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A Proposal to Harmonize BIM and IoT Data Silos using Blockchain Application

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A Proposal to Harmonize BIM and IoT Data Silos using Blockchain Applications

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Abstract−The integration of Building Information Modelling (BIM) and Internet of Things (IoT) provides significant end-to-end benefits for the architecture, engineering, construction, and operations (AECO) industry. Example applications include on-site assembly services, data localization for built environment, occupancy performance measures and many other analyses that can be used to improve the built environment. However, silos in the BIM and IoT data exchange have impacted the digital process adoption in AECO industry, which aims to change the dynamics and behaviours of the current working process. Penzes, (2018) in his report, acknowledges the AECO industry as one of the most fragmented sectors with a scattered and complex supply chain. Kelly & Dowd, (2015) reported that the prevalence of waste in AECO industry is due to old management practice and business culture, while Charlès, (2014) suggested this is a symptom of ineffective practices caused by the lack of data integration and disconnected documents between the industry players. Insufficient data for process simulation have resulted in poor productivity, high risk, and low profitability. This study sets out to critically analyse the Blockchain technology's potential to connect, integrate and advance AECO industry information exchanges and digital processes by using BIM and IoT integration use case as a methodology to identify, clarify and organize the proposed system requirements. This paper presents a comprehensive literature review to uncover the current state of BIM and IoT data silos. Moreover, an online survey assessment and a simulated test were conducted to critically evaluate, investigate, and examine the opportunities and solutions in harmonizing BIM and IoT data silos by using the Blockchain application.

Keywords− BIM, IoT, Blockchain, Digital Twin, Data Silos, Integrated

1.0 Introduction

The recent Global Lockdown following the COVID-19 pandemic has affected many businesses, workforces and multiple parts of supply chains that are not designed to be managed remotely. These businesses have suffered from a disconnected system and fragmented data, which then triggered economic loss and global recession (Paul, 2020). The "new normal" therefore, will require a smarter way of working and a higher degree of security, transparency, and trust in a data management system (AlMuhairi, 2020).

In the architecture, engineering, construction, and operations (AECO) industry, technological advancements such as BIM, and Internet of Things (IoT) have improved the accuracy of low-level assets information and collaboration between machine and human interfaces (Kjartansdóttir et al., 2017). However, the fragmented data and data silos which are commonly created by a centralized, unintegrated database system across two or multiple repositories still exist. To eliminate these obstacles, there is a need for an integrated system that can provide a transparent, unified, and trusted environment (Filipowski, 2019).

Blockchain technology emerged as a disruptive innovation to democratic data sharing in a decentralised and trusted environment. With a wide range of decentralized applications, Blockchain can be a potential solution to the disintegration of data silos (Shi et al., 2019).

This research sought to critically analyse, evaluate, and discuss the ability of Blockchain technology and its application in harmonizing BIM and IoT data silos. The discussion begins by proposing a hypothesis, and by identifying the functions of the process and technology in the AECO industry. It then outlines the challenges and opportunities for data integration. Also discussed are the theories related to the Blockchain technology potentials.

This paper is divided into three sections: The first section of this paper reports the findings from the literature review. The literature review aims to

critically evaluate the current state of the BIM and IoT integration process and challenges by presents in-depth review of collaboration silos in the AECO industry, followed by comprehensive review of Blockchain advancement in data integration and management.
The second section presents the outcome from the web survey. The survey aims to critically measure the knowledge level of AECO industry practitioners on their understanding of the Blockchain technology, while the third section reports results from a simulated Blockchain application. The application aims to critically examine and rationalize the use of the Blockchain technology as a solution for BIM and IoT integration processes.

Towards this end, a combination of literature review, survey, and action research was adopted to form a comprehensive, critical, and accurate understanding of the technologies for providing consideration and opportunity to advance and harmonize BIM and IoT data integration using Blockchain technology. This conclude the findings for this research.

2.0 Literature Review

2.1 Overview of The Key Technology

2.1.1 Building Information Modelling (BIM)

According to NBS, (2016) "BIM or building information modelling is a process for creating and managing information across a project's lifecycle. This advancement represents physical and functional characteristics, such as geometry, spatial relationship, and geographic information in a digital format to support decisions during an asset' lifecycle," and with the release of ISO 19650, a more connected and integrated BIM processes are expected (Shillcock, 2019).

2.1.2 Internet of Things (IoT)

IoT is a system that employs interconnected smart devices to transfer data using internet without necessitating human interactions or human-to-computer communication (Barnaghi et al., 2012). "The Internet of Things is a paradigm where everyday objects can be equipped with identifying, sensing, networking and processing capabilities that will allow them to communicate with one another and with other devices and services over the Internet to accomplish some objective" (Whitmore et al., 2014).

IoT deployment can be categorised based on the process capability of sensors object's recognition. The categorisation are as follows; (1) activity-aware objects, (2) policy-aware objects, (3) and process-aware objects (Fotiou & Polyzos, 2018).

Such categorisation is vital in designing the data management framework for a BIM and IoT-based application involving various objects, devices, sensors, and daily items. These objects have been increasingly applied in various smart homes products to enhance work productivity, living comfort, and entertainment.

The integration of BIM data with IoT offers a world of benefits for the AECO industry. Zhao et al., (2019) demonstrated the used of this integration in a smart bridge management for a safe, practical, and cost-effective bridge inspections. A combination of sensors and high-fidelity BIM model enables operation and maintenance (O&M) departments to receive a data rich and information of building assets for simulations and analysis.

In the real estate sector, the use of IoT devices changed how real estate firms conducted their business especially during a pandemic. For example, using a connected device allow property viewings being conducted via the internet. This will guarantee a safe human interaction without being on-site or the need to travel (Vaniukov, 2020).

On construction site, IoT applications can be used to enable machines to communicate with each other and transfer information to optimise production for assembly of materials. Construction management can be conducted according to IoT process capabilities; thus, this smart interaction, capabilities to automate process are essential to forecast and mitigate potential risk connected to construction sites (Kassem et al., 2017).

2.2 Challenges of BIM and IoT Data Integration

The integration of BIM and IoT applications can provide significant benefits to a building lifecycle. BIM teams that manage to leverage an IoT-based application would create vast opportunities for their businesses. The interweave between digital and physical assets, either directly or indirectly, will create a significant amount of information that can be utilised to improves security, minimize human effort, and save time. The availability of such data can also facilitate efficient resource utilization. However, such benefits can be achieved if only a single source of truth is established (Fotiou & Polyzos, 2018).

Current BIM and IoT integration or application tends to focus on an isolated solution; it does not cover a building lifecycle process. Such situation happens because data captured and abstracted from IoT devices and to BIM models at every project stage, whether in the form of files or isolated databases are locked-in silos. The fragmented in data management is due to traditional business processes. This creates data reliability and interoperability issues between parties. Lack of BIM and IoT data integration in the AEC industry limit the benefits of integration from being fully realised (Shahrokni & Soderberg, 2015).

Figure 1 shows the current integration, collaboration, and deliverables in a BIM-IoT framework that are segregated and locked-in silo.

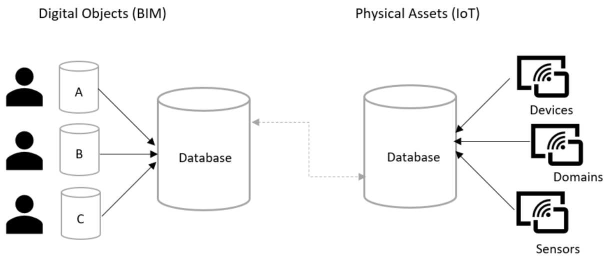

Figure 1 - Silo and fragmented data management in the current BIM and IoT process.

