A Novel Framework for Integrating Blockchain and Building Information Modelling in Construction Projects

Yasin Celik

A thesis presented for the degree of Doctor of Philosophy

School of Engineering

Cardiff University

2024

Abstract

The construction industry has experienced a variety of limitations with digitalisation, including inefficiencies in project management and collaboration, lack of transparency, and environmental sustainability concerns. In recent years, emerging technologies such as blockchain have attracted attention thanks to their potential to address these challenges and transform traditional construction practices. Blockchain offers opportunities to increase trust, transparency, automation, efficiency, and collaboration in the construction ecosystem. Despite a growing interest in the scientific field, there remains a significant gap in understanding how blockchain can be effectively integrated into construction projects, particularly in combination with BIM.

The literature review identified two main research gaps in the construction industry that motivated this research: (i) the lack of understanding and exploration toward the practical application of blockchain and (ii) the scarcity of research addressing blockchain-oriented solutions to improve information exchange in construction projects. Four research questions were developed to address these gaps and the shortcomings of existing studies by focusing on integrating blockchain with BIM to enhance construction applications: a) Can BIM and blockchain be integrated and applied in construction life-cycle stages to improve the safety, cost-efficiency, and sustainability of construction projects? b) Can a blockchain-based BIM provenance model be developed to ensure traceability and transparency of BIM data in a construction project? c) How can blockchain technology be applied to energy management systems to improve operational performance and ensure sustainable building practices? d) What are the key benefits and drawbacks of the blockchain application for the construction industry?

The research was divided into four main phases. The first phase included a literature review to identify research gaps and gather industry insights, followed by the formulation of research questions and methodology using a mixed methods approach with case studies and a questionnaire. The second phase focuses on the development and implementation of blockchain frameworks to integrate BIM by addressing challenges in the construction lifecycle and supply chain, while designing a blockchain-based BIM provenance model. This second phase provides practitioners with guidance on using blockchain for data integrity, traceability and accountability, concluding with a practical implementation guide to improve construction practices. The third phase explores the role of blockchain in building energy management to develop innovative solutions to improve energy efficiency and data management in construction projects. Lastly, the fourth phase uses a questionnaire and empirical approach to assess the effectiveness and feasibility of blockchain-BIM integration solutions, evaluate practical applications and identify areas for improvement.

The findings show that integrating blockchain with BIM can significantly improve data integrity, traceability and accountability in construction projects. The blockchain-based provenance model enables transparent and auditable tracking of changes in BIM data. In addition, blockchain may facilitate the promotion of sustainable energy practices through effective energy consumption monitoring and consumption pattern analysis. This research provides practical guidance and strategies to support construction practitioners in overcoming the complexities of blockchain-BIM integration and leveraging these innovations for better project outcomes, achieving cost efficiencies, and promoting environmental sustainability through improved data management and increasing collaboration and transparency across the building lifecycle."

Contents

List of Figures

List of Tables

Acknowledgements

I would like to express my sincere thanks to those who have made significant contributions to my academic journey. First, I would like to express my deep gratitude to Dr Ioan Petri for his invaluable guidance and mentorship, which greatly enriched my research skills. My sincere thanks also extend to Professor Yacine Rezgui for his guidance and assistance throughout my academic journey. The encouragement and support of my colleagues at the BRE Centre for Sustainable Engineering is also deeply appreciated.

I also wish to express my special thanks to Dr Masoud Barati and Dr Metin Mutlu Aydin for their collaborative efforts and invaluable insights, which have enriched my research experience.

Furthermore, I would like to thank my mother, father and siblings, for their endless encouragement and understanding during this challenging period. I would also like to thank all my friends who have supported me throughout my PhD journey.

I extend my sincere gratitude to the Turkish government for their exceptional support and for providing me with the priceless opportunity to pursue my PhD studies. Their generous sponsorship has been instrumental in enabling me to embark on this academic journey.

List of Publication

Conference papers and book chapter

1. Celik, Y., Petri, I., & Rezgui, Y. (2021, June). Leveraging BIM and blockchain for digital twins. In 2021 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC) (pp. 1-10). IEEE.

2. Çelik, Y., Aydin, M. M., Petri, I., & Potoglou, D. (2022, September). Intelligent transportation systems applications: Safety and transfer of big transport data. In International Conference TRANSBALTICA: Transportation Science and Technology (pp. 59-73). Cham: Springer International Publishing (Book Chapter).

3. Incorvaja, D., Celik, Y., Petri, I., & Rana, O. (2022, December). Circular economy and construction supply chains. In 2022 IEEE/ACM International Conference on Big Data Computing, Applications and Technologies (BDCAT) (pp. 92-99). IEEE.

Journal papers

1. Celik, Y., Petri, I., & Rezgui, Y. Integrating BIM and Blockchain across construction lifecycle and supply chains. Computers in Industry (2023), 148, 103886.

2. Celik, Y., Petri, I., & Barati, M. Blockchain supported BIM data provenance for construction projects. Computers in Industry (2023), 144, 103768.

3. Celik, Y., Barbero, I., Hodorog, A., Petri, I., & Rezgui, Y. Blockchain for energy efficiency training in the construction industry. Educ Inf Technol (2023).

Acronyms

AEC Architecture, Engineering and Construction

AGI Artificial General Intelligence

AI Artificial Intelligence

ANI Artificial Narrow Intelligence

AR/VR Augmented Reality/Virtual Reality

BEM Building Energy Management

BIBP Blockchain-enabled IoT-BIM platform

BIM Building Information Modelling

BMS Building Management Systems

CAD Computer-Aided Design

CDE Common Data Environment

CO2 Carbon Dioxide

CPS Cyber-Physical Systems

CS Cloud Systems

DAG Directed Acyclic Graph

DApps Decentralized Applications

DCDE Distributed Common Data Environment

DLT Distributed Ledger Technology

DMS Document Management Systems

DR Demand Response

DT Digital Twin

E&C Engineering and Construction

EED Energy Efficiency Directive

EPBD Energy Performance of Buildings Directive

ERP Enterprise Resource Planning

ETH Ether

FBA Federated Byzantine Agreement

FM Facility Management

GDP Gross Domestic Product

GHG Green House Gas

HVAC Heating, Ventilation, and Air Conditioning

ICOs Initial Coin Offers

ICT Information and Communication Technology

IDE Integrated Development Environment

IFC Industry Foundation Classes

IoS Internet of Services

IoT Internet of Things

IoTS Internet of Things and Services

IPFS Interplanetary File System

ITS Intelligent Transportation System

KBS Knowledge-Based System

KPIs Key Performance Indicators

LCA Lifecycle Assessment

LiDAR Light Detection and Ranging

M2M Machine-to-Machine

MaaS Mobility as a Service

MEP Mechanical, Electrical and Plumbing

ML Machine Learning

MIT Massachusetts Institute of Technology

NIST National Institute of Standards and Technology

NZEBs Virtually Zero Energy Buildings

P2P Peer-to-Peer

PaaS Platform-as-a-Service

PBFT Practical Byzantine Fault Tolerance

PEP Project Execution Plan

PII Personally Identifiable Information

PoA Proof of Authority

PoET Proof of Elapsed Time

PoS Proof of Stake

PoST Proof of Space-Time

PoW Proof of Work

Q# Quantum Developer Kit

QaaS Quantum Computing as a Service

RFID Radio Frequency Identification

RIBA Royal Institute of British Architects

RSK Rootstock

SCOs Smart Construction Objects

SDT Semantic Differential Transaction

SaaS Software-as-a-Service

SHA-256 Secure Hash Algorithm 256-bit

SLAs Service-Level Agreements

UAVs Unmanned Aerial Vehicles

WHO World Health Organization

WSNs Wireless Sensor Networks

WoL Window of Locking

Chapter 1

Introduction

1.1 Context

The construction sector, which represents approximately 6% of the global gross domestic product (GDP), plays an important role in the world economy. While there are global initiatives aimed at improving the sustainability of construction, a number of challenges highlight the urgent need for reform. These include high carbon emissions, resource depletion, excessive waste, inefficient energy use, increasing regulatory pressures, growing public demand for green buildings, the economic advantages of sustainable practices, and exciting new technological developments. This urgency is underscored by the significant contribution of the industry to greenhouse gas (GHG) emissions, accounting for 40% of global energy use and 39% of energy-related CO2 emissions. Addressing climate change and adhering to the imperative of limiting global warming to 1.5 ° C require swift and comprehensive changes in all aspects of human activity, as emphasised in the Speed & Scale action plan [1]. Recognising the critical role of the construction sector, international frameworks such as the Paris Agreement underscore its importance in mitigating the effects of climate change [2].

Similarly to many other sectors, construction is a knowledge-intensive sector, known for its fragmentation and lack of co-location of various supply chains. It is portrayed as involving a culture of "blame", leading to recurrent claims and litigation [3]. Because resources are produced and maintained in a distributed manner by different users and communities, including local organisations and government authorities, data and information are available in different formats. The PlanGrid and FMI corporations [4] study also highlights inefficiencies in the sector and reveals that a staggering $177.5 billion is spent on rework. On a global scale, it was observed that a mean of 52% of rework was attributed to poor project data and communication, resulting in a substantial financial burden of $280 billion in 2018. Rework accounts for approximately 5% of the total contract value of a project, or 7.1% of the total working hours, where 70% of all rework is caused by design errors, often due to factors such as lack of collaboration, design changes, and poor document control [5].

The construction sector has traditionally struggled with low productivity. Although this sector has experienced an annual growth rate of labor productivity of 1% in the last two decades, it has lagged behind the global average of 2.8%. This trend is highlighted in a

McKinsey report, which indicates that major construction projects often exceed timelines by 20 per cent and budgets by 80 per cent [6]. Project delays can also cost clients significantly by reducing the contractor's annual revenue and reputation for project execution. As shown in Figure 1.1, delays in the UK can reduce the value of a project by 15% and cost the global industrial sector €1.58 trillion [7].

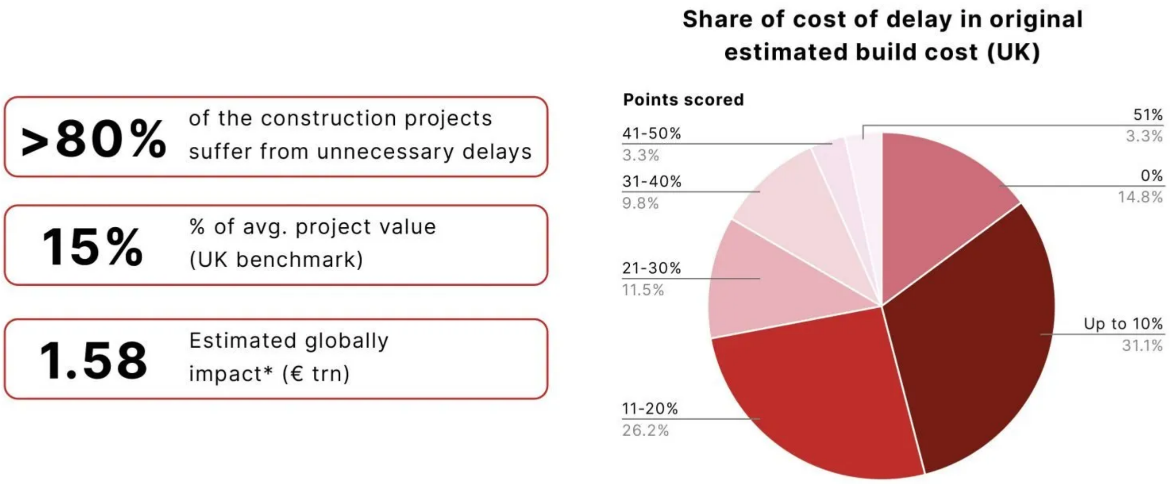


Figure 1.1: Analysis of the levels of delay in the construction industry in UK [7]

Moreover, budget overruns are a major concern in the construction sector. On a national scale, projects tend to exceed their allocated budgets by an average of 16%. Moreover, a comprehensive analysis of project data from 20 countries reveals that about 85% of these projects have experienced cost overruns in the last seven decades. According to the World Economic Forum, the digital revolution offers a promising perspective as it could lead to significant cost savings of $1.2 trillion worldwide, especially in the design & engineering and construction phases [8]. This highlights the critical necessity for the industry to embrace technological advancements as a means to increase efficiency and scalability in project collaboration, and as a fundamental strategy for future development and sustainability. In this context, digital solutions seem to lead this transformation and have the potential to enable an energy efficient construction sector with real-time emissions monitoring [1].

Therefore, digitalisation of the construction industry is necessary and involves many dimensions, including the use of digital tools and technologies, process automation, and digital project communication. The construction process is expected to be significantly transformed due to technological developments, particularly the application of building information modelling (BIM). BIM requirements for public projects in the UK highlight the global impulse towards digitalisation in construction. BIM is recognised as a revolutionary tool that enables efficient and effective information sharing and encourages better collaboration [9]. In a construction project, data exchange related to project tasks is complex, especially when dealing with multiple disciplines (e.g. architecture, structural engineering, etc.). Managing BIM across multiple projects, especially in geographically distributed organisations and locations, brings complexities related to data management, data provenance, and confidentiality [10]. These complexities can include issues related to data integration, version control, maintaining data consistency across projects, and ensuring secure and efficient data access for geographically dispersed teams. Large volumes of information can also cause challenges in data accuracy, which can affect stakeholder confidence in the BIM process [11].

The digital revolution has reshaped many industries and forced the construction industry to move from traditional hierarchical structures to a more flexible and dynamic way of working. Decentralised approaches, supported by flexible network dynamics, allow information, decision-making, and collaboration to circulate between networked individuals or nodes, promoting faster and more adaptable project management and implementation. This shift emphasises the importance of collaboration and participation of all stakeholders throughout the life cycle of a project [12]. However, ensuring reliability in data exchange, including key drawings and legal documents, as well as broader aspects of data security, transparency, and quality, remains a significant challenge among the various complexities faced by the construction industry [13]. In addition to data reliability, other challenges include project coordination, resource management, budget constraints, and compliance with regulatory requirements [14].

Blockchain, or distributed ledger technology (DLT), has been recognised for its transformative potential in various industries. This technology offers decentralised, secure data management with features such as security, transparency and data integrity without the need for a centralised authority [15]. Its applications range from powering cryptocurrencies such as Bitcoin and Ethereum to enabling traceability in supply chains, verifying the authenticity of works of art, and facilitating real estate transactions [16]. Moreover, its capabilities extend to advanced areas covered by Industry-4.0, such as cyber-physical systems, the Internet of

Things (IoT), cloud computing, artificial intelligence (AI), and it has been successfully applied in sectors such as manufacturing, finance, healthcare, cybersecurity, and transport [17]. As a secure method for recording transactions, the blockchain is suitable for legal processes and can present digital assets as evidence [18].

Blockchain technology presents a secure and efficient way to manage and record data in construction applications. The blockchain, in essence, works through a network of interconnected points, enabling information to be processed securely [19]. One of the main advantages of the construction industry is its ability to provide transparent and protected records. This feature promotes trust and accountability among project stakeholders because every piece of information is securely recorded and verified [20]. While the prospects of blockchain are promising, it is not without its limitations, especially in terms of data storage, transfer and scalability [21].

A prominent feature of blockchain is the "smart contract". This digital agreement automatically executes tasks when certain conditions are met, such as the automatic release of payments when a project phase is completed. For the construction industry, this could mean reducing delays, overcharges, and potential disputes. For example, average dispute values in the UK have increased over the years. The average dispute value in the UK is £27.48 million in 2021 (based on an approximate exchange rate of £1 = $1.3757). The average duration of disputes in the UK is just under 12 months (see Figure 1.2) [22].

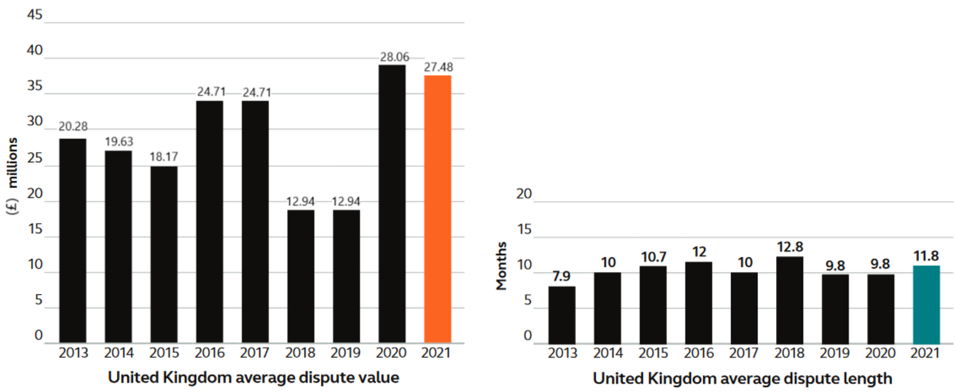


Figure 1.2: Analysis of the levels of dispute in the construction industry in the UK [22]

In addition, these digital agreements can improve safety on construction sites by ensuring that equipment operates within defined rules. They also emphasise the harmonised nature of this technology by promoting secure communication between different digital devices (such as IoT sensors, BIM systems, and mobile devices) that can exchange data on construction sites without the risk of external interference or data breach [23]. As the pressure for sustainable construction increases, the role of blockchain in promoting environmentally-friendly practices is becoming increasingly important, as reported in the literature [24].

In light of these issues in the construction industry, there is an urgent need for a complete solution that effectively addresses the gap between traditional methodologies and the dynamic requirements of the construction industry. A blockchain-enabled solution can provide both the immediate operational needs and the long-term strategic sustainability goals of the industry. Further details of the blockchain are presented in "Chapter 2".

1.2 Technological Developments in Construction

The construction industry faces important challenges, due to a variety of variables, such as payment delays, stakeholder disputes and cost overruns, cash flow management issues and the potential threat of insolvency. As discussed in the previous section, these factors often lead to conflicts and suspension of financial responsibilities. Such obstacles hinder the development of cooperation and trust among sector participants [25] [26]. In this context, it is essential to investigate the role of technology in the construction sector because it offers potential solutions to streamline processes, increase efficiency, and overcome these persistent challenges.

Digital construction practices involve various technological developments including BIM, IoT, digital collaboration tools, automation, robotics, augmented reality/virtual reality (AR/VR), and data analytics/AI. These applications have enabled a significant transformation in the construction industry through improvements in communication, collaboration, efficiency, and decision-making. For example, the BIM framework enables the creation and sharing of digital project representations [27]. However, AI and IoT are used to monitor and manage resources and processes on construction sites [28]. The adoption of innovative solutions such as blockchain has the potential to effectively mitigate payment delays, enhance transparency, and promote a more reliable and credible collaboration among various stakeholders [29].

1.2.1 Building Information Modelling (BIM) in Construction

In recent years, the implementation and development of BIM applications have played a critical role in the transformation of the construction industry. BIM has been adopted as a digitalisation framework that creates a central platform where all stakeholders can observe and contribute to a project in real time, encouraging trust and collaboration. Every change is documented and easily accessible. It also facilitates data exchange, enabling everyone, from architects to contractors, to work with the most up-to-date data. Different teams use a collaborative approach to solve problems, fault detection, and task planning with BIM. Chuang et al. show that the use of BIM facilitates efficient and effective communication and information distribution among construction stakeholders to manage projects [30]. However, a functional framework depends on BIM's ability to manage data and processes and is often associated with security and usability issues, including the risk of compromising data consistency and legitimacy [31].

Some of the limitations to the applicability of BIM for construction are summarised below:

- Interoperability challenges arise when exchange specifications are not strong enough or there is a lack of standardisation in how different BIM software packages share models. These inadequacies can result from inconsistencies in software design, limited compatibility features, or a lack of universal standards across platforms. Therefore, data exchange and collaboration become difficult and hinder the full potential of BIM integration. Integrated architecture is often unsuitable for real-time co-design and there is a lack of a mechanism to capture identified iterations in BIM model updates [32]. Interdisciplinary project coordination is illustrated in Figure 1.3.

- Barriers to a delegation of tasks and accountabilities due to overlapping roles and responsibilities, protection of intellectual property, risk mitigation and confidentiality [32].

- A BIM software platform exposes a lack of cyber-resilience, resulting in threats in data manipulation, hacking, and other cyberattacks[33].

- Time-consuming renovations and improvements, as well as other routine activities that can be automated throughout a project life cycle [31] and limited visibility in data tracking [34] lead to miscommunication between project stakeholders [35].

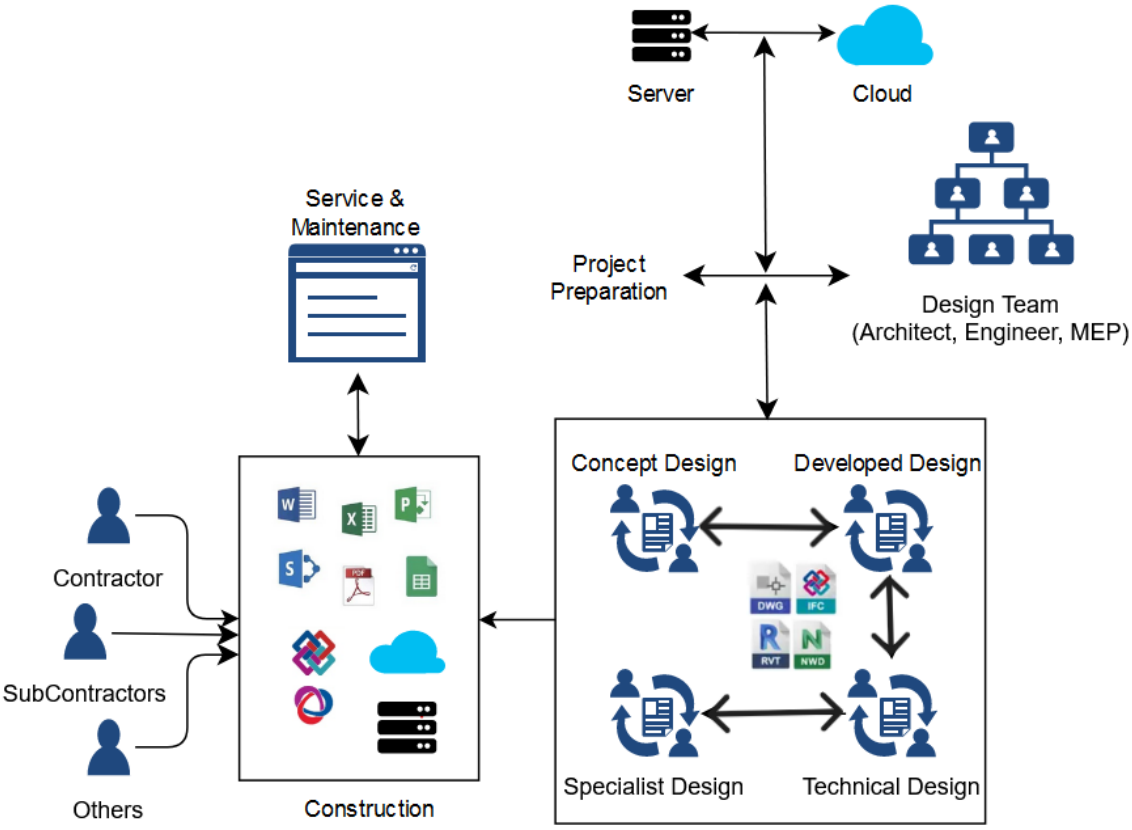


Figure 1.3: Project coordination across disciplines

For these reasons, the construction industry needs more adapted and scalable data exchanges around BIM and the common data environment (CDE), and improved flexibility for data manipulation, model consistency, and associated risks [33]. Blockchain improves BIM by addressing these limitations. Its decentralised and immutable nature ensures that BIM data remains secure and tamper-proof. Blockchain also facilitates better task delegation and accountability by providing a transparent record of all activities, which is crucial for multi-stakeholder projects. [32].

1.2.2 Provenance Models: Issue Status and Data Disruption

Provenance refers to tracing the origin and history of data throughout its life cycle. Effective data provenance is essential in construction to ensure the accuracy and legitimacy of project information. Existing systems often struggle to verify the authenticity of data, prevent fraud, and maintain data integrity [36].

Current systems often struggle with:

- **Data Verification:** Difficulty in establishing verifiable data provenance and preventing fraud [36].
- **Data Integrity:** Challenges in maintaining data consistency and protecting against tampering [37].

Blockchain improves data provenance by offering a protected ledger and decentralised verification, allowing stakeholders to verifiably track every data update and change [38]. This visibility increases confidence in the decision-making process by reducing the risks of fraud and data loss [37].

1.2.3 Construction Industry Sustainability

The construction sector is one of the significant contributors to global greenhouse gas emissions among other industries, with more than 40% linked to fuel consumption. To address this, sustainable construction practices are essential. Also, data breaches and inconsistencies in administrative data transfer emphasise the need for improved sustainability management in future developments. Globally, the potential of innovative technologies to overcome challenges, especially those related to sustainable management, is increasingly being highlighted and attracting attention [39].

Blockchain presents a solution by enabling sustainable practices to be tracked and verified data in real time. It provides a tamper-proof record of energy use and material procurement, increasing accountability and compliance with sustainability standards. When combined with IoT and AI, blockchain further optimises energy efficiency and resource management, potentially reducing a building's carbon footprint by up to 30% [40].

1.3 Digitalisation and Automation in Construction

The German high-tech strategic initiative plans for 2020, published in 2011, form the basis for the fourth industrial revolution, Industry 4.0. The transition from the first industrial revolution to the fourth industrial revolution is characterised by "smart manufacturing" and a shift towards digitalisation in production [41] [42]. According to Hermann et al.[43], the key components of Industry 4.0 are cyber-physical systems (CPS), IoT, internet of services (IoS), and cognition via computer, all of which are relevant to the optimal functioning of the construction industry.

1.3.1 Industry 4.0 and BIM

Industry 4.0 is a technological framework that emphasises the digital integration of industrial processes, merging the physical and digital worlds [42]. This framework utilises technologies such as CPS, IoT, and Machine-to-Machine (M2M) communication to shape the upcoming industrial revolution. When this concept is applied to the construction sector, it is termed Construction 4.0 [41]. This approach encompasses the entire construction life cycle and leverages tools such as BIM and cloud-based CDEs to streamline processes [44]. Despite the potential of these advancements, the adoption of the construction industry has been limited due to challenges such as project complexity, fragmented supply chains, and short-term perspectives [45]. However, with the integration of advanced technologies, including AI, cloud computing, and blockchain, there is a push toward a more digitised and efficient future in construction [46] [47].

The construction industry has effectively adopted BIM for digitalisation, allowing features such as detailed design, conflict detection, and energy analysis [31]. BIM requires sophisticated data analysis and integration to provide actionable insights during the digital transition [48]. Moreover, it is essential for collaboration and digital twinning strategies throughout the life cycle of a building, highlighting the need for trust within a networked system [49]. Data should be stored and exchanged in a secure and safe environment, and be well designed to ensure efficiency and security [50]. The combination of BIM with emerging technologies such as blockchain, AI, cloud computing, and machine learning (ML) provides significant digital transformation opportunities for the construction industry [28]. At the computing level, blockchain also facilitates the creation and coordination in real time of a visualised database, enabling more effective and secure interdisciplinary collaboration [51].

The findings from the current study include:

Digital technologies, including BIM and construction project management software, have the potential to revolutionise the construction industry by increasing productivity, reducing costs, and streamlining operations [52] [53] [54]. The integration of digital tools such as BIM, ERP and project management software is crucial to effective construction management by promoting information exchange and collaboration [55]. These technologies stimulate innovation and lead to the development of new products and services [56] [57], they also increase project efficiency by facilitating the incorporation of emerging technologies such as drones, blockchain, and IoT [58] [59]. Improved stakeholder collaboration is another benefit of digital adoption in the construction industry [60] [61] [62]. These technologies offer numerous advantages, including reduced costs and increased efficiency, while [63] [13] [57] [64], they also pose challenges related to privacy and accountability [47] [65] [66]. Blockchain integration with BIM can address some of these challenges by offering a decentralised platform for efficient information sharing [67] [68] [69], and paves the way for innovative capabilities in real-time monitoring and technology integration [28] [70] [71].

