# BLOCKCHAIN AND CITY INFORMATION MODELING (CIM): A NEW APPROACH OF TRANSPARENCY AND EFFICIENCY

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***SUMMARY***: *For over a decade, digital modelling has transcended geometric representations to more advanced object-based modelling using real-life attirbutes. Digital technologies, especially Building Information Modelling (BIM) have been widely adopted in the Architecture, Engineering, Construction, and Operations (AECO) industry, while a newer niche - City Information Modelling (CIM) has emerged as an extension of BIM for urban informatics. This research proposes a framework that integrates heterogeneous CIM using a multi-level, nested data environment. The CIM is developed through a network of BIM models synchronized into a Geographic Information Systems (GIS) interface. The individual BIM models are blockchain-enabled by connecting them to a distributed ledger and shared across a network of project collaborators using a Common Data Environment (CDE) in a Building Level Framework.. The resulting CIM from the network of BIM models is shared between the asset owners in a City Level Framework. Use case scenarios are presented to illustrate the application of the research in real life, and research limitations are discussed. The study aims to improve management of buildings and urban assets, providing a more efficient and secure platform for collaboration and data sharing through a blockchain-CIM integration, providing opportunities for further research in digital modelling and smart technologies.*

***KEYWORDS***: *Blockchain Technologies, Distributed Ledger Technologies, BIM, CIM, Nested Data Environment*

***REFERENCE***: *Oluwatoyin Lawal, Nawari O. Nawari (2023). Blockchain and City Information Modeling (CIM): A New Approach of Transparency and Efficiency. Journal of Information Technology in Construction (ITcon), Vol. 28, pg. 711-734, DOI: 10.36680/j.itcon.2023.37*

## 1. INTRODUCTION

Majority of the global population now live in cities and traditional methods of managing and planning cities have reached their limits, therefore, the need for an approach shift and radical rethinking and integration of new methods and instruments cannot be overemphasized (Schmitt, 2012). Several new planning paradigms have evolved over the last two century and a half from the urban design paradigms of the 1850s to 1940s, to the procedural or master planning paradigm of the 1940s to 1990s and to the political-economy or urban management paradigm which guided the planning practice since the 1990s (Halla, 2007). The above is indicative of Bagheri and Hjorth (2006) argument for a process-based planning for sustainable development (Bagheri & Hjorth, 2007). The emergence of Industry 4.0 otherwise referred to as the fourth industrial revolution, birthing new knowledge frontiers such as Artificial Intelligence, blockchain, robotics, and the Internet of Things, has been at the core of recent advancements in urban studies. In recent times, there has been a plethora of research on the theory and application of blockchain technology, its real-life application in Architecture, Engineering, Construction and Operation (AECO) is on the increase with research demonstrating its use in digital construction logistics (Kifokeris & Koch, 2020) for example. Just as it has been in cryptocurrency and decentralized financing, blockchain technology has the potential to be another disruptive innovation in urban engineering studies, and this paper proposes a blockchain-based City Information Model (CIM) that leverages the transparent, distributed and immutable nature of constituent information in every urban component or asset and the data linking these components to facilitate effective management of these assets. The interoperability of blockchain technology and Building Information Modeling (BIM) which has been well research (Nawari & Ravindran, 2019) (Xue & Lu, 2020) (Teisserenc & Sepasgozar, 2021) (Li, et al., 2022), is further evaluated in this study. These models are proliferated at a city-scale through Geographic Information System (GIS). Information contained in these network of BIM models is decentralized, immutable and distributed throughout the lifecycle of all urban components within the blockchain, guaranteeing a holistic management of urban assets. This paper seeks response to the hypothetical questions that (1) there is improved efficiency in a digital city model that synchronizes multiple BIM models with geospatial data from Geographical Information Systems (GIS) and that (2) a blockchain-based CIM facilitates transparent urban asset management and governance.

Smart cities, often referred to as cybercities, though immaterial, they exist in parallel with reality with the capacity to affect a material reality (Boyer, 1996). Blockchain Technology (BCT) possesses the characteristics of a disruptive innovation in urban engineering studies and a component of smart cities similar to many precedent emergent technologies (Tsampoulatidis, Bechtsis, & Kompatsiaris, 2019). The success of bitcoin as the pioneer cryptocurrency has highlighted the potentials of BCT and has attracted significant interest from a broad range of fields (Aggarwal, et al., 2019). The architecture of BCT, underlined in the functionality of bitcoin and many other subsequent cryptocurrencies, is now being studied, tested and implemented across many fields (Nofer, Gomber, Hinz, & Schiereck, 2017).

The interoperability challenges with BIM and GIS due to difference in their application (Guyo, Hartmann, & Ungureanu, 2021) is surmounted using two approaches. First, BIM is integrated into GIS using python script and ArcGIS. Secondly, by using Autodesk InfraWorks – a software that already integrated BIM and GIS with a high Level of Development (LOD). This integration guarantees a holistic management of urban assets. Although Nawari & Ravindran (2019) have established the applications and potentials of BCT in relation to the BIM workflow, the use of CIM and Distributed Ledger Technology (DLT) for urban asset management has yet to be explored. Rather than simply multiplying BIM for urban purposes, the increasing sophistication of heterogeneous CIM offers a theoretical foundation for a distributed system of urban information management by integrating individual BIM models of varying semantic detail.

The following sections contain an enumeration of the research question, followed by a systematic literature review covering thematic areas such as blockchain definition, BCT-enabled BIM and it transition to CIM, geospatial integration of BIM, and BCT in design and construction. Section 4 contains the research methods using diagrammatic illustrations to discuss the research workflow. It also discusses the intersections between previous existing frameworks and how they relate to this study. Section 5 details the proposed framework and shows the task breakdown and multilayering for BIM-GIS-BCT integration while Section 6 validates the framework using real-life use cases. Discussions and conclusions are enumerated in sections 7 & 8 respectively.

## 2. RESEARCH QUESTIONS

The use of BIM technology in the AECO industry has not been without challenges. Many of these challenges can be due to various factors such as organizational limitations (Tam, Zhou, Shen, & Le, 2023), lack of institutional support (Akintola, Root, & Venkatachalam, 2017), or stakeholder's reluctance to demand its use (Adekunle, Aigbavboa, Ejohwomu, Thwala, & Nosakhare, 2021). These limitations posed by BIM in project delivery within AECO have been substantially documented. Some of these issues include information asymmetry (Zhang & Zhang, 2021), data interoperability (Elshani, Wortmann, & Staab, 2022), and loss of information leading to the integration of Product Lifecycle Management solution within BIM (Aram & Eastman, 2013). However, the prevalence of these problems suggests that more research is required to develop actionable solutions. Additionally, there is an over-reliance on human intermediaries in the design and construction workflow with respect to procurement and supply chain, which can be attributed to the mistrusting, opportunistic and adversarial nature of industry stakeholders (Cox & Ireland, 2002) (Phua & Rowlinson, 2003). Therefore, blockchain as a technology can provide a solution to these problems, resolve administrative inefficiencies, automate processes and improve collaboration and information exchange (Shojaei, 2019).

Therefore, the research aims to answer three questions. The first question evaluates the most efficient approach to develop a digital city model that synchronizes multiple BIM models with geospatial data from GIS, by merging building information with geographical location. The second question interrogates how a CIM can manage lifecycle information in the physical city using blockchain technology. Can stakeholders take decisions in a digital interface that can affect the material assets represented in the digital interface. Previous studies have proposed integrating BIM and blockchain in the Building Information Modelling workflow (Nawari & Ravindran, 2019). Therefore, the third research question evaluates the result of using a tripartite relationship between BIM, CIM, and blockchain for urban asset management.

# 3. LITERATURE REVIEW

## 3.1 Blockchain – Definition

Blockchain technology is a decentralized database that records assets and transactions across a peer-to-peer computer network, secured through cryptography (Radanovic & Likic, 2018). The absence of a central authority in this database, and the interconnection of one block of transactions to another, makes it immutable. Zheng et al (2019) classified blockchains based on their degree of decentralization: private, consortium or permissioned, and public blockchains. The consensus mechanism by which these different Blockchain Technologies (BCTs) operate distinguishes them. From private blockchains to consortium blockchains to public blockchains, the degree of centralization increases (Zheng, et al., 2019).

Blockchain technology, which was introduced to the world with the creation of Bitcoin in January 2009, has since captured the interest of many other subject areas. However, research on its application in the Architecture, Engineering, Construction and Operation (AECO) industry is relatively recent compared to other fields. Cheng et al (2021) in their bibliometric analysis and systematic literature review highlighted that the first publication of blockchain in AECO is dated at 2015.

The nature of blockchain's data storage is evidence of decentralized data. The shared ledger for record keeping, the distributed hash table which indexes what is available on the network and the mediating contract between multiple parties are the critical infrastructure of a blockchain. (Sundararajan, 2016).

## 3.2 Blockchain-Enabled BIM (BcBIM) and its transition into CIM

Building Information Modeling (BIM) involves the creation and management of physical representations of building components, incorporating data, information, and knowledge at various semantic levels (Succar, Sher, Aranda-Mena, & Williams, 2007). BIM adds one or more additional dimensions to traditional design approaches which is the information layer that describes physical properties of building components. In contrast, a City Information Model (CIM) is a method of organizing city information by extracting useful data from physical and non-physical information (Xu, Ding, Luo, & Ma, 2014). CIM combines urban environment feature classes with design process feature classes (Gil, Almeida, & Duarte, 2011). This definition may suggest that CIM is a monolithic version of BIM, but research in this paper supports the notion of CIM as a network of BIM and other information models that make up the urban space (Xu, Ding, Luo, & Ma, 2014).

A BIM-GIS collaborative workflow provides a paradigm shift in CIM by merging digital models with a geospatial database to form a spatial data model, which serves as the backbone of CIM (Jil, Almeida, & Duarte, 2011). A semantically rich CIM can be developed by integrating BIM with GIS, which is a suggestive technique for integrating fragmentary urban definitions, discourses, and ideological positions currently present as information silos in various BIM models (Stojanovski, 2013). Furthermore, the integration of BIM and GIS is crucial for geo-location and is proposed by Yu & Liu (2016) to analyze 3DGIS valuation models, which increases the accuracy of property value calculations. In CIM, blocks are synonymous with BIM models, while territories refer to geographical information, emphasizing the relationship between the two (Stojanovski, 2013).

## 3.3 Applications of Blockchain in AECO Industries

The administration and management of urban assets are critical for achieving efficiency, sustainability, and resilience in urban areas. Investing in human and social capital, as well as urban infrastructure, is essential for creating smart cities and future cities that are sustainable and resilient (Sabri et al., 2015). For instance, adopting a GIS-based land administration system by State governments across Nigeria can ultimately improve living conditions and contribute towards a reduction in slum dwellers (Faniran & Olaniyan, 2016).

The use of blockchain technology (BCT) in land administration has been gaining popularity, with its first adoption in land registration to address issues with irregularities and counterfeiting in Honduras between 2016 and 2017. Since then, blockchain-based solutions for land registration have been deployed in Brazil, Ukraine, Sweden and India (Mendi & Cabuk, 2020).

The trend of increased usage of both Building Information Modelling (BIM) and 3D Geographic Information Systems (GIS) has led to an increase in their overlap and consequent integration. This integration is essential for effective urban visualization, as CityGML, the 2D GIS that uses the CityGML data structure, has limitations in analyzing the complex physical reality of the real world. Therefore, the integration of BIM, which uses the Industry Foundation Classes (IFC) data structure, with GIS to give a semantically rich 3D city model is necessary (Salheb, Arroyo Ohori, & Stoter, 2020).

This project is part of a broader research that aims to integrate blockchain with BIM models and integrate them into GIS, creating a BIM-GIS-Blockchain loop. However, research in blockchain applications in environment, construction, and smart cities are significantly lower than studies in other subtopics such as ownership, security and privacy, and supply chain management (Zeadally & Abdo, 209). This is partly due to blockchain's data privacy issue, as reported by Microsoft (Underwood, 2016).