Findings from the literature review indicate the following four issues contributing to data fragmentation across silos in an IoT-based BIM application across project stages:

1. Security
2. Fragmented data
3. Data Ownership
4. Trust

2.2.1 Security

This lingering issue concerning IoT-based BIM applications has continued to impede the implementation of the technology in the AECO industry. According to the National Institute of Standards and Technology of the United States (NIST), security can be classified as "the protection of the confidentiality, integrity, and availability of a technology solution". The essence of security is ensuring every component function as established and assuring that authorized and unauthorized users are kept safe from possible threat (Fagan et al., 2020).

However, the connected IoT domains, devices, and sensors to the Internet raise concern about personal data privacy. IoT devices, by their nature, are vulnerable to attacks from data theft and malicious activities due to their connectivity capability. The nature of the AECO industry has also complicated IoT technologies to advance the building process (Mazhandu, 2019). Results from a survey conducted by Ahmed et al., (2017) indicates that AECO industry is slow in innovation, with the AECO professionals left behind in technology advancement due to lack of knowledge in the information technology. Finding AECO professionals with IoT knowledge is difficult.

Furthermore, "the orchestration of IoT in a highly modular environment with many moving parts and inter-dependencies between the stakeholders of this environment has led to many security issues" (Fotiou & Polyzos, 2018).

System separation and staying offline are not viable security approaches and are ineffective for business operation. The lack of seamless interoperability and integration reduce business outcomes; hence the futile attempt of adopting the IoT in AECO industry (Mazhandu, 2019).

2.2.2 Fragmented Data

The AECO industry data management environment is matured in practise. Shahrokni & Soderberg, (2015) indicated that the file-based data management is the prevalent of data management strategy in the industry. They further argued that the growth of siloed in file-based system is attributed from the traditional systems and processes practised by most businesses.

Elmualim & Gilder, (2014) gave an example of how categorisation of trade segment in the current BIM process, project teams (e.g., design team, supply team, construction team, and operations team), has made the exchange of activities between the team members and technological interoperability less feasible. This issue has contributed to significant version-control issues and various domains offer important data at different stages in the procedure which resulted in a more costly system implementation. These fragmented data management mechanisms are limiting domains access and prevent them from making a better decision. (Charlès, 2014).

2.2.3 Lack of Document Continuity

In the current BIM process, a BIM team would create graphical and nongraphical information throughout a project's lifecycle. Information was reorganised according to the top-down model and notable resources were used to process submittals, change orders, and RFIs. However, these approaches are only appropriate for small projects. In a more complex project, level of granularity and document continuity can become an issue (Charlès, 2014).

Instruments, applications, or software employed to manage business information is also a disintegration source as these devices function under the information silos model. Common interoperability issue in these sets of tools often limit data sharing between parties (Eadie & McClean, 2015).

The distinction among the drawing necessitated at different stages of a project has provided numerous continuity difficulties which caused irregularities in documentation. These issues are typically resolved at project delivery stage, but then a late change is costly and disruptive (Charlès, 2014). NBS, (2016) claims that BIM processes lack continuation at the construction, post-construction and operation stage due to fragmented processes between trades and FM operators. They explained, in the post-construction stage, a model does not represent the structure as a living element; it represents only the as-built form of the building. Even during the construction stage, a BIM model is only as good as the information provided to it. If the data is inaccurate, the model will be too. The lack of information continuation in the siloed collaboration model that is maintained within BIM is slowing the construction project from progressing (NBS, 2016).

2.2.4 Data ownership

Data can be considered as a commodity in Industry 4.0. Its function will allow companies to acquire or maintain a competitive edge. Platforms that capture a critical mass of BIM and IoT data in the near-term will be well-positioned to dominate the built environment market. They will also be challenging to defeat which is attributed to the vendor lock-in approaches which are attained when the building data are completely "transactable" for project contributors and not secured in proprietary systems. As shown in the Table 1, Opara-Martins et al., (2016) classified that there are three types of lock-in strategy are used by data vendors to control their dominance in the IoT field.

Type	Description
Data lock-in	Cloud operators make it easy to put data on the Cloud, but difficult and expensive to migrate data off
Device lock-in	many IoT platforms require the use of specific IoT devices with closed APIs that are only compatible with their respective platforms
Process lock-in	running production processes on top of data and devices further locks in users of the IoT platforms

Table 1 – IoT lock-in strategy (Opara-Martins et al., 2016)

Due to competitiveness, BIM and IoT platforms have no incentive to share data/market with their competitors. No secure mechanism exists to share data in real-time across platforms seamlessly. The lack of policy and solutions to address these interoperability issues are a massive obstacle on innovation within the AECO industry and will continue to fragment the industry into monolithic data silos. Without a new approach that enables data/device sharing and interoperability, the full potential of integrated IoT-based BIM applications cannot be harnessed (Iotex, 2018).

Furthermore, data heterogeneity is prevalent in IOT data infrastructure, which contributes to wasted prospects for businesses to generate value and to maximized functions offered by IoT rich datasets (Stacey & Berry, 2019).

2.2.5 Trust

A primary difficulty in the implementation of BIM and IoT is poor of trust among stakeholders (Hunhevicz & Hall, 2019). There are many levels of trust in a business, specifically between the staff and the management. Trust is essential for organizational communication which in force its importance as an asset for many organizations (Penzes, 2018).

Penzes, (2018) further cited, "as a general approach this trust was enabled by third parties and intermediaries who ensured the contracted parties that they have authority, transparency and legal right to do business with each other. However, this approach on a fast-paced global economy with growing complexity and volume of interaction is increasingly difficult". Transparency and trust established by a third party has become too complex as information is always concealed, and the procedure is frequently laborious and expensive. Additionally, since the 2008 financial crisis, it become clear that the system was highly vulnerable.

Mathews et al., (2017) observed that true collaboration encourages professionals to work together in the four modern pillars of procurement, simulated design, lean process, and energy efficiency design. However, Ciribini et al., (2015) observed that this requires trust in partnership, security, assurance in data reliability and information quality before true collaboration can be achieved.

2.3 Re-thinking Data Integration

The adoption of digital technologies continues to grow in the AECO industry (Three, 2019). Technology integration such as BIM and IoT could offer incremental end-to-end collaborative productivity and efficiency to produce better outcomes while retaining a healthy profit margin throughout a project's lifecycle (Digiteum, 2020). Shahrokni & Soderberg, (2015) elaborate that connecting distributed data in an integrated system is beneficial in the industrial environment to encourage collaboration among the participants. AECO actors for example, could directly link digital assets to build assets and to a structured database. Yet, until today there is no clear definition of an integrated Blockchain-IoT-based BIM process that can be utilized (Stougiannos & Magneron, 2018).

Hunhevicz & Hall, (2019) recommend project teams must consider approaches that can establish the end-to-end collaboration via a single source of truth covering their organization. Data could be stored and accessed in the cloud database through web services and not be prone to manipulation and fraudulent. The governance of those data should not be put on any centralised means that can be exposed to actors who often breach their moral duty. However, this required a robust system to ensure reliable data flow. Each business that installs IoT solutions must possess a strategy to safeguard trust, identity, confidentiality, protection, safety and security of devices and people. It is imperative to acknowledge that an IoT device or solution can be threatened at any time. Business owners must observe security as a controllable risk, along with other risks.

The literature review suggests a number of conceptual solutions for BIM and IoT integration. However, many challenges such as trust, security, data ownership, and management need to be addressed for both technologies to work together.

To achieve and deliver true integration in the BIM and IoT environment, a common system is required for keeping track of the built assets. Also needed is a system that gives definition and order to the society, which comprises security, speed, and transparency. The next section describes and justifies selecting the Blockchain technology as the answer to the issues.