Limitations on the way of digitalisation in the construction industry:

The adoption of digital technology in the construction industry presents challenges due to its inherent complexity and diversity [72]. Barriers such as lack of standardisation, [73] [74], insufficient skilled personnel, and limited awareness of the potential benefits of technology [75] hinder the integration of digital tools. The fragmented nature of the sector and the lack of interoperability of the systems result in poor data quality and availability [76][77]. Moreover, the significant initial investment required for digitalisation deters many organisations from looking for concrete evidence of the benefits of technology before committing [78] [79].

1.3.2 Blockchain for Construction Automation

The increasing adoption of digitisation is due to its capabilities to support modelling, prediction, and optimisation on various digital artefacts, as discussed and acknowledged in the recent literature [80]. However, challenges such as privacy, security, and reliability of data sources arise in the use of digital documents and data [81]. This digital transformation generates a wide range of data types, from architectural plans to work programmes. Effective management and analysis of this data is critical to enhance project management, accelerate decision making and improve project outcomes. Challenges arise in securely tracking data changes and maintaining a consistent revision history, especially when using advanced tools such as BIM [82]. Traditional methods based on centralised systems pose risks due to unauthorised or unintentional changes. To mitigate these risks, it is proposed to integrate BIM with blockchain technology, which can reduce risks, encourage collaboration, and enable better information flow between project stakeholders [83]. For example, architects can receive notifications about design changes, encryption, and storage details. Participants have complete control over their data, allowing them to grant or revoke access when necessary, a very important feature in scenarios where forged documents or licences may be found [84].

Digitalisation contributions to the construction industry on the basis of BIM and blockchain are as follows:

Automation is facilitated through the use of "smart contracts", where digital agreements with self-executing codes are automatically triggered when certain conditions are met [85]. Decentralisation ensures that data storage on a blockchain network is secure, free of biases of a single central authority, and controlled by a community of nodes [86]. Collaboration between teams, empowered by BIM and blockchain, increases productivity and autonomy by eliminating the need for intermediaries [87]. Immutable data transactions are enabled, allowing model changes and provenance records to be tracked with timestamps for verification [88]. Remote real-time monitoring and management become possible, delivering actionable insights from a distributed database [89]. Since machines are operated remotely, increased efficiency and safety are achieved and a stable working environment is promoted [90]. Improved documentation is due to the ability of the blockchain to track transactions without allowing data changes [91]. The demand for customised products and services is efficiently met through comprehensive historical data [92]. Maintenance and planning forecasts benefit from real-time data analysis, enabling early fault detection and faster solutions [93]. Data and information tracking are improved through blockchain, providing traceability in the design and review process [94]. The immutability in the blockchain minimises security breaches because each node has a copy of the digital ledger [95]. Licence management is facilitated by the blockchain's ability to record and track transactions piece by piece [94]. Digitalisation enables more effective risk management through what-if analysis [96]. Furthermore, predictive analytics and decision support are improved through real predictive data and visualisation tools [97]. Multiple participants in construction disciplines can access the blockchain network to verify the process history and track various iterations [88]. Figure 1.4 shows the contribution to digitalisation with blockchain integration through the BIM RIBA Work Plan stages.

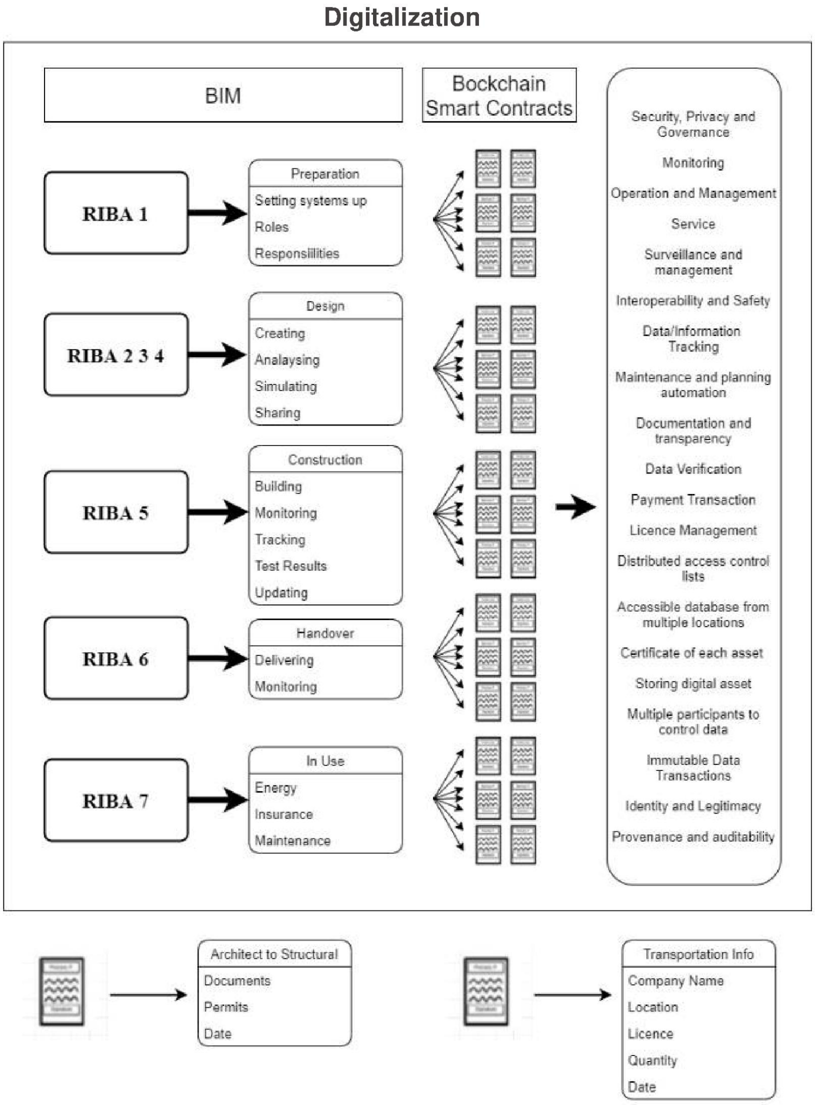


Figure 1.4: a) BIM and blockchain integration for digitalisation b) Example of the data record in data exchange c) Example of the data record with its features on blockchain

1.4 Construction Projects and Life-cycle Stages

Construction projects progress through different life-cycle phases, such as design, planning, execution, operation and maintenance, and the exchange of information between these phases is important for the success of the project. At each stage, stakeholders such as architects, engineers, contractors or government authorities need to access and share relevant data for informed decision-making.

Throughout the life cycle of a construction project, a large amount of information is generated and shared at various stages between various participants. The efficiency and management of this data exchange are necessary to bridge the gaps between construction stages and promote effective communication, strategic decision-making, and synergies between all parties involved. Today's construction environment is characterised by the convergence of digital technologies with traditional practices, marking a transition from predominantly mechanical and automated techniques to a more digital and intelligent framework. At the centre of this transformation is a consolidated project information platform that leverages advanced construction technologies, methods, AI, and data analytics. This integrated environment facilitates both project development and subsequent maintenance. As new information technologies are incorporated, the construction process is constantly evolving, highlighting the need to integrate these technological advances with progressive construction techniques and modern project management approaches [98].

In this respect, BIM emerges as a technology with significant transformation potential. This facilitates the process of information exchange by providing a digital representation of the project that all stakeholders can access [99]. In addition to BIM, other tools, such as project management software and collaboration platforms, facilitate this information exchange [100]. However, the construction industry faces unique digitisation challenges, especially during the design and construction phases. Compatibility issues arise as multiple participants contribute different data using various digital formats (e.g., IFC and DWG for design). The temporary nature of construction projects further complicates the tracking of building components equipment and personnel activities.

A BIM project execution plan (PEP) serves as a guiding framework detailing how BIM is integrated throughout the project life cycle. Identifies where BIM can be most beneficial, such as visualising structural issues during the design phase or optimising resource allocation during construction. Regular monitoring of this blueprint ensures that stakeholders benefit from the full potential of BIM [101]. As highlighted by the BIM Industry Working Group, the UK government recognises the value of BIM throughout the life cycle of a project, from inception to final demolition. The literature shows that BIM can be used in feasibility, design, preconstruction, and construction [102]. It highlights its various applications at stages such as [103] and operations and management [101]. However, the construction life cycle is not without its challenges. Issues such as cost overruns, design mistakes, safety risks, and environmental concerns can arise [104]. These problems are exacerbated by factors such as poor planning, communication breakdowns, and unforeseen events such as adverse weather or material shortages. Traditional paper-based methods compound these challenges by creating data silos and inconsistencies [105] [13].

To address these concerns, the industry is exploring various solutions, including the following:

- Enhanced project planning and management is accomplished through advanced planning technologies such as BIM, enabling stakeholders to detect potential issues early and implement necessary actions to mitigate risks [99].

- Increased communication and cooperation among project stakeholders eliminates misunderstandings and conflicts [106].

- The implementation of digital technologies such as BIM, blockchain, and AI enhances the accuracy and efficiency of project management while minimizing the likelihood of errors [20].

- Standardization and interoperability of data and technology platforms enhance the sharing and exchange of project information among stakeholders, decreasing data silos and improving cooperation [13].

The adoption of blockchain technology is intended to address the identified issues given in this section and others by leveraging its features and capabilities. It can facilitate better communication and collaboration between project stakeholders, leading to a more productive and harmonised working environment. The project could also benefit from new construction techniques that have the potential to reduce costs, minimise losses, and optimise the construction process using blockchain technology.

1.5 Research Questions and Objectives

In response to challenges previously mentioned in earlier sections, blockchain technology is emerging as a promising method to revolutionise the construction industry by increasing collaboration, transparency and sustainability [127]. The literature review identified two major research gaps in the construction industry: the lack of research on practical applications of blockchain technology and the scarcity of studies addressing blockchain-driven solutions to improve information exchange in construction projects. This study therefore aims to fill this gap by investigating the feasibility, benefits and challenges of integrating blockchain into construction applications. Utilising the existing literature on the limitations of BIM and the transformative potential of blockchain, it seeks to develop innovative blockchain-driven solutions adapted to construction projects.

This research aims to address these research gaps by focusing on four key research questions. The research questions and objectives are given below:

1. Can BIM and blockchain be integrated and applied in construction life-cycle stages to improve safety, cost-efficiency and sustainability of construction projects?

    - Objective 1.1: Explore the potential integration of BIM and blockchain technology at different stages of the construction life cycle to improve safety, efficiency, and sustainability.
    - Objective 1.2: Investigate how the integration of BIM and blockchain technologies can support collaboration across disciplines in the construction industry by promoting accountability and visibility in the supply chain.

2. Can a blockchain-based BIM provenance model be developed to ensure traceability and transparency of BIM data in a construction project?

- Objective 2.1: Develop a blockchain-based BIM provenance model that enables secure and immutable tracking of BIM data throughout the entire life cycle of a construction project, including data creation, modification, and utilisation.
- Objective 2.2: Apply the developed blockchain-based BIM provenance model in a real-world construction project to assess its feasibility, effectiveness and practicality.

3. How can blockchain technology be applied to energy management systems to improve operational performance and ensure sustainable building practices ?

   - Objective 3.1: Investigate the potential of blockchain technology to support energy management in the built environment.
   - Objective 3.2: Explore how blockchain can streamline data management providing a real-time energy sensing and control capability to advance energy efficiency and sustainability goals in the construction industry.

4. What are the key benefits and drawbacks of the blockchain application for the construction industry?

   - Objective 4.1: Analyse how the integration of blockchain technology impacts the general performance of construction projects, using ROI and key performance metrics.
   - Objective 4.2: Extract evidence from community consultations about limitations and the current challenges around the adoption of digital technologies in the construction industry.

This thesis aims to advance the integration of blockchain technology and BIM into the construction industry. It focuses on investigating the feasibility and potential benefits of incorporating blockchain into various stages of the construction life cycle to enhance security, cost efficiency, and sustainability. The study outlines the unique advantages of integrating BIM and blockchain throughout key phases, including design, planning, procurement, construction, and facilities management. The research involves developing a blockchain-powered BIM data model to enable data traceability and transparency of objects throughout construction projects. This includes building a sophisticated BIM model and designing smart contracts to record the life cycle of BIM data and objects immutably. Additionally, the study explores blockchain's potential to support energy efficiency interventions in the built environment, showcasing practical applications and developing a framework for more efficient and sustainable energy practices. In general, this thesis aims to provide insights and practical solutions for the technological integration of blockchain and BIM, contributing to the digitalisation of the construction industry.

1.6 Contributions

This research conducts a comprehensive literature review that informs the development of a conceptual blockchain framework and analysis to determine the potential blockchain impact on the construction industry. This research explores the potential of blockchain to improve the management of BIM data, collaboration, sustainable building practices, and the integration of emerging technologies.

The contributions of this thesis are as follows.

(a) Examine the integrating blockchain technology into the construction industry, focusing on construction management and life cycle stages aiming to enhance automation, data management, transparency, traceability, and efficiency within the construction life cycle. A blockchain model is proposed to demonstrate the feasibility and effectiveness of this integration through a case study.

(b) Develop a BIM data-provenance model by leveraging blockchain technology to improve data reliability and authenticity in construction projects. A real bridge construction case study is used to demonstrate the effectiveness of the provenance model and its integration with the project BIM data.

(c) Propose a blockchain capability that can support improved energy management based on auditable energy sensing and control policies in buildings. By developing and validating a blockchain-based model, this study demonstrates the potential of blockchain to improve data accuracy, transparency, and efficiency in energy management for buildings.

(d) Providing empirical support for findings by applying an evaluation framework that includes key performance indicators (KPIs) with associated impact calculations and a questionnaire that evidences the significance of the research and improved the scientific understanding of the field while providing a foundation for future research efforts.

1.7 Thesis Outline

The structure of this thesis is visualised in Figure 1.5.

This thesis is structured as follows:

Chapter 1

This chapter discusses the main drivers for the integration of BIM and blockchain technology in the construction industry and outlines the problem statement and objectives for the research study.

Chapter 2

Chapter 2 provides a review of the existing literature and related studies exploring the integration of digital technologies into the construction industry. The chapter starts with an analysis of the impacts of BIM utilisation in the construction industry, highlighting its important role in facilitating project collaboration, and provides the basis for the integration of BIM with blockchain technology throughout the construction industry life cycle and explores how blockchain can be applied to enhance broader systems.

Chapter 3

This chapter outlines the methodological approach used in this thesis, detailing the key stages and techniques used to achieve the research objectives. It also provides an

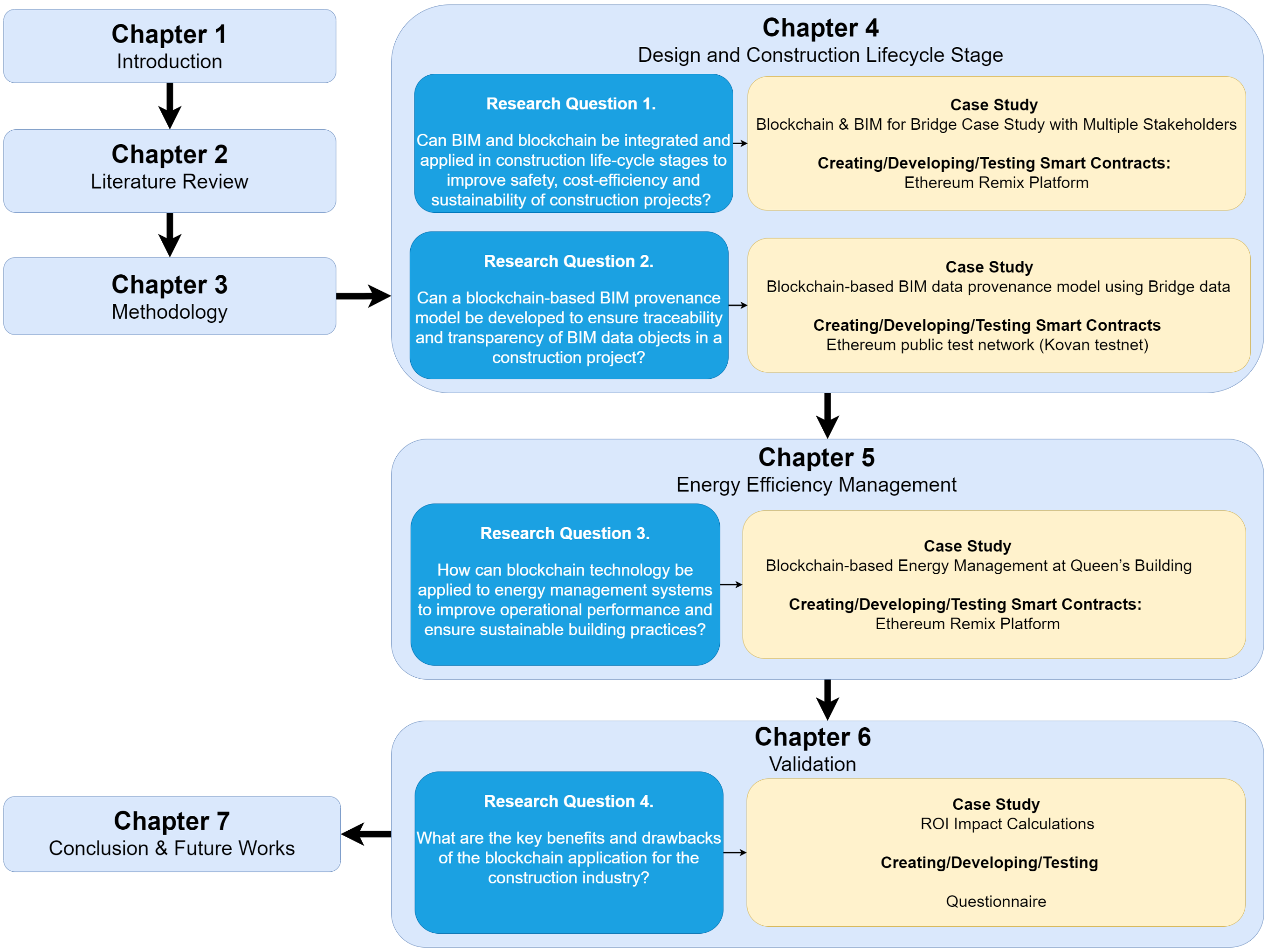


Figure 1.5: Thesis outline

overview of the research design, including the methods and processes used to collect and analyse data, and describes the steps taken to implement the study.

Chapter 4

Chapter 4 presents two scenarios considering the design and lifecycle of the construction industry. The first scenario presents a model for construction projects using the synergy between BIM and blockchain technology. This scenario highlights the importance of building trust between stakeholders while emphasizing automation and better data management. The second scenario examines the transformative impact of blockchain technology on data integrity in construction projects. A provenance model is introduced that demonstrates the benefits of blockchain integration in ensuring data integrity throughout the construction lifecycle.

Chapter 5

This chapter investigates the use of blockchain technology to improve energy management strategies in buildings. A blockchain model is proposed to support auditable energy sensing and control, demonstrated through a case study focused on monitoring and managing energy in office spaces and buildings. The case study highlights the applicability and effectiveness of blockchain-based energy management in buildings.

Chapter 6

This chapter presents the advantages and disadvantages as identified in the existing literature and case studies, including key performance indicators (KPI) and associated impact calculation. The chapter also presents a questionnaire that captures industry professionals' perspectives in order to provide a more holistic understanding of the integration of blockchain technology in the construction industry, enriched with qualitative context and real-world assessments.

Chapter 7

This chapter revisits each research questions and provides a summary of the findings and their contributions. It also provides a synthesis of the thesis, emphasizing the rigor, importance and impact of the research. The chapter acknowledges the limitations of the study and concludes with recommendations for future developments in the construction industry.

In summary, this thesis investigates the integration of BIM and blockchain technology into the construction industry. The introductory chapter establishes the contextual framework and states the research questions and objectives, while Chapter 2 provides a literature review examining the implications of BIM and blockchain throughout the construction industry life cycle. Chapter 3 carefully details the research methodology. Chapters 4 and 5 case studies showcasing the application of blockchain technology in different areas of the construction industry. Chapter 4 presents a model for BIM-blockchain integration. Chapter 5 explores the use of blockchain for energy management in the built environment. Chapter 6 presents an analysis of the advantages, barriers, empirical findings, and validation through KPI and questionnaire that contribute to the understanding and effective application of these technologies in the construction industry. Finally, Chapter 7 synthesises key knowledge, addresses research questions, and suggests strategic directions for future research.

Next Chapter: Literature Review

The following section provides a literature review examining the integration of blockchain technology into the construction industry, alongside sustainability initiatives and emerging technologies. The next chapter will explore the benefits of combining blockchain with BIM, highlighting its potential to enhance project management and stimulate innovation in the industry. The chapter will also examine the applications of blockchain in collaborative applications, supply chain management and energy efficiency in buildings, aiming to provide an overview of current research while identifying gaps in this area and opportunities for future advancements.

CHAPTER2

Literature Review

This chapter examines the integration of blockchain technology in the construction industry alongside sustainability initiatives and next-generation technologies. Focussing on the benefit of blockchain with BIM in construction, this chapter explores its potential for project management and industry innovation. It also explores blockchain technology and its potential benefits, starting with collaborative practices and BIM adoption. Additionally, this chapter explores how blockchain can support supply chain management and its role in energy management in buildings to assess its potential to improve sustainability practices. This exploration aims to provide information on current research directions and identify areas for future construction work.

2.1 Introduction to the Domain of Research

The adoption of blockchain technology in various sectors has attracted attention thanks to its decentralised nature and potential to increase transparency, security, and efficiency. In the construction industry, the integration of blockchain has become an increasingly attractive and important topic. To delve deeper into this area, a comprehensive literature review has been conducted to explore the various ways in which blockchain technology can be utilised in construction processes. This exploration aims to reveal both the potential advantages and challenges of incorporating blockchain into the construction industry. The current state of research is analyzed to understand the implications of blockchain adoption in the construction industry. Through this exploration, this chapter attempts to shed light on the potential benefits and challenges inherent in the application of blockchain in construction projects. The trajectory of the literature review process is not only to analyse and synthesise existing knowledge but also to identify research gaps. The review of the literature on the integration of blockchain in the construction industry follows a systematic approach, as presented in Figure 2.1.

The first step involved defining keywords covering various aspects of the topic. Key words used in this thesis include blockchain OR distributed ledger OR smart contract AND ("building information modelling" OR BIM OR construction industry OR the AEC

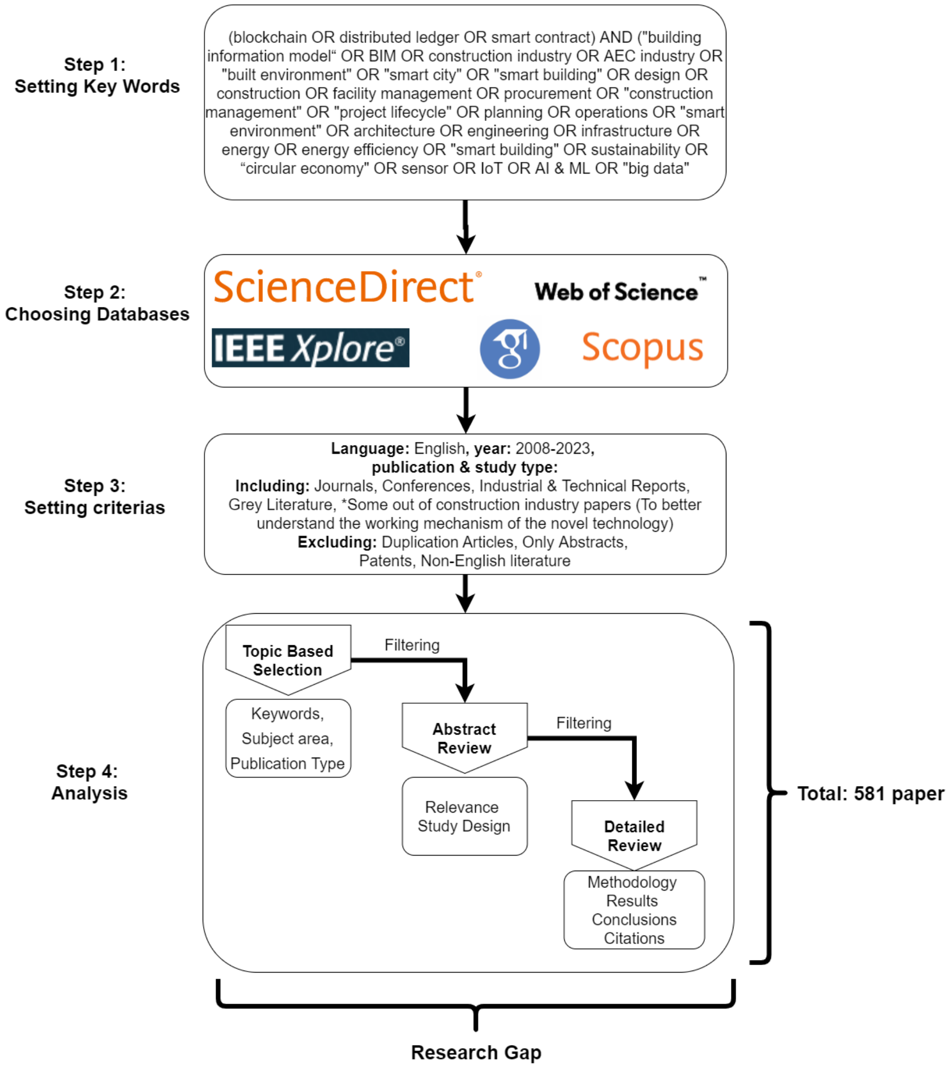


Figure 2.1: The stages of the review process

industry OR built environment OR smart city OR design OR construction management OR project lifecycle OR planning OR operations OR smart environment OR architecture OR engineering OR infrastructure OR energy OR energy efficiency OR smart building OR sustainability OR circularity OR IT OR AI & ML OR big data). Comprehensive databases such as Google Scholar and Scopus were then selected to provide a broad coverage of scientific research. Ongoing submissions from ResearchGate were also evaluated to include additional sources such as conference proceedings and industry reports. Specific criteria were set, including language (English), year of publication (2008-2023), and the inclusion of various types of publications. This process ensured that the relevant literature was obtained while excluding duplicate articles, abstract-only records, patents, and non-English publications. The review process begins with subject-based selection filters such as relevant keywords, specific subject areas and publication types. During abstract review, abstracts are assessed for their relevance and study design to ensure that they are aligned with the research objectives. In the detailed review, selected articles are assessed for methodology, results, conclusions and citation impact.

A wide range of research articles from 2008 to 2023 was analysed, as shown in Figure 2.2. The period from 2008 to 2023 is considered critical for blockchain research, especially in the construction industry, as it started with the publication of the Bitcoin whitepaper introducing blockchain technology. The early years (2008-2013) marked the initial development of blockchain, followed by significant innovation (2014-2017) exploring its potential applications in construction, such as supply chain management and project tracking. From 2018 to 2023, the focus shifted to mainstream adoption applying blockchain to increase transparency, reduce fraud and improve collaboration between stakeholders in construction projects.

