurrencies such as Bitcoin. Blockchain relies on distributed encryption and hashing to store immutable records viz-a-viz many of the existing cybersecurity solutions on the market. Blockchains offer enhanced security performance as true Blockchains are distributed and do not require the trust of an individual member of the group or network.

Although they considered the traditional hash decryption commonly used in Bitcoin to be impractical in Built Environment contexts, Pärn and Edwards (2019) found that Blockchain technologies do offer an added layer of cybersecurity for connected assets and devices (Pärn and Edwards, 2019).

More recent investigations into security encryption techniques with Blockchain have demonstrated that the hash encryption method is not suitable for securing resource-constrained IoT ecosystems, yet alternative lightweight encryption schemes can complement IoT cybersecurity better (Taylor et al., 2020). The most commonly suggested lightweight blockchain encryption methods for IoT include: attribute-based encryption (Derler et al., 2019) and identity-based encryption (IBE) (Ateniese and de Medeiros, 2004);

In homomorphic encryption[10] for cybersecurity applications in IoT, the use of Blockchain encryption includes permitted access control for devices (Dorri et al., 2017), secure tracking of data management, prevention of malicious access to sensor data, securing historic IoT connections and sessions, and detecting malicious behaviour (Taylor et al., 2020). Other commonly alluded to cybersecurity applications of Blockchain encryption include: data storage and sharing (Yue et al., 2017), network security (Bozic et al., 2017), data privacy (Fu and Fang, 2016), and validity of wireless internet access points (Niu et al., 2017).

2.2.3 Distributed Storage

The internet has accelerated innovation by being one of the great equalisers in human history but increasing consolidation of control threatens that progress. Distributed data architectures are also being applied to internet data storage. Distributed filing systems stay true to the original vision of an open, flat web by delivering technology to make that vision a reality.

Currently, Hypertext Transfer Protocol (HTTP) downloads files from one computer at a time instead of getting pieces from multiple computers simultaneously. Peer-to-peer distributed filing systems save significantly on bandwidth (up to 60% for video) making it possible to efficiently distribute high volumes of data without duplication (Nguyen et al., 2009). The application of a blockchain layer can further enhance this with resilient and traceable data storage.

[10] Homomorphic encryption is a form of encryption that permits users to perform computations on its encrypted data without first decrypting it.

2.2.2 Tokenization

In the data security context, Tokenization is the process of substituting a sensitive data element with a non-sensitive equivalent, a token with no extrinsic or exploitable meaning or value. The token is an identifier that maps back to the sensitive data through a tokenization system. The mapping from original data to a token uses methods that render tokens infeasible to reverse in the absence of the tokenization system, for example, using tokens created from random numbers (WEX, 2017). The tokenization system provides data processing applications with the authority and interfaces to request tokens, or detokenize back to sensitive data.

Non-Fungible Tokens (NFTs) have recently emerged as the mechanism of choice for digital art and other assets. In simple terms, they also define a new economic mechanism to manage IP and data servitization. They represent a plausible proof of ownership but also a fundamental mechanism that can be further developed into a sovereignless accountability chain.

2.2.4 Computational Legal Contracts and DAOs

Smart contracts are similar in structure and philosophy to their offline counterparts in that they promise a set of services in exchange for some form of value. The main difference here is that they are implemented digitally and substantially automated. Thus, a physical or digital action is triggered when a certain set of criteria (defined in code) is met. For example, property rental agreements can be encoded with conditions that enable a landlord to release a smart locking device, once a rental payment is made (Sharma, 2020).

Smart Legal Contracts (SLCs) can be designed to have single or multiple signatures to authorise transactions when certain criteria are met in the contract.

The programming of Computational Legal Contracts is currently a challenge. However, domain specific solutions for Computational Legal Contracts like Ciccero (Accord, 2021a) and Ergo (Accord, 2021b) are currently being developed in collaboration with the Construction Blockchain Consortium and the Accord Project (Accord, 2021c). This allows more sophisticated executable business logic using a programming language specifically engineered for legal agreements and to create reusable, machine readable natural-language contracts and clauses using a templating system.

A ‘Decentralised Autonomous Organisation’ (DAO) is a collection of cross-linked computational contracts modulating each other. The original expression DAO came from The DAO - an organisation designed to be automated and decentralised using smart contracts in the blockchain. It acted as a form of venture capital fund, based on open-source code and without a typical management structure or board of directors. To be fully decentralised, The DAO was unaffiliated with any particular nation-state, though it made use of the Ethereum network. The developers of The DAO believed they could eliminate human error or manipulation of investor funds by placing decision-making power into the hands of an automated system and a crowdsourced process. The

DAO was designed to allow investors to send money from anywhere in the world anonymously and provide those owners with tokens, allowing them voting rights on possible projects (Reiff, 2019).

3.0 BIM-Blockchain Synthesis: An Analysis of Potential Benefits

Summary

- *This chapter surveys industry on BIM maturity to indicate how much progress needs to be made to educate users and implement/integrate new and existing technologies.*
- *It considers the impact of entrepreneurs and startups in the industry and the potential of SMEs wider participation.*
- *It outlines the potential disruption caused from cybersecurity threats and attacks, including Blockchain hash encryption and what makes Blockchain secure, as well as overcoming mounting cybersecurity threats with Blockchain hash encryption.*
- *It discusses data representation and transparency opportunities in the industry.*

3.1 BIM Maturity in Context

In this section we examine the role of BIM in the digital transformation of the Built Environment and in bringing the AECO industry closer to the vision of Industry 4.0, where emerging technologies combine in cyber-physical integration. This includes consideration of the meaning of 'BIM maturity', and the distinction between the selective, localised adoption of BIM and its wider diffusion. The scene is set for how the inclusion of Blockchain technology with BIM can help to meet some of the challenges and remove some of the systemic barriers in order to accelerate the digital transformation of the creation and functioning of the Built Environment.

3.1.1 The Evolution of BIM

BIM has been articulated in maturity models such as the 'BIM Levels' (0-3) adopted by the UK BIM Task Group. Similarly (Succar, 2009, p. 357), identified BIM as 'an expansive knowledge domain' with expanding boundaries that start with object-based modelling (Stage 1) and proceed via model-based collaboration (Stage 2) and aspiring to network-based integration (Stage 3). The process is one of increasing integration and distribution, both in terms of participants and the applications they use.

In 2018, the International Organisation for Standardisation issued the ISO 19650 standard (Churcher et al., 2019; ISO, 2020), which outlines the concepts and principles for information management at a stage of maturity described as "building information modelling (BIM) according to the ISO 19650 series". It aims to set out the requirements for digital transformation of the UK's Built Environment by making BIM according to the ISO 19650 series business as usual. The new suite of ISO 19650 documents provides recommendations for a framework to manage information including exchanging, recording, versioning and organising for all actors and is applicable to the whole lifecycle of any built asset, including strategic planning, initial design, engineering, development, documentation and construction, day-to-day operation, maintenance, refurbishment, repair and end-of-life. The ISO 19650 can be adapted to assets of any scale and complexity, so as not to hamper the flexibility and versatility that characterise the large range of potential procurement strategies and so as to address the cost of implementing this standard.

