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Computer-Aided Design AND APPLICATIONS

Empowering Digital Twin Through BIM–Blockchain for Carbon Disclosure of Certified Green Buildings

Adam Fitriawijaya[1] and Jeng Taysheng[2]

[1]National Cheng Kung University, adam@unsri.ac.id
[2]National Cheng Kung University, tsjeng@ncku.edu.tw

Corresponding author: Adam Fitriawijaya, adam@unsri.ac.id

Abstract. The global adoption of green building practices driven by environmental sustainability concerns has increased the demand for certified green buildings. However, the lack of robust and transparent carbon disclosure mechanisms hinders an accurate assessment of their environmental performance. The paper advocates integrating blockchain into the BIM-digital twin system to ensure secure and transparent carbon disclosure. Blockchain's decentralized and immutable nature guarantees data integrity and promotes stakeholder trust. A conceptual framework reveals potential benefits, including enhanced carbon reporting accuracy and improved stakeholder collaboration. We address challenges like data privacy, technological barriers, and standardization issues, offering recommendations to overcome these impediments. This approach empowers certified green buildings with a robust carbon disclosure mechanism, fostering transparency and facilitating the transition to a more sustainable AEC industry.

Keywords: Digital twin, BIM, blockchain. carbon disclosure, green building certification.
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1 INTRODUCTION

Carbon dioxide (CO_2) emissions are the primary driver of world climate change [1]. The AEC sector, responsible for a staggering 39% of global greenhouse gases, can significantly contribute to curbing climate change. In response to these issues, carbon disclosure has emerged as a vital strategy for transparency and accountability [2]. By quantifying and disclosing carbon emissions, we can identify areas for improvement of green building certification, encourage more energy-efficient practices, and foster responsible construction and operational choices [3].

Carbon disclosure is an essential component of green building certification programs. A meta-analysis by Dalton and Fuerst of 42 studies between 2008 and 2016 showed that green building certifications yielded a rent premium of 6% and a sales premium of 7.6%. Other research found that spaces certified by WELL or Fitwel –which focus on health and wellbeing– could attract effective rents that were 4.4% to 7% more per square foot than nearby, non-certified, and non-registered peers

[4]. Carbon footprint assessment and certified green building are two different frameworks, for example, requiring integration between the framework providing a critical measurement of a building's carbon footprint and the certification systems, which is a set of rating systems and tools to assess a building or a construction project's performance from a sustainability and environmental perspective. On the other hand, certified green building pertains to recognizing a building's overall sustainability and environmental performance based on established standards. To date, several platforms are a combination of these two frameworks, namely Green Badger for LEED Certification, EMS Software with ISO 14001-compliant system, and GRESB (Global ESG Benchmark for Real Assets), and there are several third-party certification bodies. There is a need for an integrated platform to support data integration and document an authorized green building certification process.

Building information modelling (BIM) with digital twin technology can play a significant role in carbon disclosure to manage and reduce carbon emissions in the construction and building operation processes. Digital twin technology is poised to reduce building carbon emissions by 50-100%, lower operating costs by 35%, and enhance productivity by 20%, bolstering its significance in combatting climate change. BIM answers challenges in the carbon disclosure process, which previously tended to be less integrated and more reliant on manual and traditional methods, potentially leading to inefficiencies and missed opportunities for optimization. BIM is foundational data for dynamic digital replicas of physical assets, supporting informed decision-making, efficient construction, and improved asset performance. This process relies on the collaborative gathering and updating of information at crucial stages of the project[5], which reduces the likelihood of disagreements between various parties involved. BIM has played a pivotal role in enabling the integration of DT technology, which generates virtual replicas of physical assets, offering instantaneous information and analytical insights[6]. Through the Internet of Things (IoT), the interconnection of BIM and digital twins facilitates the seamless integration of real-time data and digital representations, optimizing decision-making processes across the asset lifecycle.

Implementing these systems in the context of certified green building can lead to data management challenges, a lack of transparency, and data security, which can hinder achieving sustainability goals. BIM and digital twins can account for accuracy and efficiency in sustainable assessments from data collection to carbon reporting according to procedures [7]. This technology describes data use and efficiency as limited to manual to digital switching. Furthermore, independent certification bodies are needed to validate the results of sustainable assessment calculations to maintain credibility, accountability, and transparency in the certified green building process. Yet, this process is still prone to errors and procedural violations. Even though it requires rigorous verification to ensure adherence to specifications and validation to verify real-world behaviour, trustworthy twins contribute to informed decision-making and sustainable assessments; there may still be uncertainty regarding ascertaining the validity of every product resulting from the carbon disclosure process.

Recently, blockchain has been a revolutionary technology with significant implications for data management and security [8-10]. Blockchain can enhance security and trust [11], transparency and immutability [12], provenance [13] and traceability [14], efficiency and automation [15], and cost savings [16]. In the context of carbon emissions tracking, it can ensure the integrity and authenticity of data throughout its lifecycle. For example, by employing blockchain, the risk of misrepresentation due to incomplete inputs can be mitigated [17, 18]. It establishes a transparent and immutable ledger that holds all participants accountable, ensuring that the data presented is accurate and trustworthy. The accuracy of the disclosed emissions data demands robust verification mechanisms. Blockchain, by design, can facilitate a transparent and auditable verification process [19, 20]. This functionality helps build trust among stakeholders and regulatory bodies, fostering confidence in the reported emissions data. Furthermore, up to this point, extensive research and literature have delved into the process of carbon disclosure through the integration of blockchain with BIM [21]. Additionally, BIM-blockchain integration has the advantages of immutable change recording, ownership proof & future of blockchain in BIM, blockchain for ownership of digital BIM components, blockchain linking digital to physical in BIM, and decentralized CDE (Common Data Environment) via blockchain and cloud storage[22].

In this research paper, we present a novel framework that combines the integration of three innovative technologies, digital twin, BIM, and blockchain, which emerge as a promising solution to address the pressing issue of carbon disclosure in certified green buildings. The main innovation of our research is the comprehensive integration of these three technologies into a unified framework that leverages their strengths and synergistically enhances their combined impact. The framework enhances the accuracy and transparency of environmental performance assessments to support urban planners and policymakers in making data-driven decisions.

This innovative approach addresses several critical challenges in urban infrastructure management: holistic integration framework, enhanced environmental, social, and governance (ESG) evaluation, transparency and trust, scalability, and real-world application. Therefore, we employ scenario-based illustrations to demonstrate the application of our integration diagram, followed by a thorough review and analysis of several related papers to contextualize and validate our proposed approach. These practical implications underscore our research's importance and potential impact in advancing sustainable urban management.