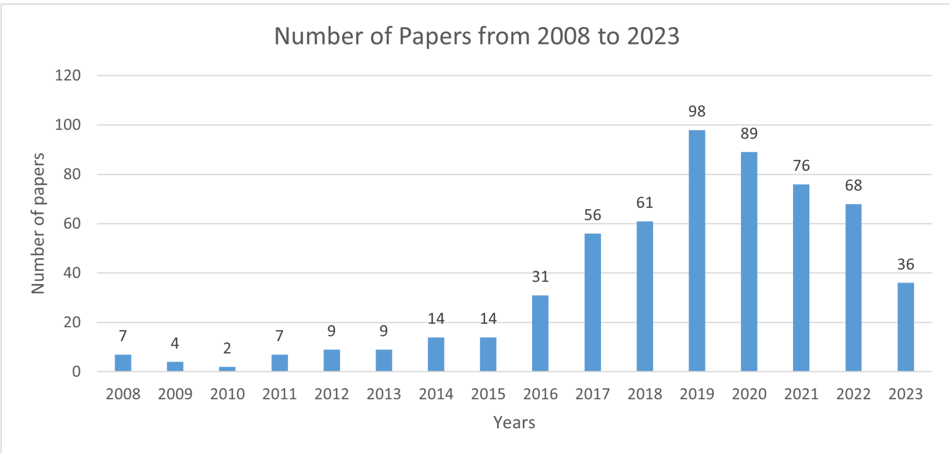


Figure 2.2: Number of papers reviewed within this thesis cover periods that range from 2008 to 2023.

The analysis of this period reveals the advancement of blockchain across the entire construction industry. The analysis focused specifically on a comprehensive collection of 581 research articles using tools such as NVIVO and Mendeley to improve the academic integrity and significance of the study.

To present the complete picture of the research, two different processes were applied: co-occurrence mapping, which visually identifies the link between keywords, and co-authorship mapping, which sheds light on the relationships between authors and their respective scientific contributions. The NVivo and VOSviewer software tools have been used as a facilitating mechanism to perform these analytical procedures. VOSviewer provides a graphical framework for the analysis of bibliometric data. The co-occurrence mapping process covered the entire range of keywords and used the entire count method to execute. The analysis shows a strong correlation between the implementation of blockchain and the construction industry.

Keywords showing high frequencies serve as markers of prominent areas of focus within the research. The most frequently occurring keywords include: "blockchain" (258 occurrences), "smart contract" (225 occurrences), "BIM" (167 occurrences), "information management" (160 occurrences), "IoT" (163 occurrences), "digital twin" (132 occurrences), "construction industry" (125 occurrences), "security" (117 occurrences), "lifecycle" (89 occurrences) and "applications" (75 occurrences). Examination of the co-occurrence network of keywords can be seen in Figure 2.3.

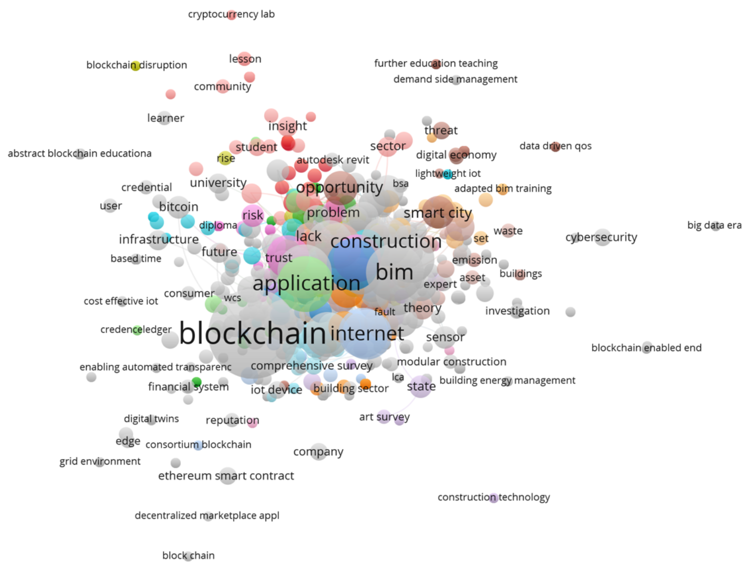


Figure 2.3: In-depth examination of the network of keyword co-occurrence.

The collaboration map in Figure 2.4 reflects a distributed structure in which elements and functions are distributed between multiple nodes. The authors Whang Y., Whang J., Li Y., Huang X., Li Q., Li S. and Liu J. are at the centre of the most extensive collaboration cluster. Within this category, Whang Y. and Whang J. stand out as the authors of the majority of the most cited papers. Perera S., Li J., Kassem M., Senaratne S. and Nanayakkara S. have made significant contributions to blockchain research in the construction industry, earning the distinction of being the most cited authors.

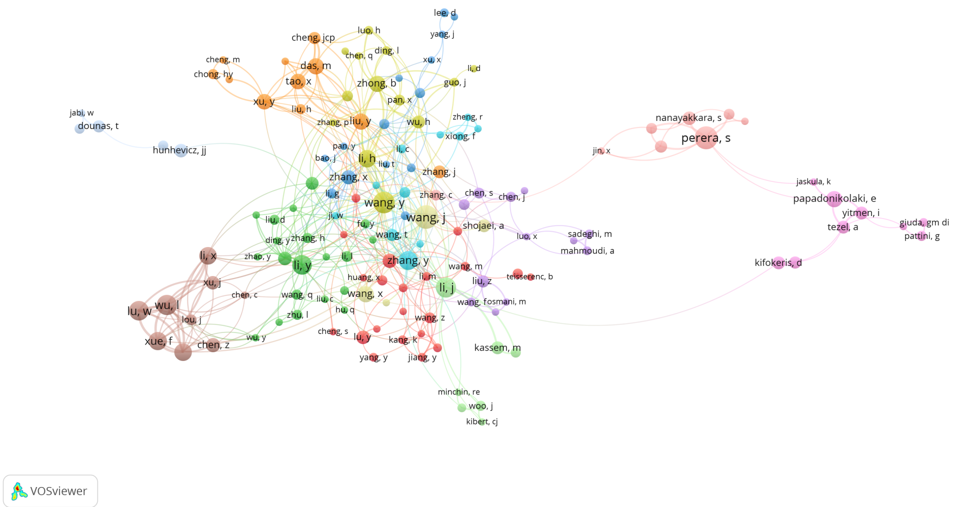


Figure 2.4: Network for author cooperation

2.2 Key Findings from Related Studies

The literature review presents a synthesis of findings from a wide range of research papers focusing on introducing, integrating, and utilising blockchain technology with BIM, particularly in the construction industry. Over the past few years, the construction industry has experienced a wave of innovation powered by blockchain technology. Some of these developments are as follows: the authors examine the development of a blockchain-based system that enhances traceability and transparency [107], introduce a construction management system built on blockchain principles for enhanced trust

[108], and highlight the integration of digitalisation through blockchain for improved collaboration [109]. Nguyen et al. (2012) developed a comprehensive blockchain taxonomy, shown in Figure 2.5, to provide information on the various classifications, functionalities, and applications of blockchain. However, the existing literature shows that there is a gap in exploring the potential of blockchain in the construction industry.

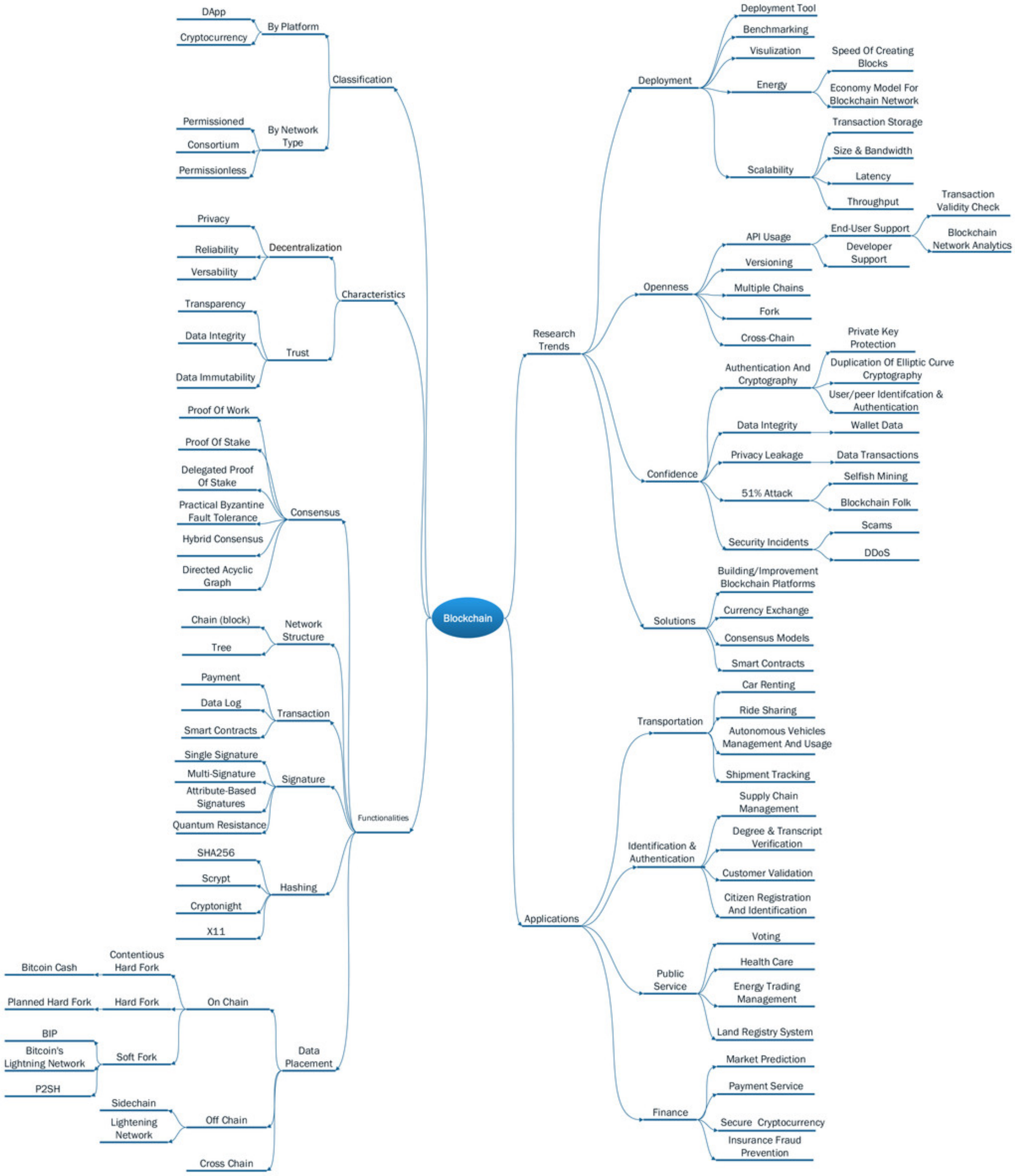


Figure 2.5: Blockchain taxonomy [110]

An ongoing challenge in the industry is the emergence of payment delays and disputes between stakeholders, often exacerbated by bankruptcy and cash flow disruptions. [26]. To overcome these challenges and promote a more trustworthy cooperation environment, the integration of advanced technologies such as blockchain is considered essential [29]. Parn & Edwards [14] emphasised the importance of a secure CDE, highlighting the susceptibility of the construction industry to cyberphysical threats. They suggest that the decentralised nature of blockchain technology can provide a solution for the protection of sensitive digital infrastructure data, particularly within the BIM environment. Another important study [31] highlights the synergy between blockchain and the BIM process and suggests that blockchain has the potential to improve security, data storage, and management capabilities in the BIM environment. While BIM acts as a digital channel for the exchange of information between construction projects, the incorporation of blockchain's smart contracts could revolutionise the procurement process by offering enhanced flexibility in contract management and payment processing. This integration can also address common industry issues such as data traceability and ownership [31].

Once data is stored in the blockchain, it becomes immutable and provides a tamper-proof and traceable record of all transactions [111]. Blockchain consensus protocols and cryptographic techniques can significantly save time and costs by streamlining transactions. This technology also holds promise for enhancing confidentiality, privacy, and data ownership in BIM-centred projects [112]. The concept of smart contracts, essentially computerised agreements, has the potential to redefine trust between stakeholders [113] [114].

Despite its transformative potential, blockchain adoption in the construction industry is still in its infancy [115]. However, its capacity to address critical challenges in the industry and reshape traditional operational paradigms highlights its potential to revolutionize the construction industry, as blockchain's natural abilities to facilitate secure collaborations and ensure data integrity position it as a valuable asset for the future of the industry [113] [116]. A comparison of the advantages of blockchain in the construction industry compared to traditional systems obtained from the review of the literature is presented in Table 2.1.

These and additional studies are given in Table A.1 (Appendix A.1.). Theanalysis identifies several critical criticisms prevalent in existing blockchain studies in the construction field, ranging from limited practical application to an emphasis on technical complexities. These studies have observed theoretical frameworks that lack real-world validation, studies that narrowly focus on specific aspects of blockchain integration, and a lack of empirical evidence supporting proposed solutions.

Table 2.1: Overview of the potential benefits of using Blockchain technology in construction projects.

Aspects	Traditional Construction	Construction with Blockchain
Transparency	Limited transparency in supply chain and project management [34] [117]. Stakeholders may not have access to complete and accurate information, which can lead to issues and delays [118] [119].	Greater transparency in supply chain and project management due to the immutability of data on Blockchain [120] [121]. All stakeholders can access and verify information, resulting in fewer disputes [122] and faster decision-making [123].
Project management	Centralized project management and decision-making with a higher risk of errors [11] and delays [124].	Smart contracts for decentralised project management provide more accuracy and fewer mistakes in decision-making [31] [125][126]. All stakeholders can participate in decision-making, leading to faster and more accurate decisions [127] [128].
Payment processes	Manual processes for payments and invoicing may result in delays and disputes [129]. Payments may be delayed or disputed due to errors or disagreements [130].	Automated payment processes through smart contracts may result in faster payments and reduced disputes [126]. Payments are automatically triggered when conditions are met leading to faster and more accurate payments [120] [131] [105].

Continued on next page

Table 2.1 – continued from previous page

Aspects	Traditional Construction	Construction with Blockchain
Documentation	Manual documentation processes may lead to potential errors and lost documents or misfiling [132] [133].	Automated and secure documentation processes with the use of Blockchain, reducing the risk of errors and lost documents [64] [31] [134]. All documents are stored on the Blockchain, ensuring their security and availability [71][112] [13] [135].
Quality control	Limited quality control mechanisms, potential issues and rework [136]. Quality may be compromised due to a lack of monitoring or quality control processes [136] [137] [138] [139].	Improved quality control mechanisms through the use of Blockchain [13] [140]. Quality control processes can be automated and monitored in real-time [57] [125] [141] [90] [28].
Supply chain management	Limited visibility and traceability in the supply chain [142] [143]. The supply chain may be opaque, making it difficult to track or verify information [137] [144] [139].	Improved visibility and traceability in the supply chain through the use of Blockchain [145] [105]. The supply chain can be tracked and verified on the Blockchain [146] [147] [148] [149] [142].
Cost management	Limited cost management mechanisms, leading to potential cost overruns [150] [71] [119]. Costs may be difficult to track or predict, leading to potential overruns [139] [151] [152].	Improved cost management mechanisms through the use of Blockchain [13] [153] [64] [105]. Costs can be tracked and predicted in real-time on the Blockchain, ensuring accurate budgeting and cost control [134] [90] [126].
Collaboration	Limited collaboration and communication between stakeholders [13] [154] [155]. Stakeholders may not have access to complete and accurate information [155] [152] [124] [69] [143].	Improved collaboration and communication between stakeholders through the use of Blockchain [156] [87] [51]. All stakeholders can access and verify information on the Blockchain [157] [158] [159] [160].
Sustainability	Limited ability to track and verify sustainability efforts [161] [154] [119]. Sustainability efforts may not be accurately tracked or verified, leading to potential issues with compliance or reputation [155] [162] [148] [163].	Improved ability to track and verify sustainability efforts through the use of Blockchain [161] [57] [154]. Sustainability efforts can be tracked and verified on the Blockchain, ensuring their accuracy and legitimacy [57] [145] [105].

Limited practical application: Some studies propose theoretical frameworks without practical validation, potentially limiting their real-world impact [164] [34] [127].

Narrow scope: Some studies narrowly focus on specific aspects of blockchain integration and ignore the implications of BIM and blockchain integration [165] [166] [167].

Lack of empirical evidence: Some studies lack empirical validation, relying on hypothetical scenarios or simulations [162] [144] [168].

Overemphasis on technical details: Some studies over-emphasise technical aspects without addressing practical challenges [125] [169] [170].

The research attempts to fill these gaps by examining the applicability of blockchain in various construction domains covering BIM data provenance, supply chain management and energy management. By providing practical insights and solutions, the aim is to catalyze advancements in the construction industry's adoption of blockchain technology. A mixed-method approach was used combining primary evidence from a real construction project with secondary evidence from research studies.

2.2.1 The Adoption of BIM in the Construction Industry

BIM is a digital technology that is widely used in the construction industry to facilitate the design, construction, and management of construction projects. It requires the creation of a digital representation of a construction project encompassing both geometric and nongeometric data, including spatial relationships, quantities, and properties of building components [61].

BIM has two main aspects. First, it is a process that involves creating and using a digital model to reduce information gaps throughout the construction project. This is achieved through collaboration between key participants who can add, retrieve and update model data. Second, BIM is a digital model that serves as a structured repository of information for the building at each stage of its life cycle. The model contains smart 3D components that are linked through data [171].

BIM has had a significant impact on the digitalisation of the construction industry, and several companies are embracing it as a key tool to improve the effectiveness and efficiency of their construction operations [52] [56] [172] [42] [173] [53]. The review and analysis of relevant literature and case studies show that digitalisation and automation technologies in the construction industry have reached a stage where they are commercially available and accessible to the general public. The widespread adoption of these technologies promises significant impacts on the industry, the companies involved, the environment, and the general population. Although the construction industry is poised to benefit from these developments, it is essential to address specific challenges and concerns to achieve a successful and meaningful digital transformation [173].

Among the most significant effects of BIM on digital construction are:

- Project design and planning: BIM enables construction professionals to develop comprehensive digital models of construction projects, which can be used to enhance project planning and design. Using BIM, construction professionals can detect possible challenges, conflicts, and opportunities in an early stage of the project and make informed design and construction decisions [62] [174].
- Communication and collaboration: BIM facilitates cooperation and communication between diverse construction specialities and stakeholders. Using BIM, construction workers can communicate and coordinate project information in real time, thus avoiding the disagreements and inaccuracies that might arise when using conventional communication techniques [99].
- Productivity and efficiency: BIM may increase efficiency and productivity in the building process by minimising the need for human data input and paperwork, as well as by automating operations such as quantity takeoff and scheduling [61].
- Project performance and quality: BIM allows construction professionals to examine and optimise the performance of construction projects in terms of energy efficiency, durability, and sustainability. Using BIM, construction professionals can find opportunities to improve the quality and performance of a project and make

informed decisions on the materials, systems, and procedures employed [106].

- Project management: BIM may improve project management by providing a single source of truth for project information and by allowing construction professionals to monitor project progress in real time. Using BIM, construction personnel can monitor the progress of the project, identify delays or problems, and take corrective action as necessary [175] [176] [171].
- Risk and cost management: By giving precise cost and risk estimates for building projects, BIM can improve cost and risk management. Using BIM, construction professionals can identify possible cost and risk drivers at an early stage of the project and establish strategies to reduce these costs and risks [177].
- Project documentation: BIM may assist in project documentation by providing a single source of truth for project information and empowering construction workers to develop and maintain accurate and current project records. Using BIM, construction professionals can eliminate the need for manual data input and documentation, as well as improve the quality and completeness of project records [178] [179].
- Quality and safety: BIM may assist in safety and quality by providing a single source of truth for project information and by allowing construction professionals to detect and solve possible safety and quality concerns early in the project's life cycle. Using BIM, construction experts can improve the safety and quality of the project, as well as reduce the probability of accidents and defects [180].

The construction industry's automation and digitalisation journey consists of several key stages. The adoption of BIM improves the construction process by facilitating improved communication, collaboration, and early resolution of issues, increasing general efficiency [99]. Next, the integration of robots, drones, Augmented reality (AR), 3D printing, and autonomous vehicles increases productivity and precision on construction sites, accelerating processes and reducing costs [181]. Emerging cloud-based project management tools enable data-driven decision making while minimising errors and misunderstandings by promoting communication and collaboration between project teams

[182]. The next stage emphasises the application of sensors and analytical tools for comprehensive data collection and analysis, providing valuable information for continuous process improvement [183]. At the same time, it is vital to invest in workforce training to enable professionals to master emerging technologies such as BIM and automation, thus maximising the technological potential of the sector [184]. Furthermore, the integration of blockchain, AI, and IoT is further improving construction operations. AI supports tasks such as project planning, while blockchain improves supply chain management and transaction transparency. IoT, through the provision of real-time data, improves decision-making and operational efficiency [185].

2.2.2 Distributed Ledger Technologies (DLT)

Distributed ledger technologies (DLT) is a term that is often used interchangeably with blockchain. Although blockchain is a leading type of DLT, it is important to view blockchain as a subset of DLT rather than a direct comparison. DLT operates on a distributed, peer-to-peer (P2P) network, eliminating the need for a centralised authority to mediate transactions. Blockchain, the technology that originally was the foundation of Bitcoin, has evolved into a secure and hack-resistant mechanism for processing digital transactions. Its structure involves transactions being grouped into blocks and confirmed by a P2P network using proof-of-work (PoW) consensus. However, alternative consensus mechanisms such as proof-of-stake (PoS) and proof-of-authority (PoA) are emerging, demonstrating the versatility of DLT [126].

A blockchain is a specific type of DLT characterised by its structure of interconnected sequential blocks. Originally developed as the basis for cryptocurrencies, blockchain technology has evolved to provide secure and immutable transaction processing. The main features of the blockchain are:

Decentralization: Transactions are verified by a network of nodes rather than a central authority, promoting trust and transparency among participants [186].

Immutability: Once data is recorded in a blockchain, it is nearly impossible to alter it. Each block contains a cryptographic hash of the previous block, forming a secure and tamper-proof chain [20].

Transparency: All participants in the network can view the transactions recorded on the blockchain, ensuring transparency and enabling real-time auditing [15].

Security: Blockchain employs cryptographic techniques and consensus mechanisms, such as proof-of-work (PoW) and proof-of-stake (PoS), to secure transactions and maintain the integrity of the ledger [21].

Smart contracts are self-executing agreements with the terms and conditions directly written into code and deployed on a blockchain. They automate and enforce contract terms without the need for intermediaries, providing several advantages:

Automation: Smart contracts execute automatically when predefined conditions are met, reducing the need for manual intervention and expediting processes [187].

Transparency: The terms and execution of smart contracts are visible on the blockchain, allowing all parties to verify and audit the contract's execution [188].

Security: The blockchain secures smart contracts, making them resistant to tampering. Once deployed, smart contracts are immutable and can only be altered with network consensus [189].

Efficiency: By automating contract execution, smart contracts streamline processes, lower costs, and reduce administrative overhead [190].

Flexibility: Smart contracts can be customized to accommodate various business rules and conditions, making them adaptable to different applications and industries [23].

DLT, blockchain, and smart contracts represent a transformative shift in digital technologies, offering enhanced security, transparency, and efficiency across a range of sectors. In the context of data security, blockchain's decentralised nature ensures the reliability of BIM data by addressing concerns about unauthorised access. Smart contracts further facilitate collaboration and differentiate it from traditional methods by automating rules and reducing disputes [191]. This integration represents a transformative change in the construction industry toward a more flexible, efficient, and transparent future [192]. More detailed information on the specific features, applications and challenges of blockchain technology is provided in the further sections.

2.2.3 Collaboration in Multi-disciplinary Construction Projects

Collaboration is an important part of the construction industry, especially when a large number of stakeholders and disciplines are involved in multidisciplinary projects. Effective collaboration can improve communication and coordination between stakeholders and disciplines, transparency and accountability, efficiency and productivity, and the quality and performance of a project [193]. However, collaboration can be challenging due to the complexity of construction projects, the diversity of stakeholders and disciplines, and the use of multiple digital technologies, tools and platforms, procedures and protocols, and other techniques. Therefore, construction professionals should adopt methods and methodologies that facilitate efficient collaboration in multidisciplinary projects [194].

The construction industry often suffers from a lack of cooperation between stakeholders, which hinders performance throughout the process. Improving collaboration can lead to increased efficiency throughout the building's life cycle [173]. BIM acts as a catalyst for data exchange, allowing disciplines to collaborate and share information more effectively [195]. Figure 2.6 shows a BIM project environment.

CAD software applications such as ArchiCAD and Revit incorporate intelligence to minimise modelling errors and technical deficiencies, as well as enforce regulatory constraints. These programs apply an object-oriented methodology and provide basic BIM capabilities [196]. Additional applications have been created to utilise the data inherent in BIM models for tasks such as model integration, system analysis, fault detection, and facilities management (FM). BIM is recognised as an IT-enabled strategy that facilitates design integrity, virtual modelling, simulations, and access to decentralised building data [197]. BIM servers such as EDMmodelServerTM enhance BIM capabilities by facilitating multidisciplinary collaboration and providing a platform for direct data integration, storage, and sharing [198]. BIM servers function as collaboration plat-

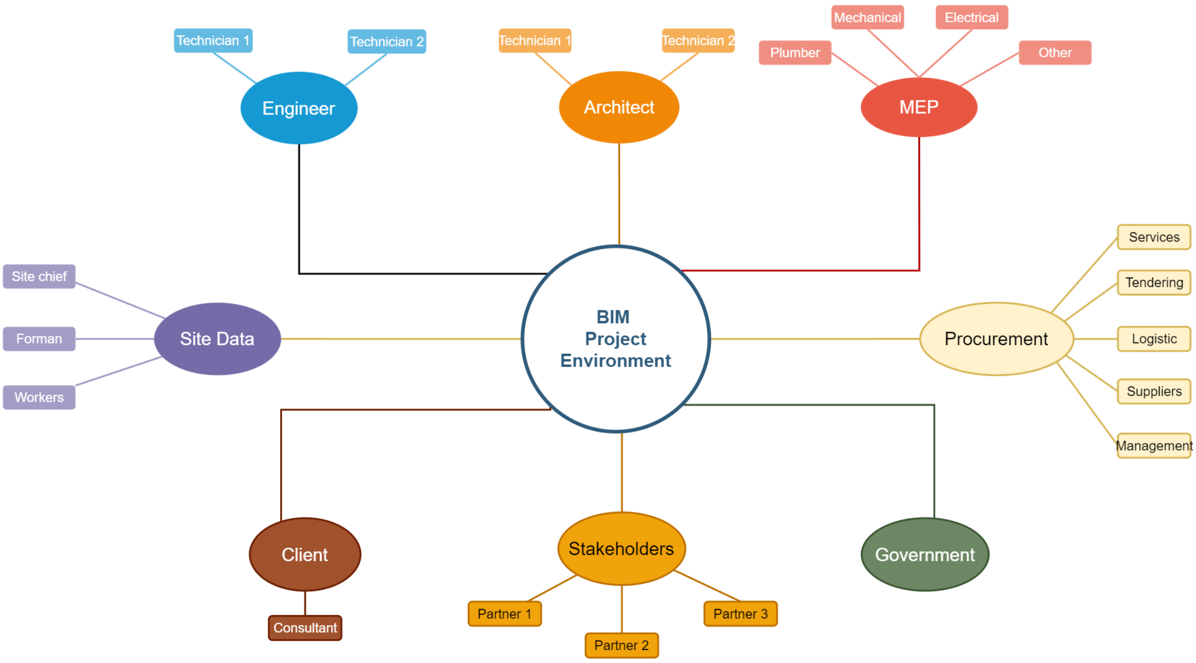


Figure 2.6: BIM project environment

forms that store building information and allow local programs to integrate, analyse, and exchange it [199]. The purpose of BIM servers is to facilitate communication and collaboration between design tools, analytical tools, facilities management tools, and document management systems (DMSs) throughout a building's life cycle [197]. BIM servers are intended to facilitate the integration and sharing of intelligently embedded 3D model data, while DMSs are primarily concerned with collaboration through the exchange of 2D documents and drawings [61].