Inter-blockchain communications need to be enabled and improved on, and interoperability amongst different blockchain platforms is key to unlocking its diverse applications (Qasse, Abu Talib, & Nasir, 2019). Blockchain research in construction has birthed a number of use cases, but this study will focus on two major applications that incorporate BIM, namely Digital Twins and Internet-of-Things.

The most active stages of blockchain research are in engineering and construction stages (Xu, Chong, & Chi, 2022) in areas such as blockchain-enabled smart contracts (Hunhevicz, Brasey, Bonanomi, & Hall, 2020), using blockchain technology and smart contracts for BIM (Chung, Caldas, & Leite, 2022) and in its ability to resolve disputes in the construction industry (Mahmudnia, Arashpour, & Yang, 2022).

### 3.3.1 Blockchain and Digital Twins

Digital Twins refer to the process of merging the virtual world and real world, and has become a widely accepted tool in the Architecture, Engineering, Construction and Operation (AECO) industry due to its ability to enhance cross-disciplinary collaboration (Sahal, Alsamhi, Brown, O'shea, & Alouffi, 2022). Lu et al (2020) demonstrated the use of Digital Twins for asset monitoring in building operations and maintenance, utilizing anomaly detection. Digital Twins surpass BIM models by providing a semantically richer model that is constantly updated and can simulate scenarios and possibilities using artificial intelligence-based techniques (Lee, Lee, Masoud, Krishnan, & Li, 2021). The application areas of Digital Twins are expanding beyond AECO to include manufacturing, aviation, healthcare, and more.

One of the most commonly used techniques for modeling Digital Twins is through as-built BIM, although semi-automatic geometric digital twinning approach using 3D image recognition technology and CAD drawings can also achieve digitization within a shorter period of time (Lu, Chen, Li, & Pitt, 2020).

Recent research has proposed the use of blockchain technology in Digital Twins for improved collaboration and data reliability. Sahal et al (2022) suggested a framework for blockchain-based collaborative Digital Twins for pandemic alerting, while Lv et al (2022) utilized blockchain to ensure the security of the digital mapping process of IoT. Salim et al (2022) proposed a framework for securing IoT environments against cyberattacks using blockchain-enabled Digital Twins and Smart Contracts for security and authentication.

### 3.3.2 Blockchain and Internet of Things

The technology of Internet-of-Things (IoT) involves the real-time transmission of data between the physical and digital environments for various purposes, including testing and optimization of scenarios. Unlike traditional internet, which relies on humans for information, IoT empowers computers to gather and exchange data autonomously (Ashton, 2009). The emergence of IoT has transformed the way data is shared across various sources (Barricelli, Casiraghi, & Fogli, 2019). Smart IoT primarily involves the connection, processing, and implementation of data (Nagajayanthi, 2022). To ensure security and privacy in smart homes, Dorri et al. (2017) proposed the use of always-online devices to manage, monitor, and control communication within and outside the homes. These devices incorporate a private blockchain that enhances data integrity, security, and privacy (Dorri, Kanhere, Jurdak, & Guaravaram, 2017). Additionally, Huang et al. (2020) presented a data management approach for digital twin that utilizes a peer-to-peer network to improve data sharing efficiency and authenticity among participants (Huang, Wang, Yan, & Fang, 2020).

## 3.4 BIM-GIS Data Integration and Interoperability.

The integration of Building Information Modelling (BIM) and Geographical Information Systems (GIS) is a complex task that requires a formal framework to exchange information between the two systems. However, semantic mismatches and differences in granularity of both models are problems that need to be addressed. Laat & Van Berlo (2011) suggested that the AECO sector needs to start working with central model servers for full integration of BIM and GIS. CityGML is considered a pioneering standard for 3D city representation (Gröger & Plümer, 2012). The integration of BIM and GIS enables visualization of BIM models within a broader context of 3D geolocation, producing a more realistic model of the physical world.

3D city models are currently being used in dozens of application domains for diverse purposes such as geo-visualization and visibility analyses (Biljecki, Stoter, Ledoux, Zlatanova, & Coltekin, 2015). To accurately situate BIM models in a GIS environment, adequate mapping and transference of coordinate systems is important. Kang & Hong (2015) proposed a software architecture that separates geometrical information from that related to the relevant properties for effective integration of BIM into a GIS-based facilities management system.

Deng, Cheng & Anumba (2016) used an instance-based method to generate the mapping rules between IFC and CityGML for accurate mapping between the two schemas. Song et al (2017) reviewed 96 high-quality research articles from a spatio-temporal statistical perspective and concluded that the utilization of BIM-GIS integration in the AECO industry requires systematic theories beyond integration technologies. Liu et al (2017) studied different combination methods developed to solve different problems and concluded that BIM and GIS interpret 3D modeling from two different perspectives.

Wang, Pan & Luo's (2019) review of the applications of BIM-GIS integration in the field of the sustainable built environment proposed an upgrade of the IFC and CityGML for improved accuracy of BIM-GIS data integration and to enhance data interoperability. Zhu et al (2019) proposed an Open-Source Approach (OSA) to retrieve geometric information in IFC through the spatial structure of IFC and convert it into shapefile by developing an automatic multipatch generation algorithm (AMG). They also concluded that shape files are the most-used exchange data format in GIS to support 3D geometry in other non-GIS 3D software packages like SketchUp.

In general, Shirowzhan et al (2020) suggested that future research should examine compatibility as a critical component of BIM adoption, and therefore, this paper explores one of the numerous approaches for BIM interoperability in the form of python-GIS integration. Overall, BIM-GIS integration is a complex task that requires the development of formal frameworks and the adoption of new technologies to address semantic mismatches, differences in granularity, and coordinate system mapping.

## 4. RESEARCH METHODOLOGY

To conduct a thorough review of the literature, relevant books and articles were selected based on the key concepts and critical subtopics of discussion. These subtopics include the state-of-the-art of blockchain technology, the city, building information modelling, city information modelling, BIM and GIS integration, and applications of blockchain within the AECO industry.

The proposed blockchain-CIM framework consists of two parts. First, the study introduces a suitable distributed ledger to record activities within the digital assets in the BIM, which can take the form of a plug-in for the BIM application. Second, the BIM data from building models is integrated with CityGML data from geographic information systems to create a City Information Model. An overview of the research methodology is provided in Figure 2, which begins with a literature review, followed by the identification of research gaps and the formulation of hypotheses. A framework is then proposed to address these hypotheses and is validated with illustrative examples and use case scenarios. The study conducted a systematic literature review that aims to comprehensively identify, evaluate, and synthesize all the available and relevant research on blockchain in construction in order to establish a research trend within the field. The first stage of the research involves a systematic review of literature within the field by searching Web of Science and Scopus databases using the key phrases ‘Blockchain’ and ‘Architecture, Engineering and Construction’. A number of papers have been examined blockchain within the AECO industry (Xu, Chong, & Chi, 2022). Therefore, the focus of this research is to respond to questions 1) how to efficiently develop a CIM, 2) how CIM can manage lifecycle information of assets and 3) how BIM, CIM and blockchain can facilitate urban asset management.

A Web of Science (WoS) search using key phrases ‘Blockchain’ and ‘Architecture, Engineering and Construction’ produced 146 valid results, which were visualized separately using cite space while a Scopus search using the same key phrases produced a total of 7527 results which were manually analyzed. Figure 1 and Tables 1-3 below show the result of a co-citation analysis of the Web of Science (WoS) results. These articles are visualized under 7 major keyword clusters namely; encryption, distributed ledger, innovation adoption, digital technology, cloud computing, AEC(O) and access control.

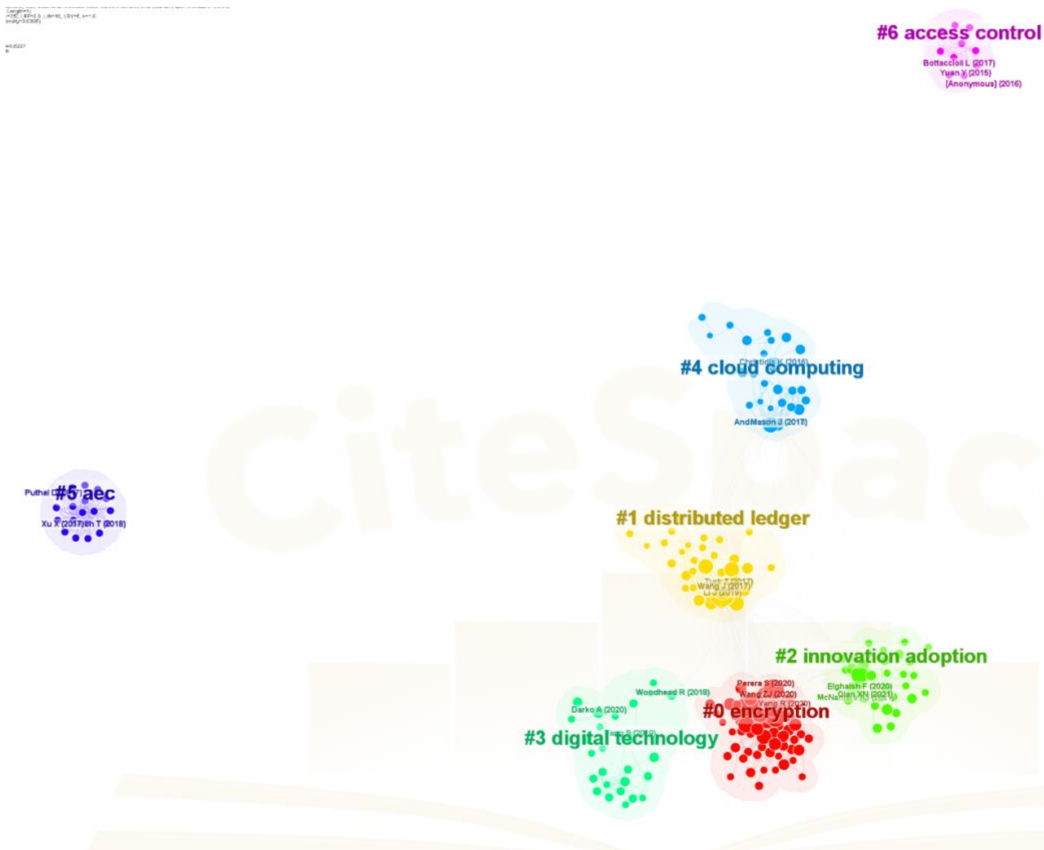


*Figure 1: Co-citation clusters of WoS articles on Cite Space.*

*Table 1: Citation Counts for WoS articles.*

| Citation Counts | References | DOI | Cluster ID |
|---|---|---|---|
| 35 | Li J, 2019, AUTOMAT CONSTR, V102, P288 | 10.1016/j.autcon.2019.02.005 | 1 |
| 28 | Wang ZJ, 2020, AUTOMAT CONSTR, V111, P0 | 10.1016/j.autcon.2019.103063 | 0 |
| 26 | Turk Z, 2017, PROCEDIA ENGINEER, V196, P638 | 10.1016/j.proeng.2017.08.052 | 1 |
| 26 | Yang R, 2020, AUTOMAT CONSTR, V118, P0 | 10.1016/j.autcon.2020.103276 | 0 |
| 26 | Perera S, 2020, J IND INF INTEGR, V17, P0 | 10.1016/j.jii.2020.100125 | 0 |
| 25 | Wang J, 2017, FRONT ENG MANAG, V4, P67 | 10.15302/J-FEM-2017006 | 1 |
| 25 | Xue F, 2020, AUTOMAT CONSTR, V118, P0 | 10.1016/j.autcon.2020.103270 | 0 |
| 23 | Sheng D, 2020, AUTOMAT CONSTR, V120, P0 | 10.1016/j.autcon.2020.103373 | 0 |
| 20 | Hunhevicz JJ, 2020, ADV ENG INFORM, V45, P0 | 10.1016/j.aei.2020.101094 | 0 |
| 18 | Nawari NO, 2019, J BUILD ENG, V25, P0 | 10.1016/j.jobe.2019.100832 | 0 |

The publications dated between 2017 to 2020 had the most citation counts, with Li, J, (2019) having the most citation counts on Cite Space with 35 citations which falls under the cluster #1 (distributed ledger).