This study aims to provide an overview of research trends and assess the potential of the introduced technologies in the building industry by analyzing recent research. Therefore, the research objectives are as follows:

- Examine the present application of digital twin, BIM, and blockchain technologies to investigate their current usage and explore potential applications within the context of the study by reviewing and comparing relevant current studies.
- Identify the research gap and subsequently propose further development of the framework. Specifically, the research will explore the implementation of digital twin technology to create potential scenarios, the utilization of BIM for comprehensive building information management, and the application of blockchain to enhance transparency and security in certification processes
- Examine the impact of this integration on various aspects, such as data interchange, interoperability, validation, and verification within the certification framework.

The findings of this study have the potential to revolutionize green building practices by improving certification processes and promoting environmental sustainability through innovative technological integration.

The paper follows the organization outlined in the following sections: After the introduction, it describes the leading enabling technologies and the imperative integration of BIM, DT, and IoT in enhancing design efficiency. Section 3 is an example scenario to explore the BIM blockchain's function to strengthen transparency, sustainability, and data security. Sections 4 and 5 define the methodology used for the study and discuss the limitations of the research. Section 6 presents findings and discussions addressing potential challenges, interfaces of the technologies, research gaps, and proposed solutions. The two last sections are the conclusions and the list of references.

2 BIM, DIGITAL TWIN, AND IOT INTEGRATION: ENHANCING DESIGN EFFICIENCY

The relationship between BIM and the IoT is vital for improving design effectiveness in the construction sector. It helps show how a building or infrastructure project will look before construction. It typically comprises comprehensive 3D models detailing building elements, materials, systems, and spatial relations. In contrast, IoT involves continuously fixing sensors and other devices into physical assets and environments to collect data on-site with real-time interactions [23].

Combining data from BIM and IoT produces 'smart buildings' or 'digital twins' – dynamic, real-time additions to BIM models that represent building assets. IoT sensors in built spaces pick up data for virtually any building, including temperature, humidity, occupancy, energy consumption, and equipment performance. These sensors' findings are fed to a BIM model, enriching the asset with actual building operation and performance information in real-time [23].

Fundamentally, this integration can unleash a wealth of information about building performance and occupant behaviour, helping designers and other stakeholders make optimal and informed decisions about building design, energy performance, and maintenance. For instance, using real-time data from IoT sensors, designers can build dynamic control algorithms that optimize building designs for energy efficiency, occupant comfort, and building performance [24]. Using real-time occupancy data, for instance, designers can dynamically tailor lighting and HVAC settings based on occupancy information in any given space or zone, maximizing occupant comfort and optimizing energy consumption. Similarly, real-time data about equipment performance can inform new and improved maintenance schedules.

Furthermore, the combination of BIM and IoT allows for data-informed decision-making throughout the design. For instance, using data related to weather and energy consumption, designers may test different building designs in existing buildings to simulate the effects of a new building's shape and modelling on building performance. This type of analysis can determine changes in the heat flow pattern, for instance, or the amount of artificial light required, which allows designers to make more informed design decisions in real time. Real-time data availability also reduces design flaws during the conceptual stage, preventing costly rework during construction.

3 SCENARIO AS AN EXAMPLE

This chapter explores hypothetical scenarios to illustrate the challenges and complexities of integrating various technologies at different scales. These scenarios highlight common issues encountered in real-world integration applications. While the specific details of the scenarios are hypothetical, they are informed by previous research and observations in the field. These scenarios are not based on particular case studies but aim to capture broader trends and challenges related to integration. Throughout the chapter, we delve into the intricacies of integrating multiple layers generated by different technologies, such as those encountered in city-scale integration, supply chain management, and financial systems. While the scenarios are hypothetical, they are grounded in the real-world complexities of integration, including the problem of data accuracy and standardization. By examining these scenarios, we aim to illuminate the multifaceted nature of integration challenges and explore potential solutions.

3.1 Integrating Digital Twins, BIM, and Blockchain for The City Management Scenario: Enhancing Transparency, Sustainability, and Data Security

This scenario, shown in **Figure 1**, illustrates the use of digital twins with BIM, smart systems, and blockchain at the city scale. It is a fundamental scenario illustrating the integration of various technological components on a city-wide scale, amalgamating them into a cohesive infrastructure unit to actualize digital twin, BIM, and blockchain Integration across various potential scenarios. We adopted the digital twin's diagram model for smart cities [25], which defines the layers built on each other, incorporating additional information and then developing it based on findings aligning with our research objectives.

The city's physical infrastructure is intricately linked to the digital realm by integrating IoT devices, CIM (City Information Modeling), a blockchain platform, and a dynamic digital twin. This fusion provides real-time insight into the city's layout and the environmental impact of its buildings. Their environmental data, like energy use and emissions, seamlessly integrates into the digital twin via BIM and IoT. This platform empowers stakeholders to monitor, analyze, and disclose building carbon footprints, curbing greenwashing and enhancing transparency. However, addressing challenges like data accuracy and standardization is crucial for fully realizing this potential.

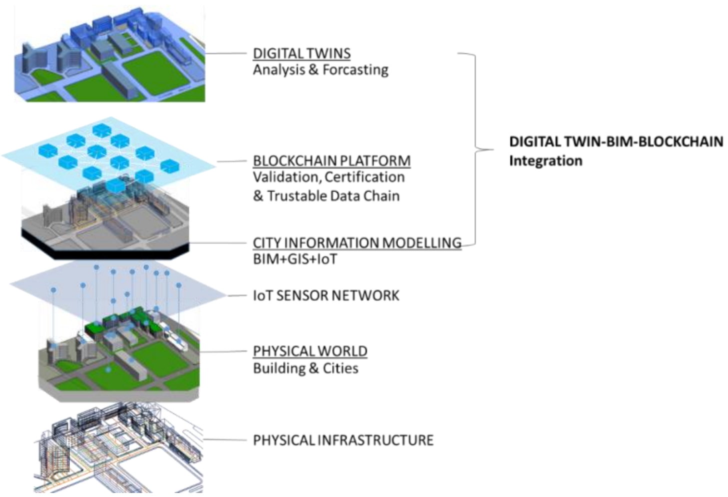


Figure 1: An overview scenario of a digital twin platform on the city scale, including BIM–blockchain integration.

The IoT sensor network connects physical assets to digital assets, and the CIM model enables visualization and analysis of the urban environment. The digital twin platform builds a virtual model of the physical city, which can be used to optimize the planning and management of physical infrastructure, leading to the creation of smart cities. The IoT supports digital twins for governing cities effectively. For instance, leveraging the digital twin facilitates the simulation of design projects, predicting outcomes before execution and preemptively identifying potential issues. The IoT system enhances the city's innovation through the utilization of information and communication technology (ICT), including cloud computing, artificial intelligence (AI) / machine learning (ML), and big data. This technology empowers the city to progress and thrive by addressing challenges such as increasing urbanization.