Liu et al. [200] found that improving communication and cooperation between individuals can increase productivity and improve decision-making processes. Collaborative processes have been shown to reduce errors, encourage cooperation and minimise costs [99]. Collaboration and workflow management were examined as methods to improve team communication and productivity [201]. Collaborative decision-making processes within organisations have been found to benefit from improved collaboration, reduced costs, and simplified processes [202]. In construction and engineering, federated cloud systems enable the connection of multiple cloud platforms to facilitate collaboration between project stakeholders by facilitating data exchange, resource sharing, and improving communication and cooperation [173].

The integration of blockchain with BIM for building projects has the potential to transform the management of construction projects by facilitating more efficient and effective information sharing and stakeholder collaboration. However, the application of these technologies in the construction industry has not yet reached a sufficient level [152]. This thesis aims to address these challenges in the BIM environment by seeking to increase trust and collaboration between disciplines contributing to process efficiency by facilitating monitoring and ensuring data is recorded in a secure, transparent and immutable manner.

2.2.4 Construction Lifecycle with BIM and Blockchain

Based on the subject of collaboration discussed in the previous section, the integration of blockchain with BIM in construction projects arises as a transformative strategy. The aim is to facilitate and elevate the collaborative processes discussed above by using these technologies. This integration promises to create improvements in information sharing and stakeholder collaboration, ultimately increasing efficiency and effectiveness of construction project management.

Analysing the potential advantages and limitations resulting from blockchain and BIM, especially in the field of construction projects, serves as a fundamental step in the development and validation of effective solutions. This oriented research contributes to the emergence of new tools and methodologies specific to the construction industry aimed at improving collaboration, cost effectiveness, and general productivity [203]. Moreover, digitalisation has the potential to incentivise the development of BIM in applications where the identification and diagnosing of faults are needed. In addition, novel technologies can lead to increased productivity, decrease the probability of failure, shorten manufacturing schedules, and provide new market opportunities in the construction industry [204].

Blockchain's Role in Enhancing BIM Processes

Integrating blockchain with BIM improve the accuracy and reliability of construction project records by creating tamper-proof, accurate transaction logs, reducing the risk of data errors or inconsistencies [140] [64]. This combination can also enhance information exchange and collaboration among stakeholders through a decentralised platform that reduces the need for manual data entry, accelerating information sharing while ensuring integrity [152]. In addition, the integration of blockchain with BIM can enable a more optimised project management process by creating a secure common data environment that improves communication and collaboration between various stakeholders and disciplines [190].

Authenticity in BIM Data Through Blockchain

Stakeholder engagement for the mainstreaming of building technologies needs an integrated strategy to enhance collaboration between individuals, stakeholders and technology. BIM makes project data accessible to various users in the construction project at various stages, such as design and data management, simulations, and project scheduling [205]. One of the challenges of BIM is the identification of roles and responsibilities, and concerns include intellectual property protection, risk allocation, third-party safety and security, and the availability of technological intermediaries [197].

Integrating BIM with blockchain can make the verification and storage of physical, digital, and application resources more transparent. Blockchain uses a collaboratively determined validator to update a distributed ledger block by block. In construction projects, the blockchain consensus process selects a leader discipline to verify credentials and ensure that nodes accept the leader block as valid for inclusion in the blockchain [206]. Blockchain also prevents data and copyright tampering by disseminating and protecting verified information to all nodes [207]. In addition, blockchain's decentralisation provides a secure alternative for information storage, data processing, operation, and trust for data management in digital environments with high security standards. Although blockchain technology is being extensively studied in various sectors, its adoption in the construction industry is still in its early stages [208].

Tao et al. [209] introduce a confidentiality-minded framework (CMF), which is a privacy-oriented framework that leverages blockchain for data security. It has an access control mechanism that protects critical BIM data in the blockchain ledger and innovative design strategies for coordinated collaboration in the access-controlled network. New design methodologies are established in the CMF to aid design coordination within the access-controlled blockchain network. An illustrative design example has verified the practicality and performance of the proposed CMF with favourable latency and storage cost. In addition, the findings show that when project participants interact within the CMF, sensitive BIM data is successfully kept confidential. Xue, Fan, Lu & Weisheng [179] present a novel semantic differential processing (SDT) approach to minimise information redundancy with BIM and blockchain integration. Their approach manages BIM changes as SDT records and compiles them into a consensus instead of storing the entire BIM or signature code in blockchain. These findings suggest that blockchain integration can improve the traceability of data transactions, while ensuring accountable data sharing about the project among stakeholders.

Implementation of Blockchain in Life-cycle Stages

Given that blockchain has not yet completed its development, organisations should adopt blockchain for specific applications and only where this technology can provide tangible benefits. The RIBA Business Plan [210] is a recognised industrial process involving the various stages of a construction project. Table 2.2 shows a general process for integrating blockchain with BIM and how the process develops in relation to the steps in the RIBA Work Plan. This depiction of the BIM process is inspired by the RIBA work plan described in various comparative research papers and books. Starting from the preparatory stages, blockchain integration is demonstrated, including account creation, roles and responsibilities, and the progression of the process through various stages to ensure adoption in real applications.

Table 2.2: Step-by-step Blockchain adaptation process to BIM according to RIBA Work Plan

RIBA	BIM	BLOCKCHAIN
0- Strategic Definition.	-Business Case and Strategic Brief and other core project requirements. -Establishing a Project Program for the entire life cycle of the project.	-Getting general information about Blockchain and finding use cases regarding a project. -Advise clients on the purposes of Blockchain considering advantages and disadvantages. -Trying to find an answer to those questions: -> Does the project need Blockchain? -> If it is needed, which type of Blockchain can be more suitable? (Public, Private, or Consortium, etc.)
1- Preparation	-Advise BIM clients, taking into account advantages and risks. -Advise clients on the designer's requirements and integrity and scope of integrated service, including the appointment of a BIM model manager. -Define long-term responsibilities in the project construction process. -Define inputs and outputs of BIM and post-occupancy's scope evaluation. Identify the scope of BIM surveys and investigate reports.	-Identify the impact of BIM and Blockchain integration on the project. -Define which Blockchain-based technology will be used in the project? (Ethereum, Hyperledger, etc.) -Prepare a Blockchain-based system considering project requirements. -Define general responsibilities and duties regarding the questions: -> Who will create Smart Contract and control the Blockchain? -> Who will coordinate BIM work packages? Prepare the execution plan.
2- 3- 4- Design	-BIM pre-start meeting with the stakeholders for the project. -Evaluation of strategic analysis options for the initial model sharing with the design team. -Define the major design elements (such as prefabricated components), build parametric structures at the concept-level for all the main elements. -Facilitating access to BIM data for the entire design team. -Provide data sharing and integration for design coordination and detailed analysis involving data links between models. -For environmental performance and region analysis utilize BIM data. -Facilitating project planning information from the main design to the client. -Assessing for the 4D and/or 5D models.	-Monitoring and managing BIM and Blockchain workflow. -Recording and timestamping of BIM model sharing with the design team and all types of project documents. -Create Smart Contract with the Design team and others. -Preparing and planning BIM Work Packages in relation to the project specification. (see Chapter 4)
5- Construction	-Export BIM data and Offsite manufacturing and onsite Construction according to the Construction Programme. -Enable data sharing for those who are participating in the project. -Integrating and analyzing a detailed model. -Enable BIM model's accessibility to Contractor(s) and Subcontractor(s). -Review with the Contractor the construction sequence (4D). -Agree timing and scope of "Soft Landings". -Coordinate and release of "End of construction" BIM record model data. -Use of 4D/5D BIM data for the purposes of project administration.	-Create Smart Contract with the Contractor and Subcontractors and those that are involved in the project. -Recording and tracing completed BIM work packages and associated transactions. -Controlling and checking BIM updates and transactions of BIM work Packages
6- Handover & Closeout	-Performing the necessary procedures for the handover of the building. -Conclusion of the construction contract and handover process. -Study of information on parametric objects contained within the data of the BIM model.	-Creating Smart Contract for handover and managing transactions. -Sending building documents to Blockchain to record and make an immutable data record.

Continued on next page

Table 2.2 – continued from previous page

RIBA	BIM	BLOCKCHAIN
7- In Use	-Undertake in Use services according to the Schedule of Services. -Feedback and maintain a relationship with the Client until the end of the building's life.	-Setting an auto-payment system for regular payment. -Creating Smart Contracts for payment services. -Insurance: Auto-payment can be set for regular payment. -Maintenance: Blockchain can be used for recording maintenance of the building for an immutable history and payment without third parties. -Energy: Blockchain along with artificial intelligence (AI) can identify consumer energy behavior and forecast energy demand (see Chapter 6)

2.2.5 Sustainability in Construction Projects

The construction sector is an important actor in the global economy, accounting for about 6% of the global GDP, and has significant implications on a global scale. Despite the collaborative efforts being made now around the world to promote sustainability in the construction sector, there is compelling evidence that these efforts should be amplified urgently to have a genuinely revolutionary impact on the construction industry [211].

Sustainability in construction, which includes environmental measures such as material recycling, water conservation, and energy efficiency, has been extensively addressed in the literature [212] [213]. The use of blockchain with smart contracts can improve procurement strategies, especially when managing risks associated with supply disruptions [214]. This technology promotes a trusted trading mechanism that allows stakeholders to transact without intermediaries, thus streamlining authentication processes and reducing costs [215].

There are several potential benefits of using a blockchain to support supply chains, including increased trust, transparency and accountability between different entities. Process automation is enabled through the use of smart contracts, including real-time tracking and tracing of assets. Blockchain certification is proof of identity, authenticity or conformity; there are no data silos or centralised points of failure. Blockchain improves product safety and compliance with compliance standards [134]. A case study [161] explains how blockchain can benefit supply chains and enable circularity. However, these are mostly in the pilot phase.

Supply Chain Management

Blockchain technology has the potential to revolutionise the construction industry by focusing on supply chain technologies with a social dimension to improve environmental performance [212]. Environmental metrics such as greenhouse gas emissions, wastewater, electricity consumption, and the use of harmful substances can be effectively measured and controlled by implementing smart contracts with blockchain technologies [213] [214]. This is especially crucial in terms of reducing risks associated with supply chain disruptions and increasing reliability, provability, immutability, and transparency to counter environmental factors. Notable examples of blockchain applications in supply chains include Walmart's initiatives in China, where blockchain has demonstrated the potential to increase efficiency and accountability in the industry by significantly reducing the time required to track food sourcing [216] [217].

Blockchain is a transformative technology as the construction industry seeks innovative solutions to increase efficiency, reduce risks, and improve sustainability. By addressing environmental concerns, improving supply chain traceability, and promoting transparent transactions, blockchain has the potential to reshape traditional processes in the construction industry and become more sustainable and efficient.

2.2.6 Energy in the Built Environment

Many countries, including major carbon emitters such as Australia, Brazil, China, the European Union, Japan, South Korea, the United Kingdom and the United States, have committed to achieving carbon neutrality by 2050 or 2060. Given that buildings contribute significantly (37%) to global emissions, achieving net zero carbon performance in the built environment is a critical imperative [218]. Challenges such as the growing demand for building materials, increasing energy needs, and the lack of local targets pose barriers to carbon neutral endeavours [219].

To achieve net zero targets and decarbonise the built environment, both critical goals for sustainable development and "digital construction" success depend on integrating technology into construction processes, maximising resource efficiency, and improving overall project outcomes. In the context of modern construction projects, concerns have arisen around the rapid exchange of data, covering issues of data security, privacy, and accessibility [220] [221]. Blockchain technology is emerging as a solution to these concerns by providing a sophisticated platform for numerous construction-related transactions, offering unique features such as decentralisation and immutability that contribute to increased flexibility, transparency, and efficiency in construction processes [222]. As the built environment transforms to achieve sustainability goals, the adoption of blockchain addresses data security issues and provides the foundation for a more flexible and transparent construction ecosystem [223].

Blockchain for Energy Management in Buildings

The integration of blockchain technology with the current building energy management system (BEMS) provides a promising path to achieving improved energy efficiency and sustainability in the built environment. Recent studies [224] [225] [226] ave highlighted the possibility of using blockchain's decentralised and immutable ledger to record real-time data from BEMS sensors, including heating, ventilation, and air conditioning (HVAC) parameters in a secure manner. This method assures data accuracy and transparency, encouraging confidence in energy management efforts [227]. Deployed on the blockchain, smart contracts automate energy transactions and facilitate peer-to-peer energy trading, developing a more dynamic and efficient energy marketplace within the building ecosystem. By incorporating data from the HVAC system into the blockchain, smart contracts can autonomously control and monitor HVAC operations [228]. The combination of BEMS and blockchain, enabled by data oracles, provides real-time monitoring and predictive analytics for the future, allowing building operators to proactively adjust HVAC settings in response to changing energy demands. In addition, the integration enables peer-to-peer energy trading within the building or community, further increasing energy efficiency and cost savings. The literature highlights the potential transformative impact of integrating blockchain technology with

BEMS, including HVAC, towards sustainable and smart energy management strategies [229] [230].

The integration of blockchain technology with sensors, IoT devices, AI and machine learning (ML) algorithms for the development of autonomous and adaptive energy management systems is currently under investigation [231] [232] [221]. Blockchain-based energy management systems can adjust energy consumption using data from real-time sensors, implement demand response strategies, and manage energy distribution for improved efficiency and sustainability [185]. To maintain machine learning models in these systems, continuous data input from IoT devices is crucial for model adaptation, and regular retraining ensures accuracy and responsiveness to changing conditions. Blockchain's secure, tamper-proof environment further increases the reliability of the data used in these models, promoting trust and reducing errors.

In an IoT ecosystem, everyday transactions involve direct digital transactions between smart devices and users. Blockchain technology ensures that these transactions are protected. Biswas and Muthukkumarsamy [233] designed a blockchain-based security framework for smart city data transfer using an Ethereum platform integrated with the BitTorrent protocol, supporting stability by ensuring consistent performance and fault tolerance, and scalability. and scalability. Meanwhile, blockchain combined with Eris, smart contracts, and two-factor authentication, as proposed by Wu [234], improves data privacy by detecting malicious IoT devices. Danzi et al. [235] presented a model detailing the data flow between IoT devices and blockchain networks, where devices synchronise with mining nodes to access updated block information. The intertwining of IoT and blockchain for construction sites enables a decentralised data management system that improves real-time monitoring, thus increasing efficiency, reducing costs, and promoting sustainable construction [236]. This reduces the inefficiencies observed in traditional construction due to insufficient real-time data and communication [237].

The adoption of new technologies in modern construction management ensures the efficient use of energy in projects. Key strategies include: integrating smart meters for accurate energy consumption data and forecasting [238], adjusting equipment operations during energy peak times [239], and using real-time monitoring to align construction energy demands with supplies [240]. Researchers and practitioners have become increasingly interested in the potential of blockchain to revolutionise energy management in buildings and smart communities in recent years. Using blockchain and sensors, researchers aim to develop autonomous and user-centric energy management systems that can adapt to the needs and preferences of individual building occupants [241] [242].

Another key advantage of using blockchain in buildings is the decentralisation of the system, which eliminates the need for a central authority to manage and secure data. This considerably reduces the risk of a single point of failure and enhances the overall security of the system. Furthermore, the transparency provided by blockchain ensures accountability and improves the general trust in the system because all stakeholders can view the actions taken by IoT devices [243]. Using blockchain, buildings can protect sensitive data, reduce the risk of a single point of failure, and enhance overall trust in the system [244].

Table 2.3 summarises the limitations of traditional energy management systems and the solutions proposed using blockchain. Lack of transparency, centralised control, concerns about data security, rigidity, and high operational costs are common problems with traditional systems.

As a result of the literature survey, some of the following opportunities in the construction industry have been itemised:

- Automation: Project automation, sensor implementation, AI, and smart contracts contribute to reducing the possibility of human error. Risk management for building projects can be supported by documenting and verifying coding with smart contracts [120]. Smart contracts can also automate the execution of work packages with task groups designed for automation (see Chapter 4), speeding up the process and reducing conflicts [245].

Table 2.3: Limitations of Traditional Energy Management System and Proposed Solutions with Blockchain

Traditional Energy Management system	Proposed Solutions with Blockchain
Lack of Transparency [246] [247] [248] [249]	- The utilization of smart meters and IoT devices for real-time data recording on the Blockchain. - Transparency and accountability are ensured through the accessibility of the Blockchain to all stakeholders. - Smart contracts can automate data verification and energy transactions for accuracy.
Centralized Control [13] [250]	- The utilization of Blockchain technology facilitates the implementation of a decentralized technique for energy management, wherein transactions are conducted directly between peers. - Smart contracts facilitate the implementation of automated and transparent energy trading among participants. - Without a centralised authority, energy distribution can be more efficient and equitable as long as transparent and consensus-based rules are in place.
Data Security Concerns [251] [252] [253]	- The utilization of cryptographic techniques is employed by Blockchain to ensure the security of energy consumption data. - The Blockchain's consensus mechanism ensures that data is immutable and resistant to manipulations. - To avoid unauthorized access and data manipulation, participants must agree on the validity of the data.
Inflexibility [231] [254] [255]	- Smart contracts on the Blockchain can be programmed to adapt to changing energy demands. - Data analysis using AI and ML algorithms can dynamically optimize energy consumption. - Automated adjustments based on real-time data help ensure efficient energy usage.
High Operating Costs [256] [257]	- Energy efficiency interventions through Blockchain-based systems can reduce operational expenses. - Smart contracts enable automated and streamlined energy transfers to reduce costs. - Transaction costs and administrative costs are decreased when intermediaries are eliminated.

- Proof of ownership and provenance: Ownership, intellectual property rights, and legal protections can be recorded and clarified for collaborative BIM models for properties ranging from cars to buildings to bonds, resulting in increased trust between parties[137]. Demonstrability is also improved with real-time supply chain tracking of products and services, while logistics processes can be simplified, enabling more comprehensive and timely reviews [245].

- Monitoring and recording: Immutability improves the accountability and real-time monitoring of resources in construction projects and supply chains by providing transparency to contracts and transactions [258]. Increased coordination and accountability can improve project control in an open construction project and deliver more automated and accelerating workflows [137].
- Efficiency: Automating operations enables resource reallocation, minimisation of management costs, and time efficiency [137]. A construction process can be managed more efficiently because the customers have more control over project duration, cost, and scope with BIM. Processes become more intuitive and simplified [162], enabling stakeholders access to the ledger, which is particularly useful in design and planning [259].
- Decentralisation: Smart contracts can automate operations and transactions, while blockchain reduces the need for third parties while enabling transaction execution. A contract and its initiator agent do not need to communicate with each other after the blockchain application is initiated and deployed [260]. A higher level of automation can be achieved around the use of algorithms and rules to enable smart contract self-execution, self-enforcement, self-validation, and self-limitation.
- Digitalisation: Stakeholders are given a virtual copy of an existing physical artefact during its life cycle stages. All transactions in the BIM life cycle can be recorded in real-time as a reliable resource for determining roles and responsibilities [162]. Data can be exchanged within a wide range of disciplines, increasing communication and confidence between stakeholders [261], ensuring a higher order of automation and security around data model operations.

However, there are some limitations to how widely blockchain can be used in the construction industry. In terms of regulation, the pace of technological advancement is outpacing the establishment of standards, which delays maturity [31]. In particular, blockchain's open ledger system poses privacy risks, especially in permissionless architectures [31] [262] [263]. Other challenges include technical barriers [264], lack of standards [265], and limited scalability [266]. The hesitations towards blockchain adoption are often attributed to lack of knowledge and perceived risks [267] [268] [269]. Other challenges are described in the following sections.

2.3 Next Generation Construction Technologies

The construction industry has traditionally been slow to integrate new technology and has been characterised by inefficient processes, high levels of waste, and low productivity. In recent years, however, the need for digitalisation and automation to improve efficiency, reduce costs, and increase productivity in the construction industry has been increasingly recognised. Some developments, primarily BIM, are seen to need improvement [270]. The adoption of technology in construction projects can range from basic equipment and tools to advanced software and automation systems [78]. One of the key drivers for technology adoption in construction is the need to overcome ongoing challenges, such as cost overruns, project delays, and safety concerns [74]. The construction industry is naturally complex and the use of new technologies can support streamlined processes, reduce errors and increase efficiency [271]. Likewise, new technologies can provide insights and data that can be used to optimise project schedules and improve decision-making [272].

The technologies that are most frequently associated with the construction industry recently include blockchain, AI, ML, quantum computing, IoT, cloud computing, and robotics. These technologies offer various benefits that can assist construction companies to remain competitive and meet the changing demands of their clients [56]. Other technologies being adopted in the construction industry include 3D printing, drones, augmented reality, and virtual reality. These technologies can be utilised for various tasks, such as site surveying, construction planning, and quality control. The adoption of technology in construction projects can also lead to increased safety because it can be used to monitor and control construction site conditions in real time [52].

2.3.1 Blockchain Technology

Blockchain, a decentralised ledger technology known for its strong security and data integrity, operates without a central authority and enables all network participants to maintain identical, real-time copies of the ledger [273]. The decentralised architecture of blockchain, supported by cryptographic techniques, ensures transaction confidentiality and immutability while maintaining user anonymity through pseudonyms [274]. Blockchain combines a distributed database, consensus algorithms and advanced cryptography to prevent unauthorised changes and make it adaptable for applications in finance, supply chain management and beyond [142][146] [153]. The basic components of the blockchain are summarised in Table 2.4.

Table 2.4: Components of Blockchain

Component	Description
Distributed Ledger	A digital ledger that records transactions across a network of computers, which can be accessed and updated by anyone with permission.
Cryptography	The practice of securing communication from third parties by converting plaintext to ciphertext.
Public Key Cryptography	Also known as asymmetric cryptography, uses two keys to encrypt and decrypt data, namely a public key that is available to everyone and a private key that is kept secret.
Hash Function	A mathematical function that converts input data into a fixed-size output, typically used for verifying the integrity of data.
Consensus Mechanism	A process for agreeing on a single version of the truth in a distributed network, such as Proof of Work (PoW), Proof of Stake (PoS), and others.

Continued on next page

Table 2.4 – continued from previous page

Component	Description
Smart Contracts	Self-executing contracts with the terms of the agreement directly written into code, which can automate the execution of complex transactions.
Nodes	A computer or device in a blockchain network that participates in the verification and validation of transactions.
Mining	The process of adding new blocks to a blockchain by solving complex mathematical puzzles using computational power.
Wallets	Software used for storing public and private keys, addresses, and digital assets.
Transactions	An interaction between two entities involving the transfer of digital assets or activities involved in digital assets, which is recorded in a block.

On the blockchain, any computer owner can verify transactions and work as a miner. Miners use a mathematical problem solving method called mining to create new blocks, eliminating the need for third-party verification, such as traditional banks. The PoW mining technique, which involves multiple computers solving complex puzzles, ensures the security and integrity of the system with alternatives such as PoS offering similar functionality [275]. This decentralised network maintains transaction verification and history, ensuring redundancy and preventing tampering. Unlike traditional systems such as online banking where a centralised authority monitors transactions, blockchain relies on a network of nodes, enhancing reliability and security by distributing transaction history across multiple nodes and allowing redundancy in case of node failures or incorrect data transmission [276].

Blockchain introduces self-executing contracts, called Smart contracts, which are computer programs stored on a blockchain network that automatically execute the terms of an agreement between two or more parties. These contracts provide transparency and compliance by embedding the terms of the agreement in immutable code. The development and implementation of such contracts requires specialised tools. Influenced by programming languages such as Python, C++ and JavaScript, Solidity is Ethereum's proprietary language for smart contract development [277]. Using contract-orientated programming, Solidity enables developers to include both data and logic in contracts, similar to classes in traditional object-oriented paradigms. The Remix Integrated Development Environment (IDE) provides a platform for coding, testing, and deploying smart contracts within the Ethereum framework. It facilitates the conversion of high-level Solidity code into Ethereum virtual machine (EVM) bytecode, which is crucial for execution on the blockchain [278]. Additionally, Metamask acts as a vital hyperlink between web browsers and the Ethereum blockchain, while Ganache provides a secure environment for simulating the Ethereum network during risk-free contract testing.

Before a smart contract is placed on Ethereum's mainnet, it undergoes extensive testing on testnets that follow unified standards for consistency and reliability. Ethereum provides several testnets, including Ropsten, Rinkeby, Görli, and Kovan, which is known for its stability, spam resistance, and regular block schedules due to its Proof of Authority (PoA) consensus model. Once the smart contract is placed on one of the test networks such as Kovan, the contract's behaviour is monitored and metrics such as transaction success rates, gas usage and state changes are evaluated. This methodical approach ensures that the contract has reliability, security, and deterministic execution characteristics when transitioning to the main network. When initiating a transaction, the individual signs it with their private key and submits it to a timestamp server for approval. Multiple transactions are aggregated into a block, cryptographically hashed, considering all prior blocks. This process creates an immutable record of all transactions, safeguarding against fraud and verifying each transaction using the owner's private key [279] [280].

Blockchain mining creates a genesis block, adds transactions to blocks within size limits, and uses the SHA-256 algorithm to generate a hash with a specific nonce. Miners compete to find a hash that meets criteria such as leading zeros, through PoW, earning Bitcoin rewards with a 21 million limit, halving every 210,000 blocks, shifting from coin rewards to transaction fees once all bitcoins are generated, maintaining scarcity and value [20] [119] [281].

2.3.1.1 Smart Contracts

The concept of smart contracts was introduced in 1994, defining them as computerised transaction protocols that execute the terms of a contract. However, the introduction of blockchain technology has made it feasible to create smart contracts in a safe and decentralised way, removing the need for middlemen and giving more accountability and transparency. The purpose of smart contracts is to automate the execution of legal agreements, such as the transfer of assets, payment processing, and the performance of contractual obligations, and to ensure that these agreements are executed in a tamper proof and irreversible manner [187].

Smart contracts have several potential uses in many areas, including banking, real estate, healthcare [282], finance, and supply chain management [141]. In the finance sector, for example, smart contracts can be used to automate the settlement of financial instruments such as stocks, bonds, and derivatives and to facilitate the development of new financial products and services [283]. In the real estate market, smart contracts can be used to automate the transfer of property titles, simplify the administration of property rents, and eliminate the need for intermediaries such as real estate agents and lawyers [284]. Smart contracts may be used in healthcare to automate the maintenance of medical records and guarantee the secure transfer of patient data. Medical records, diagnoses, treatments, prescriptions, allergies, and other health information are usually included. Healthcare requires secure and efficient data management and transfer to provide effective care while protecting patient privacy and data security. These healthcare processes can be automated and secured with smart contracts [282].

A translation between a traditional contract and a smart contract with subsequent transformation details is presented in Figure 2.7. This shows an overview of how smart contracts operate in a blockchain and identifies (i) terms and conditions specification,

(ii) coding under the determined condition in blockchain, (iii) conditions are met and the smart contract executes itself, (iv) outcomes are recorded in the blockchain, and (v) authorities and users can analyse events. To create a smart contract, the parties must first define the relevant objectives for each party and the parties must agree on the expected outcomes. Collaboration parties (disciplines) will adjust the parameters and requirements that must be met for a transaction to occur.