3.1.2 BIM as a Catalyst for Digital Transformation

From around ten years ago **(Eastman et al., 2011; Tobin, 2013)** to more recent discussions **(Love et al., 2020; Ma et al., 2018; Pärn and Edwards, 2017)**, BIM has been considered not only as a useful tool that sustains and improves existing practices but as a potentially disruptive technology - what Orlikowski **(1992)** calls a *"trigger of structural change"* - for the AECO industries. BIM has been considered as a fundamental link in the convergence of cyber-physical systems **(Li, et al., 2019)** and a crucial element in the construction industry's route to Industry 4.0 **(De Luca et al., 2021, pp. 219–242; Maskuriy et al., 2019)**.

The distinction between disruptive and sustaining technological innovations is explained by Bower and Christensen **(1995, pp. 43–53)** who observe that organisations "*are unwilling to use a disruptive product in applications they know and understand*". In the case of BIM, this manifests in the selective adoption or 'cherry picking' of BIM reported by Krystallis et al. **(2019)**. In Succar's BIM Stage 3, the collaborative use of integrated models across the project lifecycle is disruptive, in that it "necessitates major reconsideration of contractual relationships, risk-allocation models and procedural flows" [ref]. To reach this 'tipping point', the innovation must (i) establish a sufficient and pervasive hold within its business environment, and (ii) must also overcome some systemic barriers. These challenges are dealt with in turn.

3.1.3 Establishing a Sufficient and Pervasive BIM Maturity

The concept of BIM maturity has been widely-considered and much-debated. In the UK, for example, NBS has published (each year between 2011 and 2021[11]) an annual report on the uptake of BIM and its reported benefits **(NBS, 2021, p. 15)**. Twenty-five systems that purport to measure BIM maturity were evaluated in a report for the Centre for Digital Built Britain by Kassem et al. **(2020)**. The majority focus on individual organisations; only six relate to projects. The report notes the need to assess the maturity of the whole supply chain, concurring with the conclusion of Papadonikolaki et al. **(2015)** that exploiting the full benefits of BIM depends on BIM maturity throughout that project's supply chain, rather than that of individual organisations within it. This pervasiveness, in turn, depends on organisational capability and interoperability (or standardisation) of information flow within the project supply chain. Furthermore, it should be added that in order to be sustainable - in a business context where project teams form, dissolve, and re-form with different actors - the pervasiveness must be replicated at sector level.

[11] The NBS conducted and published the National BIM Survey from 2011 to 2020. From 2021 onwards, the NBS will conduct and publish the Digital Construction Survey.

3.1.5 Overcoming the Systemic Barriers

Even when these conditions are met, there remain systemic barriers within the AECO business environment that might prevent BIM evolving into a disruptive innovation. Some of these are firmly embedded in the economics of behaviour. In an information-sensitive environment such as construction, this is manifested in the lack of trust and imperfect collaboration highlighted by almost every industry report since that of Sir Michael Latham (1994). The same problems persist when the information is digital: for example, Bolpagni et al. (2016:435) identify issues of "security, confidence in data, [and] quality assurance of information" as the greatest barriers to the diffusion of BIM. These are the very challenges that can be addressed by the implementation of Blockchain technology in BIM work processes (see, e.g. Nawari & Ravindran (2019, pp. 209–238)) as Blockchain brings with it the "key advantages of inherent immutability, transparency and the way it redefines the trust relationship by offering solutions that are fast and secure and can operate publicly or privately" (Li et al., 2019).

3.2 Addressing asset whole asset lifecycle

From inception to completion of a construction project, data flow informs the business case, the geometry, the manufacturing and construction process, the operations and facilities management of the built asset and the eventual decommissioning of the building's systems and recycling/reuse of its parts and materials.

Currently, this workflow is characterised as a *fragmented*[12] and *non-destructive*[13] collection of processes aiming to reiterate the knowledge of a constructed asset over its pre-existence and existence timeline. Although the situation has improved with the adoption of BIM, this is by no means efficient and/or optimum in current project execution. The non-destructive nature of data generation in BIM and beyond multiply the virtual representation in arrays of copies and versions, when in reality only one representation should be used by the AECO *Federated Team*[14]. The Digital Twin has to include asset representation as well as human-to-machine (H2M) and machine-to-machine (M2M) interaction models. This is critical for the utility of the Digital Twin. The Digital twin is only as good as the cyber-physical systems updating its knowledge base.

To address the use of Blockchain in the AECO industries, one has first to address the total lifecycle of buildings and the current technological toolkit the industry has available. Only then can we make a sensible assessment of

[12] An organization's knowledge on its business processes represents valuable corporate knowledge because it can be used to enhance the performance of these processes. In many organizations, documentation of process knowledge is scattered around various process information sources. Such information fragmentation poses considerable problems if, for example, stakeholders wish to develop a comprehensive understanding of their operations.

[13] Non-destructive editing (sometimes called NDE for short) is a method of editing in Digital Design Tools that allows you to make changes to a digital assets without overwriting the original version data. This means that it is always possible to backtrack on adjustments made to an asset as needed, retaining flexibility and keeping the features and properties of the original asset intact. However, this multiplies the data and information that asset contains.

[14] A federated model is a combined Building Information Model that has been compiled by amalgamating several different models into one (or importing one model into another).

what can be solved exclusively by Blockchain, which Blockchain applications can represent an enhancement to current AECO technologies, and which processes and applications would be better off left without Blockchain.

3.2.3 Data and Information Entities and Dependencies

A data entity is an object in a data model, and this data is typically designed by breaking things down into their smallest parts that are useful for the virtual design and construction (VDC) process. A data dependency is a situation in which a program statement refers to the data of a preceding statement. This is often used to discover data dependencies among statements in dependence analysis.

The entities and dependencies in the concept of a building have shifted to including most knowledge of its production and use. This includes construction information, material specification and details, how people interact with a built asset and its operational performance, to name a few. The time period that data is collected and stored has also been altered with the industry realising the value of the building data being produced in the design and construction phases throughout an assets lifecycle. It is the utilisation of the data in the operation and maintenance of built assets that may gather new insights and streamline existing processes with the introduction of previously inaccessible asset data, in turn, enabling better informed decision-making. This body of knowledge can have many ‘form factors’ and representations, from a legal document to Business Intelligence (BI) dashboard, from 2D architectural projections to an immersive mixed reality experience. With their deployment and use differing between each Digital Twin use case representation.

The economics and the cost or a value to own or to use those entities and/or transport them between different states, has an impact on the BIM project development. For example, taking a 3D model to a level of application of a physical building will cost significant money and there is a value to having them.

The recently published Digital Twin toolkit report **(Walters, 2019)** highlights the importance of developing a business case for building a Digital Twin to examine the benefits and costs of creating one, as well as show it is worthwhile. The report states that “t*he digital twin can be an expensive asset delivering value over a number of years*”, thus, quantifying the value a Digital Twin is expected to unlock for money is a vital step to justify the decision of developing and owning one. The report suggests investigating value of developing a Digital Twin to cosider Natural, Social, Human, Manufactured and Financial aspects.

3.2.5 Key BIM Production Challenges and the New Challenges Emerging

When considering the key properties of Blockchain technology and its application in the AECO sector, there are some contradictions that can be immediately spotted.

Transparency vs. Confidentiality / Control: This whole thing of transparency versus confidential confidentiality and control so whenever transparency is a really good thing, on the other hand, you might need confidentiality and you want to control the information.