The CIM layer shows that one of the most critical digital twin requirements for smart cities is representing real-world city forms and structures in a virtual 3D city model [26-29]. Using a 3D model with BIM and the Geographic Information System (GIS) enables obtaining information. On this meta-level, cities all over the world are currently moving forward with this development by creating CIM, which not only collects geographic data but also encodes the characteristics of objects (roads, buildings, bridges, vegetation), as well as the relationships between these objects, to support informed decision-making and enable new services for city residents [30].

The blockchain layer can monitor the data gathered by the sensors for IoT security, preventing them from being duplicated by any incorrect data, such as transfer data, without requiring a trusted third party. Blockchain technology stands out for its capacity to address scalability, dependability, and privacy challenges, allowing for device coordination, tracking millions of linked devices, and transaction processing. This technology is regarded as a system of systems, with integrated solutions and protection necessary to complete its functionality. This is accomplished by examining every technical and physical component within the IoT ecosystem.

In this layer, blockchain technology is integrated as a critical component of the urban management service, providing a secure and efficient Internet-based verification and transactions system. Its implementation has the potential to revolutionize the management of smart cities by facilitating the synchronization, integration, and governance of various city functions in a transparent and privacy-enhancing manner [31]. In addition, smart cities have benefited from blockchain, such as improved cybersecurity, enhanced healthcare, better waste management, simplified education, increased energy savings, and efficient mobility [32]. Besides, BIM-blockchain integration features several potential applications that might be developed, including an immutable record of changes, proving ownership of a model, proving ownership of digital components, linking digital to physical, and a decentralized everyday data environment (DCDE) [33]. The concept of system & technology as a support system that utilizes blockchain has advantages such as security, liability, and transferability for supporting BIM to collect data as digital components and enabling truly live BIM models as physical counterparts. Moreover, BIM might collect vast data throughout a project's lifecycle by developing a database.

In integrating BIM with blockchain for smart cities, blockchain technology offers solutions for securely accessing BIM models. It provides reliable tracking of updates, including the identification of users, timestamps of modifications, and the nature of changes made. Enabling blockchain technology can be an effective solution in developing information technology to support urban operations and make them more efficient and safe, especially in data exchange [34]. Furthermore, by using smart contracts, blockchain technology can reduce complexity and allow for greater transparency and trustable verification across the data chain [35].

3.2 City Development: Integrating Digital Twin, BIM, and Blockchain for Sustainable Supply Chains and ESG Analysis

Reflecting on the scenario illustrated in **Figure 1**, we focus on the development of the city utilizing digital twin and BIM technologies integrated with blockchain for secure and transparent data sharing, as depicted in **Figure 2.** Our attention is directed towards building a sustainable supply chain for manufacturing, considering two factors.

- ESG principles: ESG stands for environmental, social, and governance. In the paper context, ESG principles refer to the criteria used to evaluate a company or project's impact on the environment, society, and corporate governance [36, 37]. ESG principles are building sustainable supply chains and manufacturing with green building certification that comprehensively assesses project, stakeholder, and environmental impacts. There are several factors related to those principles, including carbon emissions, resources, employee welfare, community impact, and considerations of ethical behaviour.
- ESG analysis: ESG analysis refers to evaluating a building project's impact on the environment, society, and governance (ESG principles) by considering ethical and transparent management of the project. Using ESG analysis, investors and clients can make more informed decisions about their involvement in a project and assess its sustainability and impact [38].

For example, a building project with multiple components and processes involves stakeholders, resource procurement, design and manufacturing, delivery, customer use, and recycling. By engaging investors and clients, this project undergoes an evaluation using ESG criteria, considering its impact on the environment, society, and corporate governance. Here, BIM blockchain is applied to evaluate potential emissions and increase transparency.

The construction and operation of buildings, transportation systems, and infrastructure are contributors to greenhouse gas emissions. As illustrated in **Figure 2**, in the urban context, it is imperative to consider tracking the carbon footprint of the supply chain system and building operations and the amount of carbon emissions from the production and maintenance of the technology used in managing the city ecosystem. It can identify opportunities, improvements, and optimization, resulting in efficient and sustainable city operations.

3.3 Enabling Sustainable and Transparent Finance Framework through BIM and Blockchain Integration

In this section, as depicted in **Figure 3,** we proposed the scenario of finance framework for the AEC industry's supply chain management, consisting of the project workflow, cash flow, and bank review processes.

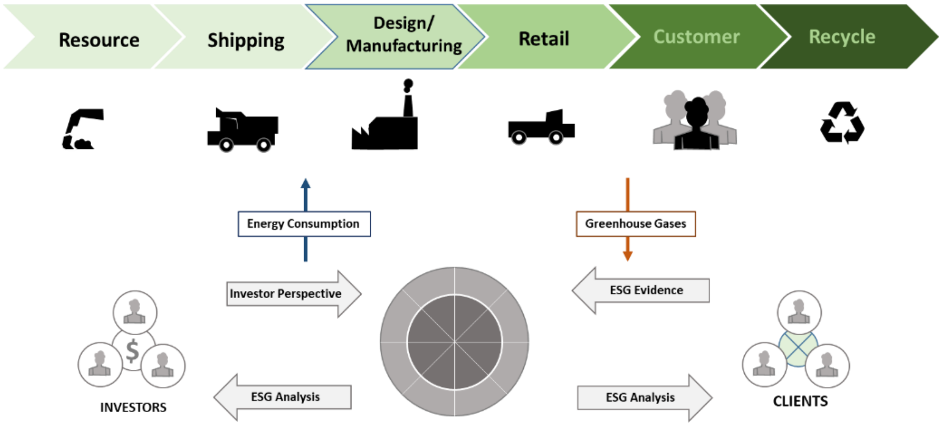


Figure 2: The scenario of the supply chain - manufacturing ESG development.

It is highly relevant to the development of sustainable and environmentally friendly cities. Incorporating BIM and other advanced technologies in the AEC industry has brought about significant changes in supply chain management, and this framework seeks to keep pace with these changes by integrating various financial aspects into the supply chain management system. This scenario is the result of the development of our previous study on the integration of BIM - blockchain - supply chain management [39], then investigate several frameworks such as the relationship between BIM and supply chain management; BIM and IPD integration[40-42] which explains BIM facilitates information flow across supply chains, IPD teams (collaborative teams members and stakeholders), and; supply chain finance models [43].