2.4 Blockchain: Definitions and Characteristics

"Blockchain technology is a growing list of records or "Block" that is occupied with collective databases. Every block comprises a cryptographic hash of the previous block, performed data, and timestamp". The validated data in the blocks are confirmed and secured by a peer-to-peer (P2P) network, which collectively adheres to the consensus mechanism (Narayanan et al., 2016).

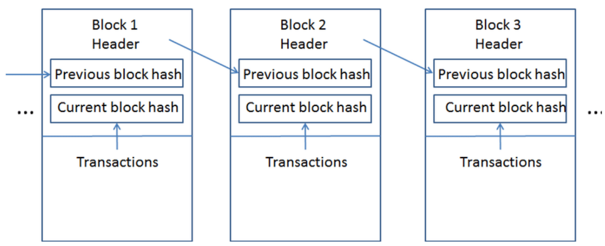

Figure 2 – Basic Blockchain transaction mechanism

The Blockchain technology can be considered as the distribution of trust; it allows people to share their data with others in a verified, immutable environment. The data are administered by a trust-free system, but the realisation of the trust hinges on on the framework of generating the trusted interfaces (Hawlitschek et al., 2018).

The Blockchain technology also allows individuals, organisations, and domains to have full rights and control over the sharing, collaboration, and privacy of their information without having to rely on third-party intermediaries (Casino et al., 2019). This process (Figure 3) and the key characteristics of the technology are discussed in the following section.

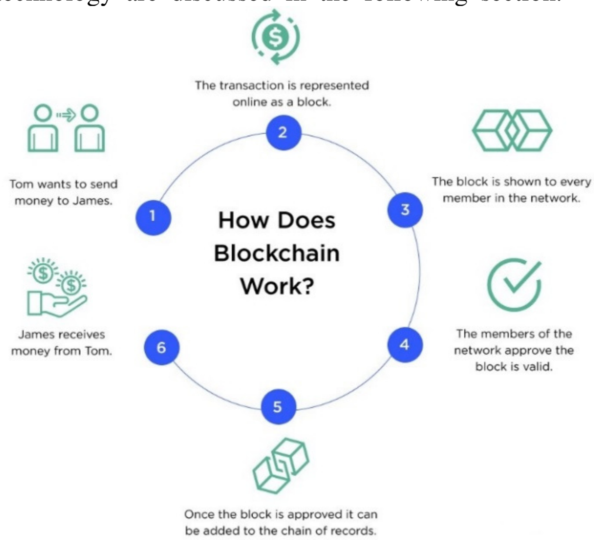

Figure 3 – Blockchain processes (Kravchenko, 2018)

2.4.1 Immutability

Immutability refers to the capability of Blockchain of restoring records of data across a peer network of a computer system without losing its accuracy. Each transaction contains a hash of the previous transaction thus making it very difficult to tamper (Casino et al., 2019).

Immutability is highly desirable for a supply chain ecosystem. In a Blockchain-based supply chain process, a consensus mechanism is used to improve transparency and provide greater traceability of products or services. Every transaction (including origin, transit, and price) is recorded in an immutable ledger, allowing trust to form and transforming a set of information into the creation of value (Shi et al., 2019).

2.4.2 Transparency

The usage of Blockchain enables the attainment of transparency by permitting users read-only admission to prior dealings and the capability to review the content of smart contracts. This aspect is valuable for goods that have to be traced in the supply chain (Kshetri, 2018). Although transparency is necessary in numerous businesses, such aspects might not be applicable and universal. Private users might be worried about privacy issue over their sensitive personal data, and businesses might experience the fear of sensitive information leakage (Treiblmaier & Clohessy, 2020).

2.4.3 Decentralized nature

"Decentralization refers to the process of distributing and dispersing power away from a central authority." Blockchain is planned as a decentralized, circulated system; consequently, the technology does not have any single point of failure, establishing its resilience, efficiency, and democracy. Decentralisation provides each member a chance to become a network's processors (Anderson, 2019).

2.4.4 Consensus

The advanced consensus procedures across network nodes have established the realisation of decentralisation. Such protocols guarantee that the responsibilities of accumulating transactions and producing new blocks adhere to stringent instructions, which do not contain bias. The most popular consensus algorithm was applied in Bitcoin, the "proof-of-work" (PoW) mining, is founded on unravelling a mathematically challenging puzzle with dynamically modifiable difficulties (Yuan Wang, 2018). In other words, the Blockchain consensus can lead to new powerful processes for many areas, applications, and organisations.

2.5 Applicable Uses of Blockchain Technology

In this section, several applicable uses of Blockchain technology to the AECO industry are discussed. Some of these applications can be served for a more specific integrated data management solution or collaboration processes for any new construction projects.

2.5.1 Distributed ledger

Distributed ledger technology (DLT) is a consensus replicate of an asset database which is communal and synchronised across a peer-to-peer network of numerous sites, locations, or establishments (Walport, 2015). DLT can possibly address privacy and security issues through its undisputable qualities which are unaffected by hacks and modifications (Harish et al., 2017).

DLT can aid in solving numerous BIM and IoT problems. It can confirm the incorruptibility of information through the immutability and identification of the person making changes along with facts of the variations. This facet enables improved logging and tracing of intellectual property and copyright, contributing to improved assurance of relevant stakeholders to cooperate (Li et al., 2019)

2.5.2 Smart contracts

Smart contract features an important role in the Blockchain development. It offers an exclusive interface for "machine-to-machine interaction which provides a safe, trusted, self-managed record and transfer of assets. A smart contract combines user interfaces, protocols, and promises articulated through those interfaces, thus permitting associations to be made formal and protected over public networks. A smart contract will allow users to deploy a metadata on a Blockchain network in a verified environment, directly through deterministic procedures, therefore allowing numerous issues to be address without requires validation from a third party" (Hanada et al., 2018). Indirectly, such feature, promises lowers the legal costs of any project (Shi et al., 2019).

A smart contract has its properties in the Blockchain, and therefore, the former cannot be changed unless all the actors involved agree to the alteration. Therefore, a smart contract manages and preserves its records of assets on the Blockchain, consequently permitting it to function as an escrow for two or more parties involved in a specified transaction. Since a smart contract exist in the Blockchain, it is practically clear and susceptible to manipulation (Lipton & Levi, 2018).

The smart contract functions as an independent payment entity on the Blockchain, which could deterministically perform payment for contracting job after the completion of a job. Automation in many types of repetitive tasks traditionally performed by people can reduce the time, costs, and risks associated with them (Kinnaird & Geipel, 2017).

The smart contract offers a stimulating prospect for BIM and IoT data exchange methods to directly confront trust issues between the exchanges in both technologies.

2.5.3 Peer-to-Peer Network

"Peer-to-peer network is a distributed and connected computers system or "peers" on the Internet. It enables a highly resilient consensus mechanism for the Blockchain without the need for any intermediary" (Christensson, 2006). Nakamoto,

(2009) in his whitepaper states that the peer-to-peer (p2p) network in P2P electronic cash, Bitcoin, helps to prevent double-spending in a transaction by establishing a consensus to record a public transaction. This application can also be incorporated to different practices that requires transactions such as project management, payment, procurement, asset management, and supply chain management. The P2P network at its core can serve as an application for communication management and data validation for an IoT-based BIM application (Nguyen, 2016).

In summary, Blockchain promotes trusted transactions using smart contracts which allows automatic data transmission throughout system-wide assets. The constant physical-to-digital-to-physical cycles encouraged substantial development in comparison with conventional supply chains, contributing to an innovative, entirely connected, and reliable digitalised supply network (Subic et al., 2018).