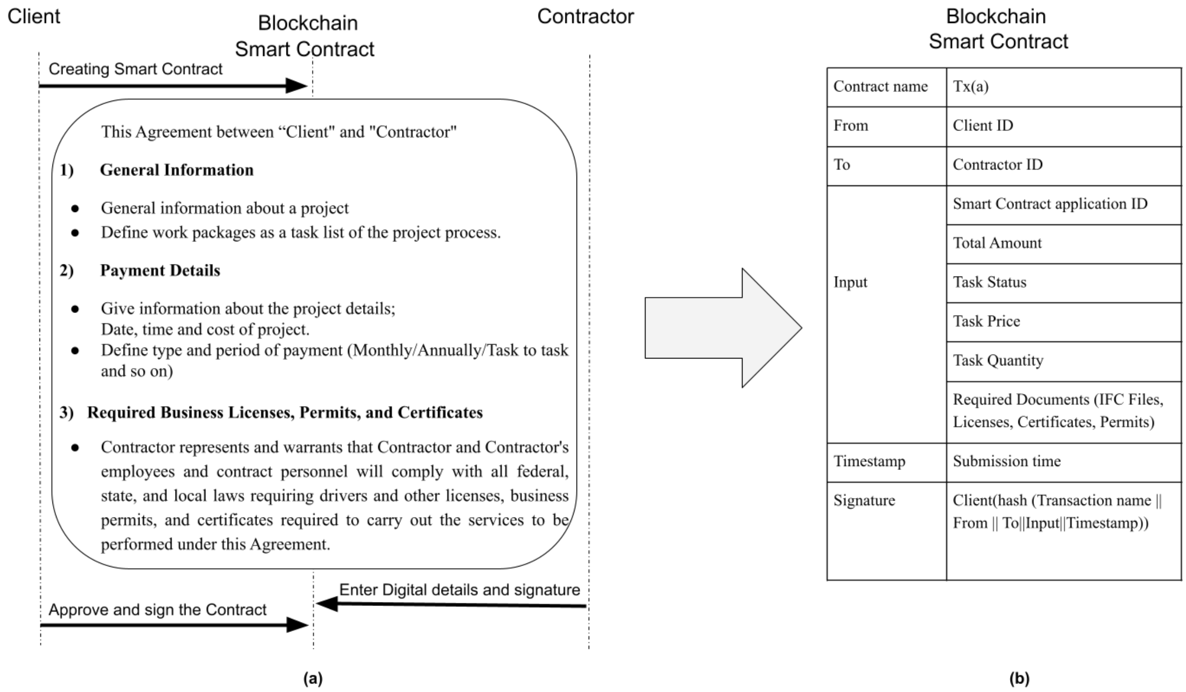


Figure 2.7: Example of a) traditional contract type and b) smart contract type [285]

All specifications and contract clauses are then written with computer logic and coded in a programmatic way. The smart contract will then be sent to the blockchain and will be executed on its own when specific criteria are activated. Users must use external owner accounts to launch a smart contract to perform a transaction with a contract account. This account is authenticated with the private key of the initiator and forwarded in the blockchain to other nodes. Other users may use the created public key to verify the validity of the transaction to ensure that the initiator is the entity that has activated the transaction [286]. When a majority consensus is reached, the transaction will be added to the ledger, the smart contract will be executed, and the results will be recorded. As the status of the blockchain changes over time, it is modified on all nodes of the network, and the outcomes cannot be altered. Due to the computational resources needed to manage the proof-of-business framework, any transaction that causes a change of status in the Ethereum blockchain requires a transaction fee. The transaction launcher pays in Ethers, which are part of Ethereum's local value network.

2.3.1.2 Blockchain Types and Characteristics

In general, there are three main types of blockchain (i) public, (ii) private, and (iii) consortium, where each type is suitable for a specific use case [287]. Known for its transparency and decentralised nature, the public blockchain promotes resistance to censorship and universal accessibility by allowing anyone to access and observe the transaction history [288]. In contrast, the private blockchain offers permissioned transactions that increase security by requiring the consent of the participants and the verification of the central organisation [289, 290]. It is similar to a multi-storey private building where permission is required to enter, but once inside, participants can move around freely. Finally, the consortium blockchain strikes a balance by involving a community of organisations in network management, offering the collaborative advantages of public and private blockchains [291]. This model can be particularly efficient for a variety of businesses, with participation ranging from central banks to governments, creating a dynamic mix of accessibility and control. The types of blockchain are first presented in Table 2.5 and are then described.

Hybrid blockchains combine the features of public and private blockchains, providing both transparency and privacy, and are ideal for applications that require both security and scalability, such as supply chain management [292] [267]. Federated blockchains are permissioned networks maintained by multiple organisations, offering the benefits of decentralisation with the control of private blockchains, which are widely used in sectors such as banking and healthcare [293]. Sidechains are parallel blockchains connected to a primary blockchain, allowing assets to be transferred between the two, providing additional scalability and flexibility [294]. Sharding increases the scalability of the blockchain by dividing the network into smaller subnets or shards, each processing a portion of the transactions and addressing the scalability challenges of traditional blockchains [295]. Hashgraph, a DLT, uses a directed acyclic graph (DAG) for secure and highly efficient consensus suitable for high performance applications [295].

Table 2.5: Type of Blockchain

Blockchain Type	Characteristics	Permissioned/Unpermissioned
Public Blockchain	Anyone can join the network and participate in the consensus process. Transactions are transparent and visible to everyone. Example: Bitcoin	Unpermissioned
Private Blockchain	Permissioned network where only authorized nodes can participate in the consensus process. Transactions are private and not visible to everyone. Example: Hyperledger Fabric	Permissioned
Consortium Blockchain	A hybrid model where a group of organizations join together to form a permissioned network. Consensus is achieved through a predefined group of nodes. Example: R3 Corda	Permissioned
Hybrid Blockchain	A combination of public and private blockchains. It offers the benefits of both public and private blockchains. Example: Dragonchain	Both (can be permissioned or unpermissioned)
Federated Blockchain	A group of organizations or institutions control the consensus process. It's a permissioned network where nodes are pre-selected and known to each other. Example: Ripple	Permissioned
Sidechain	A separate blockchain connected to the main blockchain through a two-way peg. Sidechains enable scalability and the development of new use cases. Example: Rootstock (RSK)	Both (can be permissioned or unpermissioned)
Sharding Blockchain	A type of blockchain that partitions the network into smaller groups (shards) to process transactions in parallel, improving scalability. Example: Zilliqa	Permissionless
Hashgraph	A consensus algorithm that uses virtual voting to achieve consensus. It claims to be faster, fairer, and more secure than blockchain. Example: Hedera Hashgraph	Permissioned

2.3.1.3 Consensus Mechanism

An integral part of blockchain technology is to select an entity to publish the next block in the chain, whose efforts are rewarded in cryptocurrency. This competition between nodes requires consensus mechanisms that allow users with a lack of trust to cooperate harmoniously. To achieve this, various consensus methods such as PoW [296], PoS [297], PoA [298], Proof of Elapsed Time (PoET) [297] are used, each with different advantages and disadvantages (as summarised in Table 2.6). The consensus process involves solving cryptographic challenges, which is a resource-intensive task, followed by network verification and then adding blocks to blockchain.

Table 2.6: Consensus of Blockchain and its Advantages and Disadvantages

Consensus Mechanism	Description	Advantages	Disadvantages
Proof of Work (PoW)	A mining process that requires nodes to solve complex cryptographic puzzles to validate transactions and add blocks to the chain.	Secure, decentralized, resistant to tampering, incentivizes miners.	High energy consumption, slow transaction times, vulnerable to 51% attacks.
Proof of Stake (PoS)	A consensus mechanism that determines the right to add blocks based on the node's stake or investment in the network.	More energy-efficient, faster transaction times, less vulnerable to 51% attacks, more scalable.	Potentially less secure than PoW, less decentralized, can lead to centralization of power.
Proof of Authority (PoA)	A consensus mechanism that relies on a set of pre-approved validators to validate transactions and add blocks to the chain.	Faster transaction times, more energy-efficient, more scalable.	Less decentralized, more susceptible to censorship, validators can become a central point of failure.
Proof of Elapsed Time (PoET)	Nodes are randomly selected to validate transactions and add blocks based on a randomly assigned wait time.	Low energy consumption, secure, efficient.	Limited scalability.

Continued on next page

Table 2.6 – continued from previous page

Consensus Mechanism	Description	Advantages	Disadvantages
Delegated Proof of Stake (DPoS)	Similar to PoS, but instead of nodes being selected randomly to validate transactions, users can vote for delegates to validate transactions on their behalf.	More democratic, scalable, faster transaction times, more energy-efficient.	Potential centralization of power among the delegates, less secure than PoW.
Practical Byzantine Fault Tolerance (PBFT)	A consensus mechanism that requires nodes to reach a consensus on transactions through a multi-step process that involves sending and verifying messages.	Fast transaction times, energy-efficient, fault-tolerant, scalable.	Requires a fixed number of nodes, less decentralized, can be vulnerable to attacks if more than a third of the nodes are compromised.
Federated Byzantine Agreement (FBA)	A group of trusted nodes work together to reach consensus on transactions and add them to the chain.	Highly scalable, low energy consumption, fast.	Centralized, less decentralized.
Directed Acyclic Graph (DAG)	Each transaction is validated by referencing previous transactions, allowing multiple transactions to be validated simultaneously.	Highly scalable, fast.	Less proven, vulnerable to certain types of attacks.
Proof of Space-Time (PoST)	Nodes validate transactions and add blocks to the chain based on their storage capacity and time used to mine the block.	Energy-efficient, low resource consumption.	Limited adoption, less proven.

These mechanisms are tailored to different types and use cases of blockchain networks. For example, PoW ensures consistent block generation but has been criticised for its energy consumption, while PoS prioritises energy efficiency and security against attacks [296]. PoA is suitable for reliable private blockchains, PoET increases scalability but requires reliable scheduling resources [298], DPoS brings democracy but can centralise power [245], Practical Byzantine Fault Tolerance (PBFT) offers speed and efficiency for permissioned blockchains but is vulnerable if many nodes are compromised [245], Federated Byzantine Agreement (FBA) combines the principles of PBFT and PoS [299], DAG increases scalability in a non-linear manner but is susceptible to doublespending attacks [300], and Proof of Space-Time (PoST) makes efficient use of storage and time, especially compared to PoW [301].

2.3.2 Challenges of BIM and Blockchain

The adoption of blockchain and BIM in the construction industry faces several challenges and limitations. These include:

Lack of guidelines and interoperability: The lack of guidelines and interoperability between blockchain and BIM impedes data transfer and access in the construction industry's multi-working environment [13].

Transformation of project management: The implementation of blockchain and BIM technologies may require a transformation in the way construction projects are managed, as well as the roles and responsibilities of various stakeholders [99].

Interdisciplinary collaboration and security concerns: Blockchain and BIM adoption in construction requires interdisciplinary collaboration and addressing security and privacy concerns, making their implementation even more complex [64].

Although blockchain can provide a secure and transparent platform for information exchange, it is important to protect sensitive or confidential data. Similarly, BIM can serve as a centralised repository of project information, which highlights the importance of regulating access and ensuring data confidentiality [164]. To overcome these challenges, realistic methods for combining blockchain and BIM in construction projects need to be developed and validated. This involves creating new frameworks, tools, and techniques for organising and analysing construction data. Furthermore, the impact of these technologies on various dimensions of the construction industry, such as efficiency, quality, safety, cost reduction, and collaboration, should be thoroughly studied [302].

Research on blockchain adoption in construction has identified several limitations, including the following:

Regulatory and standardisation challenges: Due to the rapid pace of technological advancements, regulations and standards are struggling to keep pace, resulting in a lengthy process for the establishment of adequate guidelines [31].

Scalability and privacy concerns: In the collaborative environment of permissionless blockchain architectures, where all participants have access to the ledger, privacy violations can occur as transaction histories become visible to all [31] [262] [263]. Furthermore, the energy consumption of blockchain networks such as Ethereum raises environmental concerns and could hinder progress towards achieving net zero targets [303] [304].

Lack of standards and interoperability: The lack of standards in blockchain can lead to interoperability issues between different blockchain networks and disciplines, limiting widespread adoption [305].

Regulatory difficulties are due to the special nature of blockchain development, and some countries impose restrictions on its implementation [306] [307]. As blockchain networks grow, scalability issues arise, and current technology is falling behind traditional financial systems in transaction processing capacity [308]. The volatility of blockchain, especially cryptocurrencies, is affected by market sentiment, regulatory changes, and technological advancements [309].

2.4 Summary and Discussion

The opening of this chapter presented the relationship between emerging technologies and the construction industry, with a special emphasis on the transformative potential of blockchain technology. As the construction industry seeks innovative solutions to challenges related to transparency, efficiency, and security, blockchain offers a paradigm shift that could redefine traditional operational frameworks.

The literature survey shows that some papers review blockchain and subsequent applications in the construction industry [34] [164] [310] [311] by presenting a system that facilitates financial transactions using smart contracts by coding the costs charged, benefits, and cost savings of integrated project delivery (IPD) projects [312]. The solution is designed and proposed to address challenges such as data security and authorisation management in the use of central BIM work processes [31] [20]. Other researchers have used a simulated setup activity to validate the conceptual relationships provided [305] in the proposed framework, which incorporates emerging information technologies such as cybersecurity and blockchain characteristics into a typical university BIM curriculum [180]. Furthermore, the potential cost savings of a real estate firm adopting blockchain have been studied [313] and a multidimensional structure for the implementation of distributed ledger technology (DLT) in the construction industry has been proposed [162]. Moreover, the emergence of blockchain is demonstrated by highlighting the adoption and progress of construction firms using this technology [314], examining the conceptual basis for the design of an automated payment system, and evaluating the role of smart contracts in allowing cash flow to be efficiently and autonomously conditioned on the status of product flow [188].

The implementation of blockchain technology in the construction industry has shown that it can enhance end-to-end design and construction process process efficiency [127] and data flow [315]. The primary advantage of blockchain is its ability to provide an advanced solution to the trust problem by providing a permanent [316], immutable [317]. and reliable [318] network that is capable of removing intermediaries [319] and automating processes due to its prominent decentralisation [143], accountability [320], and consistency characteristics [321]. Researchers have also discovered that by connecting the BIM work process with blockchain, change tracking [322] and data ownership [148] may be achieved. In addition, research in the literature has revealed that blockchain can execute and release transactions when conditions are met [323] [64], and encourage a collaborative decentralised building environment [119], increasing both the level of traceability [203] and the monitoring [324] and management in real time [122] [154]. In addition, blockchain can overcome the challenges of file redundancy [156] by creating a secure file storage system to ensure accountability [325], transparency [144], and trust [149] by providing a single source of truth [118].

Despite the general knowledge of the blockchain, many companies have not yet been able to find ways to integrate it into the industry thoroughly. Businesses are showing particular interest in blockchain, but real adoption is lagging. Gartner estimates that blockchain will generate more than 3 trillion dollars in annual commercial value by 2030 while 10 % to 20 % of the global economic infrastructure will operate in blockchain-based systems by 2030 [326]. Rafati Niya et al. [327] have argued that peer-to-peer buying and leasing smart contract-based applications can meet the functional and legal requirements of automatic purchases and lease agreements using Ethereum on blockchain.

This literature review concludes by exploring the challenges of BIM and blockchain. This chapter shows how blockchain and digital tools are embedded in the complex process of a construction project.

Next Chapter: Methodology

The next chapter examines the methodology adopted for this research, emphasising a mixed method approach within a pragmatic philosophical framework. It outlines the scope of the study with a particular focus on the applications of blockchain technology in the construction industry. In addition, the chapter provides insights from case studies and practical scenarios that demonstrate the real-world implications of blockchain integration. The chapter also explores how blockchain can be utilised throughout the RIBA Work Plan, providing a detailed approach to tackling issues throughout the construction project lifecycle.

CHAPTER3

Methodology

This chapter provides an overview of the literature review and related work concerning the application of blockchain technology in the construction industry including a road map for the research undertaken in this thesis. It outlines the methodological approach and key stages necessary to achieve the research objectives, presenting insights from case studies and practical scenarios that illustrate the implications of blockchain integration and improve understanding of its applications. In addition, this chapter demonstrates the utilisation of blockchain throughout the RIBA Work Plan process, offering an approach to addressing key issues throughout the construction project life cycle.

3.1 Research Methodology

Existing literature highlights some of the key limitations in the current use of BIM technologies, particularly with regard to integration challenges and interoperability constraints. Nawari [328] highlights the need for increased transparency and accountability in the management of BIM data, indicating how these issues hinder effective collaboration in construction projects. One of the prominent challenges in BIM is the clarity of roles and responsibilities, with concerns about intellectual property protection, risk allocation and safety being critical barriers [329]. In addition, popular platforms such as Autodesk Revit and ArchiCAD, despite their widespread adoption, expose BIM data to risks of unauthorised modification, which can damage trust between stakeholders and disrupt project coordination [330]. Recent research has proposed blockchain as a promising solution to these challenges.

The integration of blockchain technology in construction offers significant improvements over traditional methods. Traditional construction suffers from limited transparency, leading to delays and disputes due to incomplete or inaccurate information [34] [117]. Blockchain enhances transparency with immutable data records, allowing all stakeholders to access and verify information, thus reducing disputes and accelerating decision-making [120] [122].

While traditional project management is centralized and prone to errors and delays, blockchain's smart contracts enable decentralized decision-making, improving accuracy and speed [31] [127]. Communication and collaboration often suffer in traditional methods due to poor information sharing [13]. Blockchain provides a secure, shared platform for better coordination and reduced misunderstandings [156]. It also enhances monitoring of sustainability efforts, ensuring accurate tracking and compliance, which benefits reputation [161]. Lastly, blockchain improves supply chain transparency and traceability, allowing better material tracking and reducing errors [142] [145].

Building on the identified gaps in the literature and addressing the complexities of integrating blockchain and BIM in construction, the research onion structure developed by Saunders et al. [331] is adopted to develop the research methodology seen in Figure 3.1. The research onion is an organised and layered strategy that highlights the essential processes required to create a comprehensive research methodology.

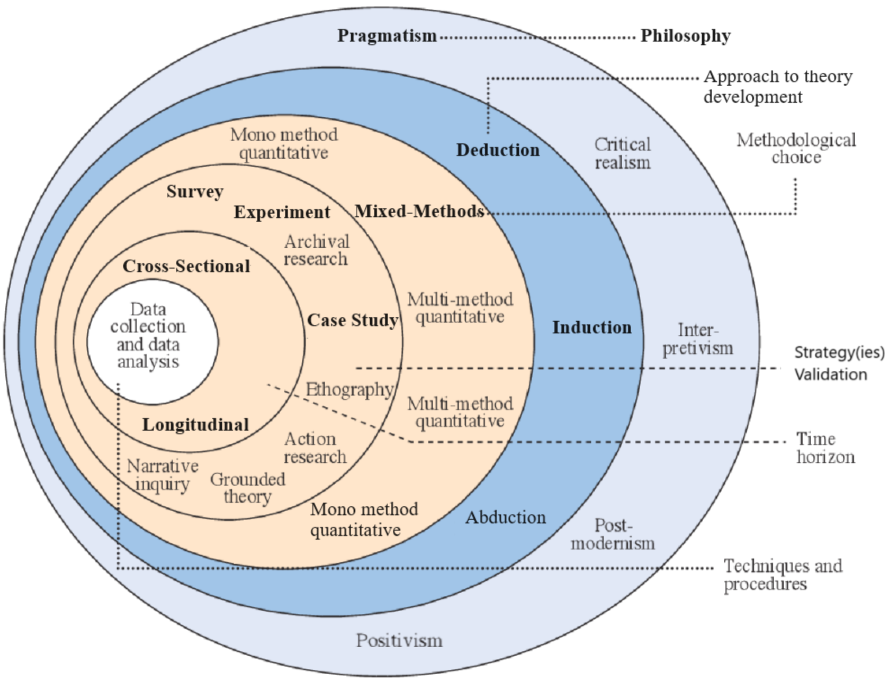


Figure 3.1: Saunders' Research Onion concept[331]

The research onion, a metaphorical representation of the research process, guides us through the layers that cover philosophy, approach, strategy, choices, time horizon, techniques, and procedures. This research utilised a mixed methods approach including case studies, practical application and a detailed literature review to achieve a comprehensive understanding. This methodology is in accordance with developing a new model through the application of innovative technology. Table 3.1 presents the key features of the research within the framework of Saunders' research onion.

Table 3.1: Characteristics of the research within the Saunders' research onion concept

Layer	Aspect	Characteristics in the Research
Philosophy	Pragmatism	Emphasis on practical outcomes and solutions, allowing flexibility
Approach	Mixed-Methods	Combination of Quantitative and Qualitative Methods
Strategy (Validation)	Problem-Solving	Construction of a framework, development of a road map, and application to real-world issues
Choices	Flexibility	Various methods employed, including literature review, framework development, case studies, experts knowledge (questionnaires), and impact calculation
Time Horizon	Flexible	Combination of cross-sectional (literature review) and potentially longitudinal (case studies/questionnaires) elements
Techniques	Eclectic	Utilisation of various techniques such as literature analysis, framework development, case studies, questionnaires, and impact calculation
Procedures	Iterative and Flexible	Adaptive and problem-solving approach, allowing for ongoing refinement and adjustment.

This adaptability provided that the research design remained responsive to emerging insights and challenges, allowing continuous refinement and adjustment.

3.2 Refined Scope of the Research

The literature analysis motivates the research by highlighting two main research gaps, as well as the shortcomings of the construction industry, which is analysed in Chapter

2: (i) a lack of research into the practical application of blockchain technology within the construction industry and (ii) a scarcity of research addressing blockchain-oriented solutions aimed at improving information exchange within construction projects.

- *Practical Application of Blockchain in Construction Projects:* While blockchain technology has shown applicability in various industries, its application in the construction industry is relatively unexplored. The existing literature lacks comprehensive research on how blockchain can be integrated into construction processes throughout the project life cycle. In particular, the absence of studies that examine the potential benefits and challenges of combining blockchain with BIM is noteworthy.
- *Blockchain-Driven Solutions for Information Exchange in Construction Projects:* Another important gap is the lack of research on blockchain-driven Solutions specifically designed for collaboration, transparency, trust, and data/information exchange in construction projects. The complexity of construction processes requires efficient and transparent communication between stakeholders. However, existing studies do not adequately address how blockchain can be leveraged to facilitate information exchange, enhance collaboration and mitigate risks throughout construction projects.

Addressing these research gaps is essential to open the transformative potential of blockchain technology in the construction industry. Investigations in these areas aimed to provide valuable insights into the feasibility, benefits, and challenges of integrating blockchain into construction practices. Furthermore, filling these gaps will enable the development of innovative blockchain-driven solutions adapted to the specific needs of the construction industry, ultimately increasing efficiency, collaboration, transparency, and sustainability in construction.

This investigation focuses on the theoretical and practical implications of BIM and blockchain in the construction industry based on the research questions. The objective of this investigation is to address this gap by focusing on four core research questions:

- Can BIM and blockchain be integrated and applied in construction life-cycle stages to improve safety, cost-efficiency and sustainability of construction projects?
- Can a blockchain-based BIM provenance model be developed to ensure traceability and transparency of BIM data in a construction project?
- How can blockchain technology be applied to energy management systems to improve operational performance and ensure sustainable building practices?
- What are the key benefits and drawbacks of the blockchain application for the construction industry?

To address these questions, this research attempts to examine current academic papers and empirical investigations in order to explain the variety of applications, benefits, and drawbacks involved in the adoption of blockchain. The objectives of this research are to investigate the possibility that blockchain may be used to improve several aspects of the construction industry, such as the BIM project life cycle, supply chain management, smart building and energy management. The objectives of the research are as follows.

- Explore the potential integration of BIM and blockchain technology at different stages of the construction life cycle to improve safety, efficiency, and sustainability.
- Investigate how the integration of BIM and blockchain technologies can support collaboration across disciplines in the construction industry by promoting accountability and visibility in the supply chain.
- Develop a blockchain-based BIM provenance model that enables secure and immutable tracking of BIM data throughout the entire life cycle of a construction project, including data creation, modification, and utilisation.
- Apply the developed blockchain-based BIM provenance model to a real-world construction project to assess its feasibility, effectiveness, and practicality in enhancing project data management.
- Investigate the potential of blockchain technology to support energy management in the built environment.

- Explore how blockchain can streamline data management providing a real-time energy sensing and control capability to advance energy efficiency and sustainability goals in the construction industry.
- Analyze how the integration of blockchain technology impacts the general performance of construction projects, using ROI and key performance metrics.
- Extract evidence from community consultations about limitations and the current challenges around the adoption of digital technologies in the construction industry.

The methodology used for each research question (RQ) presented in Table 3.2 is described below.

Table 3.2: Methodology for Each Research Question

Research Question	**Framework**	**Case Study**	**Testing Environment**
RQ1: Can BIM and blockchain be integrated and applied in construction life-cycle stages to improve safety, cost-efficiency and sustainability of construction projects?	BIM-Blockchain implementation in the construction lifecycle: Examines how blockchain can be integrated with BIM throughout various stages of construction projects to improve data management and project efficiency.	New Bridge Project: A construction project involving the design and construction of a new bridge, used to test the application of the BIM-Blockchain framework.	Ethereum Remix virtual environment: A development tool for testing smart contracts and blockchain applications in a simulated environment.
RQ2: Can a blockchain-based BIM provenance model be developed to ensure traceability and transparency of BIM data in a construction project?	Blockchain-based BIM data provenance model: Focuses on creating a model that tracks and verifies the provenance of BIM data using blockchain technology to enhance data integrity and traceability.	New Bridge Project: The same bridge project was used to test the effectiveness of the blockchain-based BIM data provenance model in maintaining data integrity throughout the construction process.	Ethereum public test network (Kovan testnet): A public blockchain test network used to validate the model in a real-world-like environment with simulated data.
RQ3: How can blockchain technology be applied to energy management systems to improve operational performance and ensure sustainable building practices?	Blockchain-based auditable energy sensing and control: Investigates how blockchain can be used to monitor and control energy consumption in buildings, ensuring accurate and tamper-proof energy data.	Queen's Building: A real-world building used to apply and assess the blockchain-based energy sensing and control framework for auditing energy use.	Ethereum Remix virtual environment: The same tool used in RQ1 for testing the energy management system's blockchain applications in a controlled setting.
RQ4: What are the key benefits and drawbacks of the blockchain application for the construction industry?	Developing KPIs & Questionnaire	ROI calculations: Focuses on identifying key performance indicators (KPIs) and performing return on investment (ROI) calculations to assess the effectiveness impact of blockchain implementations in construction.	Questionnaire: A tool used to collect feedback and insights from industry professionals regarding the impact of blockchain on construction practices.

Chapter 4: Implementation of BIM-Blockchain in Construction Lifecycle

The methodology for RQ1 involves the development of a framework that integrates

BIM with blockchain technology to enhance various stages of the construction lifecycle. Verification focuses on confirming that the framework meets predefined design specifications and operational requirements. To validate this framework, a case study is conducted using a new bridge project, which allows for practical evaluation and refinement. The framework was then tested using the Ethereum Remix virtual environment, providing a simulated platform to evaluate its integration and performance in a controlled environment. This approach ensures that the BIM-blockchain framework is applicable and effective in real-world applications; verification ensures compliance with design standards and validation confirms its practical relevance.

Chapter 4: Blockchain-Based BIM Data Provenance Model

For RQ2, the research focuses on creating a blockchain-based model specifically for tracking the provenance of BIM data. This model aims to enhance data integrity and traceability throughout the construction process. Verification is performed by testing the model for conformance to design specifications and functional correctness. The effectiveness of this model is tested through a case study on the new bridge project, providing insights into its practical application. Further validation is achieved by deploying the model on the Ethereum public test network (Kovan testnet), which offers a realistic environment to evaluate the model's scalability and performance in a real-world scenario. This process ensures that both the design and operational aspects of the model are verified and validated.