This scenario represents the automation of payment processes and the real-time tracking of transactions, ensuring greater efficiency and predictability in the supply chain. Integrating impartial third-party blockchain technology in the bank review processes will ensure transparency and security in financial transactions. It means that a neutral and trusted entity will oversee the financial transactions taking place within the supply chain management system as a secure digital ledger that records all the financial transactions made between the stakeholders in the supply chain, including clients, contractors, providers, and banks [14, 44-46]. Additionally, blockchain technology ensures that the records are tamper-proof, transparent, and immutable, as they are verified and validated by all parties involved. It eliminates the need for intermediaries or mediators in financial transactions, reduces the risk of fraud, and increases the security and efficiency of the supply chain management system [14, 44, 45, 47]. The overall effect of this finance framework will be the creation of a more stable and predictable payment flow, reduced risk of payment defaults, and an increase in the efficiency of the supply chain.

3.4 Enabling Sustainable and Transparent Finance Framework for Smart Low-Carbon Cities Through BIM and Blockchain Integration

Figure 4 illustrates another scenario to support the finance framework: how to implement the process flow of the finance framework application. We consider certain steps in adding the flowchart to ensure a trustable data chain:

1. Login: Users must create an account and log in to access the blockchain system.
2. Uploading data report: Users can upload their data report onto the blockchain system.
3. Assessing data report: An impartial third party will evaluate the uploaded report to ensure its accuracy and reliability.
4. Legal attest processing: The assessed data report will be processed to verify its authenticity and credibility.

5. Validating data in the system: The validated data report will be automatically stored in a decentralized cloud powered by a decentralized application (such as BNS, Polygon) with API Certification. The decentralized cloud can generate identity evidence for the blockchain system.
6. Authentication key: Once the legal attest is complete, the users (developers, banks, governments) can fetch an Authentication key as a transaction.
7. Data transactions: The users can perform data transactions on the blockchain system.
8. Verification: The government, developers, and banks can download verification from the blockchain to confirm the authenticity and credibility of the data report.
9. Repeat process: Users can repeat the process for other legal attests such as green building, smart building, building fire test, qualified manufacturers, ESG reviews, and other documents.

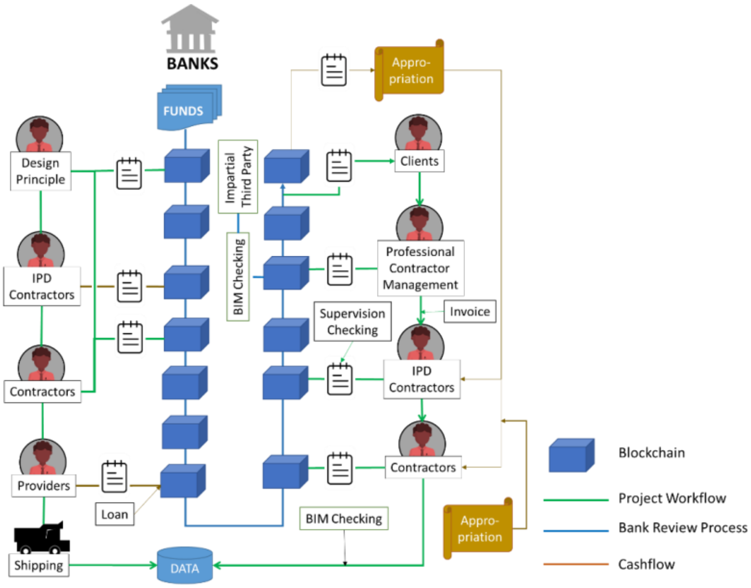


Figure 3: The scenario of finance framework for the AEC industry's supply chain management.

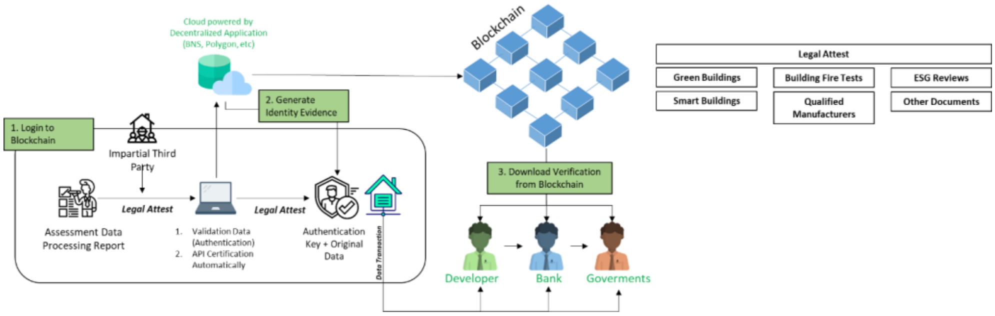


Figure 4: Trustable data chain.

Integrating Digital Twin, BIM, IoT, and Blockchain technologies is essential for sustainable, efficient, and transparent urban infrastructure. The scenarios show that these technologies enhance infrastructure monitoring and management, ensure transparent and secure data sharing and financial transactions, facilitate thorough ESG evaluations, and streamline supply chain operations. This integration demonstrates the transformative potential of these technologies in advancing certified green buildings and promoting sustainable urban development.

From the entirety of the scenario, we have distilled several key points.

- Integration of technologies: Discuss the integration of digital twins, BIM, and blockchain in urban management systems that focus on data security, sustainability, and transparency.
- Framework–based research approach: highlights the proposed framework as an approach method for describing the components of integration from the technologies (digital twin, BIM, IoT) on a platform as a case study in the context of urban planning
- Use blockchain and its innovation: Explore blockchain technology and focus on its features (distributed ledger technology, smart contract, dApps, consensus mechanism, tokenization)
- ESG principles integration: Shows how blockchain works in the integration of digital twin and BIM, which focuses on increasing efficiency, transparency, traceability, and data exchange, based on ESG principles in overcoming the gaps identified in this research
- Supply Chain Transparency: Highlighting enabling blockchain for sustainable supply chain management
- AEC Industry Transactions: Highlight financial transaction development in the AEC Industry by empowering digital twin and BIM integration.
- Financial system enhancement: Emphasize the impact of blockchain technology on financial systems to improve efficiency, security, and transparency.
- Validation and reliability: Focus on third-party validation through blockchain technology and the role of trust and reliability in financial systems and supply chains.

4 RESEARCH METHODS

Undertaking a comprehensive literature review is imperative to establish and strengthen the fundamental understanding of a subject, uncover potential areas of research deficiency and complexity, and delve into previous scientific endeavours to unearth innovative concepts and circumvent redundant investigations.

This research employs the example scenario in the previous section coupled with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology to investigate the integration of digital twin, Building Information Modeling (BIM), and blockchain technologies for green building certification. In **Table 1**, we concluded several points from the scenario, which we then organized into categories to provide a framework and boundaries for observing findings during the literature review, subsequently incorporating reviews within the discussion chapter.