3.0 RESEARCH DESIGN

Introducing Blockchain characteristics into the collaboration dimension in BIM and IoT processes could lead to better collaboration and information sharing because the integration can redefine the trust relationship between the parties. As a highly secured distributed system with interoperability capabilities, the Blockchain technology has the potential to drive innovation in an IoT-based BIM application.

This research proposes Blockchain as the key technology to support AECO digital transformation thus enabling data transfers and value between the heterogeneous IoT-based BIM applications via cross-chain communication. The technology could complement BIM and IoT technology by providing trusted data to inform decision-making and optimise business processes throughout a project's life cycle.

This research was evaluated, examined, and tested using two methods of gathering data. First method used is a web survey where the self-selected but voluntary and anonymous. Respondents requires to visit the published Microsoft Forms website and filled the questionnaires form online. The opening questions were formatted to locate demography and roles of the respondents, it then flows into a series of indicator about Blockchain technology characteristics, obstacles and potential use case in AECO industry. The survey closing with an open-ended question, given respondents an opportunity to raised opinions about this research in general. The survey aims to critically evaluate the knowledge level of AECO industry practitioners on their understanding of the Blockchain technology. The results from the survey reflect their perception on the Blockchain spaces for AECO industry.

An action research was then conducted to critically examine the potential of the Blockchain application particularly smart contract in harmonizing data silos for a more secured, integrated, and trusted BIM and IoT environment. A simulated application was tested to gain a deeper understanding about the potential solutions or issues and informed judgment can be achieved.

3.1 Web Survey

The web survey findings highlighted in this paper reflect the participants thinking and perception in the Blockchain spaces and the potentials impact of the technology in AECO industry. The survey polled a sample of thirty AECO professionals in three countries twenty from Ireland, two from Qatar and eight from Malaysia with twenty-four represents AEC organization and six represents O&M department.

Findings from the survey suggest a promising digital transformation for many organizations. Thirteen participants implemented more than 50% BIM and IoT processes in either projects or their businesses process but have very low to no uptake of the Blockchain technology. The results indicate an improve use of smart devices in construction projects and Digital Twin for process automation during operation and maintenance phase.

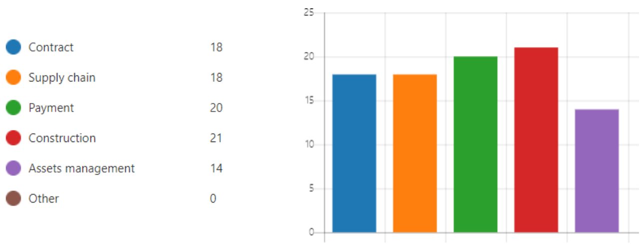

Fig. 4 – Blockchain technology potential use cases in AECO industry

The findings also imply the respondents' optimism about the ability of the Blockchain to potentially play a role in BIM and IoT integration. Twenty-one participants agreed that the character of Blockchain properties could offer a massive opportunity for the industry to become more effective, transparent, productive, and sustainable. The Blockchain technology, BIM and IoT could be utilised for better interoperability in construction, supply chain, payment, contract, and procurement.

However, Figure 4 the twenty-one participants acknowledged, such integration requires a high level of knowledge and understanding of the technology.

Though respondents are confident by eliminating old working culture, improve security and find suitable use case for businesses could lead to more take on Blockchain adoption and more impactful digital transformation in their organisation.

The respondents also believed that an integrated project delivered through an IoT-based BIM application secured by Blockchain technology would dramatically improve project visibility and data reliability. Such integration would allow the technology to exchange a structured database that can be shared for design and construction automation, energy simulations, fabrication, and the development of artificial intelligent (AI) thus increasing operational efficiency and enhancing risk analysis.

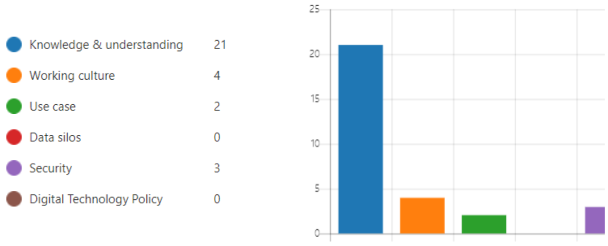

Figure 5 – Blockchain adoption obstacles in AECO industry

3.2 Action Research: A Simulated Application

This section presents the development of a Blockchain application to demonstrate the possible connection between BIM, IoT, and Blockchain. A simulated test was conducted to explore the various software packages used for Smart Contract developments. The objective of the test was to critically evaluate the value of the Blockchain characteristics in harmonizing BIM and IoT data silos. The test also served to demonstrate the potentials of the Blockchain-based applications, particularly Smart Contract and Distributed Ledger Technology (DLT) to be leveraged in creating a trusted Blockchain backed BIM and IoT cloud systems.

3.2.1 Methodology

A test of a simulated application, which allows data to be measured and evaluated, were conducted to achieve the objective of the study. A simulated application was developed platform to articulate these investigations. The programmed application, a smart contract, was created to demonstrate the combined roles and functions of each technology in securing, distributing, and establishing trust in a shared data environment. Technology roles, characteristics, application functions, software and hardware used in this test were listed in the Table 2.

Technology	Actors	Characteristics	Roles in AEC industry	Applications	Software
Building Information Modeling (BIM)	Design team Supply team Construction team Operation team	Collaboration	Process for creating and managing information and decision on a construction project across the project lifecycle	Software based model authoring, Cloud based collaboration and file management	Revit Forge
Internet of Things (IoT)	Device Sensors	Emit and transmit and signals	Uses endpoints to sense and capture connected data	Sensors Devices	MxChip IoT Hub
Blockchain	Miners P2P network	Immutable Decentralized Distributed	Maintain trust and verifiable ownership for multiple parties	Distributed ledger Consensus Smart contract Cryptocurrency	Blockchain Workbench Visual Code

Table 2 – Convergence of technologies

3.2.2 Overview

The smart contract serves to:

1. maintain historical data from an IoT device (see below) and BIM models in a distributed ledger
2. embedded the smart contract between the nodes in the system
3. provide hash-based security, verification of identity and provenance data ownership
4. provide consensus and agreement models for shared information, and
5. create a trust less data management

In this test, the smart contract provides information about a living quality scenario of a meeting room with a specific focus on the use of temperature and humidity information. For this purpose, an IoT device with a temperature and humidity sensors was installed in a meeting room to capture and provide data for the BIM model elements and DLT. This information serves to facilitate reliable data exchanges between the environments. With this information, several statements can be made for quality evaluation of performance or products of the measured room. These findings were derived from a process comprising the following four steps:

1. by defining the application (smart contract) parameters and requirements.
2. by designing a harmonised theoretical BIM-IoT-Blockchain framework.
3. by establishing an implementation approach, and
4. by evaluating the results.

3.2.3 Define the Smart Contract parameters and requirement

The purpose of this section is to identify the parameters and requirements for the Smart Contract configuration metadata (source code). The configured source code defined the high-level workflow policies and interaction model of the Smart Contract.