Provenance: Then there's the challenge of provenance - who made it who owns it. All the tool chains used. Does the industry have to maintain provenance?

Immutability vs. errors (deliberate or accidental): If it is possible to make data immutable, how can a project mitigate errors? (this being deliberate or accidental). On the one hand we want this thing to be immutable, on the other hand, errors do happen and how you correct them.

Longevity: Many buildings last longer than a few human generations. What digital preservation strategy is the most appropriate for an increasingly digitised industry?‘I took this BIM model. I ran this version of this simulation software. I got this result used to inform this output, we are tracking the whole toolchain. This is challenging.

3.3 Impact of Blockchain for BIM Management

During pre-construction, project teams that wish to combine BIM and Blockchain can define in the BIM execution plan (ISO, 2020-2) how the information management aspects of the project can be carried out. In two consecutive paper, Dounas and Lombardi (2019; 2019) propose four levels of BIM to Blockchain integration which can be defined at this stage:

- 1) Blockchain operating inside BIM environment;
- 2) BIM and Blockchain connected through the web;
- 3) BIM and Blockchain integrated through a Blockchain node (e.g. Ethereum node);
- 4) BIM database implemented as a decentralised database.

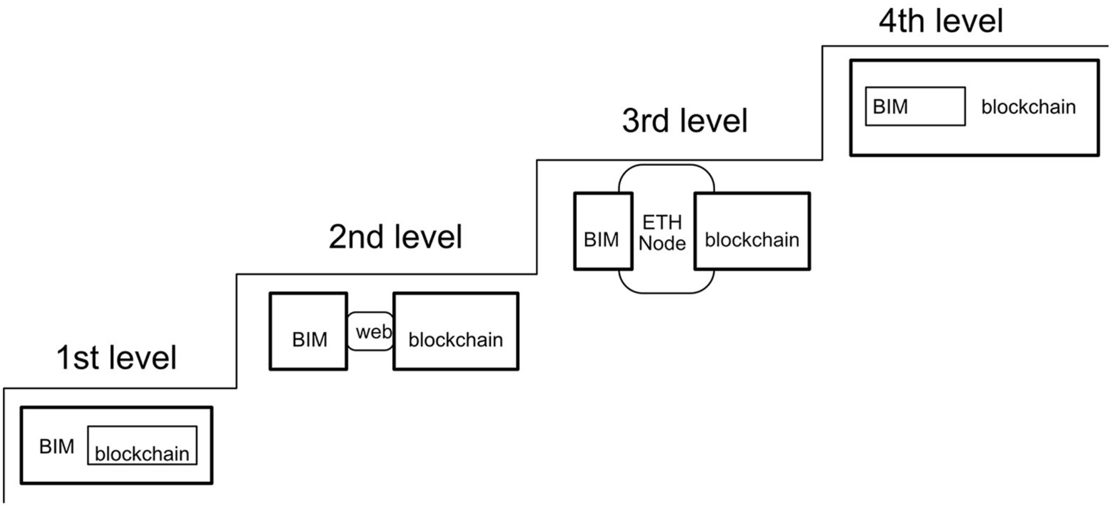

Figure #: Four levels of BIM to Blockchain integration (Dounas et al., 2021)

One opportunity is for Blockchain to act as the infrastructure to ensure trust, immutability and legibility of design responsibilities. This can create a layer for interoperability between digital software tools that communicate with the Blockchain. It would enable distributed project teams to author BIM models using the different design software on the same project, and avoid lock-in with one specific software vendor. The resulting implications might be a distributed design environment using BIM and Blockchain. As an example, Dounas et al. (2020) developed a BIM to Ethereum software prototype. Their proposed framework utilises Blockchain to navigate issues of consensus, trust, transparency, responsibility and incentivisation between designers. They structured the prototype in a manner that allows interoperability between digital tools that can communicate with the Ethereum Blockchain. Similar tools may be developed in the future to use the Blockchain as the main tool to record design information in a resilient manner. The project team can use Blockchain to record the sequence of design changes and steps in decision making as the project evolves over time (Dounas et al., 2021).

In respect to the construction delivery impact, almost all actors agree that complete data sets are important to hand over to an owner at the end of construction. However, there is often little incentive for the multiple stakeholders to provide these complete datasets during construction project delivery. As a result, data sets are often incomplete and low-quality at the end of a construction project. This creates rework or hinders opportunities to use data during future activities of the facility lifecycle (e.g. facility management, renovation, demolition).

Blockchain can offer a new crypto-economic incentive system to motivate actors to provide complete data sets. A research study conducted at ETH Zurich in Switzerland prototyped an Ethereum-based Blockchain system to incentivize the creation of high-quality data sets. The process traces and saves project data while incentivizing participants through reward tokens. The simple case study - conducted in collaboration with local industry participants - simulates how the prototype can function in a typical design-bid-build process. The detailed setup and findings can be found in the case study (Hunhevicz et al., 2020). Overall, it was found that such

Blockchain-based incentive systems have the potential to not only incentivize high-quality data sets, but also change the way of tendering and related construction processes. While the imagined incentive mechanism seems promising to motivate stakeholders to provide correct data drops, there is a need for future research to study different and specific incentive systems for the introduced purpose based on financial, reputation, or other possible tokenized reward structures.

Blockchain can also be used in collaboration with other technologies to govern Digital Twins during construction delivery. For example, to monitor progress and automate payment to trade contractors, Hamledari and Fischer (2021) prototyped a system that translated construction progress data collected by an unmanned aerial vehicle (i.e. a drone) and unmanned ground vehicle (e.g. Spot by Boston Dynamics) into payments. They also used ERC721 token to transfer lien waivers; each token represents the rights to physical property for which the payment is made. Lee et al. (2021) use Blockchain to time-stamp the virtual positioning data of a prefabricated brick, showing how project-related information can be shared across stakeholders through an integrated Digital Twin and Blockchain environment. Hunhevicz et al. (2022) implemented performance-based smart contracting by connecting blockchain to real-time energy performance data streaming from the Siemens Digital Twin platform.

3.3.1 Potential Asset Management Changes

Building components have long lifecycles. In some cases, the lifecycle of a building or infrastructure project lasts longer than the lifespan of the firms that build it. Smart contracts can be used to incentivize best practice over long time cycles, beyond the lifespan of firms.

Blockchain creates the opportunity for producing immutable and transparent records of these assets that can persist throughout the entire lifecycle (Hunhevicz and Hall, 2020). A record of information for both physical and digital assets can be provided on the distributed ledger. There are many potential applications for asset management. For digital building assets, there can be a record of ownership for BIM to protect IP among collaborating firms. For physical assets such as property or building products, a transparent record of ownership can be created. One example is the creation of material and product passports with product and provenance-related information for record keeping throughout the supply chain. For example, a material passport can be used to trace the carbon footprint of products in a building (Shojaei, 2019). Future building owners could make their carbon footprints transparent on a public Blockchain to benchmark their carbon performance. Such digital assets would become accessible to support decisions of relevant actors. Furthermore, assets can be further securitized and traded even while in use in a building. For example, one could trade the ownership rights to the steel beams or steel rebar found within a building, which should appreciate in value over time. These rights can then be sold to dismantling and recycling companies at the end-of-life of the building.