Points of scenario	*a*	*b*	*c*	*d*
Integration of technologies	√			
Framework-based research approach	√			
Use blockchain and its innovation		√		
ESG principles integration			√	
Supply chain transparency			√	
AEC industry transaction				√
Financial system enhancement		√		

Validation and reliability	√

Table 1: Points of scenario [48]. (a) Integration and Application, (b) Benefits and enhancements, (c) Sustainability and ethical consideration, (d) Financial system improvements.

To integrate scenarios with the PRISMA methodology, follow these steps:

- Conduct a systematic literature search using tailored keywords to find relevant studies on integration technologies. Screen and select studies meeting predefined criteria, documenting the process transparently.
- Extract pertinent data from selected studies, focusing on technology applications and outcomes relevant to scenario elements.
- Analyze and synthesize the data to identify common themes and patterns across studies, aligning them with scenario assumptions.
- Integrate synthesized findings with scenarios, mapping evidence from literature onto scenario elements to highlight convergence or divergence.

A protocol has been developed to specify the carefully planned proceedings and eligibility criteria and to select and identify the data of documents. According to Shamseer et al. [44], A protocol is vital in a systematic review. It delineates predefined eligibility criteria and methodological approaches, fostering uniformity among the review team and upholding accountability, research integrity, and transparency.

Searching approach: All materials and papers selected at each evaluation phase were available to all researchers via cloud-based storage. Data sheets were created using a cloud-hosted document tool, allowing seamless teamwork among individuals in diverse places. This tactic enabled enhanced control and uniformity in conducting the systematic review. The study incorporates a search technique to identify and retrieve the most minor publications.

The search tools employed encompass Web of Science (http://www.webofscience.com) and Scopus (http://www.scopus.com). Scopus offers a more extensive array of sophisticated search features compared to the Web of Science. Scopus allows the customization of search queries with precise criteria. After conducting these queries, Scopus yielded 47 publications, while Web of Science produced 262. The cumulative outcome across both platforms resulted in a total of 310 publications.

The keywords applied in the search engines were: "digital twin”" AND bim AND (blockchain OR ""smart contract"”) AND (""green building certification"" OR certi* OR ""certified green building*"" OR ""carbon disclosure"") AND (LIMIT-TO (SRCTYPE , ""j"")) AND (LIMIT-TO (DOCTYPE , ""ar"")). Subsequently, to broadly examine the implementation of the digital twin, BIM, and Blockchain, we employed the keyword " digital twin," bim ''blockchain'' "or smart contract". **Table 2** presents the search criteria applied to Scopus and Web of Science databases.

Data selection involved analyzing titles and abstracts and examining introductions and conclusions. In the first step, document matching criteria were chosen collaboratively in pairs to minimize bias. The second step mirrors the first: to appraise documents based on introductions and conclusions. All selected documents were assessed for methodological quality in the extraction phase, not limiting final choices.

Database	*Search Filters*
Scopus	*Search in article title, abstract, keywords
	*Document type: Article
	*Source type: Journal
	*Data range: 2013-2023
	*Language: All

Web of Science (WoS)	*Search in topic
	*Document type: Article
	*Data range: 2013-2023
	*Language: All

Table 2: Databases and search filters, [48].

5 RESULTS

We retrieved 310 articles from Scopus and Web of Science, excluding those duplicated in both databases. Subsequently, we examined the titles and abstracts, leading to 124 articles. Afterwards, we analyzed the introduction and conclusion sections, resulting in a final selection of 58 documents. Following a thorough review, 43 articles fully adhered to the review protocol depicted in **Figure 5**.

Table 3 displays the names of the journals included in the review. The journal that published the majority of the studies is "Cluster Computing: The Journal of Networks, Software Tools and Applications, " succeeded by "The International Journal of Construction Management," "Buildings," "Business Strategy and the Environment," "Journal of Supercomputing," and "Automation in Construction."

The review comprised 48 documents from 38 different journals. Notably, "Cluster Computing: The Journal of Networks Software Tools and Applications" contributed four selected documents, emphasizing linking multiple computers to enhance computational power. The International Journal of Construction Management also provided four papers concerning various aspects of construction projects. "Buildings" and "Automation in Construction" each contributed three documents focusing on the construction sector. "Buildings" covers broad topics related to design and management, while "Automation in Construction" highlights technological advancements. These journals likely contribute to exploring BIM, blockchain, and digital twin integration.

Figure 6 shows that this study considered research papers from 2013 to 2023, excluding 2019, and found a pronounced rise in studies, peaking between 2022 and 2023. Aligned with the paper's objectives, a meticulous review of 48 documents emphasized coherence with research themes, including digital twin, BIM, and blockchain. Topics explored encompassed carbon disclosure, green building certification, and phenomenon attributes. Among the 48 documents, 18 offered insights into the phenomenon's characteristics and classification.

Number of articles	*Number of documents*	*Area of interest*
Cluster Computing: The Journal of Networks Software Tools and Applications	4	Distributed and parallel computing
International Journal of Construction Management	4	Construction and infrastructure development
Buildings	3	Building design and development
Business Strategy and the Environment	3	Business strategy
Journal of Supercomputing	3	High-performance computing systems
Automation in Construction	3	Digital technologies in construction industries
Electronic Commerce Research	2	Electronic commerce

Environmental Science and Pollution Research	2	Environmental science
Multimedia Tools and Applications	2	Multimedia technologies and applications
Operations Management Research	2	Operations research
Soft Computing	2	Application of computational techniques
Sustainability	2	Sustainable development
Others (one document per journal)	16	
Total	**48**	

Table 3: Number of articles included in the review per journal [48].

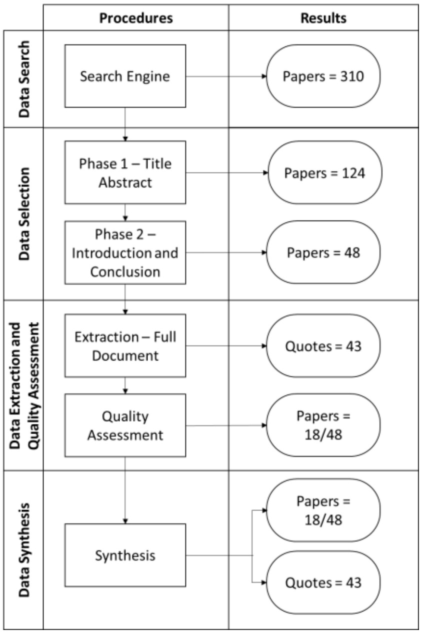


Figure 5: Results achieved at each stage of the systematic review process [48].