Since Microsoft Azure only support Ethereum based blockchain, Solidity was chosen as Programming language deployed for this test. “Solidity is an object-oriented, high-level language for implementing smart contracts. Smart contracts are programs which govern the behaviour of accounts within the Ethereum state. In this sense, Solidity is a collection of code (its functions) and data (its state) that resides at a specific address on the Ethereum blockchain” (Revision, 2020).

```
pragma solidity >=0.4.25 <0.6.0;
contract AirQuality
{
    //Set of States
    enum StateType { Created, InTenancy, Completed, OutOfCompliance}
    enum SensorType { None, Humidity, Temperature }
    //List of properties
    StateType public  State;
    address public  Owner;
    address public  InitiatingTenant;
    address public  Tenant;
    address public  PreviousTenant;
    address public  Device;
    address public  ContractorOwner;
    address public  ContractorObserver;
    int public  MinHumidity;
    int public  MaxHumidity;
    int public  MinTemperature;
    int public  MaxTemperature;
    SensorType public  ComplianceSensorType;
    int public  ComplianceSensorReading;
    bool public  ComplianceStatus;
    string public  ComplianceDetail;
    int public  LastSensorUpdateTimestamp;
    constructor(address device, address ContractorOwner, address ContractorObserv
er, int minHumidity, int maxHumidity, int minTemperature, int maxTemperature) pub
lic
    {
        ComplianceStatus = true;
        ComplianceSensorReading = -1;
        InitiatingTenant = msg.sender;
        Owner = InitiatingTenant;
        Tenant = InitiatingTenant;
        Device = device;
        ContractorOwner = ContractorOwner;
        ContractorObserver = ContractorObserver;
        MinHumidity = minHumidity;
        MaxHumidity = maxHumidity;
        MinTemperature = minTemperature;
        MaxTemperature = maxTemperature;
        State = StateType.Created;
        ComplianceDetail = "N/A";
    }
    function IngestTelemetry(int humidity, int temperature, int timestamp) public
    {
```

Figure 6 – Smart Contract language implementation using Solidity

The configuration metadata contains application name, description and roles that defines the data ownership, permission control and security within the blockchain application. A set of distinct roles are defined based on functionality.

Name	Description	Parameter
Created	Contract has initiated and tracking in progress	
In tenancy	Tenant is currently occupying room	
Out of compliance	Indicates that the living space is not met H&S requirement	**Temperature** Min = 18deg Max = 23deg **Humidity** Min = 40% Max = 60%
Complete	Operation and maintenance have been carried out	

Table 3 – Smart contract States

The configuration metadata consists of the contract properties, functions, and states as defined in the Table 4. This describes information flow of one or more stages and actions of the Smart Contract.

Name	Description
InitiatingTenant	The first participant who occupies the room
Tenant	A party who occupy the room
Device	A device used to monitor temperature and humidity of the room

Observer	The individual or an organization monitoring the room
Contractor	The individual or an organization who provides operational and maintenance services

Table 4 – Application roles

3.2.4 Design the methods used for the data harmonization

The architecture for the build, manage and deploy solutions for the Smart Contract application was first defined. This test was carried on Vendor-Locked solution due to the limitations of the Open-Software and Open-Protocols available during this study.

Microsoft azure platform was utilized as the common data platform for building, managing, and deploying solutions for the smart contract applications. Microsoft Azure also provides a cloud service such as IoT hub, virtual machines, SQL server, Blockchain Workbench etc. that can be used to automate data processing for a smarter and more efficient IoT and Blockchain data management.

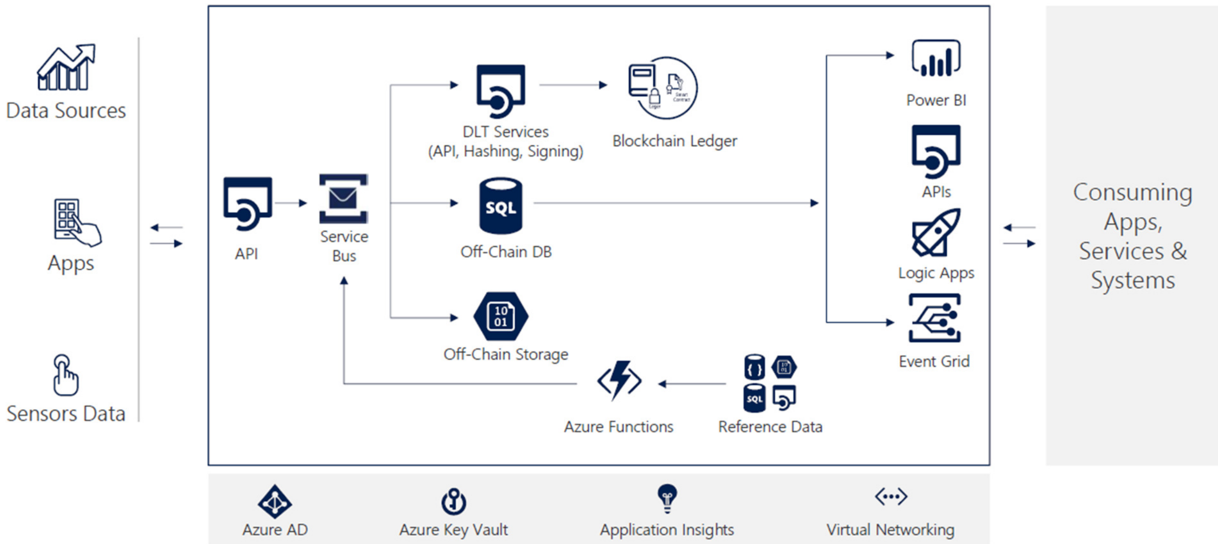

Fig. 7 - Microsoft Azure IoT and Blockchain Architecture solution (Microsoft, 2020)

Harmonization of the system was evaluated across three environments:

1. A BIM environment which represents the project deliverables in terms of model element for both 3D and information contents (object properties). Interconnectivity between BIM model and the Azure platform was achieved via Autodesk Forge protocols.

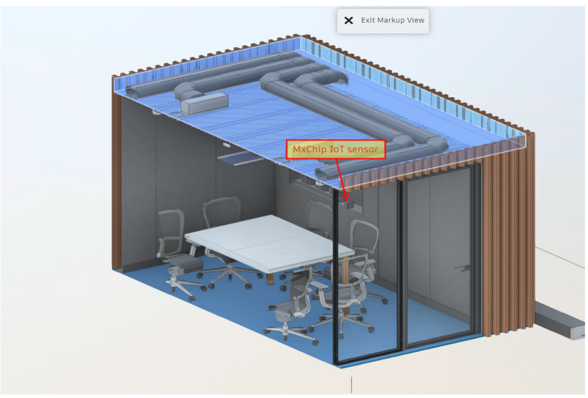

Fig. 8 – Virtual twin model represents IoT information

2. An IoT environment which "represents the actual delivery of the physical asset, goods, and services where IoT-based verification and authentication of the performance can occur" (Li et al., 2019). Azure MXchip IoT Devkit was used to develop and prototype the IoT solutions on the Microsoft Azure IoT hub. The Real-time data captured from these registered sensors for each space were published to an IoT hub and were forwarded to a Smart contract application on the Azure Blockchain Workbench.

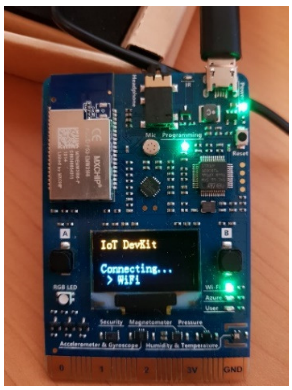

Figure 9 - MXchip IoT Devkit

3. A Blockchain environment, which consists of a set of services that allow users to deploy Blockchain applications on the cloud. In the Azure platform, Blockchain Workbench provides the deployment solutions for the Smart Contract including blockchain stack, application templates, and support for IoT integration. This helps to simplify the development and ease experimentation with prebuild applications. The time taken to develop the Blockchain applications could be reduced significantly.