Material passports on the Blockchain can also be used for quality assurance in global construction projects or to enable the reuse of materials at a later stage of a building towards a circular economy (Pellegrini et al., 2020). Certification of products and buildings could also profit from the availability of this trusted data. However, there are still open questions about how to certify and verify the cyber-physical relationship for material passports on the Blockchain, ensuring that physical changes to the product that occur are indeed the same as the digital asset.

3.4 BIM for GovTech

One of the ways to guarantee secure distribution of data at scale is the use of zero-knowledge proof technics. A collaborative protocol implementing zero-knowledge proofs must necessarily require interactive input from the verifier. This interactive input is usually in the form of one or more challenges such that the responses from the prover will convince the verifier if and only if the statement is true, i.e., if the prover does possess the claimed knowledge.

The new party's acceptance is either justified since the replayer does possess the information (which implies that the protocol leaked information, and thus, is not proved in zero-knowledge), or the acceptance is spurious, i.e., was accepted from someone who does not actually possess the information.

Companies benefit from new collaborative BIM systems and the application of zero-knowledge proof technics can greatly enhance collaborative bim for GovTech. A number of new platforms have emerged to propose all-in-one solutions promising accelerated time-to-market, Zero IT Footprint, Risk Mitigation and IP Protection and Data Silos elimination (OnShape, 2021).

BIM development platforms can be virtualized for instant deployment on any computer or mobile device, enabling teams to work together globally and rapidly. Teams can experiment on creating embedded options and design alternatives together or independently from one another without affecting each other's work. Real-time design reviews, commenting and simultaneous editing enable a collaborative workflow where multiple design iterations can be completed in parallel, and when approved, the best elements can be merged into the final design. Product specifications and drawings can be instantly shared with manufacturing teams or suppliers to get the best possible product to market before the competition.

Virtualization and Zero IT Footprint means that BIM production software requires no downloads, installations, or license codes. Administrators can instantly provision and deprovision seats to scale their design team and meet fluctuating business needs. Built-in version control eliminates the need for Product Data Management (PDM) systems with dedicated servers and network infrastructure, software upgrades and licensing. This frees IT teams from CAD and PDM maintenance and empowers the design team.

When managing risk and IP Protection, traditional file-based CAD and BIM files are subject to unauthorized duplication, data breaches, or accidental sharing. A permissioned data-driven architecture can avoid security risks as files and data are stored and tracked with version history, allowing you to audit or roll back changes as needed. Strict, role-based access control keeps your design data secure at all times. Every designer, engineer, contractor, or supplier involved in the product design lifecycle is given specific permissions and rights. Instant deprovisioning means when a contract is complete, or an engineer leaves the company or changes roles, you can immediately revoke their access to the project.

By eliminating data silos national project teams are now able to make a design change and team and national stakeholders can instantly see and benefit from this change by orchestrated, built-in version control. Distributed teams can simultaneously explore alternative design ideas and converge on the best solution. It is possible to share models with suppliers to get earlier quotations, or send early prototypes to relevant departments. Up-to-the-minute analytics and reporting tools offer greater transparency to project stakeholders, and enable easier project management.

Although a completely integrated national BIM infrastructure is not in place yet in countries like the UK, such a infrastructure becomes more at reach with the advent of DLT and Blockchain validation processes.

3.5 Developing Resilience in the Digital Thread

A 'Digital Twin' of the built environment is a cyber-physical system emerging from the BIM process with input of current performance data from the asset (the 'physical twin') via live data flows from sensors. A Digital Twin can perform different activities or functions. These Digital Twin Uses can be combined in various ways to create new automation and efficiencies. For example: energy use and recovery, carbon modelling and planned maintenance.

Trust, whether that be in the people, process, or the data involved in Digital Twin creation is cited as being a key tenet of Digital Twin development, defined as a core principle in the CDBB's Gemini principles (Bolton et al., 2018) to be used in the development of the UK's National Digital Twin programme (Walters, 2019). However, this also highlights a roadblocks to Digital Twin development and echos a sentiment that can be traced back to the Latham Report (1994).

If the UK is to realise its aspirations to become a world leader in the development of Digital Twin, building on the successes of its BIM implementation, there must be efforts made to address the ingrained distrust within the industry. Blockchain may present an avenue to explore solutions as it is in essence a trutless mechanism.

3.6 Tokenised Federated Learning

Tokenizing BIM computational processes can represent a revolution in how BIM as a single source of truth is configured. This is particularly true if we consider how federated learning can be embedded in smart contracts running on a blockchain.

Standard machine learning (ML) approaches require centralising the training data on one machine or in a datacenter. For ML models trained from user interaction with mobile devices, a distributed approach can be used to federate this learning process using the distributed data out there.

Currently, Federated Learning enables mobile phones to collaboratively learn a shared prediction model while keeping all the training data on device, decoupling the ability to do machine learning from the need to store the data in the cloud. This goes beyond the use of local models that make predictions on mobile devices (like the Mobile Vision API and On-Device Smart Reply) by bringing model training to the device as well (McMahan and Ramage, 2017).

This approach seems well suited to BIM processes and technologies, where the current federated model improves by learning from data on local computers holding the local BIM models, and then summarises the changes as a small focused update. Only this update to the model is sent to the cloud, using encrypted communication, where it is immediately averaged with other user updates to improve the shared model. All the training data remains on user devices, and no individual updates are stored in the cloud.

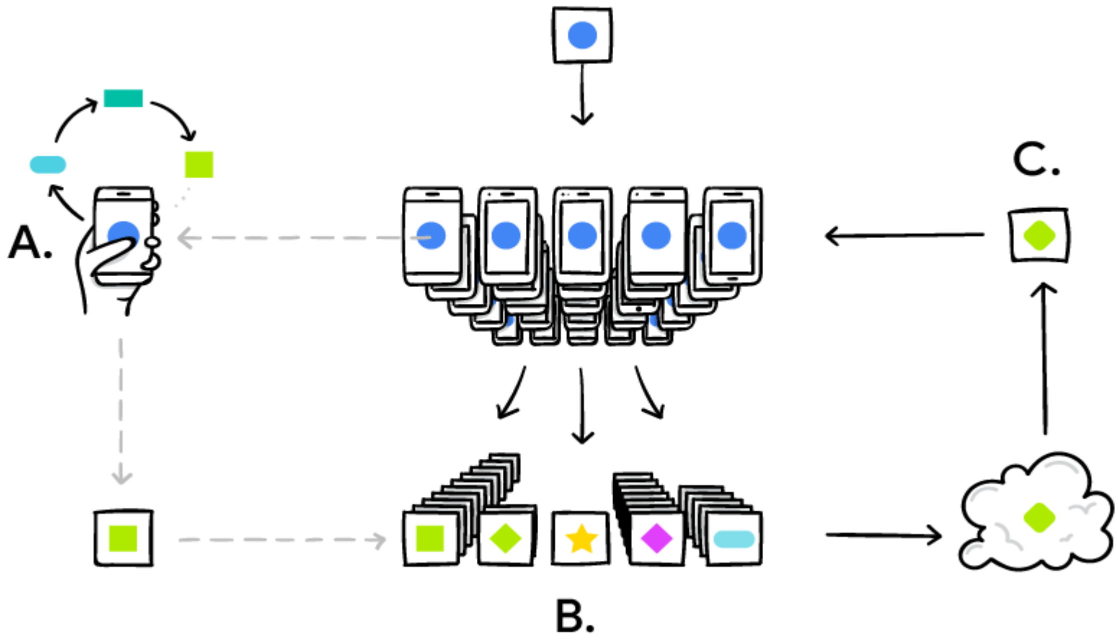

Figure #: Personalises phone model locally, based on personal usage (A). Aggregated user updates (B) to form a consensus change (C) to the shared model, after which the procedure is repeated.