In **Figure 7**, The analysis strongly emphasizes integrating technologies (46%) such as digital twin, BIM, and blockchain, highlighting their potential to address sustainability challenges. A substantial percentage of papers (46%) adopt framework-based research approaches, emphasizing the significance of structured methodologies in studying technology integration's implications for sustainability. Efficiency and transparency (48%) appear as key thematic emphases, while the integration of ESG principles (17%) and supply chain transparency (10%) receive comparatively less attention. Limited discussion encompasses financial system enhancement (12%), AEC industry transactions (8%), and validation and reliability (6%), suggesting potential areas for further exploration in leveraging technology for sustainable development within the AEC industry. The data suggests that while there is a strong focus on integrating advanced technologies to enhance efficiency and transparency in the AEC (Architecture, Engineering, and Construction) industry, other important areas like ESG principles, supply chain transparency, financial system enhancement, and validation and reliability are underexplored. These gaps highlight opportunities for future research to create a more comprehensive understanding of how technology can contribute to sustainable development within the industry.

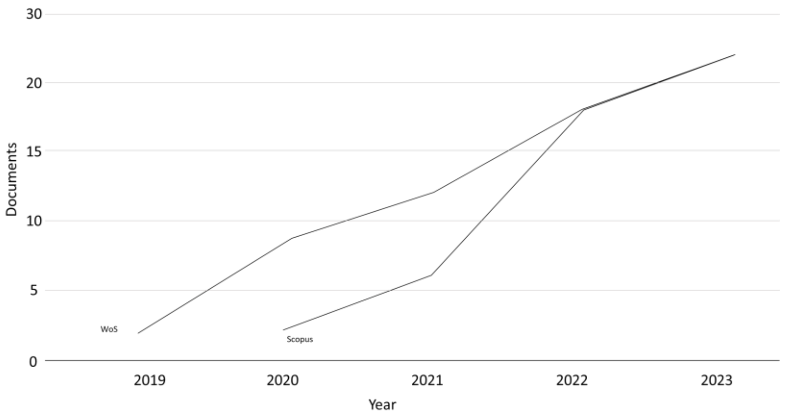


Figure 6: Evolution of the number of reviewed documents over time [48].

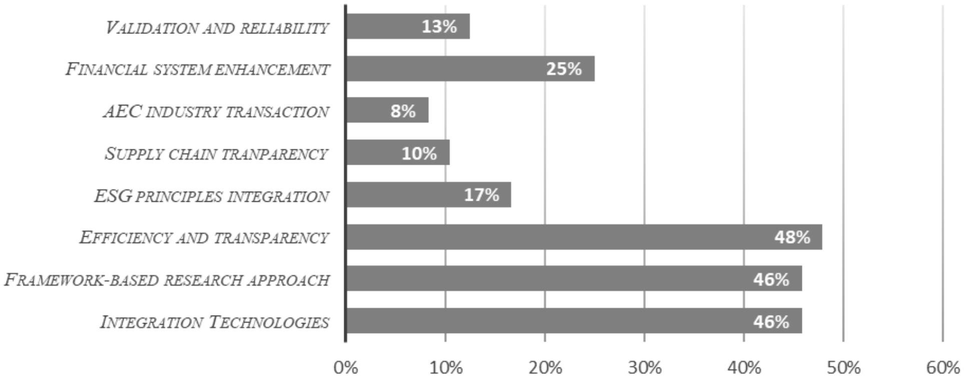


Figure 7: Distribution of discussion topics and percentages [48].

6 FINDINGS AND DISCUSSION

6.1 Converging Technologies (Integration Digital Twin, BIM, and Blockchain) for Sustainable Built Environments

The reviewed papers highlight the intersection of digital twin, BIM, and blockchain technologies within sustainability, supply chains, and construction. While some directly address integration challenges, others offer valuable insights. Notably, the adoption of blockchain in sustainable construction projects faces barriers, emphasizing the need for innovative solutions. Comprehensive datasets capturing carbon emissions across diverse building portfolios may be limited or fragmented, potentially impacting the robustness and generalizability of findings. The potential of digital twins for sustainability assessment [49], safety management [50, 51], and decision-making [52-58] is evident. Integrating BIM and blockchain can enhance data consistency, security, and transparency [55, 59-62]. However, practical implementation and overcoming technological barriers remain critical. As the built environment evolves, these converging technologies hold promise for more efficient, transparent, and resilient practices.

The discussion of these topics centres on the practical implications of integrating Digital Twin, BIM, and Blockchain. Stakeholders must navigate challenges related to interoperability, data privacy, and scalability. While blockchain ensures trust and immutability [56, 57, 63-65], its adoption requires addressing regulatory, governance, and standardization issues related to green building certification. Digital twins with IoT offer real-time insights [24, 50, 62, 66, 67], but their implementation involves data synchronization, model fidelity, and user engagement. BIM is a foundation, but harmonizing it with blockchain and digital twins demands collaborative efforts. As industry awareness grows, strategic roadmaps and interdisciplinary approaches will drive successful integration, ultimately shaping a more sustainable and interconnected built environment.

6.2 Sustainability, Green Building Certifications, and The Role of Technology: Enhancing Accountability and Preventing Greenwashing

Integrating Digital Twin, BIM, and Blockchain technologies offer significant potential for advancing green building certification, ESG principles, and carbon disclosure practices in the AEC industry [68, 69]. Leveraging these technologies enables proactive identification and mitigation of environmental impacts, streamlines ESG reporting processes, and enhances data transparency. However, limited discussion around integrating ESG principles and supply chain transparency suggests areas for further research emphasis. Incorporating these technologies can address these gaps, facilitating comprehensive monitoring and reporting of ESG metrics and advancing carbon disclosure practices.

The surge in sustainability and ESG investment reporting has widened the gap between proclaimed sustainability achievements and actual efforts dedicated to ESG integration and impact measurement. This gap fosters practices such as greenwashing and competence greenwashing, where companies misleadingly market products or services as environmentally friendly or exaggerate environmental expertise without credible evidence[70, 71]. Additionally, a research paper on other ESG fields shows that more substantial ESG transparency is associated with lower firm valuation. Investors value companies with better transparency at a discount than those with weaker transparency[72]. Understanding ESG transparency and its impact on firm valuation is crucial for sustainable supply chains.

Sustainability-oriented digital twins and blockchain technology can help combat greenwashing by verifying and rectifying exaggerated claims. It ensures the integrity of green building certification processes and promotes genuine environmental accountability, thereby driving sustainability initiatives in the built environment.

6.3 Blockchain Integration with BIM and Digital Twins

Combining blockchain technology with BIM and digital twins can offer some promising benefits, but there are also inherent limitations. Blockchain helps improve data security, transparency, and trustworthiness within these systems [55, 58, 68, 73]. It ensures the real-time information from BIM models fed into digital twins maintains its integrity. This integration streamlines the tracking and optimization of building performance, helping align it with green building certification requirements. However, scalability remains a significant challenge. The current architecture struggles to process large volumes of transactions quickly. Proposed solutions like sharding and off-chain transactions are still experimental and not fully proven.