3.2.5 Implementation

With the established configuration metadata and framework design, the actual implementation can be carried out. The following diagram articulates the possible data flow harmonization across the three environments. In this scenario, the first stage (state) of the workflow is "a requestor (role) takes an action (transition) to send a request (function). The next stage (state) is a responder (role) takes an action (transition) to send a response (function)" (Microsoft, 2019). A more detailed explanation regarding the application implementation workflow is outlined in the steps below and is shown in Figure 9.

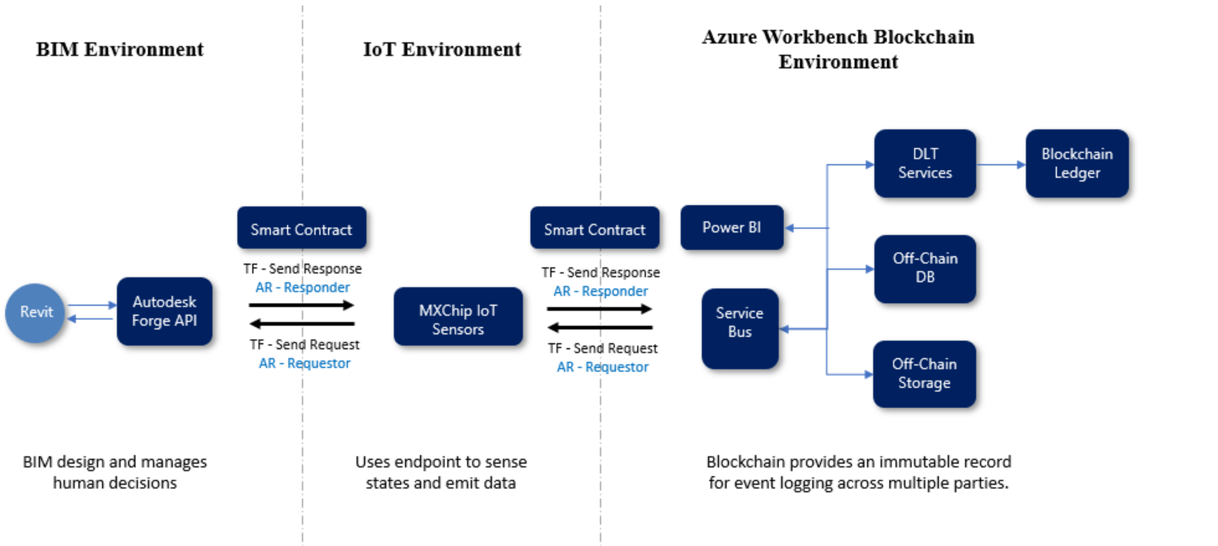

Figure 10 – Harmonization of information flow across environments

3.2.6 Workflow

Step 1 - The simulated application showcases an example of a smart contract process with BIM and IoT monitoring for health and safety compliance. The MXchip IoT Devkit with a temperature and humidity sensors was installed in a meeting room to capture and provide telemetry data. Set of parameter Compliance rules were specified and must be met for the room to be considered safe by the occupants. Acceptable range target parameter set as below;

Temperature
Min = 18deg Max = 23deg
Humidity
Min = 40% Max = 60%

Step 2 - BIM models were initiated to web viewer to host metadata from digital assets. BIM models that were authored in Autodesk Revit were used as a virtual twin to provide an accurate representation of geometrical data for web-based data monitoring and reporting. The Revit model were then translated into Serial Vector Format (SVF) via Postman; the collaboration platform for API development so that it can be rendered in the web viewer. The web app is used to visualize data captured from the sensor.

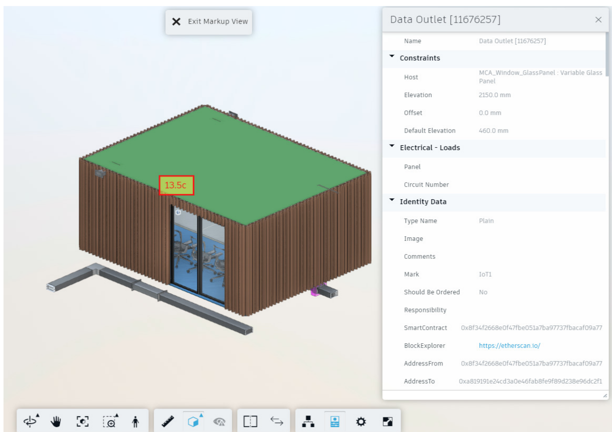

Fig. 11 – BIM and IoT metadata in the web viewer

Step 3 – Data from IoT sensor were linked into the digital model in the web app via a call function coded in JavaScript. This brings all the 3D visualization to the IoT application in the Azure IoT hub.

Step 4 – With the web app setup, a smart contract then can be deployed. This contract enforced a specific function according to parameter specified earlier. The humidity and temperature rules measurement were specified by initiating counterparty and deployed to the Blockchain Workbench. The smart contact application was built to secure the transactions data between multiple counterparties at any given time. This contract collected telemetry information from IoT devices installed in a location and enforced contract specifics related to conditions during occupation. Specifically, receiving and evaluating temperature and humidity data against an agreed upon acceptable range. If the IoT device identifies that the telemetry is out of the acceptable range, the contract will shift into an out of compliance state and appropriate O&M action need to be carried out. The smart contract functions translated in the Figure 11 and Figure 12.