Federated Learning has lower latency, and less power consumption, while ensuring privacy. Another immediate benefit, in addition to providing an update to the shared model, is that the locally improved model can also be used immediately to service on-going needs.

3.7 Addressing Cybersecurity

The construction industry is gaining increased attention and is an easy target for attacks. According to the report by FireEye (Sanger and Perlroth, 2020), the Construction/Engineering industries have climbed the rank of targeted industries from eighth place in 2018 to fifth place in 2019. The top three in 2019 were Entertainment/Media, Financial, and Government.

Another trend is that employees of smaller organisations have been the focus of email threats (such as spam, phishing, and email malware) when compared to those in large organisations. This is concerning because the supply chain of construction projects is mostly composed of SMEs, which generally do not devote sufficient resources to IT and security to mitigate the threats. The 2019 Internet Security Threat Report (ISTR, 2019) indicated that the construction industry was the third industry (after Mining and Wholesale trade) with a higher percentage of users targeted. Better investigation and a call for action is necessary to mitigate these risks in the AECO industry.

3.7.1 Cyber Threats and Vulnerabilities in the Built Environment

Throughout history, buildings and infrastructure have provided us with a physically secure sanctuary, protecting us from theft and malicious attacks. Today's environment is no exception and offers the same practical physicality. However, contemporary operations and maintenance (O&M) works have become increasingly dependent upon an expansive web of cyber-physical connectivity (Karabacak et al., 2016) and this connectivity has been achieved via a union of smart sensor-based network technologies, advanced computerisation and computational intelligence techniques (Bessis and Dobre, 2014). Seen in the context of virtual assets, the data and information generated throughout a development's whole lifecycle from the initial design, construction and eventual occupancy is the basis for the spread of knowledge, and insightful business intelligence as well as an invaluable commercial commodity. According to the U.S. Computing Community Consortium, smart infrastructure is the integration of sensor computing and communication capabilities with traditional urban and rural physical infrastructure such as roads, buildings and bridges to increase efficiency, resilience and security. In other words, each physical component or system of national critical infrastructure (buildings, roads, etc.) is digitally twinned in virtual space.

Cyber-space is described as the global, virtual, computer-based and networked environment, consisting of 'open' and 'air gapped' internet, which directly or indirectly interconnects systems, networks, and other infrastructures and that is critical to society's needs (European Commission, 2022). Within the vast expanse of cyber-space, three partially overlapping territories exist - the world wide web of nodes accessible via URL, the internet consisting of interconnected computers and the 'cyber-archipelago' of computer systems that exist in isolation from the internet within a so-called air gap (sometimes referred to as the Purdue model) (Kello, 2013). A CDE hosted on any of these territories can be considered to be exposed to cyber-physical attack.

During a cyber-attack, codes are utilised to interfere with the function of a computer system either for strategic, ambiguous, experimental or political purposes (Nye, 2017). Expanding on this definition, it can be said that cyber-attack constitutes: “any act by an insider or an outsider that compromises the security expectations of an individual, organization, or nation.” (Ghandi et al., 2011).

Actual cyber-attacks can take many forms. They may be in the form of publicised web damages, information leaks, denial-of-service attacks (DoS), and other cyber actions that can be related to national security or military affairs. Cyber-physical attacks can cause disruption or damage to physical assets and pose serious threats to public health and safety or the destruction of the environment.

3.7.2 Motivation of Cyber Actors

Cyber-criminals have made it their business to be able to harness the basic and real value of digital assets (BSI, 2015) and they can decipher the digital economy and its intricacies more astutely than those in the areas that are under attack (Kello, 2013). The most prominent ‘WannaCry’ ransomware attack in May 2017 was a worldwide cyber-attack by the WannaCry ransomware cryptoworm that targeted computers that were running Microsoft’s Windows operating system. The attacked data was encrypted, and ransom payments were demanded in the Bitcoin cryptocurrency. This showed the sophisticated measures that can be deployed by cyber-criminals in identifying, extracting and monetizing data found. While the value of digital assets to their owners and creators can vary, cyber-criminals manipulate data and information to encrypt, ransom or sell it piecemeal (Marino and Manic, 2016; Nicholson et al., 2012)

There have been several prominent instances of unsecured critical infrastructure assets being physically damaged by cyber-crime, and these have been widely reported upon (Peng et al., 2015). These include: the STUXNET worm that disarmed Iranian industrial and military assets at a nuclear facility (Lindsay, 2013); and the malware ‘WannaCry’ mentioned earlier that caused significant damage to the UK’s National Health Service (NHS) patient database, German railway operations as well as businesses around the world (Clarke and Youngstein, 2017).

Cyber-attacks remain a national security threat for the prosperity of a digital economy and the functionality and safety of the digital Built Environment (Karabacak et al., 2016). There have been many reports on the many different threats posed and these present real challenges, as cyber-attacks often enjoy anonymity as the malicious activity they are (Fisk, 2012; Kelly, 2015).

3.7.3 Mounting Threats from BIM and Digital Twins

The national infrastructure of the Built Environment is now considering Digital Twins as part of cyber physical systems (CPS). This has various social and physical dimensions posing significant vulnerability for cyber physical attacks. Digital Twins have a direct impact on the physical world as they monitor and control Physical Twins. This increased connectivity to digital networking systems open up opportunities for attacks. CPSs primary function is to act on the physical world and this has the potential to cause serious physical harm or disruption as a result of cyber security information breaches. These attacks can range from business operation interruption, brand damage, health and safety implications, IP theft, unwanted access to enterprise systems and dismantling national critical infrastructure.

Digital Twins in the Built Environment can broadly be organised into five types (component, asset, process, system and network of systems) where the information included in each level ranges from the component level including the granular information regarding a component (e.g., air filters, fans) to the network of systems, which is the oversight of a city scale Digital Twin encompassing the Built Environment with all its assets, processes and systems. The deployment of Digital Twins in the Built Environment means a growing share of networked components that are digitally connected through the internet on site and in off-site situations. The two trends contributing towards an increased cyber vulnerability arising from the recent technological advancements include, the growing number of interconnected systems enabled via the internet, sometimes through a simple USB key and the increased usage of cloud technologies. Despite the advantages brought by AI-using sensors, automatic data transfer and operational automation within the buildings, digital systems are massively at risk of malicious intrusions and cyber-attacks.