The Scopus search yielded 7,527 papers in total. By limiting the subject area to engineering and environmental sciences, the number was trimmed down to 4,362. This number was down to 4,114 when only English language publications were considered. By excluding keywords with no direct relevance to architecture, engineering and construction such as healthcare, human behavior, power, 5G, there were 1,841 results. After limiting the results to scientific publications such as conference papers, journal articles, books and book chapters, and checking for duplications, there were 1,406 valid results. The top ten keywords in the valid results are shown below.

*Table 2: Research Keywords and Hits.*

| S/N | Keyword | Number of Hits |
|---|---|---|
| 1 | Blockchain | 351 |
| 2 | Block-chain | 135 |
| 3 | Internet-of-Things | 130 |
| 4 | Construction Industry | 103 |
| 5 | Industry 4.0 | 101 |
| 6 | Sustainability | 98 |
| 7 | Sustainable Development | 85 |
| 8 | Supply Chain Management | 79 |
| 9 | Smart Contract | 73 |
| 10 | Information Management | 70 |

The table below shows that there has been a steady increase in scientific research in Blockchain in the AECO industry since 2016 with a peak of research activities in 2022.

*Table 3: Publication Counts Per Year.*

| Year | Number of Hits |
|---|---|
| 2023 | 357 |
| 2022 | 492 |
| 2021 | 306 |
| 2020 | 156 |
| 2019 | 74 |
| 2018 | 20 |
| 2016 | 1 |

Following a detailed analysis of thematic distributions of the papers reviewed from Scopus and WoS, coupled with review of previous works as discussed in Section 3.0, blockchain research is prevalent in AECO industry, albeit at construction and administration stage of projects (Hunhevicz, Brasey, Bonanomi, & Hall, 2020) or at design stage where blockchain is integrated with BIM (Chung, Caldas, & Leite, 2022) (Nawari & Ravindran, 2019), not much research suggested the potentials of a blockchain-enabled project implementation from inception through design to project delivery. The framework discussed aims to bridge this gap.

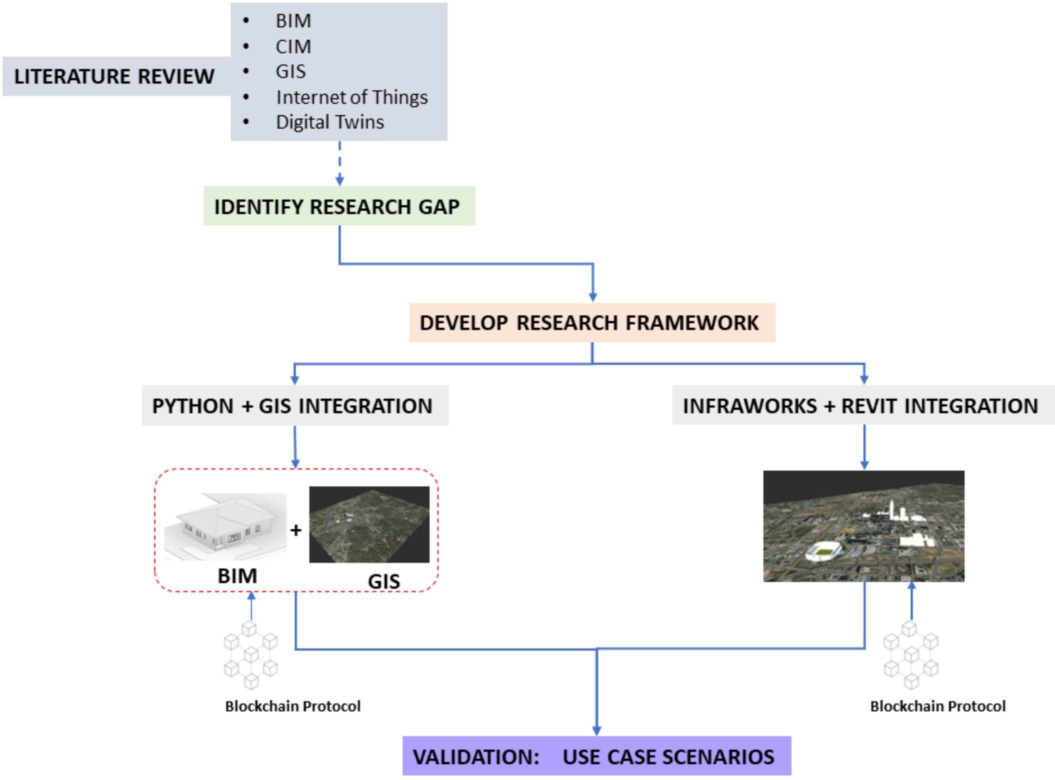


*Figure 2: Research Methodology.*

## 5. PROPOSED FRAMEWORKS

Figure 3 below displays the overlapping interactions among existing frameworks of earlier researches, which also highlights the gap which this study seeks to bridge. The CIM-GIS framework has already been explored in many software applications while the blockchain-GIS framework has also influenced a number of theoretical research. However, blockchain enabled CIM with GIS integration offers a new frontier for blockchain research.

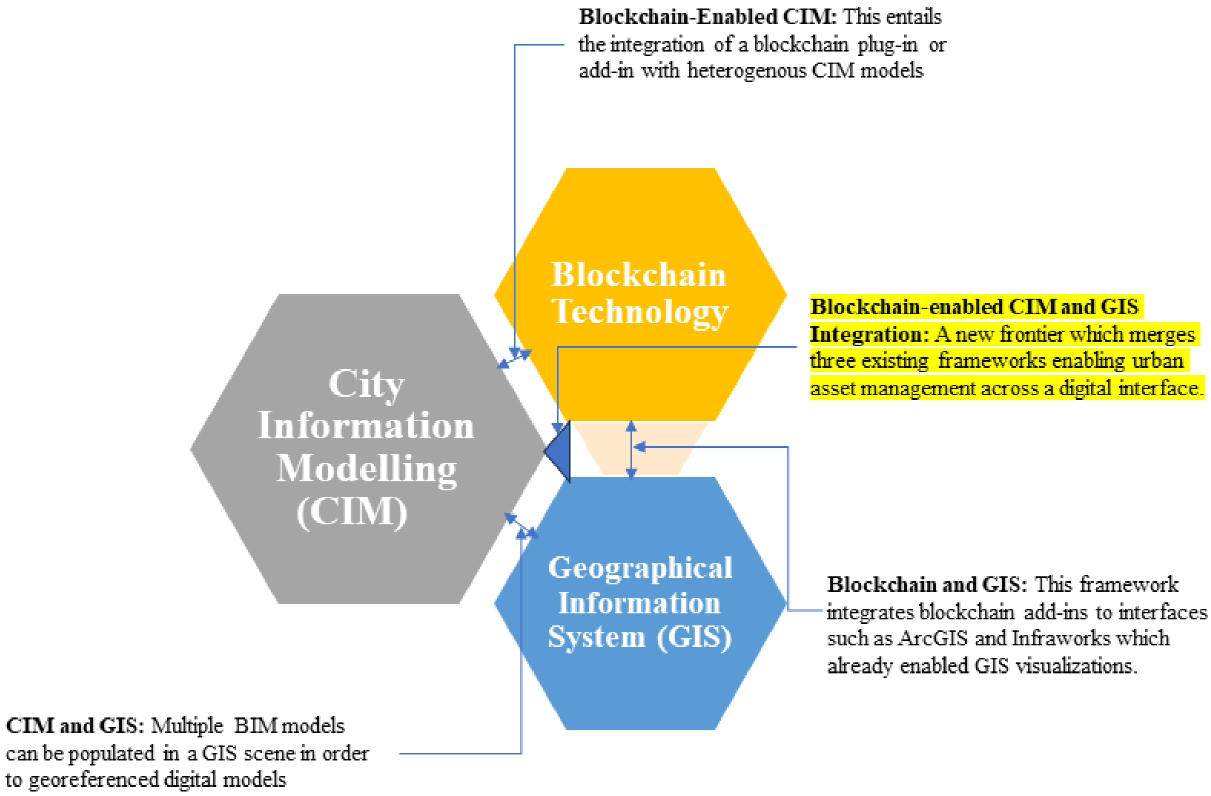


*Figure 3: Outline of the proposed framework.*

Figure 4 outlines the four major stages of the developed blockchain-enabled solution for asset management using CIM. In stage 1, a nested Common Data Environment in two layers is proposed, with the building level CDE housing the individual BIM model(s) integrated with a suitable blockchain protocol, and the City Level CDE interacting with other stakeholders within the city/municipality. Stage 2 involves identifying a suitable blockchain protocol, which could be an existing plug-in or add-on to the BIM application, or a newly developed one. BIMchain is proposed as the blockchain plug-in to BIM in this paper, with stakeholders formatted into transaction user groups and smart contracts used for managing data exchanges between them. In stage 3, the blockchain-enabled BIM is integrated with GIS using a python script to allow BIM models to be imported into a GIS interface and visualized with respect to geospatial information. Finally, in stage 4, the proposed model is validated and evaluated through two scenarios, with Scenario 1 demonstrating the feasibility of a blockchain CIM across the project lifecycle, and Scenario 2 demonstrating the efficiency of the model in project data management and exchanges of ongoing projects. Figure 5 below illustrates two nested levels of interaction components, namely the blockchain-BIM (bcBIM) building level framework and the BIM-GIS city level framework, with three major components identified: the BIM component, the GIS component, and the DLT component. The bcBIM building level framework concentrates on the design, construction, and lifecycle management processes and workflows. As suggested by Nawari & Ravindran (2019) and Sreckovic et al (2021), this framework employs blockchain (BC) and smart contracts (SC) to enable traceable documentation and transactions throughout the design and construction ecosystem. Based on the hybridized bcBIM model, the city level framework digitizes the correlation between buildings and their geographical context.

Previous research studies have put forward the idea of a Common Data Environment (CDE) as a solution for secure data storage of digital assets, interdisciplinary coordination, management, and versioning of information containers. These studies include Sreckovic et al. (2021), Wang et al. (2017), and Pishdad-Bozorgi et al. (2020). Building on this concept, the present study proposes a nested multi-layered CDE that includes a *Single BIM model* (SBM) scenario, a *Single Model plus Context* scenario, a *multi-model plus context model* (MMCM) and the City Level Data Environment (MMCM). The SBM represents a subset of the larger MMCM and is used in the building level framework, while the MMCM is used in the city level framework.

While the different frameworks employ different standards, they are not mutually exclusive, and coupling both concepts is necessary to complete the urban blockchain loop. Both the building level and city level frameworks use a private consortium blockchain, but it is possible that a public blockchain may be suitable in certain cases once the adoption of this framework becomes more widespread. In both frameworks, smart contracts are used as service solutions to automate agreements and payments when and where necessary. To explain the coupling of both frameworks, a use case demonstration is provided after briefly introducing each framework.