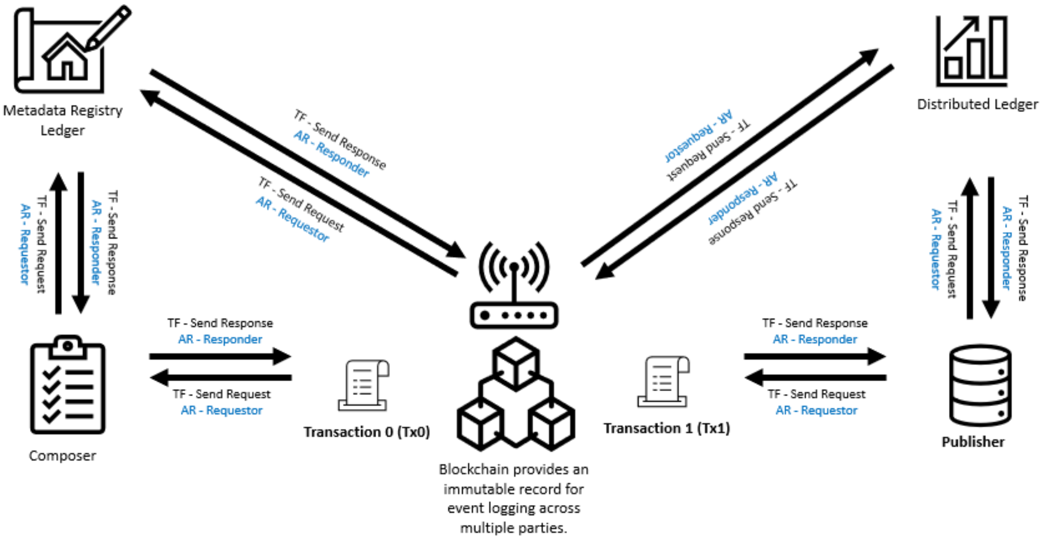

Figure 12 – Smart Contract functions

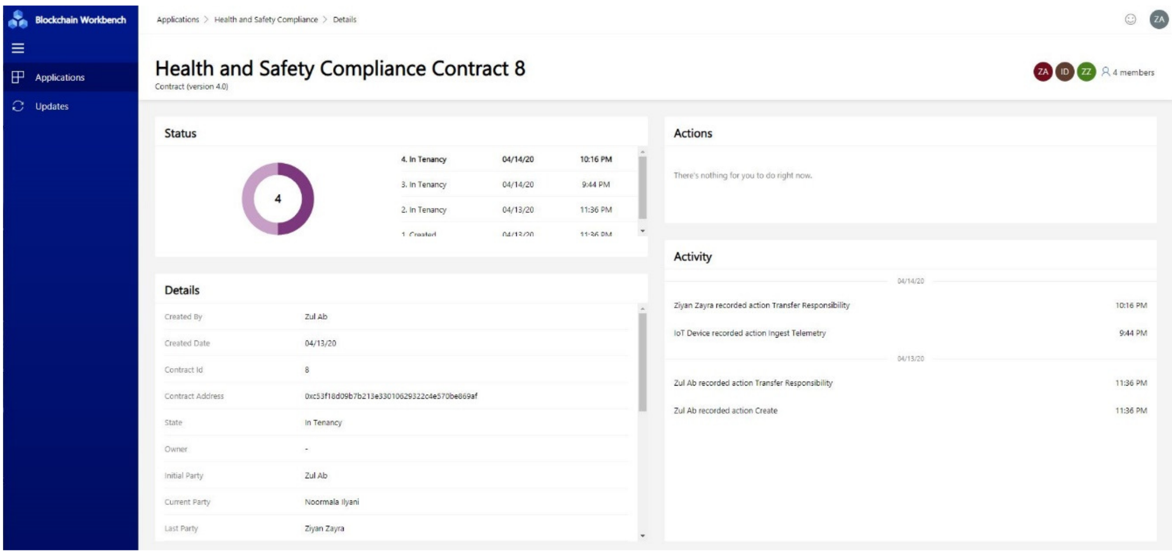

Figure 13 - Azure Blockchain Workbench Smart Contract applications

Step 5 – The monitoring process was automated by the Logic app which performs "two actions – one related to user creation and the other to delivering the telemetry data. The Logic app is then pointed at the Service Bus which is populated by the IoT Hub" (Microsoft, 2020). The Logic app (Figure 14) by default is configured to get triggered every minute to process any new message that is delivered by the IoT hub. Upon finding a new message, the Logic app creates messages as appropriate for user creation or executing the "Ingest Telemetry" function (Microsoft, 2020) until the life cycle is completed.

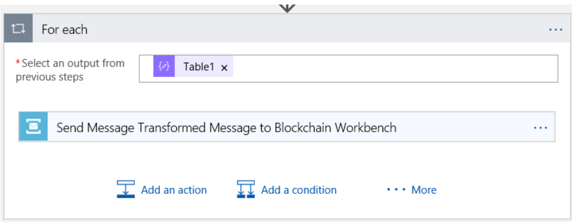

Figure 14 – Logic App functions

Step 6 - The time-series events and activity were recorded inside the Blockchain distributed ledger validated by Ethereum Blockchain consortium. The DLT contained some data, the hash of the block and the hash of previous block. In this instance, each block stores the details information about temperature, humidity and occupancy. Once data recorded inside the Blockchain, details of the contract become immutable. This information can be viewed at any point in time in the Blockchain explorer (Figure 15).

Blockchain Application Name

Air Quality

Blockchain Explorer

Block Number	Application	Block Timestamp	Block Hash	Transaction From	Transaction To	Transaction Hash	Blockchain Ledger
1354	Air Quality	10/05/2020 19:40:18	0xf07eecacf04d39f6146dcef15cca9ac94219cee72cb2b30122b30a2ed1f21581	0x06726a939033fec66213dfc7981c6fd4b130d1ee		0x8311147d1b778f861cc2558041da4993e8bf0ed1f143bac5d57c50c505564a4e	Ethereum
1702	Air Quality	10/05/2020 20:09:18	0xeacecc6d58c5637a126de530dcfc3f3f52f59f25df7ccf82f02103913a594bba	0x87c447966afe67456cad87deaa8e19a1b72a04d4	0xb99b74b2db27d51084162f850e71d5b180f85b7e	0xa0ea7e236225232de1c690bde4478daa8eaad3484b8ba14a473ca11f28803538	Ethereum
1361	Air Quality	10/05/2020 19:40:53	0x44953da936f1813103c3e7e5b0a63d44ec57b3537489716cc07508021cbb489d	0x06726a939033fec66213dfc7981c6fd4b130d1ee	0xb99b74b2db27d51084162f850e71d5b180f85b7e	0xfedd157292abdbb90bbcd9a053b766f1e7507d5cd58c6b97aa7998da608e851c	Ethereum

3

Smart Contracts

Contract ID	Application
1	Air Quality

Figure 15 – Blockchain Explorer

4.0 FINDINGS

The simulated application, though small in scale, was able to critically examine the ability of the Blockchain technology in leveraging the potential of Blockchain applications in the build environment. The findings from this action research study present the benefits of using Blockchain technology particularly smart contract to build a robust BIM and IoT applications. The results from this test also form a conclusion of this chapter.

Upon examination, a connected and distributed system does not have a single point of failure that commonly cause by human error. Data received from IoT device and to BIM model was validated, recorded, and registered in the distributed ledger by a network of Blockchain consortium that formed from a multiple virtual machine. This network of computer validates data simultaneously. This offers a foundation for a more transparent, secure, and better business model. This underlying mathematical system will not only allow appropriate access to verified data thus improving quality control over individual data element but also give maximum flexibility over what data is shared and how. Such a holistic view of a single source of truth among participants can be achieved when trust is distributed, and consensus is applied to transactions with no central point of failure.

As demonstrated in the application, the BIM models became a virtual sensor from which non-measured information of the current state of the space can be obtained. The virtual model was then integrated with Autodesk Forge to enable an intuitive visualization through its 3D model. Furthermore, the virtual models can be used for developing operator training simulation systems, troubleshooting, production optimization and failure diagnoses. This is a powerful application during the O&M stage.

Further examination finds that the underlying verified time-series datasets from BIM and IoT devices are useful for predictive data intelligence in the built environment and, to obtain an accurate future prediction, ie; a sequence of day-to-day air temperature datasets can be used to forecasts the life expectancy of materials. The integrity and validity of information presents in the Blockchain network constructs a world of analytics potential for technology such as deep learning, machine learning (ML) and artificial intelligence (AI) to train and create a robust neural network (Sgantzos & Grigg, 2019).

The smart contract results also indicate that by automating workflow can contributed to improving the data processes. Without intermediaries, the smart contract enables a faster and efficient data models operation process. This multi-directional integration of smart contract and Blockchain applications in the BIM and IoT process will ultimately provide a value that can facilitate organisations improving their productivity, quality, and transparency in collaboration.

Furthermore, the Blockchain technology supported the standardisation of data by setting up a harmonised digital platform for BIM and IoT data accessibility. The combination between these technologies could offer greater data provenance and complete traceability of known events between multiple parties in the collaborative silos.