3.7.4 Relevant Cybersecurity Frameworks

In response to the challenges of cybersecurity, the US Cybersecurity Enhancement Act of 2014 (CEA) aims to assist owners and operators of critical infrastructure to identify, assess and manage cyber risks without placing additional regulatory requirements on those owners and operators. The National Institute of Standards and Technology's (NIST) Cybersecurity Framework (NIST, 2018) integrates cybersecurity activities into the organisation's risk management processes. The framework acknowledges the different threats, risks and vulnerabilities to different organisations and their tolerances. Its five functions include identify, protect, detect, respond and recover. The framework offers guidance to achieve specific outcomes rather than narrates how the outcomes should be achieved leaving flexibility to the organisations implementing cybersecurity processes. In addition to the Cybersecurity Framework, NIST is consulting on cybersecurity with regard to the IoT (NIST, 2016) and their inherent cybersecurity capabilities to mitigate risks to the users of such IoT-equipped devices. From a manufacturer perspective, the goal is to recommend six foundational cybersecurity activities. A set of capability core baselines for IoT devices is provided as a starting point for manufacturers to consider, though it is not mandated.

In the UK, the National Cyber Security Centre's (NCSC) Cyber Assessment Framework (CAF) (NCSC, 2022) is a tool for assessing cyber resilience in organisations. Its 14 principles considers general governance, but also a number of other topics such as risk, asset, supply chain, data and system security and proactive security. In line with NIST's Cybersecurity Framework, the CAF provides a checklist of outcomes rather than a 'to-do' list with assessment of principles centred on indicators of good practice.

4.0 Application Analysis

Summary

- *Chapters 2.0 and 3.0 review the technologies that can improve problems in BIM processes and the appropriateness of Blockchain for current BIM and VDC challenges.*
- *This chapter examines the scope for implementing Blockchain solutions in BIM systems, and how this must take into account the current BIM compliance and legislation, context and challenges.*
- *It highlights immediate opportunities including design and manufacturing accountability chain, further automation, digital fabrication, and improved project coordination.*
- *Future opportunities could include better security, automated management and contractual arrangements and mechanisms via the federated team and BIM framework and improved procurement processes via the BIM model and Digital Twin.*

The industry should develop a Blockchain-BIM overlay considering further automation of construction processes and its ramifications in adaptive supply chains and computational legal contracts. Adaptive systems using stigmergic coordination have been proposed (Dounas et al., 2021) and preliminary evidence of the suitability of transparent and traceable agents activity in decentralised operations shows a good fit for the fragmented nature of the AEC industry.

Standardisation of data across time, scales and expertise is critical for the running of Smart Contracts. Blockchain proposes a digital network of value suitable to sustain digital transformation of the construction sector. However, its nascence brings several challenges. On a base level, its functions have been proven for financial transactions (e.g., Bitcoin)—'Blockchain 1.0' (Swan, 2015)—but, as a socio-technical system for ‘Blockchain 2.0’ and ‘Blockchain 3.0’ applications, there are many factors still to overcome. These challenges indicated in the Appendix are presented in the context of the current construction sector environment. The challenges are not specific to any one Blockchain so may be applicable to some networks and not others. They are transient and it is expected they will be solved in time as the technology advances and new Blockchain-based applications emerge. The challenges have been categorised into three ‘AECO Super-Challenges’: cultural resistance – those challenges that could deter individuals and organisations from adoption of Blockchain; technological ecosystem integration – the challenges related to integrating Blockchain and Smart Contracts with other existing technologies (e.g., IoT, BIM technologies) and the challenges that exist between cyber and physical worlds; and practicability – challenges that refer to the practical implications of adopting Blockchain and Smart Contracts in construction.

The list of opportunities in the ***Appendix*** indicates the potential of Blockchain in the construction sector. These opportunities are achieved through four aspects that Blockchain and Smart Contracts integrated with other technologies aim to deliver: digitalisation, transparency, immutability and trust. Like the challenges, the opportunities have been categorised into three 'AECO Super-Opportunities': cultural acceptance – the opportunities brought about by Blockchain and Smart Contracts that could sway individuals and organisations into accepting these new systems; technological ecosystem integration – the opportunities that can be derived from the addition of Blockchain and Smart Contracts into existing systems and the additional value that they could bring; and practicability – the positive practical implications of these new technologies that will change processes to support advancement of the construction sector.

Cultural Resistance vs. Acceptance

The sector is currently characterised by cultural resistance and change, particularly with regards technological advancement, processes and new technology. However, acceptance of Blockchain is required by individuals and organisations to achieve widespread success. Challenges around resistance could be addressed through demonstrating value through proof-of-concepts and real-world applications that offer tangible benefits to individuals, organisations and the sector. There is much to be done around changing the perception of Blockchain that, in its early days, was characterised by DarkNet activity where anonymity of cryptocurrencies was exploited by criminal actors. However, today, many applications are beginning to demonstrate applications beyond the perceived negative activity to bring about democracy and distributed power through new protocols. Engagement and education with the sector will play a large part in changing resistance to acceptance.

Technological Ecosystem Integration

A key component of the success of Blockchain and Smart Contracts is having a sufficiently robust ecosystem for their implementation. While many platforms exist to address many of the technological integration challenges, there is still no one system that can offer each of the pillars security, speed and decentralisation required for a 'perfect' platform; typically there is a trade-off of one for the others. A survey of the fundamental properties of Blockchain (immutability, non-repudiation, integrity, transparency and equal rights) found that only Bitcoin and Ethereum meet these properties (Hunhevicz and Hall, 2020). However, neither can currently compete with the likes of Visa for speed of transaction processing. Solutions for the hardware and software requirements of Blockchains and Smart Contracts (e.g. bandwidth, data authentication, interoperability, on-chain/off-chain storage, data longevity, redundancy, energy consumption) remain open challenges for some networks but the rate at which technology advances today will likely see these challenges resolved in the near future. Indeed, the merge of Ethereum from a proof-of-work (PoW) to a proof-of-stake (PoS) consensus mechanism demonstrates the response to some of the real and perceived challenges of Blockchains where the PoS platform requires 99.5% less energy consumption that PoW to validate transactions (Kessler, 2022).

Practicability

The ability of these technologies to make real and lasting change lies in acceptance and technology options as discussed above, but also in the feasibility of integrating these technologies into everyday operations. Here, consideration needs to be given to ease of use and implementation of Blockchain and Smart Contracts by those it could benefit. It has long been discussed that regulatory reform is required in the construction sector to reflect current practices and encourage better standards (Li et al., 2019). Many governments and policy making bodies are working to develop national and international standards that incorporate Blockchain and Smart Contracts and legal precedents are slowly beginning to emerge (Cohen and Chen, 2022). As adoption of these technologies increases in other sectors, their successes will encourage proliferation into the construction sector. Some applications will directly cross over whilst others will require some adaptation to the uniqueness of the construction ecosystem. All things considered, Blockchain and Smart Contracts are only tools to be exploited, it is how the sector chooses to apply them and integrate them with other systems and technologies that will make a difference.

5.0 Recommendations

Summary

- *This chapter presents an analysis organised as endogenous and exogenous perspectives on BIM processes and technologies in relation to Blockchain.*
- *We present an adoption roadmap to manage transition, identifying some of the major opportunities for the industry.*

Opportunities in the application of Blockchain in BIM processes are plentiful but there are internal and external factors influencing the adoption of Blockchain into BIM technologies and processes. This requires cultural change and new business models, posing socio-technical challenges from legislation and standards being developed for cryptoassets, data management, asset management, cybersecurity, data ownership, to name a few. What does this mean for the construction industry?