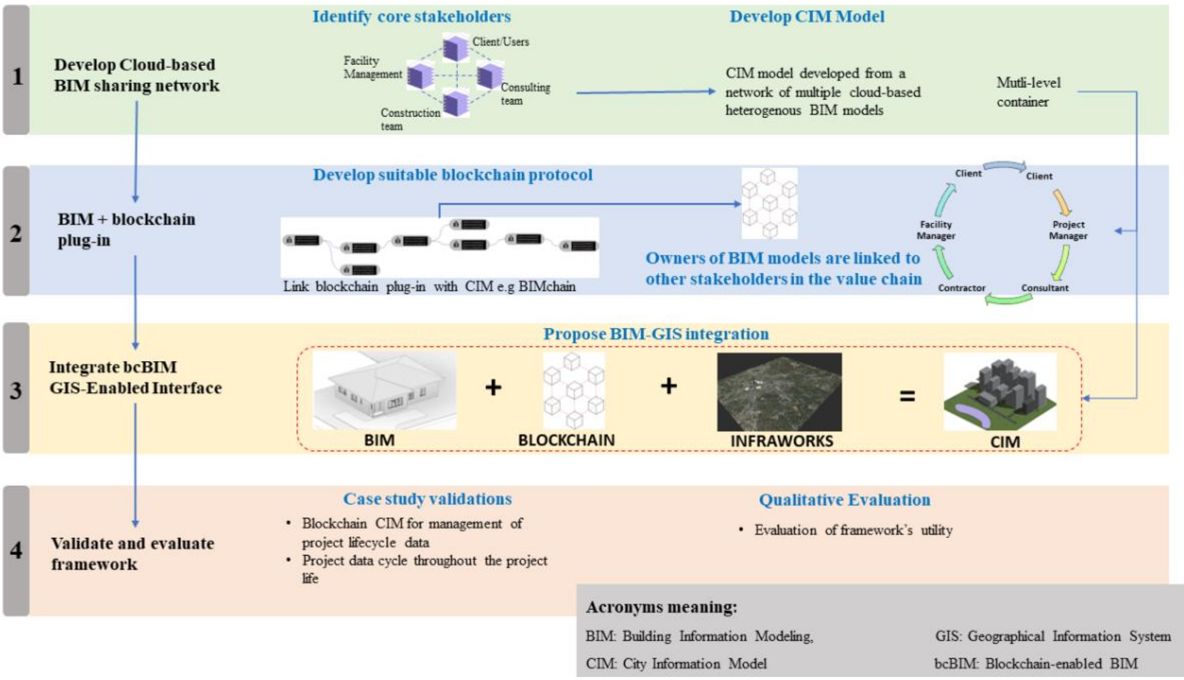


*Figure 4: Research Process Diagram.*

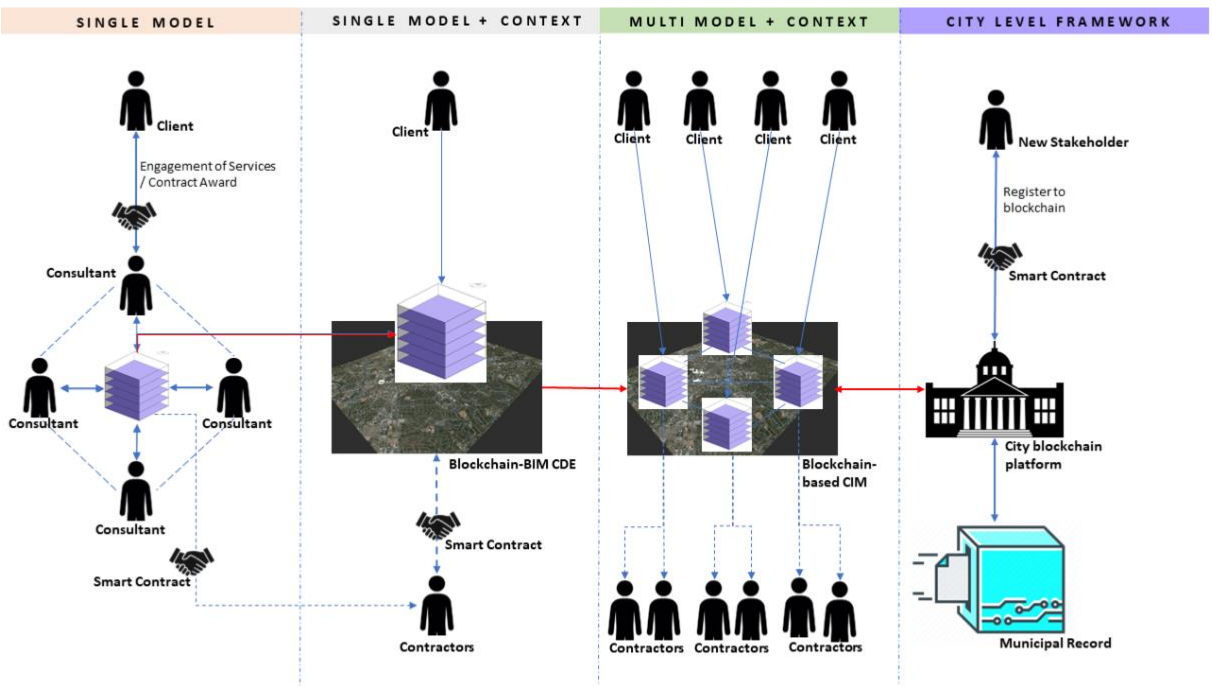


*Figure 5: bcBIM Building Level and BIM-GIS City Level Frameworks.*

## 5.1 The Multi-Level Framework

The commercial product BIMchain, developed by Lucetium SAS in Paris, France, is currently the only known integration of BIM and blockchain (Kuperberg & Geipel, 2021), suggesting that blockchain-BIM integration is not widespread in practice. However, project stakeholders, including the client or owner, project manager, technical consultants, general contractor, and facility managers need to exchange digital assets in various forms.

The multi-level framework entails a cloud-based blockchain-BIM-GIS integration. The blockchain-integrated BIM (bcBIM) represents the Building Level Framework and this involves single models (SBM) while the bcBIM-GIS integration represents the City Level Framework and this involves Multi-Model plus Context Model (MMCM). A Building Level Data Environment (BLDE) stores all information at Building Level Framework while the City Level Data Environment (CLDE) stores all information at City Level Framework.

The conceptual framework shown in Figure 6, begins with the client commissioning project consultants, and the paper-based consultancy engagement as paper-based information in the BLDE. The agreements between the client and PM also informs the design brief and the basis-of-design document which is also stored as paper-based information in the BLDE.

The technical consultants develop domain-specific design documents which the client reviews and approves. The review and approval are automated using Smart Contracts (SC) to trigger the next phase of action. The BIM model is shared amongst consultants, integrated with a blockchain protocol and stored as a central digital file in the BLDE.

The planning approval process is also incorporated into this workflow as the municipality can review the BIM model to ensure its compliance. The CLDE stores the entire BLDE and the paper-based legal ownership documentations of the client's digital asset. The BcBIM integration with GIS occurs within the CLDE. To define the relationship between an asset and its locale, the city level framework proposes a solution that enables peer-to-peer interactions among asset owners. Although owners of non-digital or non-blockchain-based digital assets may also participate at the City Level, the full potential of the solution is realized when digital assets incorporate BC and SC.

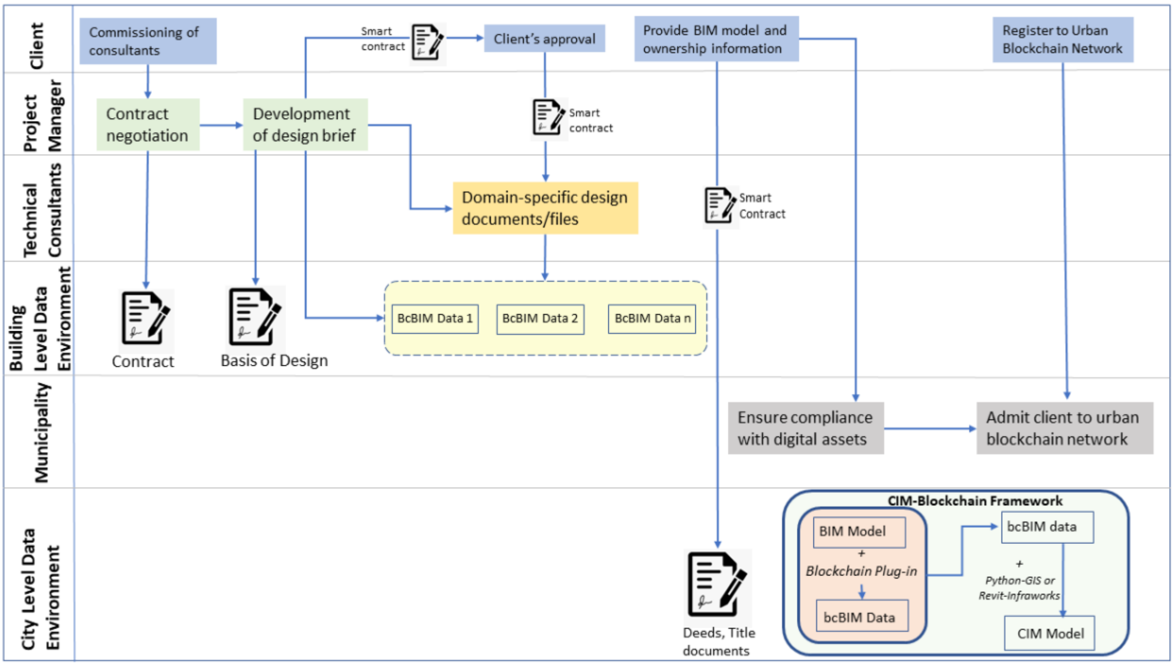


*Figure 6: The Multi-Level Framework.*

The key participants in this framework are the clients or owners and the municipal authorities. The SBM is expanded to a MMCM by merging the Industry Foundation Class (IFC) data structure of Revit with the CityGML data structure of ArcGIS, integrating the bcBIM model with GIS data. First, the asset owner provides traditional paper-based title documents, which are reviewed by municipal authorities before being uploaded to the CLDE.

While the PM administers the network at building level, the municipality serves as administrators to a private consortium urban blockchain and city level, thereby admitting new participants who may be interested in exchanging or transferring assets or information about their assets. The municipality also registers asset owners to the network using SC to record the inputs of new registrants.

## 5.2 CIM through the Integration of ArcGIS and BIM using Python Script

The python script, depicted in Figure 7 is a modified version of Esri Netherlands' script used for importing Industry Foundation Class (IFC) data. It can be run as a standalone script or in the ArcGIS python window. When preparing a Revit model for importing, it is crucial to input geographical information to accurately situate the model in the ArcGIS scene. This includes entering coordinates (LongLat) into the model. For example, a 3-bedroom residential building model with two stories located at 1116 NE 11th Terrace, Gainesville FL, 32601 is named PC26Option2.rvt. To obtain the correct coordinates, the address is searched on ArcGIS, and a reference point is identified. This point will align with one corner of the proposed BIM model.

```python
import time, arcpy, os, shutil, arcgis.gis
from arcgis.gis import GIS
from time import strftime
from datetime import datetime

def CreateBSLpackage(workSpaceEnv=None, GDBfolder_name=r"FinalProject2.gdb",
                     out_FeatureDataset=r"Building_A", spatial_reference=r"RD New",
                     Rvt_directory=None, BSL_name=r"BSLpackage.slpk",
                     nameOfBuildingL=r"BuildL_A", includeDate=False):
    if not os.path.exists(workSpaceEnv) or not os.path.isfile(Rvt_directory):
        raise NotADirectoryError("Incorrect or non-existent directory")
    out_gdb_path = os.path.join(workSpaceEnv, GDBfolder_name)
    arcpy.env.workspace = workSpaceEnv
    arcpy.env.overwriteOutput = True
    arcpy.CreateFileGDB_management(workSpaceEnv, GDBfolder_name)
    arcpy.BIMFileToGeodatabase_conversion(Rvt_directory, out_gdb_path, out_FeatureDataset,
       spatial_reference)
    arcpy.env.workspace = out_gdb_path
    datasets = arcpy.ListDatasets(feature_type='feature')
    featuresClassesList = arcpy.ListFeatureClasses(feature_dataset=datasets[0])
    for i in range(len(featuresClassesList)//2):
        arcpy.management.Delete(featuresClassesList[i])
    featuresClassesList = arcpy.ListFeatureClasses(feature_dataset=datasets[0])
    arcpy.env.overwriteOutput = True
    feature_dataset = os.path.join(out_gdb_path, out_FeatureDataset)
    arcpy.MakeBuildingLayer_management(feature_dataset, nameOfBuildingL)
    if includeDate:
        BSL_name = BSL_name[:-5] + datetime.now().strftime("%Y%m%d") + BSL_name[-5:]
    print("Creating BSL package with name ({})".format(BSL_name))
```

*Figure 7: Python Script to Create File Geodatabase.*

The coordinates and elevation of this point are 82.3110836°W 29.6626493°N 178.29 ft, which are extracted from ArcGIS and transferred into Autodesk Revit. Moreover, the ESRI Coordinate System Reference file for NAD 1983 North Florida state plane was downloaded in ArcGIS format (.prj) from NAD83(NSRS2007) / Florida North: EPSG Projection -- Spatial Reference. The file was stored in the same folder as the repository data used in this research and renamed as PC26Option2.prj. In this example, the NAD1983 projection with North Florida state plane was chosen and geo-processed into the scene.