Chapter 5: Blockchain-Based Auditable Energy Sensing and Control

The methodology for RQ3 involves designing a blockchain-based system for auditable energy sensing and control in buildings, intended to improve energy management and transparency. Verification involves assessing whether the system meets the specified design and functional requirements. This system is tested in the Queen's Building at Cardiff University, offering a real-world context to assess its impact on energy monitoring and control. Initial testing and validation are conducted using the Ethereum Remix virtual environment, which provides a platform for evaluating the system's functionality and effectiveness. This dual approach of verification and validation ensures that the system meets design specifications and performs effectively in actual use cases.

Section 6: KPIs and Questionnaire

RQ4 uses a multi-pronged approach to validate the research findings. This involves conducting a literature synthesis to identify key performance indicators (KPIs) and comparative practices relevant to blockchain integration in construction. Verification is applied to ensure that the KPIs are correctly defined and relevant. This section also includes return on investment (ROI) calculations to assess the economic impact of blockchain technology, with validation to ensure that the calculations are based on accurate and reliable data. In addition, a questionnaire was used to collect empirical data, providing insights and feedback from practitioners in the industry. Validation of this data includes assessing its accuracy and consistency to confirm the practical implications and effectiveness of blockchain technology in the construction industry.

Testing resilience, robustness and security of the systems

Various methodologies are used to ensure the resilience, robustness and security of a blockchain-based BIM solution. A comprehensive literature review identifies existing frameworks and best practices in blockchain applications, particularly in the construction industry. This basic research forms the theoretical foundation for the study and highlights the gaps in existing methodologies. Structured research was conducted to evaluate the functionality and integration of the blockchain based BIM solution. The development process using Remix IDE and Ethereum public networks includes smart contract deployment and interaction, ensuring that the system works as intended within a decentralized framework. Performance evaluations contribute to the robustness of the blockchain solution by assessing its speed, scalability and responsiveness under various conditions. Also, scenarios have been developed to simulate real-world applications of the blockchain based BIM solutions in construction processes, validating its effectiveness in addressing industry challenges. To address security, the methodologies recognize that the Ethereum network is generally considered secure, using strong consensus mechanisms and cryptographic principles, and the development was also carried out in a local environment using Remix IDE, with no online threats during the implementation process.

The hypothesis of the research

The hypothesis being investigated is that:

"The integration of blockchain technology into various processes within the construction industry—such as design, construction and energy management can lead to significant improvements enabling workflow automation, enhancing collaboration between stakeholders, improving data integrity, security and monitoring, and supporting informed decision-making. These developments encourage the implementation of more efficient and optimized practices in project management and the construction lifecycle."

3.3 Research Structure

This section will discuss the research structure that attempts to address the research questions given in the previous section. The structure of the thesis is presented in Figure 3.2

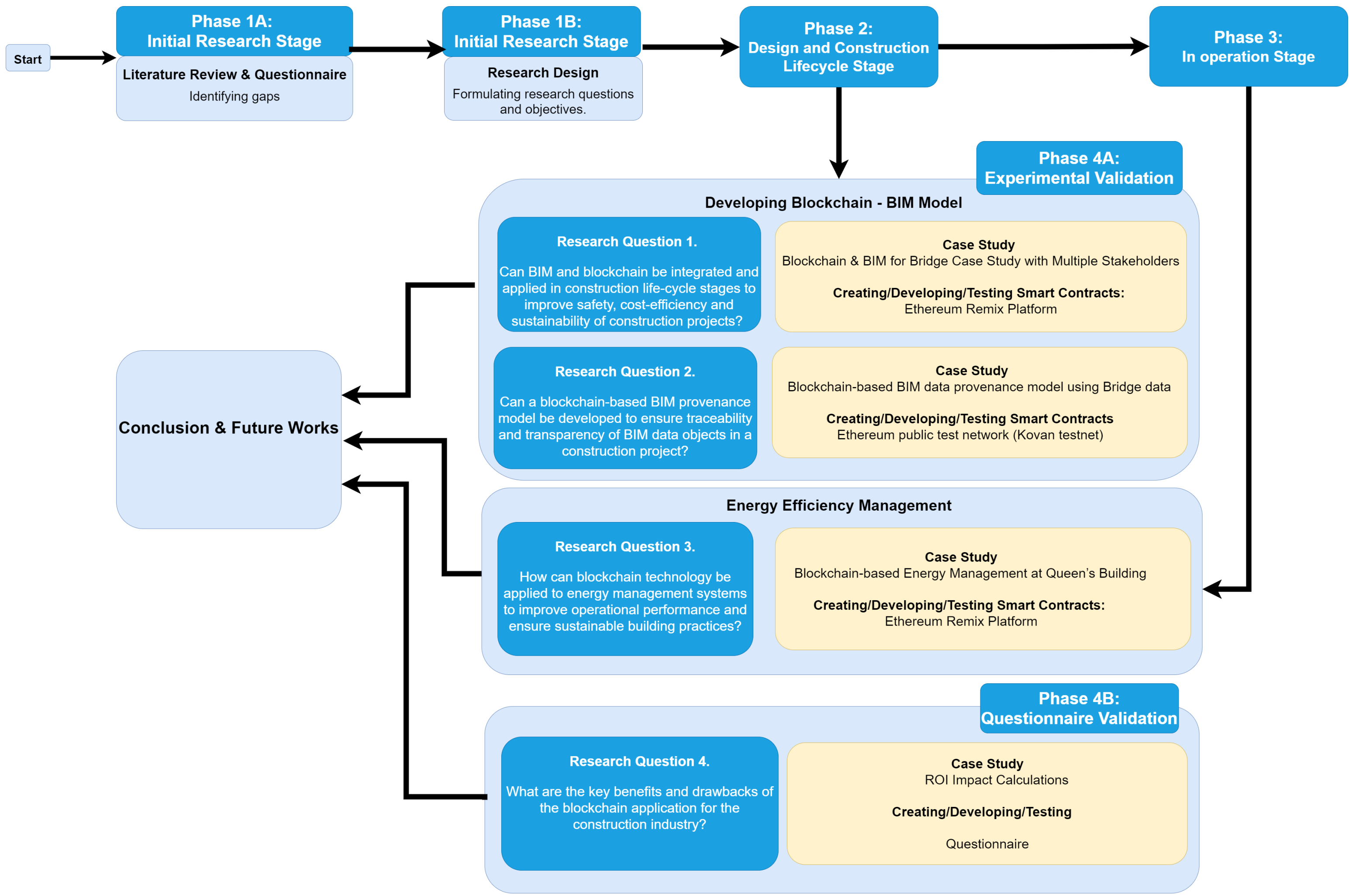


Figure 3.2: Research structure

3.3.1 Phase 1A: Initial Research Stage: Literature Review

In the first stage of the research, a literature review was conducted to identify existing knowledge and gaps in the current understanding of the topic. This involved a thorough review and analysis of relevant academic articles, books, journals and other scholarly sources. By synthesizing existing research, a foundation for the study was built and insights into areas needing further research were gained. Additionally, a questionnaire approach was used to gather information on challenges faced by the construction industry. Questionnaires were developed and distributed to industry professionals, experts, and stakeholders to obtain their views on key issues and barriers. Integrating these qualitative data with the literature review provided a comprehensive understanding of the challenges and concerns in the construction industry, informing the subsequent stages of the research.

3.3.2 Phase 1B: Initial Research Stage: Research Design

Based on the findings of the literature review and the questionnaire, this stage of the investigation involved the design of the study. Drawing from the identified gaps and insights, research questions and objectives were formulated to guide the study. A methodology was developed, outlining the approach, data collection methods, and analytical techniques to be used. This phase was essential in framing the research, ensuring that efforts were focused and structured to effectively address the identified gaps.

A mixed methods approach including case studies, a questionnaire and experiments was used to further investigate and address the identified challenges. The case studies provided context-rich insight into the complexities of the construction industry, allowing us to examine specific real-world scenarios in depth. Simultaneously, a questionnaire continued to be used to gather broader perspectives and insights from industry professionals and stakeholders. In addition, experiments were conducted to evaluate potential solutions to identified challenges. This integrated methodology and data from a variety of sources and perspectives enriched the depth of the research findings.

3.3.3 Phase 2: Design and Construction Stages

The development and implementation of blockchain frameworks, specifically designed to integrate BIM and blockchain technologies, were initiated to address the first and second research questions and facilitate implementation throughout the design and construction life cycle.

Construction Life Cycle and Supply Chain: This research examines the integration of BIM and blockchain technologies within the construction life cycle and supply chains. Exploring potential synergies between these two technologies aims to identify opportunities for increasing efficiency, transparency, and collaboration in the construction industry. This research includes analysing data exchange, exploring potential use cases, and assessing the impact on project management and decision-making processes.

BIM Data Provenance Model: This research initiative focuses on the development of a blockchain-based data provenance model specifically adapted for BIM data. The aim is to address data integrity, authenticity, and traceability concerns in BIM workflows by leveraging blockchain technology. By designing and implementing a data provenance model, the research aims to create a secure and immutable audit trail for BIM data and ensure reliability and accountability throughout its life cycle. Key components of this model include data attribution, validation mechanisms, reconciliation protocols, and scalability considerations.

3.3.4 Phase 3: Operational stage

The objective of this stage is to address the third research question and investigate the potential benefits of using blockchain to enhance energy efficiency and management during the operational stages of the construction industry. This stage facilitates energy efficiency, and empowers disciplines and individuals in the construction industry by improving data protection, collaboration, and working environments.

Energy Efficiency and Data Management: This research question focuses on investigating the potential of blockchain technology to improve energy efficiency and data management processes. The aim is to investigate how blockchain can be leveraged to facilitate more efficient energy usage, monitor consumption patterns, and manage energy data in various operational environments. The goal is to identify opportunities for integrating blockchain solutions to enhance energy efficiency practices and streamline data management procedures across different domains. Key areas of focus include the development of blockchain-based energy monitoring systems, smart contracts for energy transactions, and decentralised data management frameworks to enhance transparency, security, and accountability in energy-related operations. Through this research, the objectives are to contribute to the advancement of sustainable energy practices and efficient data management strategies in operational environments.

3.3.5 Phase 4A: Experimental Validation

The research methodology includes experimental validation to empirically evaluate the effectiveness and feasibility of the proposed blockchain-BIM integration solutions developed in the previous phases. This involves designing experiments to simulate real-world construction scenarios, collecting relevant data, implementing and testing blockchain-enabled BIM solutions, analysing results, documenting findings, and incorporating stakeholder feedback. The collected data was analyzed to assess compliance with design specifications, address performance, security and usability concerns, and lead to iterative optimisation. During this iterative process, smart contracts were refined, parameters were adjusted, and improvements were identified. Through careful testing and validation, this phase aims to provide evidence of the practical benefits and limitations of the implemented technologies, thereby strengthening the credibility and applicability of the research findings. Ultimately, this phase contributes to the advancement of knowledge and practices in the construction industry by providing empirical support for the effectiveness and applicability of blockchain-BIM solutions in real-world scenarios.

Success Criteria for Validation

Success criteria used to validate the performance of smart contracts tested in Remix IDE and the Kovan testnet. The identification of these criteria was necessary to provide a structured approach to assess whether the tests were successful and to evaluate the functionality and efficiency of the contracts. The success criteria focused on whether the smart contracts were able to correctly perform their intended functions and address various scenarios, including both normal operations and failure conditions. Testing was considered successful if the contract produced the expected results, such as correctly processing transactions and managing interactions. Any deviation, such as incorrect data processing or failure to fulfil functions, indicated a failure. In the Kovan test network, success was evaluated based on gas efficiency and transaction processing times. Gas utilisation was monitored to ensure that contracts were running within reasonable limits, while processing times were assessed to verify that transactions were completed without significant delays. While specific limits were not predefined, efficient performance was expected under typical conditions, and excessive gas consumption or delays indicated potential areas for improvement. The contracts were also analysed for their ability to handle extreme situations and failure scenarios. Successful tests included the contract rejecting invalid inputs, recovering from failed trades and maintaining reliable functionality under adverse conditions. Throughout the testing, results were compared to overall performance expectations.

3.3.6 Phase 4B: Questionnaire Validation

This sub-phase is structured with a dual objective: first, to assess the existing gaps in the construction industry; and second, to validate the research. The questionnaire was designed to address the different objectives. The first part aimed at identifying and understanding the gaps and challenges faced by stakeholders in the BIM environment. The next part aimed to gather information on user requirements and expectations regarding a blockchain-based BIM framework that serves as a validation tool for the proposed solutions. 48 experts from the European Construction Technology Platform (ECTP), including architects, engineers, academics, BIM experts and other relevant professionals, provided valuable perspectives on both the challenges in the industry and the expected features of a blockchain-based BIM framework. The questionnaire findings have guided an iterative improvement process, especially in defining the requirements for blockchain-based BIM integration.

3.4 Case Studies

An exploration of the potential applications of blockchain technology in various stages of construction life cycles has been analysed in the literature review chapter. Insights from three real field application case studies are also presented, covering bridge construction and energy management in buildings.

Bridge project

Highways England is leading a bridge construction project, where the focus is on implementing a pioneering BIM-blockchain integrated solution to enhance the project's existing data and processes. Figure 3.3 presents some sources used in the Bridge project.

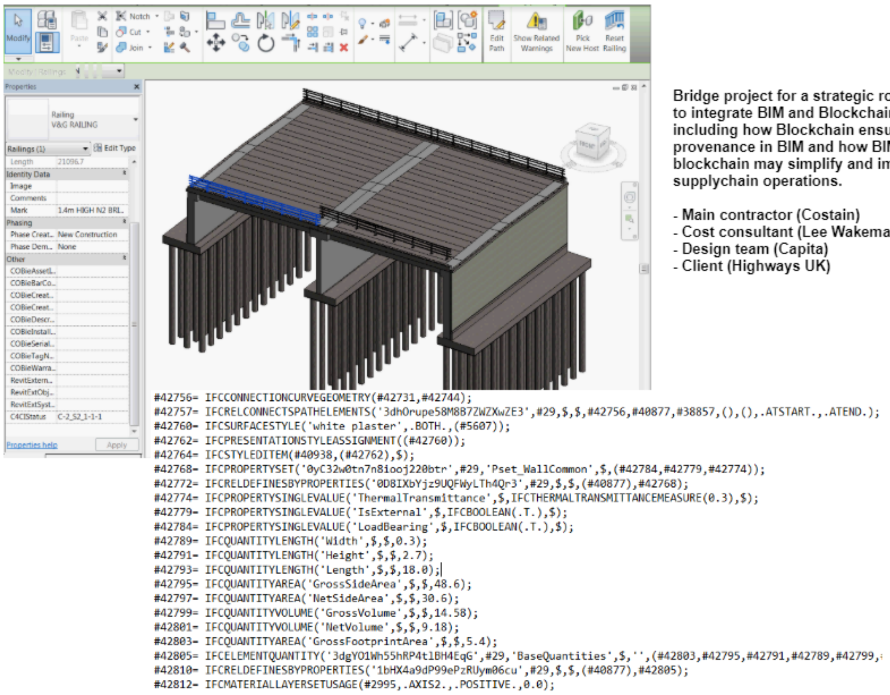


Figure 3.3: Bridge project

This validation test is an important exploration that allows us to thoroughly assess the feasibility, benefits, and challenges associated with implementing blockchain in a standard construction project environment. This project brings together a diverse multidisciplinary team with Costain as the main contractor, Lee Wakemans Ltd. as the cost consultant, Capita leading the design team, and Highways UK as the client.

This integration enables a secure and transparent flow of information throughout the construction life cycle. The aim is to address challenges in communication and collaboration by creating a unified and trusted system for data management. Generic frameworks for implementing blockchain in the BIM environment were developed throughout the process, specifically aligned with the RIBA Work Plan stages. These frameworks were thoroughly tested in a virtual environment incorporating smart contracts. The test results provided valuable insights, including cost calculations, and contributed to the creation of a road map to integrate blockchain into various stages of the construction industry life cycle.

Energy Management

Data on electricity consumption, temperature variations, and CO2 concentrations in 10 key buildings and offices at Cardiff University provide the basis for an innovative energy efficiency management project driven by blockchain technology. This scenario aims at building management and operational efficiency systems and general sustainability. The integration of blockchain into this context increases the transparency and security of energy data, providing precise recording that allows for data measures and promotes a more sustainable building environment. Figure 3.4 shows some of the data used in the case study.

The use of blockchain technology in this project ensures the integrity and security of energy-related data and facilitates a transparent and decentralised system for managing energy resources. In this case study, the main objectives revolve around energy efficiency and promoting sustainability through the integration of blockchain technology. The project aims to improve energy consumption patterns in campus buildings by using data from sensors and providing cost calculations for recording data between buildings and offices for different time intervals on the blockchain. Beyond operational improvements, blockchain plays an important role in promoting sustainability by providing a

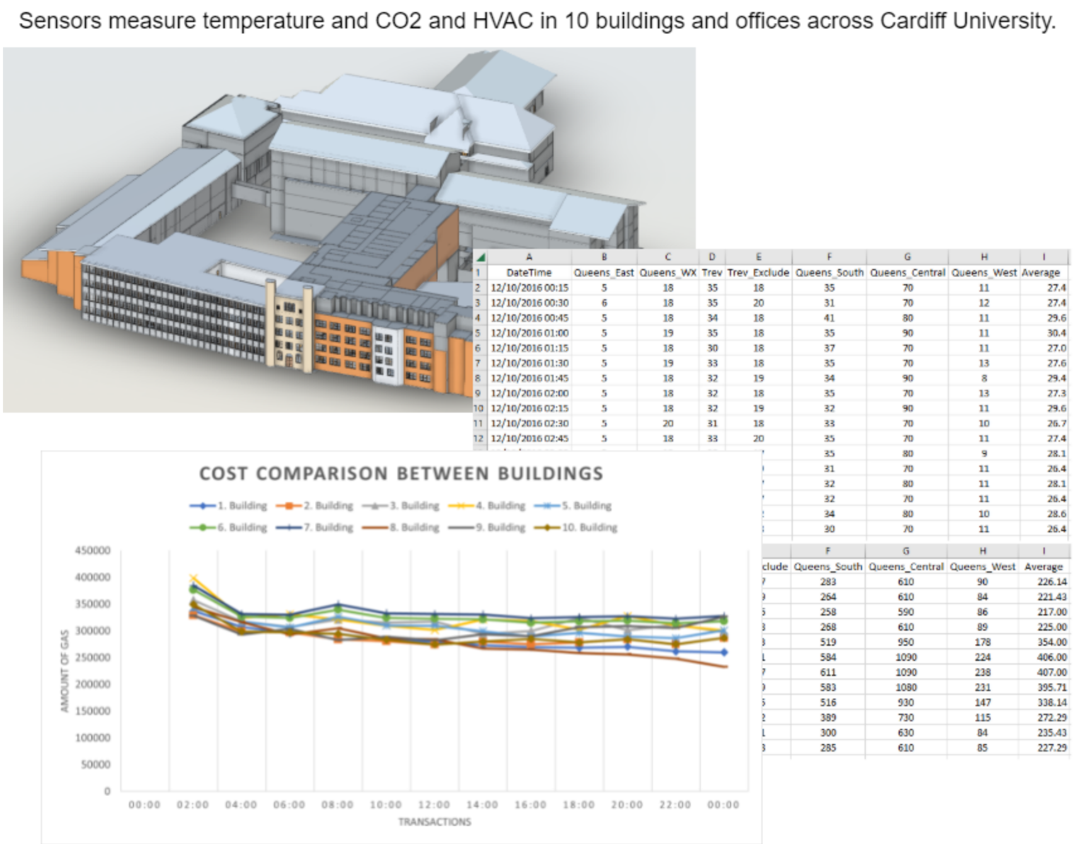


Figure 3.4: Queen's Building energy case

secure platform for transparent and accountable energy practices.

The case studies showcase the integration of blockchain technology throughout the construction life cycle, highlighting its role in enhancing collaboration, efficiency, security, transparency, and skills development. By leveraging blockchain, stakeholders can securely share data, automate processes, ensure data integrity and promote transparency, ultimately advancing the adoption of BIM and driving digitalisation in the construction industry. Through a holistic approach, this research provides actionable insights for practitioners, policymakers and researchers, guiding them to harness the transformative potential of blockchain while ensuring compatibility with existing practices. This comprehensive approach emphasises the importance of embracing innovation to advance the construction industry toward a new era of efficiency and effectiveness.

3.5 Construction Life Cycle Methodical Approach

This research pursues a methodological approach in the life cycle to examine the use of blockchain for each stage of the construction process as outlined in the RIBA Plan of Work [210]. This life cycle implementation approach allows us to comprehensively explore the applications and benefits of blockchain technology at every stage of the construction industry, including feasibility, design, construction and handover phases. For each phase, the aim was to examine how blockchain can improve collaboration, data management, transparency and efficiency, and possible integration for all phases. Through this life cycle stage methodological approach, the aim is to contribute to the body of knowledge on blockchain applications in the construction industry and provide practical insights for its implementation at various stages of the construction process.

RIBA (0) Strategic Definition

This thesis contributes to this stage by providing guidelines for project management teams to assess the strategic suitability of adopting blockchain. Through a detailed analysis of relevant literature and industry practices, decision-making criteria are provided that consider the project's complexity, the involvement of multiple unknown participants, and the need for consensus. In addition, the research highlights the importance of understanding the project context and the nature of data transactions in order to guide the decision-making process effectively.

RIBA (1) Preparation

In this stage, the goal is to provide a basic framework for the integration of blockchain into the construction industry. The efforts are centred around the development of a project brief and feasibility studies assessing the feasibility of blockchain integration and the development of practice-oriented research. An important aspect of this phase involves the creation of a road map that defines roles, responsibilities and information exchange protocols between the disciplines involved in the construction process. The aim was to develop a guide through the studies. The contribution aims to equip the industry with essential knowledge and a trajectory for the effective introduction and utilization of blockchain technology, through a synthesis of project highlights, a literature review, and a strategic guide derived from this research.

RIBA (2,3,4) Design Stage

Blockchain is being promoted as a key innovation and is envisaged as a distributed network that connects clients, contractors and stakeholders in a transparent structure that increases trust between these stakeholders. In this context, blockchain acts as a catalyst that facilitates secure and transparent data sharing and management throughout the design stage. The integration of blockchain into the design process aims to accelerate the technological advancement of the construction industry, and improve cost efficiency and the complex data sharing environment. The primary goal is to provide the potential of blockchain technology in the design stage. Incorporating blockchain into the approach is driven by the overarching goal of streamlining collaboration, facilitating efficient file management and optimising overall project efficiency. By integrating a synchronised system with BIM that leverages the capabilities of blockchain technology, the goal is to upgrade the design process, ensure reliable transactions, and contribute to a more transparent and efficient construction industry.

The Bridge project case study in Chapter 4 was based on the integration of this stage, and the main objectives of integrating blockchain into the project are to improve data source recording and sharing, advance collaboration, and optimise document management across various professional disciplines. By using smart contracts in a virtual environment, the aim is to develop practical insights that lead to the formulation of a roadmap for integrating a blockchain-based BIM environment into the construction industry lifecycle.

RIBA (5) Construction

The use of smart contracts during the construction stage is strategically designed to manage and track changes in the BIM model's design and construction phases, enabling extensive documentation and tracking of all model changes while simultaneously monitoring standard permits and legal documentation of residences. The integrated blockchain architecture of the design stage is adapted to a blockchain BIM integration involving all stakeholders in the life cycle. This transition is aimed at leveraging blockchain's potential to streamline and automate processes. By emphasizing automated processes facilitated by smart contracts, the goal is to showcase the transformative potential of blockchain and establish a framework for evaluating and implementing similar innovations in the construction industry.

The Bridge project case study in Chapter 4 was designed to illustrate how blockchain was applied in the construction phase and how the process was automated. Focusing on data provenance, collaboration, and document management across various professional disciplines, this integration aims to create a secure and transparent flow of information throughout the construction project life cycle. This case study is intended to formulate a road map for the integration of blockchain into the life cycle of the construction industry.

RIBA (6) Handover and Close Out

This stage seeks to create an immutable historical record that covers the entire project life cycle from concept to delivery. By deploying smart contracts in line with industry best practices, particularly during the design and construction phases, the goal is to establish a baseline from the beginning of the project. This approach is intended to enhance trust and transparency among all parties involved and build a high level of confidence in the integrity and accountability of the project journey. The case studies detailed in Chapters 4, 5, and 6 serve as a collaborative effort to establish a definitive record, covering the entire life cycle of the construction industry.

RIBA (7) In Use

In the final stage of the RIBA Work Plan, blockchain is being investigated in areas such as energy management, maintenance, and equipment utilisation. This approach simplifies the process of contracting and delivering service providers throughout the construction life cycle by providing a secure and unalterable record of service-related transactions.

On the Cardiff University campus, a network of sensors collects important data on electricity consumption, temperature levels, and CO2 concentration in 10 different buildings and offices. This valuable data collection for the case study is the basis for monitoring & improving energy efficiency through blockchain implementation. The main aim of the energy case study in Chapter 5 is on the effective management and operational efficiency of these buildings, covering aspects such as energy management and sustainability practices. The intention is to increase the transparency and security of energy data, ultimately facilitating the precise recording of transactions and energy data.

3.6 Vision and Value Proposition

The integration of blockchain and BIM into the construction industry offers a solution that increases security, efficiency, transparency, and collaboration throughout the entire life cycle of construction projects. Figure 3.5 presents a visual guide that identifies emerging patterns of blockchain and BIM integration, unresolved challenges, and promising avenues for future research and application.

User and Project Registration: Using blockchain for user and project registration creates a secure and transparent recruitment process. Architects, engineers, clients, and various stakeholders record their information on the blockchain, providing an immutable and tamper-proof record. This guarantees transparency and reliability throughout the project, with project registration detailed in Chapter 4.

External Registry and Data Sharing: External organisations such as government agencies and legal institutions register on the blockchain, encouraging a collaborative and transparent ecosystem. Using blockchain for data sharing creates a trusted environment for collaboration (which is provided in Chapter 4) to ensure that BIM data, certificates and other critical project information are exchanged between stakeholders in a secure and authenticated manner.

Data Tracking and Monitoring: Blockchain facilitates the tracking and tracing of various data, from resource maintenance to user activities and material status. The integration of blockchain into construction projects provides additional security,

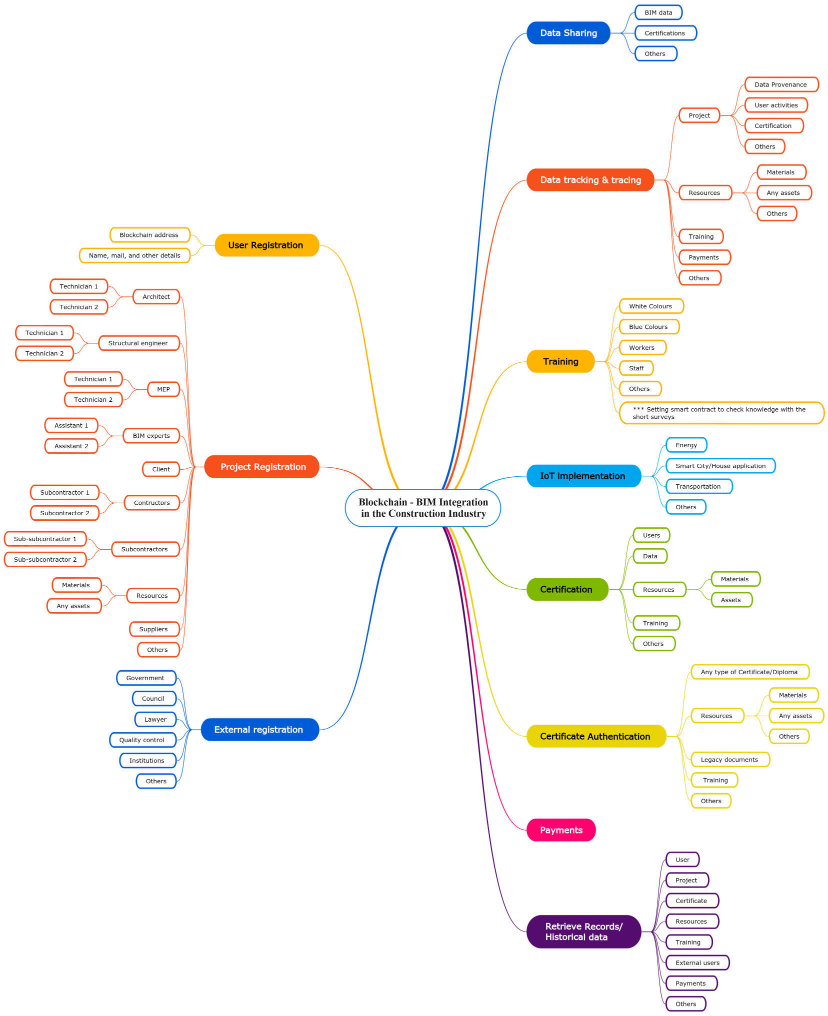


Figure 3.5: The integration of blockchain in the construction industry

ensuring the reliability of data used in decision-making processes delivered in all the chapters.