Current BIM production processes, when expertly deployed, bring high efficiency, rapid and agile project deployment and extensive project automation. On the other hand, there is a steep learning curve to attain the required level of performance. Attention in the development of BIM libraries and their use in asset information management systems has to address the emergence of Digital Twins, live data and machine learning. As digital assets become more sophisticated, develop behaviours, and are used over the total lifecycle of the physical asset, they become more valuable. This leads to ownership and liability concerns. It is highly recommended that special attention is given to the development of BIM objects outputting into Asset Management Systems and other information systems powering Digital Twins. A key recommendation is to closely couple, or perhaps merge the BIM Common Data Environment and Digital Twin Command Data Environment architectures.

There are a number of conflicting dimensions in the adoption of Blockchain in BIM processes. Transparency versus confidentiality and control is noticeable. Although transparency and the breaking down of data silos is welcome to streamline processes, the architecture of confidentiality becomes more complex and data ownership becomes critical. The key properties of immutability, provenance and traceability of blockchains has to be centric to the conception of a reviewed BIM framework.

The challenges of immutable provenance mechanisms can transform BIM production to guarantee authorships and ownership of digital assets in this emerging new ecosystem. Standard methods and procedures for maintaining this intellectual property have to provide for provenance and accountability chains. What are the impacts on business processes, legalities (IP) and financial models? BIM data will have to be prepared for decentralised finance, LawTech frameworks and GovTech automations.

Blockchains will amplify the value of BIM data. What can reliable data analytics tell us about errors, this being deliberate or accidental, in respect to projects' and stakeholders' performance and reputation? Particular attention has to be given to the immutability properties of Blockchain and how this may cause resistance to adoption in respect to one's own reputation in project participation and performance over long periods of time. The AECO industry has to rationalise what this will represent in terms of procurement and also implementation governance.

Buildings can last for many generations and Blockchain is the preferred digital preservation technology for an increasingly digitally transformed world. On the other hand, this can also create bottlenecks when verifying inputs and outputs of specific toolchains - different versions of a particular simulation software may yield different outputs. Tracking the whole toolchain is challenging but has its benefits.

As BIM is progressively being adopted at earlier stages and the value of BIM as a Business Intelligence (BI) tool is a reality. This Blockchain means that reliable data will be gathered from distributed BIM models that are more inclusive, as BIM is adopted by all tiers of construction. This has the potential to lower the project risk of cybersecurity breaches and malicious cyber attacks. As Blockchained BIM creates a solid foundation for Business Intelligence, we have to leverage this opportunity by creating the right tools to modulate AI and enable federated learning for the benefit of the industry.

Blockchain's immutability and provenance has to be in the DNA of building assets' total lifecycle from its genesis in BIM. Practitioners have to consider the cyber-physical aspects of Digital Twins when conceiving BIM assets and securing sensitive asset data of critical infrastructures with Blockchain encryption methods and zero-knowledge proof techniques. The cryptographic methods in Blockchains and Smart Contracts can enable assured open-data accessibility to aggregate value in new projects, avoiding data duplication or tampering. This becomes instrumental when considering transitioning to post-occupancy and the application of Digital Twin and IoT network fabrics. DLTs like BlockDAG may play a key role in the adoption of immutable data in isolated Digital Twins, but also in federated National Digital Twin. Governments and international efforts have to promote industry standardisation of construction data ontologies and semantics, as well as the interfacing of other verticals in this ontology (e.g. railways and highways).

Short and medium term technological and managerial interventions have to consider how 'digital threads' are managed to deliver the right data at the right time. Some solutions have been proposed (e.g. (Kraken IM, 2021)) but more real world testbeds and pilots are needed. A review of management and procurement processes is required to help the industry to understand the complexity of changes. Devices like retention deposits may be completely eradicated as obstructive procurement devices (BEIS, 2020).

In the longer term, we will have to rethink the definition of the BIM CDE to become an 'all-inclusive', integrated environment for financing (including marketplaces), design, procurement, construction and operations simulation and delivery. This CDE will inform pre-construction design analytics with real and synthetic BMS/IoT data as well as powering BI for feasibility studies and speculative studies. Data management standards will have to consider these new ‘collaterals’ and how BIM enriches enterprise and systems architectures. It is likely that any solution that does not sit within the adopted framework will counteract the aims of BIM.

Conclusion

Developments in Blockchain technology have the potential to fundamentally transform BIM development. From NFTs and tokenized Zero-Knowledge Proofs to self-mining light-weight consensus mechanisms, this fast changing landscape presents opportunities to improve BIM at enterprise and project levels, execute and deliver construction projects and migrate or exchange digital knowledge between assets - from a single building project to complex urban systems.

Blockchain is also emerging as the preferred technology to consolidate, regulate and validate OpenBIM standards, creating consensus in ontology when considering the many systems in the Built Environment. This can potentially propose a framework for seamless deployment of Digital Twins and their interfaces when considering national projects like the NDTp (Walters, 2019).

Although there is great promise in the application of Blockchain, the AECO industry culture is possibly the major obtable. We have to learn and adapt from other industries' adoption strategies, observing their successes and failures. Incremental steps are critical to deal with cultural resistance and managing transition. The technology also has to evolve and become more accessible.

The industry has to consider data sovereignty with respect to these emerging federated systems and interfaces. Akin to an international monetary system, the notion of AECO Knowledge as a Service infrastructure has to be created, merged with BIM production and management technologies, and effectively adopted to enable robust traceability of digital assets and accountability chains in the building's total lifecycle - from BIM requirements management to the intelligences gathered from running federated Digital Twins.

Glossary

A

AI:

AEC Industry:

B

BI: See Business Intelligence.

Blockchain:

Building Information Modelling (BIM): a set of technologies, processes and policies enabling multiple stakeholders to collaboratively design, construct and operate a Facility in virtual space. As a term, BIM has grown tremendously over the years and is now the 'current expression of digital innovation' across the construction industry.

Business Intelligence (BI): comprises the strategies and technologies used by enterprises for the data analysis of business information.[1] BI technologies provide historical, current, and predictive views of business operations.

C

CDM: see 'Common Data Environment'.

Cryptocurrency:

Common Data Environment:

Computer Supported Collaborative Work: A branch of computer science that addresses "how collaborative activities and their coordination can be supported by means of computer systems"

Contracts:

CSCW: See Computer Supported Collaborative Work

D

Distributed Ledger Technology: A data architecture using peer-to-peer data distribution to synchronise a ledge of transaction.

DLT: See Distributed Ledger Technology.

DRM:

DT: Digital Twins "A digital twin is a digital representation of a physical asset, process or system. It is distinguished from any other digital model by its dynamic connection to the physical twin. A digital twin unlocks value by supporting improved decision making."**(Council and Lamb, 2022)**

E

Ethereum: A turing complete

Encryption

G

GIS: Geographic Information Systems

H

Hash: a mathematical algorithm that maps data of arbitrary size to a bit string of a fixed size

Hash (parent):

I

I4.0: See Industry 4.0.

Industry 4.0:

IFC: Industry Foundation Classes

IP

M

Machine Learning:

ML: See 'Machine Learning'

MMC: See Modern Methods of Construction

P

Procurement Style:

Proof of Work: a consensus algorithm mechanism by which a Blockchain implementation can confirm transactions and produce new blocks in the chain.

Proof of Stake: a type of consensus algorithm by which a Blockchain network aims to achieve distributed consensus.