### 5.2.1 Georeferencing in Python-ArcGIS interface

To achieve a successful integration of BIM and GIS, accurate mapping is crucial. Georeferencing allows the BIM model to be displayed in its real-world location, providing a realistic view of the model in an urban setting. In this process, the floor of the model was selected for georeferencing, and the identified address at 1116 NE 11th Terrace, Gainesville FL, 32601 was located in ArcGIS, as highlighted in Figure 8. It is worth noting that the Project Base Point in Autodesk Revit serves as the reference point for placing the BIM model in the building scene. However, if the coordinate system in Revit is already accurate and matches that of ArcGIS, this step may not be necessary.

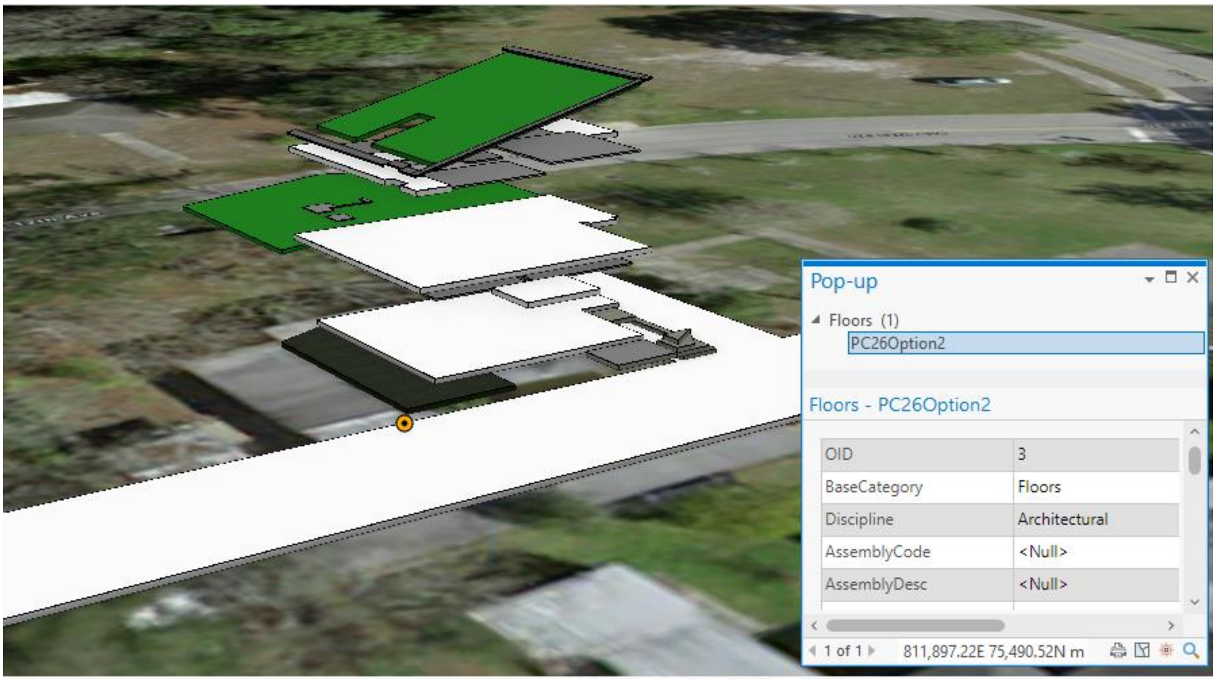


*Figure 8: Georeferenced Floors.*

Figure 8 displays only the floors that have been georeferenced at the intended location. The location where the LongLat information was obtained is marked with a red circle. In this figure, all other building elements have also been georeferenced to present the complete BIM model in the scene layer. To set up the building model, one of the requirements is to input the longitude, latitude, and elevation data into Revit. It's worth noting that the project base point, highlighted in blue, is listed as a layer in the table of contents and also appears as an object in the model. Accurately positioning the BIM model on the scene in ArcGIS depends heavily on this project base point, which corresponds precisely to the Revit model.

## 5.3 CIM through the Integration of Revit Model and Infraworks Interface

As an alternative to the above python-ArcGIS integration for City Information Models, BIM models can also be imported into an interface which already has enhanced GIS interoperability. One of such interfaces is the Autodesk Infraworks interface. Infraworks overlays elevation data on multiple data layers which represent physical features such as water areas, aerial imagery, transportation data, building data and 3D model data. This framework enables BIM models and site contexts to be visualized with maximum semantic details. Unlike the python-GIS approach, the Revit-Infraworks model preserves the Level of Development (LOD) of the BIM model almost perfectly. This integration is however feasible in two directions, as BIM models can be launched in a GIS interface to develop the City Information Model while the GIS interface can also be exported into BIM to develop the City Information Model.

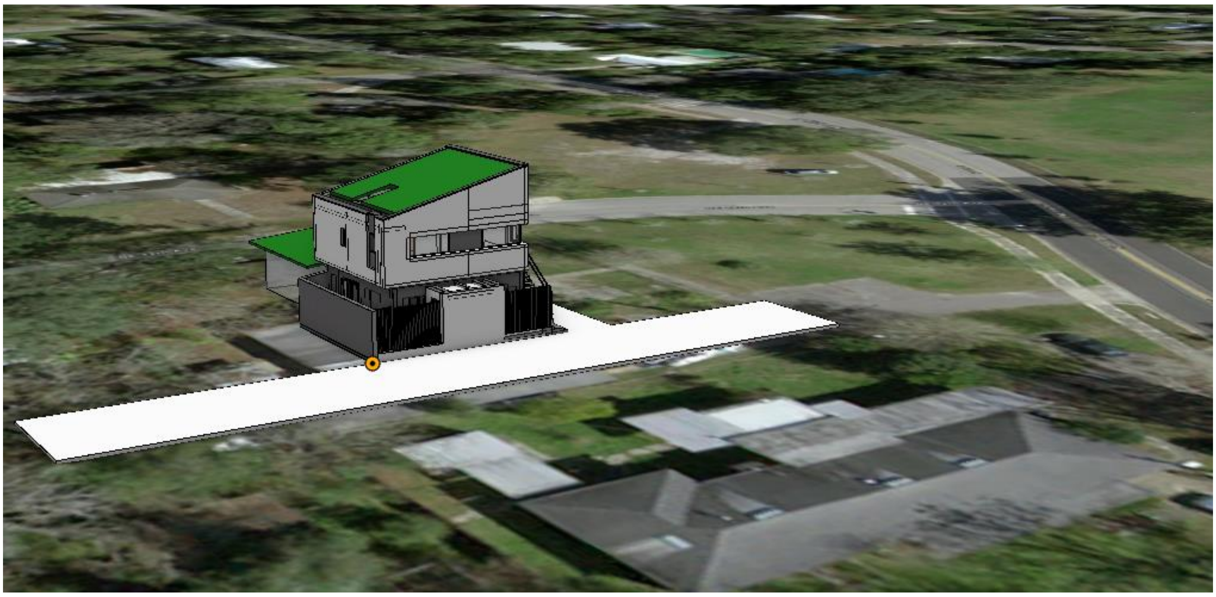

*Figure 9: Georeferenced Model.*

### 5.3.1 BIM to GIS Workflow

The same BIM file PC26Option2.rvt was launched in Autodesk Infraworks. First, the geographical context which had the same address NE 11th Terrace, Gainesville FL is selected and the GIS imagery is generated from existing satellite imagery. Figure 10 below shows the context selection.

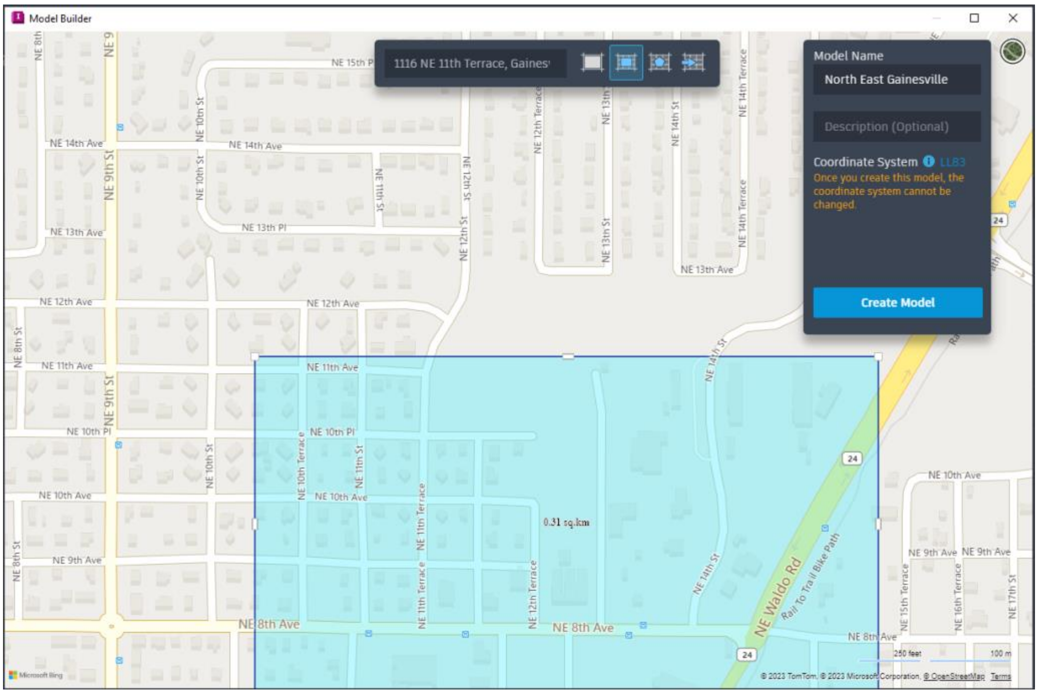


*Figure 10: Site Context Within North East Gainesville, Florida.*

Thereafter, the correct projection suitable for the site location is selected. Afterwards, the BIM model can be placed interactively on any suitable site within the GIS scene, or specific coordinates are input to ensure it is properly georeferenced. In the Infraworks interface, the properties of the various building components in the BIM model are still editable and a blockchain-enabled BIM model will still be connected to its immutable distributed ledger.

The optimal potential of this approach is to have a cluster of BIM models which represent a collection of urban assets, with each BIM asset connected to a blockchain protocol and launched in Infraworks as enumerated above. Figure 11 below shows the above BIM model in a CIM interface with the properties of its roof component highlighted as shown.