Record Retrieval: Blockchain facilitates fast and reliable access to historical records delivered in all chapters, as well as their retrieval, contributing to informed decision-making throughout the construction life cycle.

Decentralised Project Governance: Smart contracts embedded in the blockchain automate and enforce contractual agreements, streamlining workflows and minimising disputes. This encourages a collaborative environment in which decisions are traceable, accountable, and resistant to manipulation (which is demonstrated in Chapter 4).

Immutable Documentation and Audit Trails: The immutability of the blockchain ensures that all project documentation, including design plans, contracts, and regulatory compliance records, remains tamperproof. This increases the security of sensitive information providing a comprehensive audit trail that allows stakeholders to track changes, approvals, and compliance throughout the project's life cycle (which is provided in all chapters).

Effective Resource Allocation: Smart contracts optimise project efficiency and reduce the risk of resource conflict and delays. As mainly mentioned in Chapter 4, the transparency of the blockchain ensures that all stakeholders have real-time visibility into resource allocation, enabling a more adaptive and responsive construction process.

Real-Time Collaboration and Communication: Blockchain's real-time capabilities enhance collaboration and communication between project stakeholders. This real-time collaboration promotes a stronger and more responsive construction ecosystem, and ultimately accelerates project timelines (as provided in all chapters).

Predictive Analytics for Risk Management: The framework in Chapter 5 envisions an adaptive solution for energy management in the construction industry that provides the foundation for continuous innovation and improvement. Blockchain integration into a comprehensive ecosystem is driving a new era of efficiency, sustainability, and collaboration.

3.7 Summary

This chapter provides an overview of the methodology employed in this thesis and outlines a mixed method within a pragmatic philosophical framework to provide a basis for the study. The scope of this research has been carefully determined, focusing on specific aspects of blockchain technology in the construction industry. The research structure is presented and organised into four phases to address the objectives. This chapter also provides information for the case studies alongside practical scenarios that highlight the implications of blockchain integration and provide a better understanding of its applications. Finally, this chapter uses blockchain throughout the RIBA Work

Plan process to present an approach to addressing key issues throughout the construction project life cycle.

Next Chapter: Blockchain Augmented Design and Construction Lifecycle Stage

The chapter presents a real-world bridge project to demonstrate the application of smart contracts and a blockchain-based BIM framework designed to facilitate collaboration, provide secure and transparent transactions and automate project management tasks. Also, the next chapter develops and empirically validates a blockchain-based BIM data provenance model.

CHAPTER4

Blockchain Augmented Design and Construction Lifecycle Stage

This chapter focuses on addressing research questions RQ1 and RQ2, along with their corresponding objectives. This explores the integration of BIM and blockchain technology into the construction industry life cycle, aiming to revolutionise traditional practices and improve data management processes. The chapter begins by describing the potential synergies between BIM and blockchain, highlighting their combined ability to streamline construction workflows and promote transparency between stakeholders. This also introduces the concept of data provenance, and presents a novel blockchain-based BIM data provenance model designed to address the challenges of data reliability and traceability in construction projects.

In addition, this chapter presents two scenarios to illustrate the practical applications of blockchain-BIM integration. The first scenario provides an overview of how BIM and blockchain can work together throughout the construction life cycle, demonstrating their transformative impact on project management and stakeholder collaboration. The second scenario focuses on the specific use of blockchain to enhance the provenance of BIM data in a real-world bridge project, highlighting its role in ensuring data integrity and transparency throughout the project's phases. Based on these scenarios, this chapter aims to illustrate the benefits and challenges of implementing blockchain technology in construction projects, enabling the exchange of information and also enabling the industry to move forward and innovate.

4.1 Contexts and Proposed Approach

Blockchain technology is transforming the construction industry, offering a shared database accessible to all stakeholders. This database facilitates tracking, monitoring, and process automation, ultimately aiming to reduce conflicts, improve trust, and streamline operations. This chapter demonstrates how to integrate blockchain into construction practices through an examination of a real-world case study.

4.1.1 BIM and Blockchain Integration

To optimise efficiency in construction, the goal was to automate processes by integrating blockchain into various stages of construction operations. A real-world case study on a new construction bridge project is reviewed, showcasing the transformative role of blockchain in modernizing traditional construction practices. This framework examines the integration of BIM and blockchain and provides validation through demonstration. The key insights from this case study highlight the benefits of incorporating such advanced technologies into construction projects. The proposed model for the integration of blockchain with BIM is illustrated with the corresponding critical insights in Figure 4.1, showing the general plan for the implementation in a project life cycle using the stages of the RIBA Work Plan. This process is defined from the literature review, which analyses similar implementations of technologies such as BIM and then syntheses them as shown in the figure.

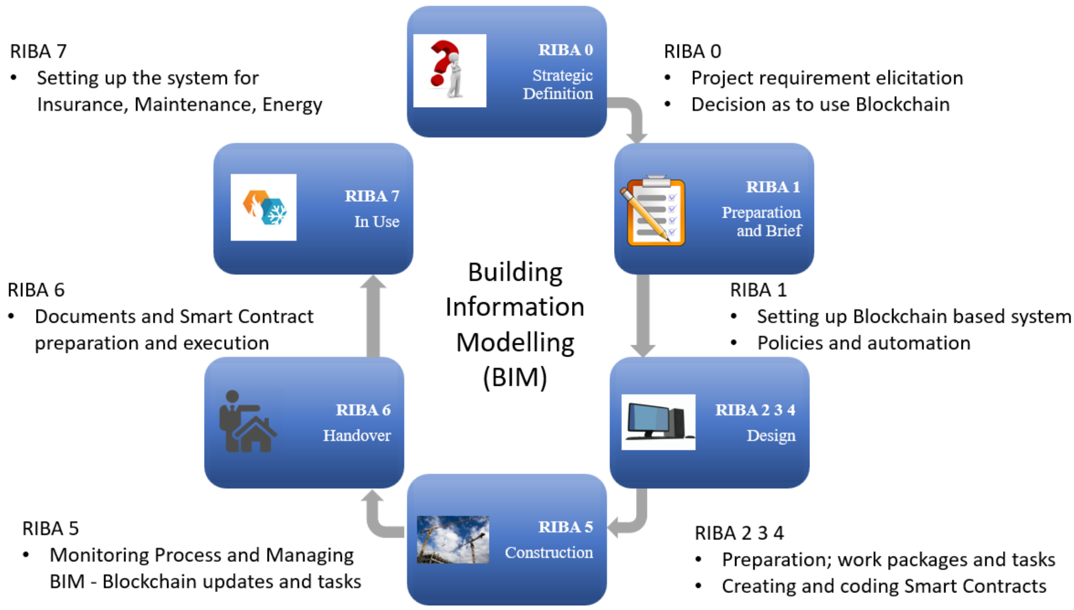


Figure 4.1: Blockchain steps with BIM for the construction life cycle

Additionally, external factors can influence each stage of the integration of blockchain with BIM throughout the construction lifecycle in the stages shown in Figure 4.1. At Riba 0, challenges such as stakeholder misalignment, regulatory uncertainties or evolving project requirements may delay the decision to use blockchain. During RIBA 1, disruptions may arise due to technical integration issues with existing systems, supplier delays, or a lack of qualified personnel to set up blockchain-based systems and policies. During Riba 2 3 4, coding errors, third-party platform issues or regulatory review delays can slow down the creation of smart contracts. For Riba 5, external disturbances such as network congestion, hardware failures or security vulnerabilities can affect the monitoring of BIM-blockchain updates. For Riba 6, delays may occur due to dependencies on external parties for documentation and the finalization of smart contracts. Finally, in Riba 7, deployment, logistical challenges, regulatory delays or supply chain disruptions may affect the deployment of systems for insurance, maintenance and energy management. These potential external factors emphasize the need for careful planning and risk mitigation at every stage.

4.1.2 Data Provenance for Construction Projects

Ensuring effective data provenance in construction projects involves several key challenges. Throughout the project's lifecycle, managing the integrity of data as it passes through various stakeholders—such as architects, engineers, contractors, and manufacturers—can be complex and prone to errors. Tracking and managing the latest versions of designs, specifications, and other project-related data is essential to avoid conflicts and ensure that all parties work with the most current information. Proper attribution of changes is crucial for accountability; without it, resolving conflicts or learning from past decisions becomes difficult. Also, traceability of changes is necessary to understand decisions made throughout the project's lifecycle, requiring comprehensive documentation and tracking mechanisms.

The design phase, characterized by its multidisciplinary nature, further complicates these challenges. Effective management of changes during this phase is critical for maintaining transparency, accountability, and accuracy. Documenting data provenance ensures that all changes are tracked, consistent, and accurately attributed, thereby improving collaboration and building trust among stakeholders. By emphasizing data provenance, stakeholders can optimize the design process, facilitate decision-making, reduce errors, and enhance communication.

Blockchain technology provides a solution for these challenges by offering a transparent, immutable system for tracking data provenance. In the BIM environment, blockchain coordinates documentation by generating unique records for each design change, update, or interaction. These records include metadata and timestamps, ensuring that each change is attributed to the responsible discipline. This creates a comprehensive, immutable audit trail that enhances transparency and reduces errors.

The process is illustrated in Figure 4.2, which depicts the interaction between the design team model file and the blockchain at various stages of development. The figure demonstrates that the registration of all disciplines, design modifications, interactions, and the associated metadata of the IFC file for the project will be systematically recorded on the blockchain.

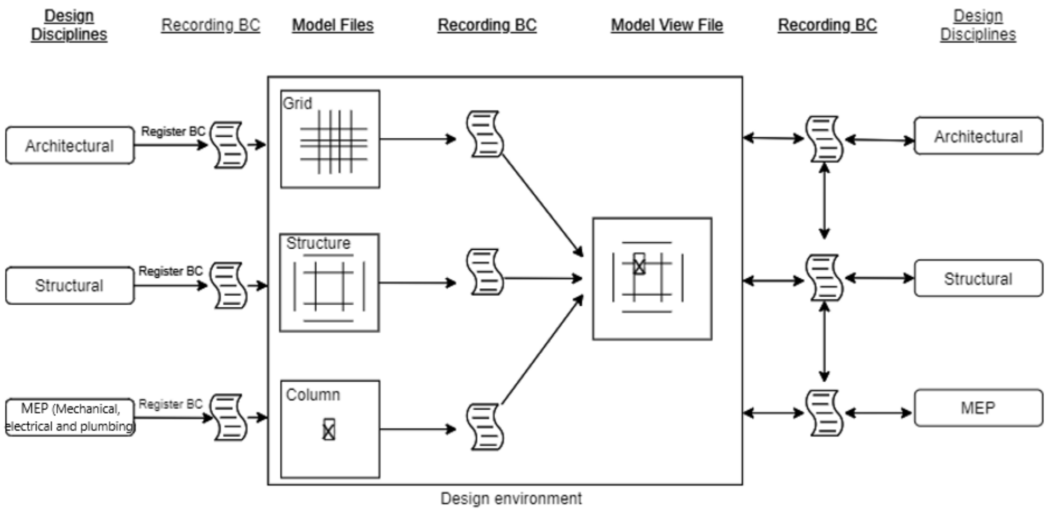


Figure 4.2: Design team model file and blockchain

Each Industry Foundation Classes (IFC) model component is stored on the blockchain with unique identifiers and metadata at the file, layer, and object levels. This approach allows for early detection of coordination issues across different disciplines and makes these issues visible, thus facilitating early conflict resolution and improving overall project efficiency. By documenting every modification, blockchain ensures that all changes are synchronized, traceable, and securely stored.

When changes occur, such as the repositioning of a structural column, the blockchain automatically synchronizes and records updates across all affected models—architects, structural engineers, and fabricators. This synchronization ensures data consistency and provides an immutable record of the design evolution, which is crucial for resolving disputes or audits. All activities are registered in the cloud and recorded on the blockchain, ensuring secure and transparent data management throughout the project lifecycle.

A trial involving three disciplines—Architect, Structural Engineer, and Client—demonstrated blockchain's effectiveness in storing and tracking IFC models. This approach improved data management and enabled collaboration, trust, and efficiency among all project stakeholders.

4.2 Blockchain-Based Data Provenance for IFC Models

Integrating blockchain with BIM is designed to increase data management related to IFC models, facilitating more effective project collaboration. This strategy presents a blockchain-based provenance framework to support trusted BIM data exchange and encourage collaboration between various project disciplines. Developed through a review of existing literature and insights from a case study, this framework aims to create a scalable and secure model for distributed BIM data sharing, thereby promoting effective stakeholder collaboration.

Development and Experimental Setup

An experimental setup is created using the Ethereum Remix platform and the Kovan testnet to implement the blockchain provenance framework. Smart contracts are developed and deployed using Solidity to manage project provenance functions. The capture of metadata from the IFC model for the BIM data provenance framework is illustrated from a bridge highway project demonstrating the integration of blockchain with BIM to effectively manage data and interactions.

Data Provenance Recording Process

In this system, every action during the construction design process is recorded on the blockchain using Proof of Work (PoW) mechanisms, ensuring the data remains immutable and trustworthy. Provenance records are compiled, published across the blockchain network, and linked with a hashed user ID to maintain privacy. The records are validated and confirmed by network nodes, providing a transparent and reliable history of data provenance. Figure 4.3 illustrates the process of recording provenance data within a BIM environment. It depicts how changes made by various disciplines (Architectural, Structural, MEP, and Client) are recorded and aggregated, and how this information is subsequently added to the blockchain.

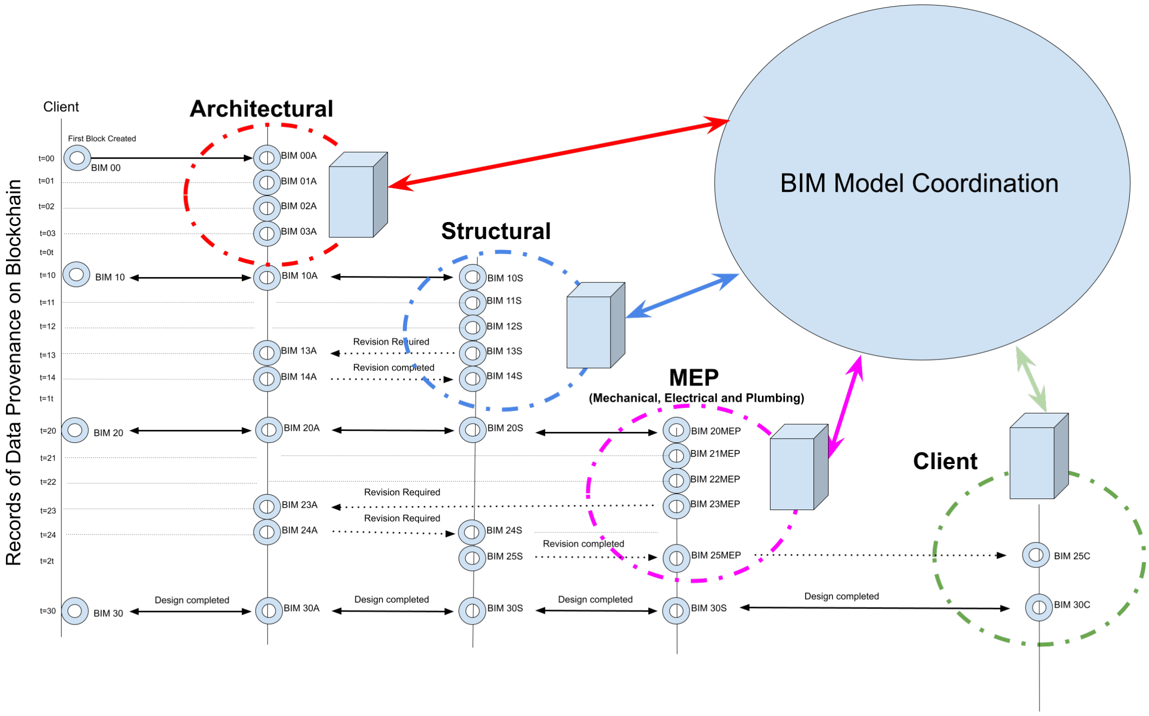


Figure 4.3: Blockchain integration with BIM data

In the BIM environment, various disciplines interact with different BIM objects throughout the design and construction process. Identifying these disciplines and objects is important for maintaining accurate and traceable records. Each discipline and BIM object is assigned a unique identifier to facilitate this process:

Discipline IDs:

- *Architect ID*: ARCH1
- *Structural Engineer ID*: STRU1
- *MEP Engineer ID*: MEP1
- *Client ID*: CLNT

BIM Object IDs:

- *Door*: Door001
- *Window*: Window002
- *Column*: Column003

Initial Metadata Recording

The initial metadata recording process involves capturing detailed information about each BIM object and recording it on the blockchain. This ensures that all attributes related to the object are accurately represented and traceable throughout the project's lifecycle. For example, consider the metadata for a door object:

Example: Door Object Metadata (Version 1.0)

- *Object Identifier*: Door001
- *Version*: 1.0
- *Type*: Door
- *Dimensions*: Height: 2100mm, Width: 900mm
- *Material*: Wood
- *Location*: Floor 1, Room 101
- *Date Added*: 01-09-2022

The process starts with the extraction of metadata, where the IFC file is parsed to extract information about the object, such as Door001. The extracted metadata typically includes the IFC object ID, object type, material properties, dimensions and manufacturer details. Following this, a blockchain transaction is created to record the extracted metadata on the blockchain. This process includes the unique IFC object ID (e.g. IFC-Door), a timestamp and a hash of the metadata to ensure integrity. The involvement of relevant disciplines is essential at this stage. The Architect (ID: ARCH123) is responsible for recording the design specifications and ensuring that the initial metadata is accurate. This may involve a review process where the Architect verifies that the extracted metadata is consistent with the design documentation. If any discrepancies are found, these need to be addressed before the blockchain transaction is finalized.

Processing Metadata Updates

Once the initial metadata for each BIM object has been created and recorded to the blockchain, it is essential to efficiently manage changes and updates throughout the project lifecycle. Managing metadata updates involves revisiting and revising previously recorded information as changes are made to the design or properties of objects. This study details how updated metadata is processed and recorded, including the extraction of new details, the creation of blockchain transactions to capture these updates, and the involvement of key disciplines. The example provided illustrates the procedure for updating metadata by showing how changes, such as changes in dimensions, are managed and recorded on the blockchain.

Example: Updated Metadata (Version 2.0)

- *Object Identifier*: Door001
- *Version*: 2.0
- *Type*: Door
- *Dimensions*: 2100mm, Width: 950mm (Width updated)
- *Material*: Wood
- *Location*: Floor 1, Room 101
- *Date Updated*: 15-09-2022

The process begins with the *detection of changes*, where automated systems identify updates in the IFC file. Following this, *updated metadata* is extracted to retrieve the new details for objects such as Door001. A *blockchain transaction* is then created to reflect these updates, ensuring that the changes are accurately recorded.

Smart Contracts

Figure 4.4 shows the integration of smart contracts with the blockchain. It highlights how a smart contract manages data from different project disciplines and ensures the processed data is recorded back onto the blockchain.

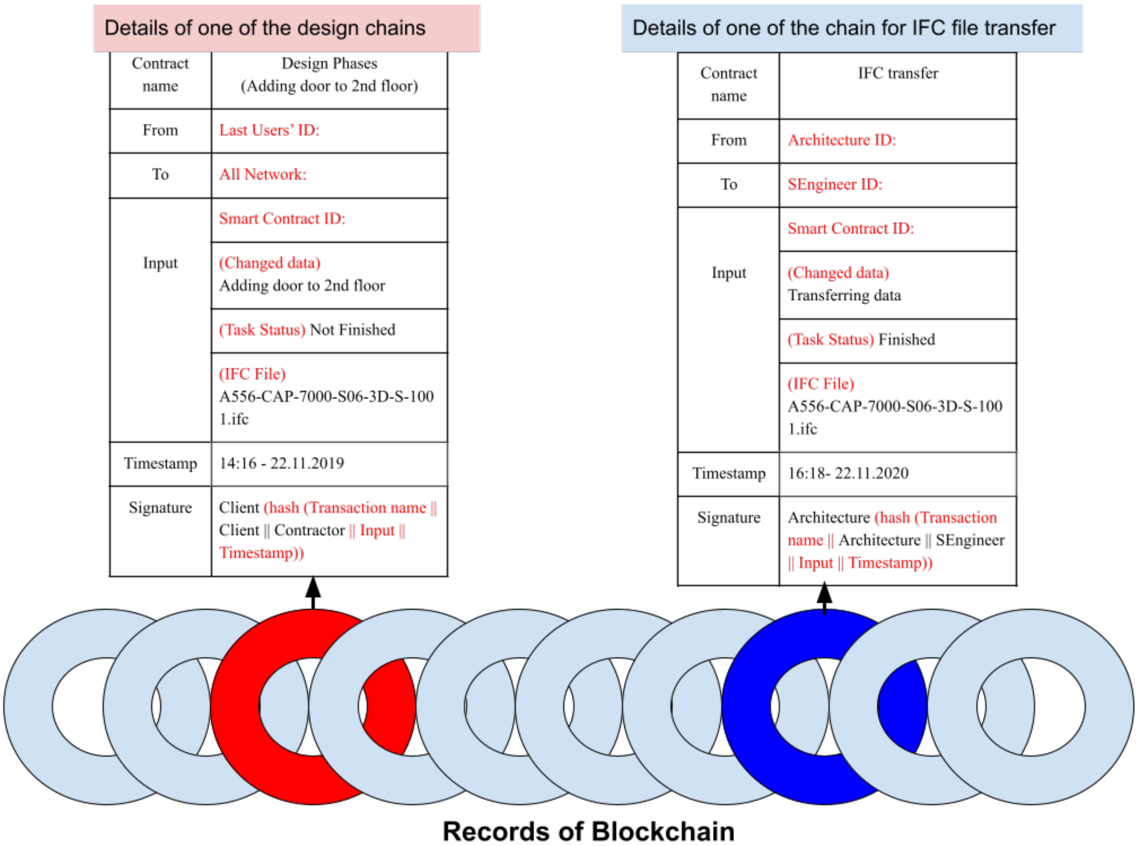


Figure 4.4: An example of saving a construction project file or an activity on the blockchain

In a bridge highway project, each team updates the BIM model as follows:

- *Architect (ID: ARCH123)*: Updates the design of Door001 (e.g., adjusting its dimensions or materials) and records the change.
- *Structural Engineer (ID: STRU456)*: Integrates these updates, such as reinforcing the structure around Door001, adds structural details, and records the changes.

- *MEP Engineer (ID: MEP789)*: Incorporates additional systems into the design related to Door001, such as HVAC adjustments, and records their updates.
- *Client (ID: CLNT101)*: Reviews the aggregated model, including all changes to Door001, with all previous updates recorded on the blockchain.

Example BIM objects as follows:

- *Door001*: Represents a specific door in the building design. Updates might include changes to dimensions, materials, or location.
- *Window002*: Represents a window, with updates potentially involving changes to size, placement, or glazing.
- *Column003*: Represents a structural column, with updates including modifications to its dimensions, material, or load-bearing capacity.

This approach provides a strategy for managing IFC models and user interactions through blockchain technology enhancing data integrity, transparency, and collaboration throughout construction projects.

4.3 BIM Data Model

In this study, the IFC model is employed to represent data within the project consortium and among participating disciplines, specifically using data from a highway bridge project. The IFC model encompasses all graphical and non-graphical information related to the bridge throughout its entire lifecycle, including planning, design, construction, usage, and operation.

The IFC model integrates both geometric and non-geometric data, as illustrated in Figure 4.5. The project data underwent review, analysis, and modifications using various software tools before being exported to an IFC file format. This format facilitates data exchange between different applications and adheres to the ISO standard 10303-21, commonly referred to as the "STEP-file" [332].

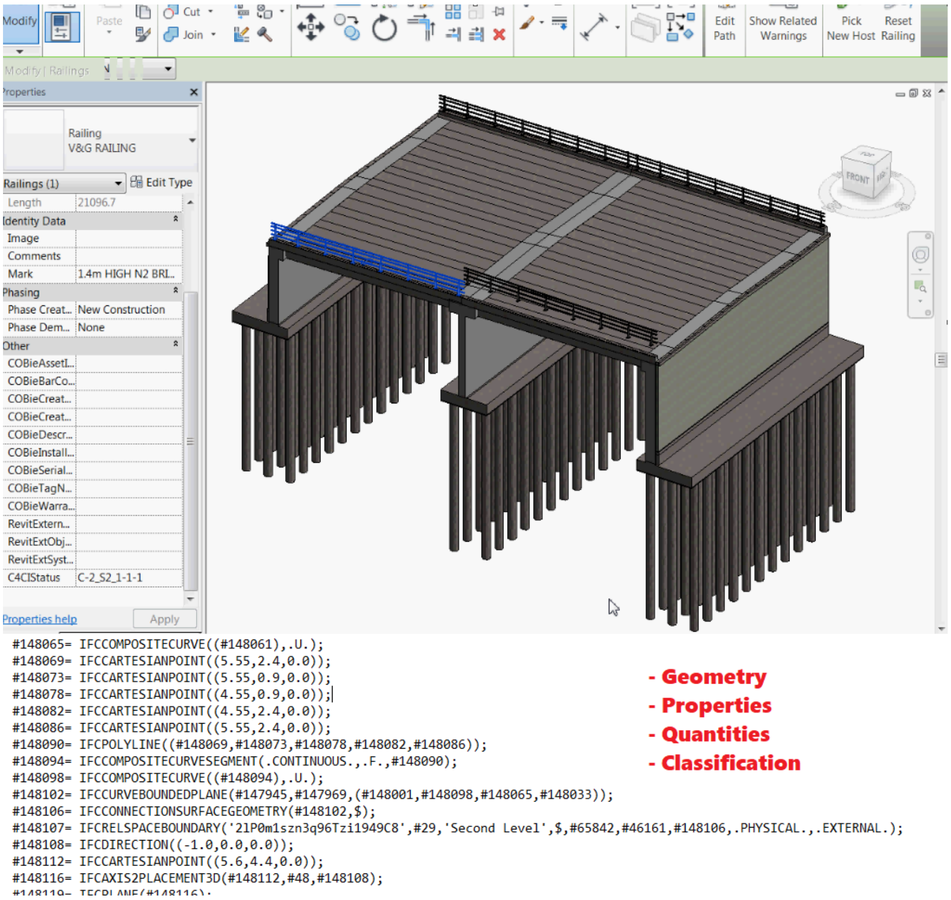


Figure 4.5: Geometric and nongeometric BIM data of the trial project

For this research, the IFC schema is utilized as a storage and transfer system for digital data, ensuring interoperability among BIM (Building Information Modeling) professionals working on the project. The IFC schema provides a comprehensive definition through various formats, including .ifc and .ifcXML, to represent hierarchically structured elements [178] [174].