R

Retentions:

S

Smart Contracts:

Supply Chain: In the UK, supply chain refers to tier 2 contractors and manufacturers. In the USA supply chain often refers to subcontractors and/or suppliers handling materials.

SME: context dependent, for 'Subject Matter Expert' see below; otherwise a Small-Medium Enterprise which is an entity comprising either less than 250 employees (Medium) or less than 50 employees (Small). Additional parameters in some jurisdictions may also include turnover limits.

Subject Matter Expert:

T

Token: a digital representation of a tangible (i.e., real or financial) or intangible (i.e., non-physical) asset, or part thereof..

Tokenisation: the process of identifying the key features and attributes of an asset to be digitally represented as a token.

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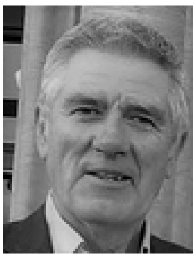
David Greenwood



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Appendix

AECO Super-Challenges	Blockchain Challenge
Cultural resistance	**Acceptance of DLT** is required by individuals, organisations and society generally to achieve widespread success. **Admissibility of Blockchain data** in the legal system requires courts to accept it as evidence. **Education, training and skills** associated with Blockchain is required for developers and users of the new systems. **Threats to job security** (e.g., automation) add to the resistance of the sector to accept Blockchain applications. **Reputation of Blockchain** is often negative due to Dark Net activity that uses cryptocurrencies for anonymity. **Resistance to change** of the sector is discussed widely, particularly with regards processes and new technology. **Current technological state of the sector** is insufficient to support implementation of Blockchain.
Technology integration	**Authentication of data** being input into the Blockchain is required – garbage in is still garbage out. **Sufficient bandwidth** for stability of the system and **reliable internet connectivity** are required. **Data storage** on-chain is costly and requires masses of space; data storage off-chain has issues of longevity. **High level of energy consumption**, for example, in Bitcoin's Proof-of-Work is an environmental concern. **Interoperability** across actors' different systems is required as Blockchain requires all parties to participate. **Latency** of processing transactions could be a problem for applications that rely on real-time data. **Malicious attacks** could threaten acceptance of Blockchain applications, particularly around cryptocurrency exchanges that have been subject to theft. **Redundancy of data** where replication of entire Blockchains is required results in issues around data storage. **Reliance on data outside the Blockchain** could represent a weakness to the system (e.g., device tampering). **Scalability** needs regarding financing/infrastructure are unknown, particularly as transactions increase exponentially. **Security and privacy of data** on the Blockchain represents a barrier for some applications where people outside of the network can access the data (e.g., public Blockchains). **Nascence of technology** equates to technical issues to be resolved prior to mainstream adoption. **Poor APIs** that are not user-friendly could deter use of Blockchain applications for non-computer programmers. The **sector is not ready for Blockchain adoption** in its current state regarding regulations, technology, processes. **Technological change in the sector** is slow so it could be some time before readiness for adoption is achieved.
Practicability	**Coding smart contracts** are subject to human error and require rigorous testing as they cannot be withdrawn once live. **Complexity of construction contracts** represents a challenge to code smart contracts for delivery of terms. **Costs of implementation** are unknown and could be prohibitive in a change-resistant sector with low margins. **Data protection/privacy** (e.g., GDPR), especially the '*right to be forgotten*' is at odds with Blockchain immutability. **Exchange rate volatility** of cryptocurrencies means they are not stable enough to be used in construction projects. **Lack of legal precedents** around use of Blockchain data in disputes/legal scenarios. A body of case law is required. **Regulatory reforms** (e.g., financial, payment, procurement) need to be made to adapt processes for Blockchain. **Role of the state is unclear** in terms of creating a suitable environment for Blockchain innovation in construction. **Smart contracts' current inflexibility** (e.g., binary logic) limit their ability to deliver elements of a construction contract.

AECO Super-Opportunities	Blockchain Opportunity
Cultural acceptance	**Better communication** as a result of transparency **Better dispute resolution** as a result of an immutable digital record acting as an evidentiary trail. **Better performance management** due to better data/information and linking objectives to payments via smart contracts. **Compensation for created value** through tokenisation. **Increased collaboration** as a result of increased transparency and trust. **New business models** such as DAOs made possible by smart contracts. **New markets** made accessible through digitalisation (e.g., new capabilities) and cross-border transactions. **Proof-of-ownership and rights** through tokenisation. **Reduced administration** where activities are automated by smart contracts. **Reduced fraud, counterfeiting, corruption** as a result of immutable recording and better interrogation of data. **Reduced human error** through automation and immutable data recording encouraging better work. **Reduced number of disputes** through new payment structures and better data recording. **Reduced transaction costs** through decentralisation of payment structures. **Security of payment** where activities are linked to contractual objectives and where funds are embedded into smart contracts upfront.

Technology integration	**Better information management** as a result of better integrated systems and tokenisation indicating ownership and usage rights. **Cross-border transactions** made simpler and cheaper through cryptocurrencies that are stateless. **Data security** built into Blockchain-based applications. **Decentralisation** through using Blockchain systems that distribute power among participants. **Disintermediation** from automation through smart contracts and new payment structures requiring fewer third parties. **Integration of services** made possible through access rights to data across organisations. **Interoperability** increases through deriving more from existing technologies through implementation of Blockchain. **Near real-time data** when systems are integrated with IoT on Blockchain without the need for intermediaries. **Predictive capabilities (e.g., in maintenance)** based on historical data within the Blockchain or from external oracles. **Processes become better and faster** through automation, better information, increased collaboration, enhanced trust. **Resilience against malicious attack** built into Blockchain technology, particularly in public Blockchains. **Time reductions** as a result of automation, proactive maintenance, better information sharing and management.
Practicability	**Better health & safety** as a result of better compliance with regulations and immutable recording of data acting as a trail of accountability. **Better risk distribution** from clarity required in smart contracts setting out roles, responsibilities and accountabilities. **Clarity in construction contracts** driven by the need to clearly define the terms of a contract to translate that into smart contract code. **Cost reductions** from lower transaction fees, increased productivity and efficiencies that Blockchain can bring. **Efficiencies** achieved through, for example, automation, predictive maintenance, better information sharing/management. **Improved workflow** through increases in collaboration and transparency signifying better accountability and project control that results in a more open project environment and better aligned clients and contractors. **Increased accountability** is achieved from clearer roles and responsibilities for smart contracts along with an immutable ledger detailing the digital thread of who did what, when. **Increased compliance with regulations** where Blockchain and smart contracts streamlining compliance processes and form applications such as automatic code compliance checking. **Increased information quality** made possible through assigning IP through tokenisation resulting in willingness to share. **Increased productivity** achieved reallocation of resources to value-adding activities and reduction of time waiting for information exchange as a result of better information management practices. **Provenance** data becomes more robust when integrated with supply chain Blockchain ledgers and into construction and operation of assets detailing all aspects about materials, products and components from cradle to grave. **Single source of truth** is achieved from a Blockchain-based, data-driven project where all participants have access to and contributed to the same ledger of information. **Streamlined processes** where projects are integrated throughout phases by the distributed ledger and smart contracts. **Sustainability** of built assets increases through sustainable design, integration with IoT for performance management. **Traceability & auditability** is significantly increased through the immutable nature of Blockchain and smart contracts.

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2022

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