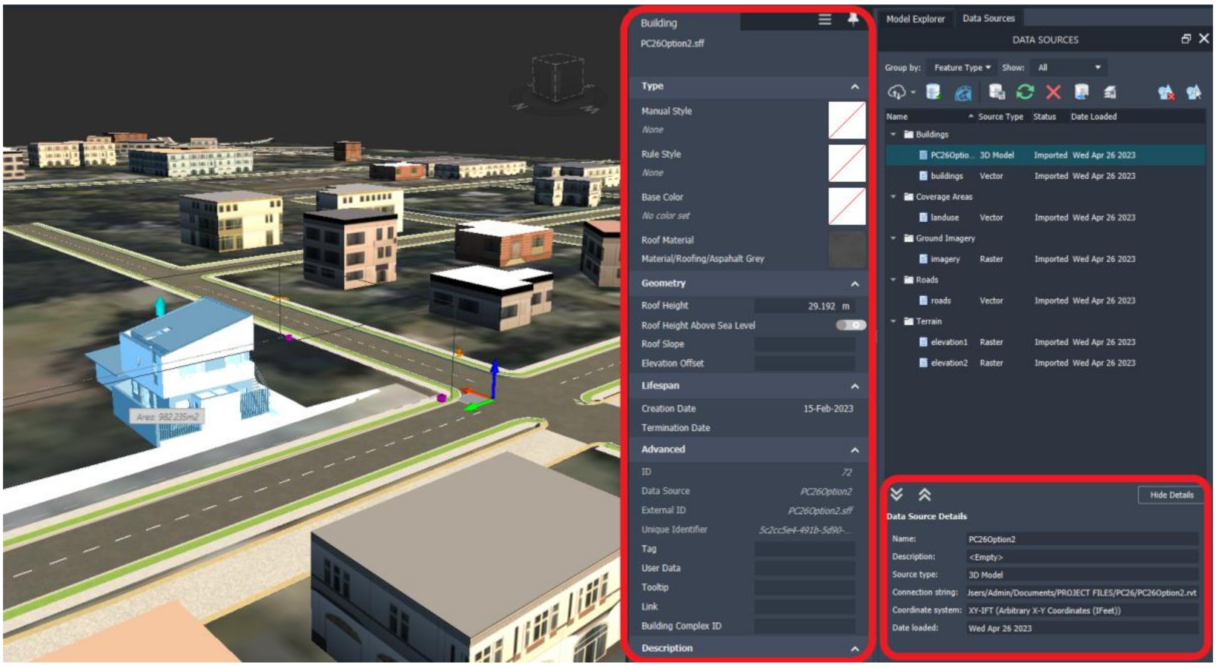


*Figure 11: BIM + Infraworks Interface with highlighted material properties of building components.*

The highlighted tabs above show valuable information that can be stored in a blockchain ledger. The highlight in the middle also known as the 'Building' tab describes the material properties and data provenance of the roof component. In this tab, the material of the roof is described under the 'type' section. The roof height and slope are described under the 'geometry' section while the creation date of 15th February, 2023 is entered as creation date under the 'Lifespan' section. Any additional information can be entered in the description panel below while there is advanced information which refer to the BIM data provenance of the building roof. Some of this advanced information are the data source, the advanced ID and the unique identifier. All of this information is stored on the blockchain protocol which is shared amongst all stakeholders involved in the delivery of the asset represented by the BIM model as shown.

The smaller highlight on the bottom right corner of the email refers to the data source details. This information describes the BIM data and it is also helpful to manage data traceability within the CIM. The CIM can be shared as .fbx or any other format which can be visualized in other BIM-enabled applications such as Navisworks and Revit.

### 5.3.2 GIS to BIM Workflow

Similar to the above approach, the site context in Figure 12 which has been converted into a GIS Scene in Infraworks, can be exported into Revit and the PC26Option2.rvt which has been georeferenced accurately in Revit can be copied into the exported site context. In this case, rather than launch PC26Option2.rvt in Infraworks, the scene is exported as .fbx file without the BIM model. This .fbx file is imported into Navisworks as shown below.

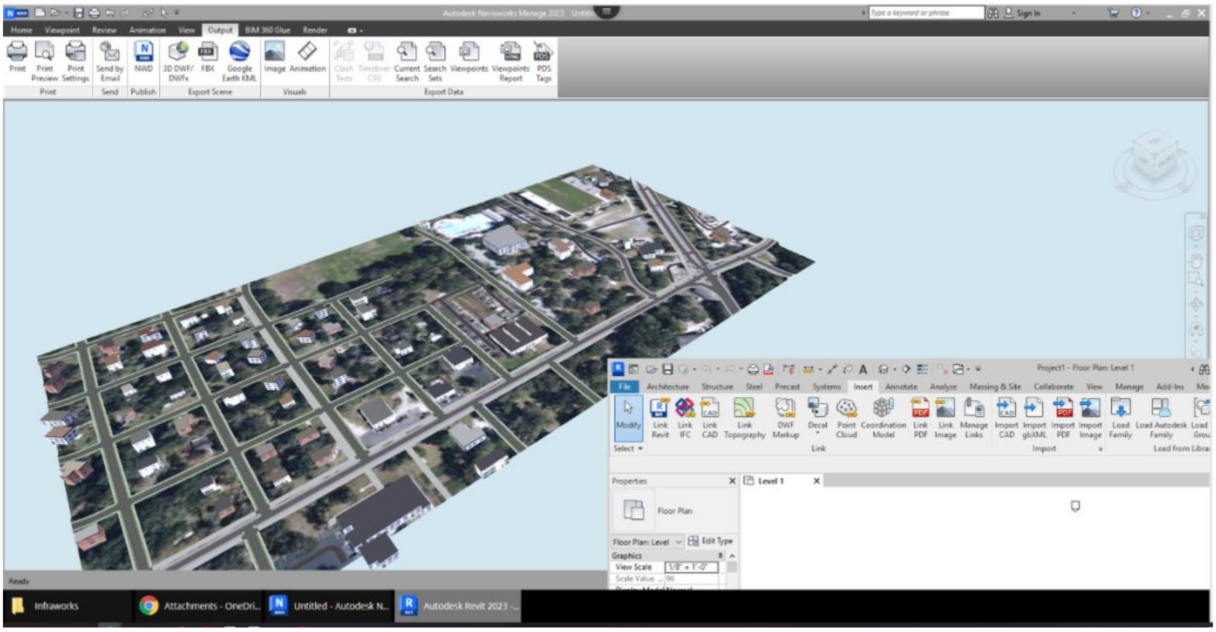

*Figure 12: Site Context as GIS scene visualized in Navisworks.*

The Navisworks model can be linked to Revit thereafter. The site context model is imported as a block model which shows the neighboring context. PC26Option2.rvt is thereby copied into the site context model to complete the CIM. This CIM however does not have the satellite imagery of a GIS scene, neither does it have a rich semantic detail. The site context model also does not convey any information, except as a geometric description of neighboring structures to the BIM model of focus. This form of CIM is more illustrative, and less descriptive, except all relevant elements in the CIM are modelled as BIM models in Revit, and the site context mass is used merely for conceptual and contextual illustrations.

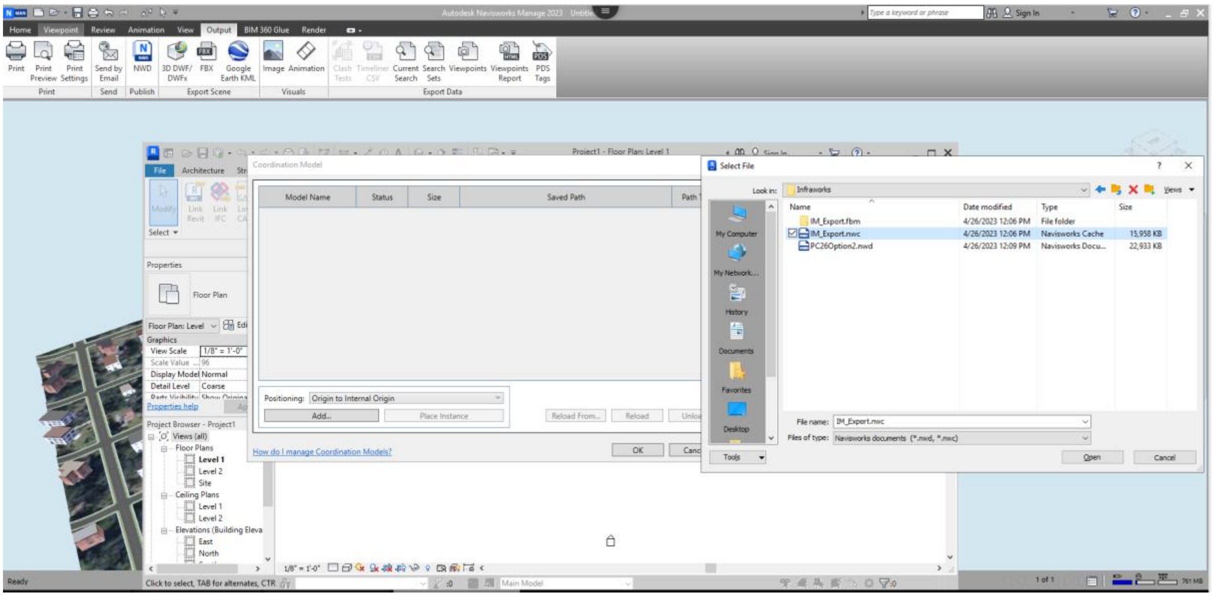

*Figure 13: Linking Navisworks to Revit.*

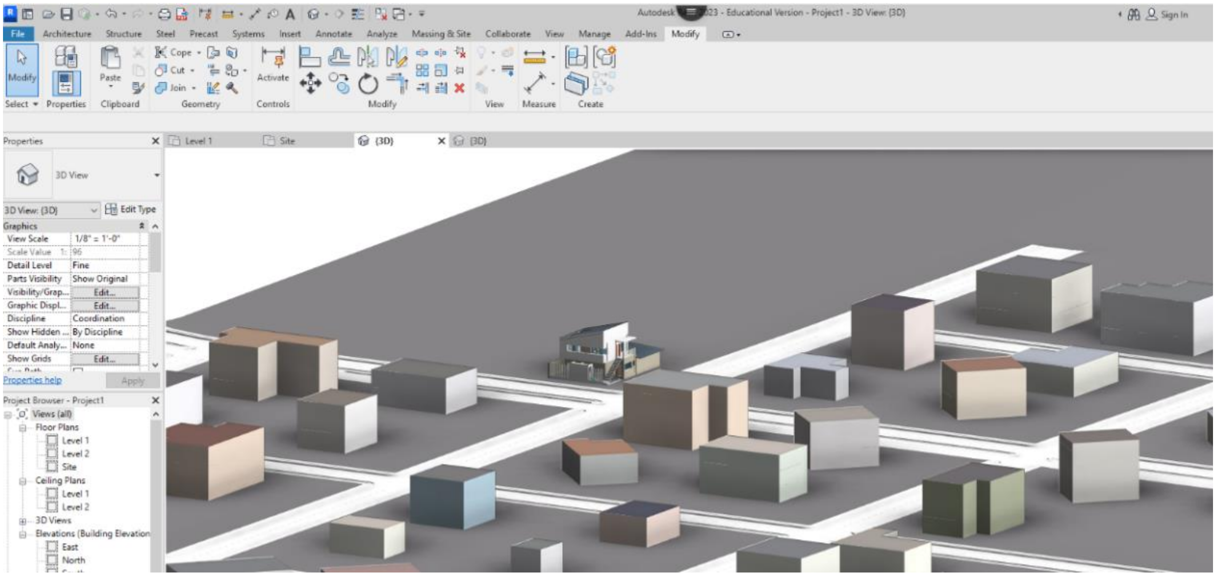

*Figure 14: Revit-based City Information Model.*

This form of CIM preserves the semantic details of the BIM model completely. All plug-ins such as BIMchain or any other blockchain protocol integrated with the BIM model at building level framework is preserved in its totality.