Blockchain technology incurs high operating costs due to its energy-intensive nature and transaction fees [61]. Maintaining network security demands significant processing power, especially for networks that use proof-of-work consensus techniques [74]. As a result, overhead costs and environmental effects come into play. Blockchain also increases transparency but comes with security and privacy dangers [75]. For example, these risks include being vulnerable to quantum computing assaults and having privacy issues because distributed ledgers are public [57]. Additionally, although blockchain increases transparency, there are particular regulatory and compliance issues because it is difficult to regulate and verify user behaviour and identification due to its decentralized structure.

Interoperability concerns prevent blockchains from being widely used because they lack defined protocols for efficient data transmission. Notwithstanding these drawbacks, continuous research and development efforts aim to address these challenges and unleash blockchain technology's full potential in complementing BIM and digital twin integration for more efficient asset management and monitoring.

6.4 Research Gaps

Despite advancements in integrating Digital Twin, BIM, IoT, and Blockchain technologies, several research gaps hinder their full potential for carbon disclosure in certified green buildings. Key challenges include interoperability and integration issues, such as data synchronization and system compatibility. Data accuracy and standardization across platforms remain critical, with future research needed to develop robust data management protocols. Scalability and performance at urban scales, regulatory and policy barriers, economic constraints, stakeholder engagement, real-world validation, and security and privacy concerns also pose significant hurdles. Addressing these gaps will enhance the effective integration of these technologies, supporting sustainable green building development and carbon disclosure.

Table 4 provides a comprehensive overview of the critical challenges and potential solutions associated with integrating Digital Twin, BIM, IoT, and Blockchain technologies in the context of carbon disclosure for certified green buildings. The table highlights specific issues such as interoperability, data synchronization, and scalability, along with practical strategies to address these challenges, including adopting standardized protocols, advanced security measures, and scalable architectures.

Technologies	*Challenges*		*Addressing the challenges*
Digital Twin	Interoperability issues	Ensuring seamless interaction between different digital twin platforms and other integrated technologies.	• Develop and adopt standardized protocols. • Implement advanced synchronization algorithms and middleware to ensure real-time data consistency and accuracy.
	Data synchronization	Ensuring data consistency and accuracy across multiple systems and real-time updates is challenging.	Utilize edge computing to reduce latency and maintain data integrity with regular audits.
	Integrating existing systems.	Incorporating existing systems into new digital twin frameworks without significant disruptions.	Conduct system assessments to identify integration points.
BIM	Data accuracy and standardization	Ensuring that all data input into BIM models is accurate and adheres to standardized formats is necessary.	Promote using industry standards like IFC for BIM data to ensure consistency.

	Complexity in Integration	Integrating BIM with other technologies like IoT and Blockchain can be complex due to differing data formats and requirements.	Adopt modular integration approaches and develop comprehensive plans to manage the complexity of integrating BIM with IoT and Blockchain technologies.
	Scalability Challenge	Scaling BIM solutions from individual buildings to city-wide implementations poses significant challenges.	Design scalable architectures using cloud and edge computing.
IoT	Real-time data accuracy	Ensuring the accuracy of data collected by IoT sensors in real-time.	Use high-precision sensors and data validation algorithms to ensure real-time data accuracy. Regularly calibrate IoT devices to prevent inaccuracies.
	Data Security and Privacy Concerns	Protecting the data collected by IoT devices from unauthorized access and breaches.	• Implement robust encryption and security protocols for IoT data. • Use Blockchain to ensure data immutability and conduct regular security audits to mitigate risks.
	Integration with the existing system	Seamlessly integrating IoT devices with existing building management systems.	Develop integration frameworks and provide training to facilitate the connection of IoT devices with existing building management systems, ensuring smooth operation.
Blockchain	Regulatory and policy constraint	Managing regulatory requirements and adhering to diverse policies.	Develop compliance strategies aligned with existing regulations and advocate for supportive frameworks for technology adoption.
	Economy feasibility	Assessing the cost-effectiveness of implementing blockchain technology in building management systems.	• Conduct cost-benefit analyses to evaluate economic viability. • Explore funding opportunities and develop cost-effective solutions to reduce financial burdens.
	Stakeholder resistance	Overcoming resistance from stakeholders who may hesitate to adopt new and unfamiliar technologies.	• Implement change management strategies to address resistance. • Engage stakeholders early, provide education on benefits, and highlight successful case studies to build trust.

Table 4: Challenges and solutions for integrating digital twin, BIM, IoT, and blockchain technologies.

6.5 Bridging Theory and Practice: The Role of Scenarios in Demonstrating Integration Technology for Sustainable Urban Development

The use of scenarios in the research paper plays an essential role in showing the practical implications and potential benefits of combining these advanced technologies. Scenarios are crucial in connecting theoretical research and practical use. They represent a story that helps different groups of people, from urban planners to policymakers, understand how Digital Twin, BIM, IoT, and Blockchain technologies can be used in real-life situations and the advantages they bring. The research moves beyond abstract concepts to actual examples by presenting detailed and context-specific scenarios, highlighting how these technologies can be implemented cohesively to address real-world challenges in urban management and sustainable development.

A number of investigations have demonstrated that several papers provide robust support for the scenarios outlined in the research studies. For instance, the study "Developing a BIM Single Source of Truth Prototype Using Blockchain Technology" aligns closely with the City Management Scenario by demonstrating the technological viability of integrating blockchain with BIM to ensure data integrity and secure data delivery in construction supply chains [59]. In the same way, this paper supports such a scenario by illustrating how statistical analysis and IoT integration can result in substantial water savings and sustainability compliance [64]. The concept of using digital twins for sustainability is also supported by the paper "A Review of Digital Twin Technologies for Enhanced Sustainability in the Construction Industry," which highlights the potential of digital twins to reduce carbon emissions through real-time monitoring and simulation [76]. This aligns with the research paper's objective of using digital twins to track and disclose the carbon footprints of buildings.

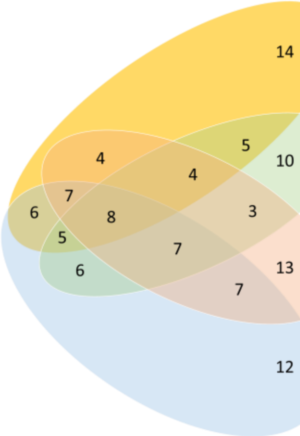
Although most related papers support the integration scenario, some present different perspectives, especially regarding implementation barriers. The paper "Investigating the Barriers to the Adoption of Blockchain Technology in Sustainable Construction Projects" identifies significant challenges, such as policy inadequacies and customer resistance [61]. These barriers differ from the seamless integration depicted in the research scenarios, suggesting that real-world implementation may face more barriers and require more potent strategies to overcome these barriers.