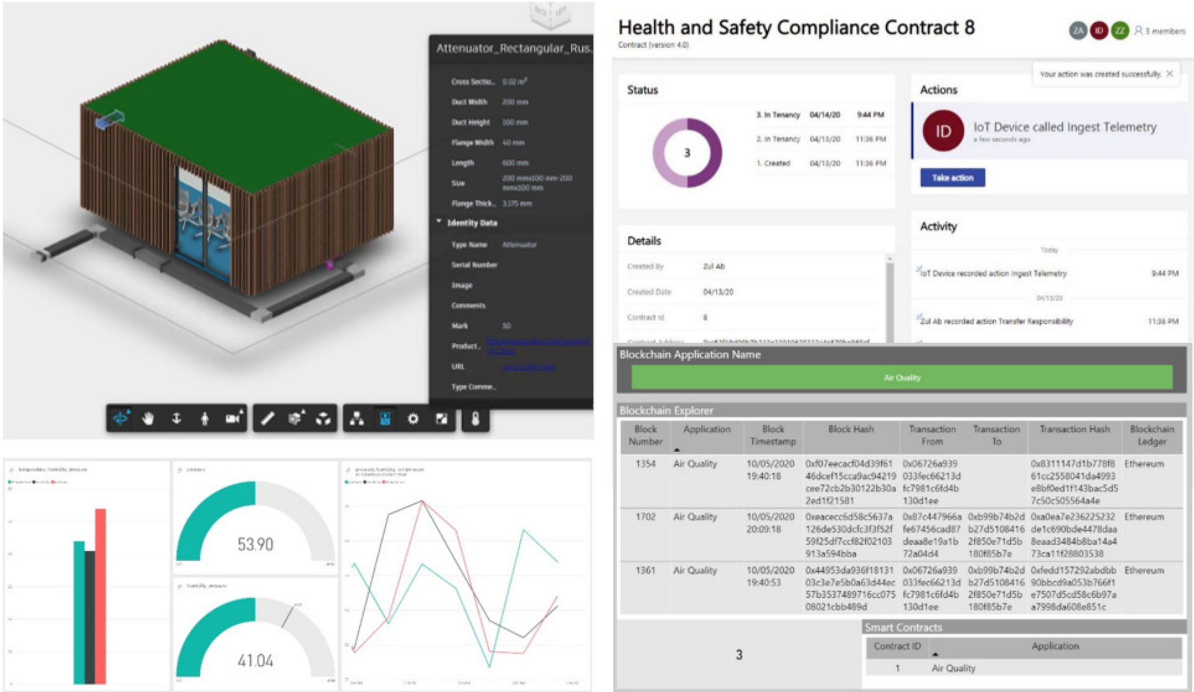

Figure 16 - A Realtime Connected Building Lifecycle with BIM, IoT Smart Contract and Distributed Ledger monitoring on Power BI dashboard.

5.0 Discussion

Blockchain technology implementations in the BIM and IoT integration promise many benefits for the AECO industry. However, this integration has shown various adoption challenges. Numerous challenges were identified from the literature review, respondent from the online survey, and were demonstrated in the simulated application, hence providing avenues for future studies.

One of the major challenges in this integration is scalability. Gartner Inc. forecasts, about 25.1 billion IoT devices were estimated to be installed by 2021 (Gupta et al., 2017). Such massive number of connected devices require a larger network for transaction verification. Increasing block size limit in the Blockchain network can cause verification delay and will turn into an expensive transactions bottleneck (Reyna et al., 2018). This scalability issues put limits to how data can be processed in a decentralized application. This limitation of the current Blockchain technology must be addressed before it can become a fully mainstream solution for the BIM and IoT integration.

Scalability issue in the Blockchain network could be solved with a new consensus algorithm, but it requires altering the Blockchain code which will expose the Blockchain network into another security challenge. Security is imminent for any decentralized businesses; any technology breach or security threat can lead to substantial losses. For example, the Decentralised Autonomous Organisation (DAO) Attack on 17 June 2016 by unknown hacker has resulted in the loss of 3.6 million Ether, or worth more than 1.3 billion dollars in today's market. The only solution to fix the flaw code was to "hard-fork the Blockchain and revert it to the safe state. This remedy defeats the core values of Blockchain, such as immutability, decentralised trust, and self-governance" (Yuepeng Wang et al., 2020). More emphasis must be placed on security policies, best practices, and intelligent security tools.

The absence of a suitable Blockchain-based platform for managing, creating, and deploying BIM and IoT services for AECO industry creates an interoperability issue and possibly new fragmented silos if implement. Therefore, future research should focus on developing a reliable blockchain network with a set of Open protocols and Open standards that promotes a community development and support all applications instead of introducing the application on specific networks. This will eliminate data lock-in by specific vendor and reduce vendor dominance in IoT market.

Numerous Blockchain projects have attempted to create solutions for every industry. The race of becoming the first and leading project has defeated the purpose of having a reliable Blockchain network, because such act simply recreates collaboration silos and has caused a tremendous amount of energy waste in the past decade. The economic challenge of Blockchain technology adoption must be evaluated carefully if not, this could be another waste for the AECO industry. Therefore, formulating regulations for economical, reliable, and accessible Blockchain network for the AECO industry is vital for the technology to grow and benefit our built environment.

The organizational challenge must also be considered. The lack of awareness and assessment in the AECO organisations is the major issue. Therefore, a strategic approach for accessing education, training, research, and development solutions must be planned. Yet such measures were understood as the common obstacles for any new technology to mature, and there are limitations as a result. Therefore, the continuation of learning and support from the industry is critical for these technologies to succeed.

6.0 CONCLUSION

Harmonising Blockchain technology in BIM and IoT data silos provides tremendous benefits for more secure, transparent, and immutable AECO business processes. These can be concluded into three main area:

1. Data management
2. Security
3. Trust

6.1 Data Management

The decentralised characteristics of the Blockchain properties can eliminate third party involvement in data management. The absence of a third party means that the data owner can have better control over his/her sensitive data. The operational resilient provided by a distributed data model will also ensure that the data are always accurate and accessible to all parties in the network.

The ability of a distributed consensus across a decentralised network without resorting to an external authority also enables business processes to be executed automatically in real-time. Automation in data processing improves validation speed in a BIM and IoT environment. Faster processing will also reduce the overall operating cost. This is an excellent economic case for businesses and supply chains.

The decentralized, automated, and fast characteristic of integrated Blockchain applications can improve the efficiency of the data sharing between BIM and IoT processes. As demonstrated in the simulated application, the automated data validation processes in the smart contract has the potential to mitigate initiatives in designing and organizing the contracts during the building life cycle. Smarter contracts management creates greater value by eliminating data silos and having a unified repository. This feature will revolutionise how contracts and processes are managed in the AECO industry in the future.

6.2 Security

Deploying BIM and IoT enables business to develop into digital enterprises which require a cohesive, companywide security strategy, and risk management strategy that includes staff at all levels. The Blockchain technology at their core can become a security pillar for this digital enterprise in safeguarding their data models. The Blockchain network can provides integrity for transacted information between employees.

Similar to digital companies, construction businesses must incorporate a holistic cybersecurity risk management strategy. With good understanding and exposures associated with BIM and IoT deployments security, Blockchain based systems and applications have the potentials to change organization culture, encourage information sharing, and improve collaboration between a BIM and IoT environment. This characteristic demonstrates that with better policies, a collaborative practice, structured data management and focus on prioritizing organization goals have the potentials of harmonizing data silos and establish a single source of truth.

6.3 Trust

Trust is the main factor of collaboration success. The immutable proof and consensus in a Blockchain application such as smart contract and DLT, can eliminate the need for data reconciliation and reduce the problem of audibility, compliance, security, data management and data governance.

A connected trusted BIM and IoT data could help to eliminate information loss and fragmented communication between architects, engineers, contractors, and facility managers. Blockchain integration could correspondingly pointedly minimise the overall costs in resolving reconciliation while mitigating errors and the build-up of unreconciled items at each stage of a project, which needs data authentication by automating trust. This ability will allow organizations to act timely consistent. Such a thought-driven process will promote ethical business and data governance between the parties involved.

Perhaps by emphasizing Blockchain's potential role in promoting better collaboration and integration between BIM and IoT environment would reveal the real benefits of leveraging these technologies would finally be utilized. Harmonizing data silos encourages the AECO industry landscape to develop into a more collaborative, flexible, and creative environment, as the community promotes a transparent, interconnected, and distributed ecosystem that upholds trust. Originality and value of the building life cycle can be redefined.

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