## 6. POTENTIAL APPLICATIONS WITH USE CASES

### 6.1 Case 1: Project Information Management

Information silos, low data interoperability and poor cross-party coordination are major challenges for implementing a BIM-enabled Building Lifecycle Management (BLM) for instance, however, there is a knowledge gap in implementing BLM for property owners in spite of efforts in academia and industry. (Li, et al., 2021). An effective and holistic project information management can be achieved using the approach enumerated in section 5.0 without the aforementioned challenges. To further illustrate the application of a BIM-BCT-SC framework, A workflow for a standard building procurement is visualized. This section discusses the benefits of blockchain in a typical Engineer-Procure and Construct (EPC) model of project delivery.

The multi-layered framework can play a crucial role in ensuring the success of the EPC procurement model. By using BIM, the turnkey contractors can create a detailed and accurate digital representation of the building, including its various components and systems. This information can be used throughout the project's lifecycle, from design to construction to operation and maintenance.

In addition, the use of blockchain technology can ensure the security and integrity of the data generated throughout the project. This can be especially important in an EPC procurement model, where the contractor is responsible for the project management from inception all through handing over.

Finally, the application of smart contracts can ensure that all parties involved in the project adhere to the terms of the agreement. This can include milestones, payment schedules, and other contractual obligations. Overall, the proposed BIM, BC, and SC framework can provide a comprehensive approach for ensuring successful project deliveries

To validate the effectiveness of the proposed framework, a scenario for transferring the concession to a new stakeholder is used. In such a scenario, a multi-layered series of inquiries will be triggered, requiring data audit and provenance in a tamper-proof database. Figure 15 illustrates the relationships between stakeholders, tasks and deliverables at different stages of project execution. The stakeholders include the Client, Project Manager, Technical Consultants, Contractor and Facility Manager. In an EPC model, there are three distinct parties, namely the Client who initiates the project, the EPC contractor who is the Project Manager, Technical Consultant and

Contractor, and the Facility Manager who takes over the physical project and the information model after handing over.

The design phase is the first step in this scenario and is described under the building level framework. The client engages the project manager (PM) and the rest of the project team, who develop a synchronized BIM model of the apartment building. After critical reviews, coordination, and approvals, which are all activated by smart contracts (SCs), the model is shared with the Municipal authorities for a planning permit.

In the stakeholder relationship, the client engages a project manager and they exchange a series of information. This information evolves into a design brief for the technical consultants. The technical consultants use the shared information to generate construction documents which the building contractors will use to execute the building contract. The contractors work with information from the technical consultants whilst maintain the contractual relationship with the client. The technical information along with other information generated by the PM may form the basis of the contract with the client. Upon project completion, the contractor hands over the completed project to the client. The client then engages a Facility Operator or Manager (FM) who maintains the effective operation of the facility or asset. All construction information (as-built documents) are transferred to the client and the FM. The FM and the client maintain a post-contract relationship similar to that of the client-PM at pre-contract stage.

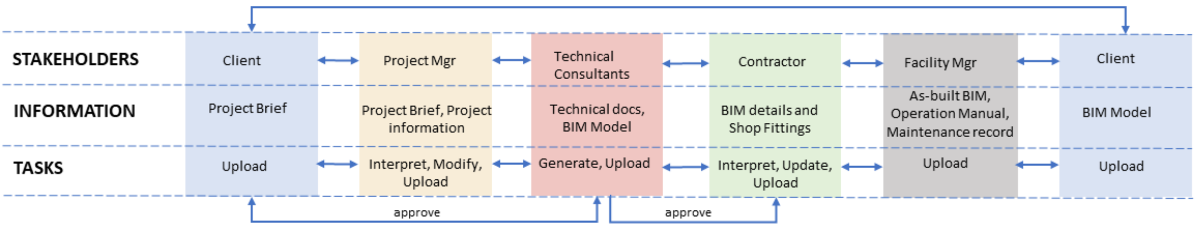


*Figure 15: Schema of Blockchain-Enabled Build-Operate-Transfer Procurement Framework.*

As the interactions shift amongst stakeholders, the information also changes. The client originates the project brief, and the project manager interpretes it and adds more information to help the technical consultants. The technical consultants generate the BIM model which contains all details regarding how the project is built. The Contractor updates the BIM model in accordance with what is built on site in an up-to-date state. This transforms the BIM to Asset Information Model (AIM). The FM maintains the BIM and records all maintenance-related activities on it. This Asset Information Model may or may not be shared with the client. Cloud-based blockchain integrated City Information Model ensures the completeness and tamper-proof nature of this workflow.

In summary, the use of the BIM, BC, and SC framework in the Build-Operate-Transfer procurement model provides a seamless workflow from the design phase to the transfer of ownership. The framework ensures that all stakeholders are accountable for their respective roles, and the use of smart contracts automates the next step once conditions are met, reducing the risk of breaches of contract. Additionally, the peer-to-peer asset exchange feature of the framework provides a transparent and secure means for stakeholders to exchange assets without requiring an intermediary.

## 6.2 Case 2: Data Exchanges Across Multi-parties

Blockchain technology can facilitating data and information transfer in project execution. With the use of a Common Data Environment (CDE), especially when it is cloud-based, information continuity and evolution amongst stakeholders is guaranteed, resulting in an information loop for every project. Figure 16 shows a stakeholder information cycle which illustrates the transformation of information as the project moves through its different phases.

The project procurement process starts and ends with the client. The information provided by the client in step 1 returns in Step 6 as a as-built BIM model or Asset Information Model. The procurement model in this case assumes that a Project Manager mediates between the clients and other consultants.

Upon completion of the construction phase, an SC prompts the client to engage Facility Managers (FM) in step 5. The FM takes over administrative authority over the as-built BIM model, ensuring that all maintenance records are synchronized with the model. Finally, in step 6, the client ends up with a copy of the up-to-date building model, which has been updated throughout the project lifecycle on the CDE.

The application example demonstrates how blockchain technology can be used to connect all processes from start to end through smart contracts. The project data management and exchanges are confirmation of the circularity of information throughout the project life, enabling all stakeholders to have access to the same up-to-date information. The BIM model serves as the backbone of this information exchange, facilitating a seamless flow of information between stakeholders.

Overall, the application example provides evidence of the potential of blockchain technology in streamlining project management and improving collaboration amongst stakeholders. By facilitating a circular flow of information, blockchain can enhance transparency, reduce errors and delays, and improve project outcomes.


*Figure 16: Stakeholder Information Cycle.*

## 7. DISCUSSIONS

This paper poses three research questions, which the proposed frameworks aim to address: (1) What is the most efficient approach to developing a city model which combines multiple BIM models with GIS data, (2) How can CIM manage lifecycle information immutably and traceably and (3) Can stakeholders take decisions in a digital interface that can affect the material assets represented in the digital interface? A subsequent analysis of the proposed framework shows that integrating BIM and GIS data is not the most efficient, given the limited functionality of current software programs such as Esri City Engine and Autodesk Infraworks. However, the framework responds positively to questions 2 and 3, as it allows for the integration of BIMchain or any other blockchain plug-in for lifecycle information, auditability, and provenance, making information flow between stakeholders more transparent and immutable.

The framework's flexibility and scalability are noted as critical, as workflows are highly context-dependent, and unforeseen events can occur during construction. The Common Data Environment is also discussed as a platform for exchanging digital information, requiring a unified interface to preview data in different file formats. The integration of BCT and SC in BIM for asset management requires a digitized approach, which may necessitate reconfiguring traditional design and construction workflows. However, privacy concerns regarding the concession of vital information by participants remain an issue.

The study contributes to existing literature on blockchain application in the AECO industry. It illustrates a concept for unified BIM and GIS with blockchain to create an immutable CIM whilst simultaneously managing peer-to-peer exchange of geo-spatial assets without third-party involvements. However, Further work would be necessary to address current research limitations such as the lack of widespread, bespoke blockchain protocol. With the increase in blockchain application in the AECO industry, further research on detailed algorithmic workings, front and back-end interfaces would be critical to addressing the current limitations.

## 8. CONCLUSION

In this study, a multilayered Common Data Environment (CDE) framework is proposed for managing urban assets using a blockchain-enabled City Information Model (CIM). First, BIM models and integrated with blockchain via the use of a blockchain protocol or plug-in within a BIM interface. This enables an immutable information model with a secure and traceable data structure. Secondly, GIS is further integrated with the blockchain-BIM model using two distinct approaches namely; via python script within ArcGIS interface, and secondly with Autodesk Infraworks and Revit. The framework's effectiveness in managing lifecycle information in a physical city is demonstrated through use case and algorithmic workings to manage asset exchanges in any transaction. The proposed framework also offers a restructuring of traditional procurement workflows to enable a seamless and auditable project development process that connects the ideation and creation phase of works to execution, operation, and maintenance.

## DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## REFERENCES


Adekunle, S. A., Aigbavboa, C., Ejohwomu, O. A., Thwala, W., & Nosakhare, E. R. (2021). Key constraints to optimal BIM penetration among Nigerian Quantity surveyors. *CM50 CONFERENCE*, (p. 66).

Aggarwal, S., Chaudhary , R., Aujla, G. S., Kumar, N., Choo, K.-K. R., & Zomaya, A. (2019). Blockchain for smart communities: Applications, challenges and opportunities. *Journal of Net work and Computer Applications, 144,* , 13-48.

Akintola, A., Root, D., & Venkatachalam, S. (2017). Key constraints to optimal and widespread implementation of BIM in the South African construction industry. *Management, 25*, 34.

Ali, S., Wang, G., White, B., & Cottrell, R. L. (2018). A blockchain-based decentralized data storage and access framework for pinger. *17th IEEE international conference on trust, security and privacy in computing and communications/12th IEEE international conference on big data science and engineering (TrustCom/BigDataSE)*, (pp. 1303-1308).

Aram, S., & Eastman, C. (2013). Integration of PLM solutions and BIM systems for the AEC industry. *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction, 30*, p. 1.

Ashton, K. (2009). “That ‘internet of things’ thing.”. *RFID Journal, 22*(7), 97-114.

Bagheri , A., & Hjorth, P. (2007). Planning for sustainable development: a paradigm shift towards a process-based approach. *Sustainable development, 15*(2), 83-96.

Barricelli, B. R., Casiraghi, E., & Fogli, D. (2019). A survey on digital twin: Definitions, characteristics, applications, and design implications. *IEEE access, 7*, 167653-167671.

Bernardini, M., Pennino, D., & Pizzonia, M. (2019). Blockchains meet distributed hash tables: Decoupling validation from state storage. *arXiv preprint arXiv, 1904*(01935).

Biljecki, F., Stoter, J., Ledoux, H., Zlatanova, S., & Coltekin, A. (2015). Applications of 3D city models: State of the art review. *ISPRS International Journal of Geo-Information, 4,* 2842-2889.

Boyer, M. C. (1996). *CyberCities: visual perception in the age of electronic communication.* . Princeton Architectural Press.

Bruyseels, K., Santoni de Sio, F., & Van den Hoven, J. (2018). Digital twins in health care: ethical implications of an emerging engineering paradigm. *Frontiers in genetics, 9,* 31.

Chung, I. B., Caldas, C., & Leite, F. (2022). An analysis of blockchain technology and smart contracts for building information modeling. *Journal of Information Technology in Construction, 27*.

Cox, A., & Ireland, P. (2002). Managing construction supply chains: the common sense approach. *Engineering, construction and architectural management, 9*(5/6), 409-418.

Deng, Y., Cheng, J. C., & Anumba, C. (2016). Mapping between BIM and 3D GIS in different levels of detail using schema mediation and instance comparison. *Automation in Construction, 67*, 1-21.

Dorri, A., Kanhere, S. S., Jurdak, R., & Guaravaram, P. (2017). Blockchain for IoT security and privacy: The case study of a smart home. *2017 IEEE International Conference on Pervasive Computing and Communications Workshops (PerCom Workshops),* (pp. 618-623). Kona.

El-Mekawy, M., Ostman, A., & Hijazi, I. (2012). A Unified Building Model for 3D Urban GIS. *ISPRS International Journal of Geo-Information*, 120-145.