Some papers suggest improving the scenario by introducing additional layers of technology and methodology. The study "Fusion of Building Information Modeling and Blockchain for Metaverse: A Survey" proposes integrating BIM and blockchain within the metaverse, enhancing virtual representation and interaction with urban infrastructure [60]. It suggests that future scenarios could incorporate metaverse applications to provide more immersive and interactive models for urban management.

Furthermore, the paper "A Secure Big Data Storage Framework Based on Blockchain Consensus Mechanism with Flexible Finality" emphasizes the importance of secure and scalable data storage solutions, which can enhance the reliability and efficiency of the proposed digital twin and blockchain integration [63]. It supports building a more robust data infrastructure to handle the large amounts of data generated by IoT devices and BIM models.

To further illustrate these points, the following diagram, in **Figure 8**, provides a comprehensive summary about the roles and interactions of Digital Twin, BIM, Blockchain, and IoT technologies in the context of carbon disclosure in certified green buildings. The diagram visually represents how these technologies integrate and collaborate to enhance sustainability efforts, improve data accuracy and security, and enable real-time monitoring and reporting of carbon emissions in urban infrastructure.

The scenarios presented in this paper play a fundamental and essential role in contextualizing and demonstrating this technology's practical application and benefits. They bridge the gap between theory and practice, anticipate challenges, and highlight the transformative potential of these integrations in sustainable urban development. Analyzing related papers shows strong evidence supporting the feasibility and benefits of such integration. However, it is essential to address specific challenges and barriers. Furthermore, we can improve the proposed scenarios by incorporating insights and improvements from related studies, ensuring they are comprehensive and practical for the real world. When used as case studies in research, scenarios provide a structured method to test theoretical frameworks and validate proposed integrations, making them a feasible approach for exploring complex systems.



The Role of Technologies		Interaction with: Digital Twin	BIM	IoT	Blockchain
Digital Twin	Digital Twin technology creates dynamic, real-time virtual replicas of physical assets, systems, or processes. In the context of city management, it links the physical infrastructure of a city to its digital counterpart, allowing for continuous monitoring, simulation, and optimization.	-	Utilizes BIM data to enhance the accuracy and detail of the virtual model, ensuring it reflects the current state of physical assets.	Receives real-time data from IoT sensors embedded in the city's infrastructure, providing insights into energy consumption, emissions, and other environmental factors.	Ensures data integrity and security, enabling transparent and tamper-proof management of city operations and environmental monitoring.
BIM	BIM provides comprehensive 3D models and detailed information about buildings and infrastructure projects, facilitating accurate design, construction, and lifecycle management.	Acts as the foundational data model that Digital Twin technology builds upon, ensuring accurate representation and simulation of physical assets.	-	Integrates real-time data from IoT devices to update and maintain the accuracy of BIM models, reflecting the actual conditions of buildings and infrastructure.	Enhances data security and transparency, enabling secure sharing and validation of BIM data across stakeholders, and ensuring reliable tracking of changes and updates.
IoT	IoT consists of a network of sensors and devices that collect and transmit real-time data from physical assets and environments. It plays a crucial role in monitoring and managing urban infrastructure.	Provides real-time data inputs to the Digital Twin, enabling continuous monitoring and analysis of the city's infrastructure and environmental impact.	Feeds real-time data into BIM models, ensuring they reflect the current state of buildings and infrastructure, and enabling proactive maintenance and management.	-	Ensures the security and accuracy of data transmitted from IoT devices, leveraging blockchain technology for secure and transparent data management.
Blockchain	Blockchain provides a secure, transparent, and immutable ledger for recording transactions and data exchanges. It ensures data security, transparency, and integrity across various systems.	Validates and records data transactions between Digital Twin, IoT devices, and BIM systems, ensuring data integrity and security.	Facilitates secure and transparent data sharing, enabling reliable tracking of updates, changes, and ownership, and supporting ESG (Environmental, Social, and Governance) analysis and compliance.	Monitors data gathered by IoT sensors, preventing data duplication and ensuring accurate data transfer without the need for a trusted third party.	-

Figure 8: The roles of technologies and their interaction.

6.6 Limitations and Future Direction

This research uses a hypothetical scenario to describe the integration between digital twins, BIM, IoT, and Blockchain. These conceptual scenarios may not comprehensively capture the complexity of the real world, resulting in discrepancies between expected and actual results.

Simplifying a complex system in a scenario can ignore important variables, resulting in incomplete or overly optimistic conclusions. The challenge is ensuring data accuracy and standardisation across systems, and existing scenarios need to be developed with further research.

Future research should focus on pilot projects and real-world case studies to validate the theoretical framework, offering insights into integrating Digital Twin, BIM, IoT, and Blockchain technologies. Additionally, government support is needed to develop a robust integration framework for interoperability, advanced data protocols for accuracy, and an extended architecture for data processing at a city scale. Regulatory research is needed to streamline compliance and cost-benefit analyses to evaluate economic feasibility and innovative funding models. Effective stakeholder engagement and security protocols are essential for successful implementation. Addressing these areas can enhance carbon disclosure and support certified green buildings.

7 CONCLUSIONS

This article has yielded findings regarding integrating digital twins, BIM, and blockchain to address sustainability challenges in the AEC industry sector. Based on our analysis, these technologies offer many opportunities to improve certified green building procedures and carbon disclosure standards. Our findings demonstrate how integrating blockchain, BIM, and digital twin technologies could transform efforts to promote sustainability. By capitalizing on these technologies' capabilities and addressing identified challenges, stakeholders can pave the way for a more sustainable and resilient future.

These technologies highlight the potential implementation for validating and managing building assets. By leveraging Digital Twin technology, stakeholders can proactively identify and mitigate environmental impacts, while BIM and blockchain technologies ensure transparency and accountability in data reporting and disclosure.

However, our analysis also revealed areas that need further research, particularly in integrating ESG principles and supply chain transparency. Addressing these gaps is crucial for maximizing the potential of technology-driven solutions in advancing sustainability goals within the built environment. The following study may focus on implementing the integrated BIM-blockchain system in different urban contexts. Researchers could use real-world case studies to evaluate this technology's adaptability and scalability in various building sizes, types, and locations. Furthermore, the study can focus on enhancing the suggested solution's compatibility with current standards and systems to ensure integration and reduce implementation-related challenges.

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Adam Fitriawijaya, https://orcid.org/0000-0002-5205-0128
Jeng Taysheng, https://orcid.org/0000-0001-9426-1436

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