Elshani, D., Wortmann, T., & Staab, S. (2022). Towards Better Co-Design with Disciplinary Ontologies: Review and Evaluation of Data Interoperability in the AEC Industry. *Linked Data in Architecture and Construction*.

Faniran, S., & Olaniyan, K. (2013). From slums to smart cities: addressing slum-dwelling in Nigeria through e-land administration. *Proceedings of the 7th International Conference on Theory and Practice of Electronic Governance* (pp. 189-189). New York: Association for Computing Machinery.

Floros, G., Pispidikis, I., & Dimopoulou, E. (2017). Investigating integration capabilities between IFC and CityGML LOD3 for 3D city modelling. *The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, *42*, p. 1.

Gil, J., Almeida, J., & Duarte, J. P. (2011). The backbone of a city information model (CIM)." Respecting fragile places. *Education in computer aided architectural design in Europe*, 143-151.

Gröger, G., & Plümer, L. (2012). CityGML–Interoperable semantic 3D city models. *ISPRS Journal of Photogrammetry and Remote Sensing, 71*, 12-33.

Guyo, E., Hartmann, T., & Ungureanu, L. (2021). Interoperability between BIM and GIS through open data standards: An overview of current literature. *Proceedings of the 9th Linked Data in Architecture and Construction Workshop*, (pp. 5-9).

Halla, F. (2007). A SWOT analysis of strategic urban development planning: The case of Dar es Salaam city in Tanzania. *Habitat International, 31*(1), 130-142.

Harris, C., & Ullman, E. (1945). The nature of cities. *The annals of the American academy of political and social science, 242(1)*, 7-17.

Huang, S., Wang, G., Yan, Y., & Fang, X. (2020). Blockchain-based data management for digital twin of product. *Journal of Manufacturing Systems, 54*, 361 - 371.

Hunhevicz, J. J., Brasey, P.-A., Bonanomi, M. M., & Hall, D. (2020). Blockchain and smart contracts for integrated project delivery: inspiration from the commons. *EPOC 2020 Working Paper Proceedings* .

Isikdag, U., & Zlatanova, S. (2009). Towards defining a framework for automatic generation of buildings in CityGML using building Information Models. *3D geo-information sciences*, 79-96.

Jil, G., Almeida, J., & Duarte, J. P. (2011). The backbone of a City Information Model (CIM): Implementing a spatial data model for urban design.

Kang , T. W., & Hong, C. H. (2015). A study on software architecture for effective BIM/GIS-based facility management data integration. *Automation in construction, 54*, 25-38.

Konashevych, O. (2021). 'GoLand Registry' Case Study: Blockchain/DLT Adoption in Land Administration in Afghanistan. *DG.O2021: The 22nd Annual International Conference on Digital Government Research* (pp. 489-494). New York: Association of Computing Machinery.

Kraft, E. M. (2016). The air force digital thread/digital twin-life cycle integration and use of computational and experimental knowledge. *54th AIAA aerospace sciences meeting*, (p. 0897).

Kuperberg, M., & Geipel, M. (2021). Blockchain and BIM (building information modeling): progress in academia and industry. *arXiv preprint arXiv*, 2104.00547.

Laat, R., & van Berlo, L. (2011). Integration of BIM and GIS: The development of the CityGML GeoBIM extension. *Advances in 3D geo-information sciences*, 211-225.

Lee, D., Lee, S., Masoud, N., Krishnan, M. S., & Li, V. C. (2021). Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in construction, 127*, 103688.

Li, L., Yuan, J., Tang, M., Xu, Z., Xu, W., & Cheng, Y. (2021). Developing a BIM-enabled building lifecycle management system for owners: Architecture and case scenario. *Automation in Constructio, 129*, 103814.

Li, X., Lu, W., Xue, F., Wu, L., Zhao, R., Lou, J., & Xu, J. (2022). Blockchain-enabled IoT-BIM platform for supply chain management in modular construction. *Journal of construction engineering and management, 148*(2), 04021195.

Liu, X., Wang, X., Wright, G., Cheng, J. C., Li, X., & Liu, R. (2017). A state-of-the-art review on the integration of Building Information Modeling (BIM) and Geographic Information System (GIS). *ISPRS International Journal of Geo-Information 6, no. 2, 6*(2), 53.

Loibl, W., Bach, B., Zucker, G., Agugiaro, G., Palensky, P., Schmidt, R.-R., . . . Brunner, H. (2015). ICT-Based Solutions Supporting Energy Systems for Smart Cities. In A. Vesco, & F. Ferrero, *Handbook of Research on Social Economic, and Environmental Sustainability in the Development of Smart Cities* (pp. 136-164). Hershey, PA, PA, USA: IGI Global.

Lu, Q., Chen, L., Li, S., & Pitt, M. (2020). Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings. *Automation in Construction, 115*, 103183.

Lu, Q., Xie, X., Parlikad, A. K., & Schooling, J. M. (2020). Digital twin-enabled anomaly detection for built asset monitoring in operation and maintenance. *Automation in Construction, 118*, 103277.

Lv, Z., Qiao, L., Li, Y., Yuan, Y., & Wang, F.-Y. (2022). Blocknet: Beyond reliable spatial digital twins to parallel metaverse. *Patterns, 3*(5), 100468.

Mendi, A., & Cabuk, A. (2020). Blockchain applications in geographical information systems. *Photogrammetric Engineering & Remote Sensing, No. 1*(86), 5-10.

Nagajayanthi, B. (2022). Decades of Internet of Things towards twenty-first century: a research-based introspective. *Wireless Personal Communications, 123*(4), 3661-3697.

Nawari, N., & Ravindran, S. (2019). Blockchain and the built environment; potentials and limitations. *Journal of Building Engineering 25*.

Nofer, M., Gomber, P., Hinz, O., & Schiereck, D. (2017). Blockchain. *Business & Information Systems Engineering*, 183-187.

Phua, F. T., & Rowlinson, S. (2003). Cultural differences as an explanatory variable for adversarial attitudes in the construction industry: the case of Hong Kong. *Construction management and economics, 21*(7), 777-785.

Qasse, I. A., Abu Talib, M., & Nasir, Q. (2019). Inter blockchain communication: A survey. *Proceedings of the ArabWIC 6th Annual International Conference Research Track*, (pp. 1-6).

Radanovic, I., & Likic, R. (2018). Opportunities for use of blockchain technology in medicine. *Applied health economics and health policy, 16*, 583-590

Raharja , U., Hidayanto, A. N., Lutfiani, N., Febiani, D. A., & Aini, Q. (2021). Immutability of Distributed Hash Model on Blockchain Node Storage. *Sci. J. Informatics , 8*(1), 137-143.

Rosen, R., Von Wichert, G., Lo, G., & Bettenhausen, K. D. (2015). About the importance of autonomy and digital twins for the future of manufacturing. *Ifac-Papersonline, 48*(3), 567-572.

Sabri, S., Rajabifard, A., Ho, S., Namazi-Rad, M.-R., & Pettit, C. (2015). Alternative Planning and Land Administration for Future Smart Cities. *IEEE Technology and Society Magazine, vol. 34, no. 4, pp. 33-73, ,* 33-73.

Sahal, R., Alsamhi, S., Brown, K., O'shea, D., & Alouffi, B. (2022). Blockchain-based digital twins collaboration for smart pandemic alerting: decentralized COVID-19 pandemic alerting use case. *Computational Intelligence and Neuroscience*.

Salheb, N., Arroyo Ohori, K., & Stoter, J. (2020). Automatic Conversion of CityGML to IFC. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, 3rd BIM/GIS Integration Workshop and 15th 3D GeoInfo Conference,, Volume XLIV-4/W1.* London.

Sani, M. J., Musliman, I. A., & Abdul Rahman, A. (2021). IFC TO CITYGML CONVERSION ALGORITHM BASED ON GEOMETRY AND SEMANTIC MAPPING. *International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences, 46.*

Schmitt, G. (2012). A planning environment for the design of future cities. In S. M. Arisona, G. Aschwanden, J. Halatsch, & P. Wonka, *Digital Urban Modeling and Simulation* (pp. 3-16). Berlin: Springer.

Shirowzhan, S., Tan, W., & Sepasgozar, S. M. (2020). Digital twin and CyberGIS for improving connectivity and measuring the impact of infrastructure construction planning in smart cities. *ISPRS International Journal of Geo-Information, 9*(4), 240.

Shojaei, A. (2019). Exploring applications of blockchain technology in the construction industry. In D. Ozevin, H. Ataei, M. Modares, P. Gurgun , S. Yazdani, & A. Singh (Ed.), *Proceedings of International Structural Engineering and Construction, 6.*

Song, Y., Wang, X., Tan, Y., Wu, P., Sutrisna, M., Cheng, J. C., & Hampson, K. (2017). Trends and opportunities of BIM-GIS integration in the architecture, engineering and construction industry: a review from a spatio-temporal statistical perspective. *ISPRS International Journal of Geo-Information, 6*(12), 397.

Stojanovski, T. (2013). City information modeling (CIM) and urbanism: Blocks, connections, territories, people and situations. *Proceedings of the Symposium on Simulation for Architecture & Urban Design*, (pp. 1-8).

Succar, B., Sher, W., Aranda-Mena, G., & Williams, T. (2007). A proposed framework to investigate building information modelling through knowledge elicitation and visual models. *Conference Proceedings Of The Australasian Universities Building Education Association, Melbourne,,* (pp. 4-5).

Sundararajan, A. (2016). *The sharing economy: The end of employment and the rise of crowd-based capitalism.* Cambridge, London: The MIT Press.

Tam, V. W., Zhou, Y., Shen, L., & Le, K. N. (2023). Optimal BIM and LCA integration approach for embodied environmental impact assessment. *Journal of Cleaner Production, 385*, 135605.

Teisserenc, B., & Sepasgozar, S. (2021). Adoption of blockchain technology through digital twins in the construction industry 4.0: A PESTELS approach. *Buildings, 11*(12), 670.

Tsampoulatidis, I., Bechtsis, D., & Kompatsiaris, I. (2019). Moving from e-Gov to we-Gov and beyond: a blockchain framework for the digital transformation of cities. *Smart Cities in the Post-algorithmic Era: Integrating Technologies, Platforms and Governance*, 176-200.

Underwood, S. (2016). Blockchain beyond Bitcoin. *Communications of the ACM*, 15-17.

Wang, H., Pan, Y., & Luo, X. (2019). Integration of BIM and GIS in sustainable built environment: A review and bibliometric analysis. *Automation in construction, 103*, 41-52.

Xu, X., Ding, L., Luo, H., & Ma, L. (2014). From building information modelling to city information modelling. *Journal of Information Technology in Construction*.

Xue, F., & Lu, W. (2020). A semantic differential transaction approach to minimizing information redundancy for BIM and blockchain integration. *Automation in construction, 118*, 103270.

Yu, B., Li, X., & Zhao, H. (2020). Virtual block group: a scalable blockchain model with partial node storage and distributed hash table. *The Computer Journal, 63*(no. 10), 1524-1536.

Yu, h., & Liu, Y. (2016). Integrating Geographic Information System and Building Information Model for Real Estate Valuation. *Proceedings of the FIG Working Week.*

Zeadally, S., & Abdo, J. B. (2019). Blockchain: Trends and future opportunities. *Internet Technology Letters 2, no. 6*, e130.

Zhang , S., & Zhang, T. (2021). Dynamic Reputation Incentive Mechanism for BIM application in construction project. *Journal of Applied Science and Engineering Innovation, 8*(1), 36-40.

Zheng, R., Jiang, J., Hao, X., Ren, W., Xiong, F., & Ren, Y. (2019). bcBIM: A Blockchain-Based Big Data Model for BIM Modification Audit and Provenance in Mobile Cloud. *Mathematical Problems in Engineering*.

Zhu, J., Wang, X., Wang, P., Wu, Z., & Kim, M. J. (2019). Integration of BIM and GIS: Geometry from IFC to shapefile using open-source technology. *Automation in Construction, 102*, 105-119.