The *.ifcXML extension of the IFC file format uses the same data schema as the *.ifc extension but presents it in XML format rather than ASCII text [178]. Both IFC and ifcXML standards are open and publicly accessible.

Revit is a BIM software widely used in architecture, engineering and construction to design and manage building projects. The process for exporting IFC metadata starts by opening the corresponding project and creating a schedule for the desired category, such as walls, doors or other building components. The user should then add the fields required for the metadata transfer, such as “Name”, “Type” or “Material”. Once the Revit program is properly configured, the export can be started by going to the File menu and selecting Export and then selecting the IFC format. At this stage, it is important to adjust the export settings to ensure that the desired program information is included. Once these settings have been completed, the IFC file is saved in the selected directory. Next, to register the exported IFC metadata on the Ethereum Virtual Machine (EVM), the first step involves converting the IFC data into a suitable digital format, such as JSON. Following this, a smart contract needs to be written in Solidity, the programming language for EVM, which will define the rules and structure for storing and managing the IFC metadata on the blockchain. Once the contract is completed, it can be deployed on the Ethereum network using development platforms such as Remix or Truffle. Libraries such as web3.js or ethers.js can be used to interact with the deployed smart contract, facilitating the transfer of IFC metadata to the blockchain. Finally, it is important to monitor the transaction to ensure that the data has been successfully recorded on the Ethereum ledger.

Blockchain Project Network

The Bridge project involves multidisciplinary teams that collaborate to produce a consolidated BIM model from which provenance data is recorded on blockchain. To ensure that the whole historical information is maintained in a tamper-proof way, the process needs blockchain trustworthy management and monitoring. The stakeholders involved in the project are the client, architect, structural engineer, and mechanical, electrical and plumbing (MEP), communicate and record their activities using smart contracts through a front-end layer (see Appendix C.1.).

Blockchain smart contracts were designed to support the provenance of BIM data in addressing the interoperability requirements of the construction project. An application programming interface (API) calls are used to process IFC objects and related metadata in order to facilitate the use of a project’s background by disciplines. This enables a distributed manipulation of these IFC objects in situations where multiple disciplines associated with a project can work on the same IFC model within the coordination system. The project partners can use a Revit plugin that connects the Revit software to the coordination framework and a filtering application that chooses IFC objects according to their compliance codes. The Revit plugin can communicate with the system to retrieve and send IFC objects based on discipline updates. Model update in the project network presented in Figure 4.6

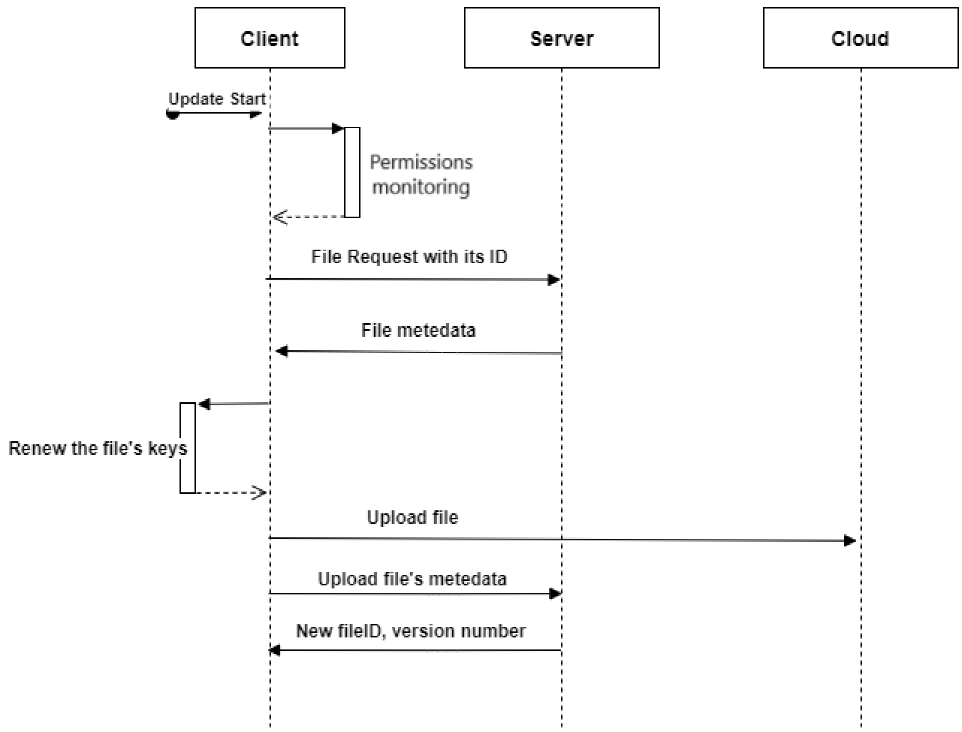


Figure 4.6: Model update in the project network

Blockchain registrations are performed on the basis of an IFC model, along with methods for data transfer and data provenance between disciplines. This enables disciplines to obtain the most recent version of an IFC object in real-time and modify the IFC model appropriately recording each operation to blockchain through data provenance. For the project network, blockchain can be accessible through a user interface designed following technical and building industry standards. The user interface has been designed to accomplish two tasks: (i) an initial interfacing of the blockchain, and (ii) continuous system administration.

4.4 Scenarios

This section presents two scenarios that illustrate the integration of blockchain technology and BIM in the construction industry. The first scenario presents an exploration of how blockchain and BIM collaborate throughout the construction life cycle of the Bridge project, demonstrating their transformative impact on project management and stakeholder collaboration. The second scenario highlights blockchain's role in providing data reliability and transparency throughout the project stages, with a focus on enhancing the BIM data provenance within the same project. Through these scenarios, the goal is to demonstrate the integration of blockchain-BIM in practical applications and the subsequent benefits in real-world construction projects.

4.4.1 Scenario 1: BIM-Blockchain in Construction Life-cycle

The evaluation is conducted with trial data from a real construction project of Highways England involving the construction of a new bridge on the A556 with data and processes provided by the project partner, Costain, as part of the Cloud-for-Coordination project [333]. This evaluation aims to demonstrate the advantages of blockchain for a multidisciplinary BIM project for the construction of a new bridge and to demonstrate the impact of using BIM and blockchain to support a more automated and efficient construction process.

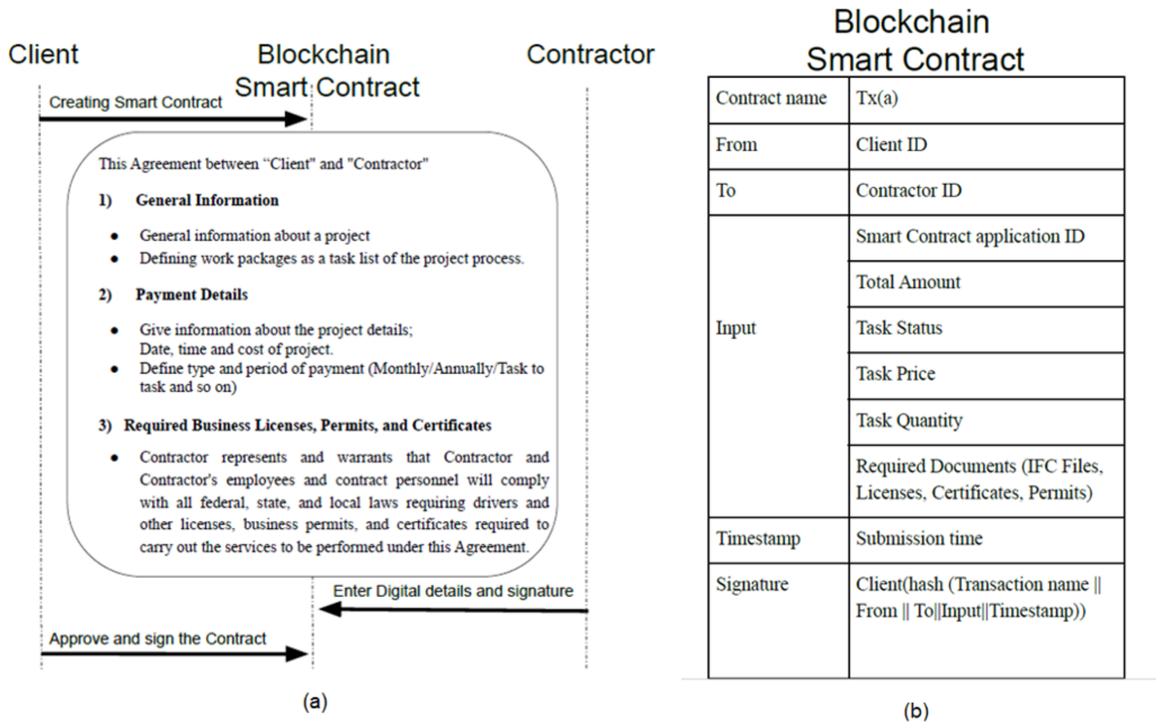
Four project disciplines were involved in the project trial, as listed below:

- Contractor: Costain
- Cost consultant: Lee Wakemans Ltd.
- Design Team: Capita
- Client: Highways England

The construction project being discussed is a bridge system with ancillaries and includes construction disciplines involved in the project's various phases.

Smart Contract

The transformation from a traditional contract to a smart contract and the subsequent operational details are shown in Figure 4.7. This figure provides an overview of how smart contracts operate within a blockchain system and highlights the following key aspects: (i) terms and conditions specification, (ii) coding under the determined condition in blockchain, (iii) conditions are met and the smart contract executes itself, (iv) outcomes are recorded in the blockchain, (v) authorities and users can analyse events.



Contract name	Tx(a)
From	Client ID
To	Contractor ID
Input	Smart Contract application ID
	Total Amount
	Task Status
	Task Price
	Task Quantity
	Required Documents (IFC Files, Licenses, Certificates, Permits)
Timestamp	Submission time
Signature	Client(hash (Transaction name || From || To||Input||Timestamp))

Figure 4.7: Example of a) traditional contract type and b) smart contract type [285]

To create a smart contract, the involved parties must first define their objectives and agree on the expected outcomes. These objectives may involve potential value exchanges, including goods or services. Each party, or discipline, adjusts the parameters and requirements that need to be met for a transaction to occur.

All specifications and contract clauses are translated into computer logic and programmatically coded. Once coded, the smart contract is deployed to the blockchain. It will then automatically execute itself when the pre-defined conditions are triggered.

Users need external accounts to launch the smart contract, initiating transactions with a contract account. This transaction is authenticated using the initiator's private key and is then forwarded to other blockchain nodes. Other users can verify the validity of the transaction using the public key, ensuring the initiator is the entity that activated the contract.

When a consensus is achieved from the majority of nodes in the network, the transaction will be added to the ledger, the smart contract will be executed, and the results will be registered. As the status of the blockchain changes over time, it is modified on all network nodes, and the outcomes cannot be altered. Due to the computational resources needed to manage the proof-of-business framework, any transaction that causes a change of status in the Ethereum blockchain requires a transaction fee. The transaction launcher pays in Ethers, which are part of Ethereum's local value network.

BIM Work Packages in Construction Management

BIM work packages are essential to the construction management process, providing stakeholders with detailed instructions, timelines, material quantities, cost estimates, and other relevant data necessary for task execution. These packages serve as guides that summarize the scope of work, making it easier for contractors and subcontractors to coordinate. By breaking down each task or project component, BIM work packages help ensure the project adheres to both requirements and timelines.

Additionally, they promote transparency, allowing all involved parties to understand their roles and responsibilities, ultimately contributing to the successful completion of the project. Tools such as Synchro and Costx are commonly used to create BIM work packages, factoring in transaction dates and costs, as depicted in Figure 4.8. These packages divide the construction process into manageable digital sections, simplifying job tracking, recruitment, and payment processes.

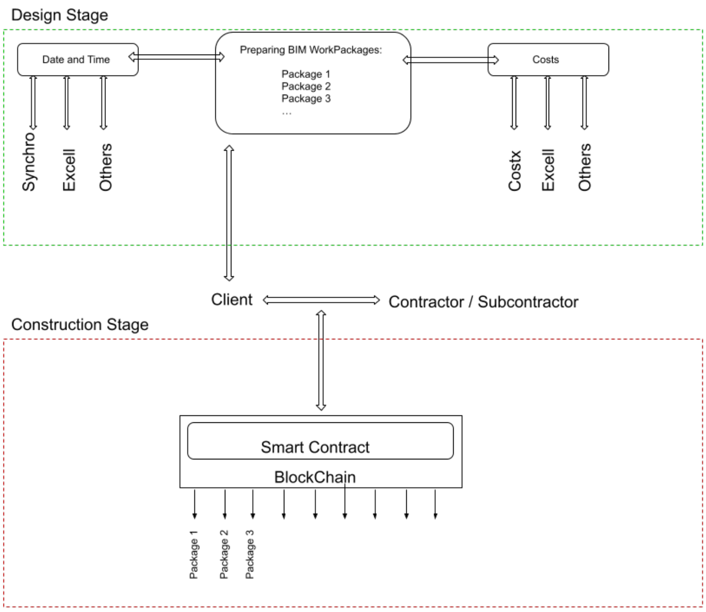


Figure 4.8: Preparing a BIM work package

Trial and Validation

In this subsection, the entire blockchain scenario is presented, including disciplines and implementations which were delivered within the project trial, as shown in Figure 4.9.

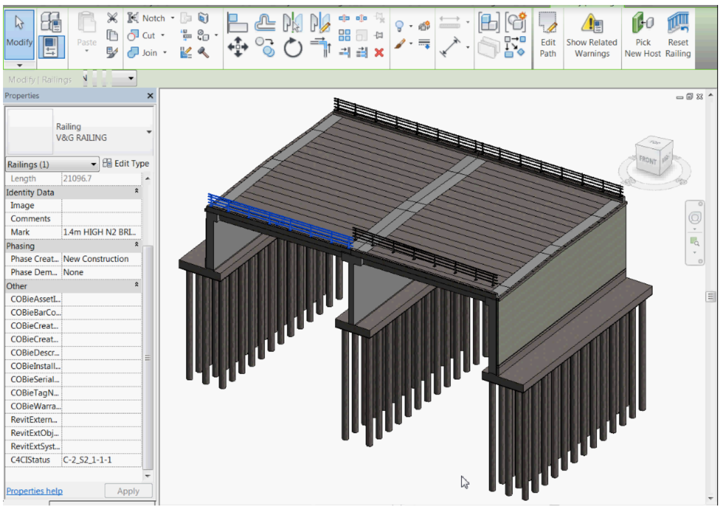


Figure 4.9: The bridge design model

As stated, four disciplines are used with the following annotations: discipline C - xontractor, discipline Q — cost consultant, discipline E — design team, and discipline O — client.

Smart contracts experiment

Ethereum serves as a basic platform for the creation and execution of smart contracts, allowing us to create smart contracts. Smart contracts are programmable agreements that automate transactions based on predefined conditions. To facilitate the development of these contracts, Ethereum provides a set of tools, including the Remix compiler. This compiler is effective in simulating the deployment of smart contracts and enables real-time debugging, allowing developers to review and refine all of the contract's elements as they write code.

In this trial, data blocks are used for transactions, with hash data signed using a digital signature from the relevant discipline. In addition, a hash is used as a function that decodes the data of the current block, including the signature and creation details of the process that connect the blocks in the blockchain. When a new block is created, the hash of the previous block is combined with the current block's data, and a new hash is generated and signed with the user's digital signature.

Step 1 – Instalments: To run the Ethereum network, users need to register because the Ethereum network is a peer-to-peer network where one or more users validate blocks in order to operate the first network. In this case, the blockchain network has a set of rules for the first block, also known as the genesis block. The genesis.json file provides a description of the Ethereum network. To start the network, a client ID was created in the P2P network, followed by the setup of a wallet for processing transactions. The network is initiated and triggered in the following phase. The next step is to build a smart contract. To continue this operation, a contract should first be written and compiled.

Step 2 - Discipline A (Architect): "Discipline A" has been registered into the system with its unique blockchain ID and created a first bridge BIM model. All changes on the model are recorded to the blockchain as seen in Table 4.1, which shows the first grid drawing after system records.

Step 3 - Discipline S (Structural Engineer): The IFC file (A556-CAP-7000-S06-3D-S-1001.ifc) is shared with the structural design team and the blockchain is configured to

Table 4.1: Recording design data to blockchain

Contract	Architect
Input	First x-axis grid created
Hash	a1075db5s54ysd9w86...
Timestamp	01.11.2020 - 9:30
Previous Block	0000000000074asd56...
New Block	0000000000074dff43a...

keep consistent records, as shown in Table 4.2.

Table 4.2: IFC file sharing between the design team

Contract	Architect to Structural Engineer
Input	A556-CAP-7000-S06-3D-S-1001.ifc file shared with the Structural Engineer
Hash	s4033d35s54ysd9w86...
Timestamp	01.02.2021 - 13:48
Previous Block	0000000000085s3d56...
New Block	0000000000085dff43a...

"Discipline S" starts to analyze the architectural drawing and to develop the structural design. During all of these stages, every step of the design and files shared between design teams have been recorded into the blockchain network.

Step 4 - Discipline C (Client): The IFC file can be shared with "Discipline C" at the same time to monitor the task process and to monitor the payment transactions. The blockchain allows monitoring and tracking of the design data, as well as document records and file sharing between design teams, at any time.

In the trial illustrated in Figure 4.10a, a smart contract has been created for the architect, structural engineer, and other design team to upload and change design records. A function has been specified to edit the variables when necessary, which only the design team was allowed to use for editing when a certain condition is met. The function was created at the end to capture the previous events and the return the design's records, as well as the design team's address. In Figure 4.10b, it can be seen that the smart contract was successfully executed.

```
pragma solidity ^0.4.16;
contract designRecord {
    bytes32 public designRecords;
    mapping(address => uint) public records;
    address public architect;
    address public structural;
    address public mep;

    function Person () private {
        architect=msg.sender;
        structural=msg.sender;
        mep=msg.sender;
    }
    function setdesignRecords(bytes32 _designRecords)
public {
        designRecords = _designRecords;
    }
    event Design(bytes32 _designRecords, address
architect, address structural, address mep);
    modifier rightPerson {
        require (msg.sender == architect);
        require (msg.sender == structural);
        require (msg.sender == mep);
        _;
    }
    function getRecords()public payable{
        emit Design (designRecords, architect,
structural, mep);
    }
}
```

(a)

(b)

Figure 4.10: a) Smart contract design records on Ethereum Remix. b) Execution of a smart contract

Prerequisites

In this work, IFC metadata is used to facilitate data transfers and encryption using hash data and digital signatures. The metadata in each block is encoded using a hash function that encapsulates information such as digital signatures and links between blocks in the blockchain. When a new block is created in the database, the previous block's hash value is combined with the properties of the latest block to create a new hash, which is then signed using the user's digital signature.

Step 0 – Instalments: To run the Ethereum network, users need to first register with the network, and initiate the first chain. The blockchain network has a set of rules for the first block, also known as the genesis block. The Genesis.json file explains the Ethereum network. To start the network fully, a client ID is created in the P2P network, followed by the wallet that will be used to process the transactions. The network is started and the next step is to create a smart contract to be written and compiled.

Step 1 - Discipline E: The process begins with "Discipline E", which generates a first bridge BIM model and uses the Data Management Systems (DDS) viewer to export it to the .ifc file to display concept, functionality, and ownership. Since Discipline E developed the model, the discipline uploads the file "A556-CAP-7000-S06-3D-S-1001.ifc" and shares it with stakeholders.

Step 2 - Discipline O: "Discipline O" converts the prepared work package or tasks to the computer code for smart contracts. For this trial, 8.1.1 - Clearing vegetation task has been selected to code for the smart contract, as demonstrated in Table 4.3.

Table 4.3: Example of the Bridge model's external works prepared as a Work Package - 8

Bridge Model - Package 8	**Quantity**	**Cost**
EXTERNAL WORKS		**639,735.84**
8.1 – Site Preparation		**2,523.30**
8.1.1 – Cleaning vegetation	504.66 m^2	2,523.30
8.2 – Fencing, Railing and Walls		**37,325.00**
8.2.1 – Walls and Screens	29.86 m	14,930.00
8.2.2 – Retaining Walls	29.86 m	22,395.00
8.3 – Piling		**574,558.54**
8.3.1 – Piling mats/ platforms	179.18 m^2	89,590.00
8.3.2 – Piling plant	1.00 IT	16,000.00
8.3.3 – Piles	104.00 Nr	188,240.00
8.3.4 – Disposal of exc. mat	1,190.02 m^3	35,700.60
8.3.5 – Cutting off tops on concrete piles	1.00 IT	3,120.00
8.3.6 – Pile tests	5.20 Nr	44,200.00
8.3.7 – Vibro-compacted columns	104.00 Nr	1,560.00
8.3.8 – Pile Caps	3 Nr	196,147.94
8.4 – Barriers and guardrails		**25,329.00**
8.4.1 – Vehicle restraint systems	84.43 m	25,329.00

Step 3 - Discipline C: "Discipline C" works on-site, attempts to complete the task, and checks the working process. When the contract "Cleaning vegetation" finishes, "Discipline C" updates the BIM model, the smart contract will automatically run, and notifications are circulated to related disciplines.

Step 4 - Discipline O: Taking an overview. "Discipline O" checks the BIM model and confirms the smart contract to record the final IFC file "A556-CAP-7000-S06-3D-S-1001.ifc" to the blockchain. Then, the amount specified by the payment transaction is released, as presented in Table 4.4.

Table 4.4: Work package into codes for the smart contract

Contract name	**Bridge Model - Package 8 (External Works)**
From	(Client ID)
To	(Contractor ID)
Input	**BIMPackage8**
	639,735.84 (Package total amount)
	(Package tasks) **8.1. Site Preparation** ☒ **8.2. Fencing, Railing and Walls** ☒ **8.3. Pilling** ☒ **8.4. Barriers and Guardrails** ☐
	A556-CAP-7000-S06-3D-S-100.ifc (Project file)
Signature	**Client(hash (BIMPackage8 || Client|| Contractor||Timestamp))**

The model proposed in this chapter demonstrates the use of blockchain technology in construction projects and its integration with BIM-based multidisciplinary collaboration. The new framework provides a solution for the construction industry, specifically addressing issues such as payment delays and contract disputes. By utilising smart contracts throughout the construction life cycle, tasks are systematically created and codified, resulting in a more streamlined and automated process. By incorporating smart contracts and timestamp recording into the ledger, potential disputes arising from contracts can be significantly reduced. The synergy between BIM and blockchain encourages enhanced collaboration between stakeholders in a highly secure environment, including clients, contractors, and subcontractors. This collaboration facilitates the sharing of trusted BIM data, thus encouraging cooperation while minimising third party involvement and associated costs.

Blockchain Deployment

The smart contract enables the creation, storage, and retrieval of package structures, and provides a transparent and immutable method for tracking and managing work packages on the Ethereum blockchain.

Solidity, a language used to generate smart contracts on the Ethereum network, is used to create a smart contract for the "BIMPackage8" workpackage (see Appendix B.1.). The contract includes a user-defined data structure named "Package" that contains the information associated with a work package. The Package structure has many elements, including "sender" and "receiver", which are strings used to hold the Ethereum addresses of the work package's sender and receiver, respectively. In addition, the structure comprises a "name" text field that stores the name of the work package and an "amount" that stores the financial value of the work package. In addition, the "projectFile" element is a string that provides the location of the project file affiliated with the work package. The last field, "completed," is a Boolean value that indicates whether the work package has been completed.

The code has been run inside the Remix environment and is seen to work as predicted, based on the code's specification of intended behaviour. The successful execution of the code in the Remix environment may be seen as evidence that the code is functional and prepared for deployment on the Ethereum blockchain, as can be seen in Listing 4.1.

Listing 4.1: Example of the successful execution of the smart contract

```
{
"string _sender": "0x5B38Da6a701c568545dCfcB03FcB875f56beddC4",
"string _receiver": "0xf8e81D47203A594245E36C48e151709F0C19fBe8",
"string _name": "BIMPackage8",
"uint256 _amount": "639735",
"string _projectFile": "A556-CAP-7000-S06-3D-S-1001.ifc"
}
```

In Listing 4.2, the "topic" entry is a string representing the event's unique identification, which is used to specify the event type. The "event" parameter is a string that records the event's name, "PackageCompleted" in this case. After the tasks are completed, the smart contract is automatically executed and the package is successfully completed.

The listing provided in the code may be used to indicate an event that has been produced by a smart contract, including information about the event's origin, its type, and any relevant parameters. This enables other parties to respond to and analyse the data provided by the blockchain network, offering a method to track and monitor the contract's status.

Listing 4.2: Example of the execution of smart contract when the workpackage completed


```
{
"from": "0xf8e81D47203A594245E36C48e151709F0C19fBe8",
"topic": "0x61056d12ef421e98b7b702b8ff2015dbad4b45ef362e58eb0b59e2fdcbfe2b39",
"event": "PackageCompleted",
"args": {
        "0": "0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2",
        "1": "",
        "packageAddress": "0xAb8483F64d9C6d1EcF9b849Ae677dD3315835cb2",
        "packageName": ""
    }
}
```


In Listing 4.3, the smart contract emits the event "PackageDueDateExecuted," which contains information about the package whose due date has arrived. The event receives the package address and package name as inputs, which may be used to identify the package that has passed its due date. This event may be used to initiate various actions, such as altering the package's status or alerting the appropriate parties that the package's due date has passed.

Listing 4.3: Example of the smart contract execution on work package deadline


```
{
"from": "0xf8e81D47203A594245E36C48e151709F0C19fBe8",
"topic": "0xb04ed2344cc68716471b1d42367e0fd3d3c911a465219fdda504ede34d5c383e",
"event": "PackageDueDateExecuted",
"args": {
        "0": "0x5B38Da6a701c568545dCfcB03FcB875f56beddC4",
        "1": "BIMPackage8",
        "packageAddress": "0x5B38Da6a701c568545dCfcB03FcB875f56beddC4",
        "packageName": "BIMPackage8"
        }
}
```

4.4.2 Scenario 1: Experimental Results

This study conducted within the Remix IDE established a testing environment to emulate real-world scenarios encountered in construction projects. Within this environment, interactions and transactions involving key stakeholders such as clients, architects, structural engineers, and MEP engineers were analyzed. Smart contracts were leveraged to facilitate the execution of these transactions and interactions. Data was collected throughout the iterative testing process to assess the performance and cost-effectiveness of these transactions. In addition, the deployment of smart contracts was facilitated, and their functionality was closely monitored in the simulated environment. These insights played an important role in improving and optimising processes and systems, ultimately leading to improvements in both efficiency and effectiveness. During the test, a total of 81 transactions were executed amongst the various disciplines (Figure 4.11 indicates that there are 51 transactions because some transactions happen simultaneously with different transactions.) These exchanges were recorded, and the resulting data was evaluated to determine the overall gas price associated with the interactions. The gas price is a measure of the cost of completing an Ethereum blockchain transaction, and it is commonly calculated in Wei, the smallest unit of Ethereum.

The smart contract has a certain allowance of gas spent depending on the number of actions performed and the gas price of the requested codes. The smart contract has no standard fixed conversion price; determining any gas price depends on the sender and the code quality. According to the test findings, the total price of gas associated with the 81 activities was 6270082 Wei. This sum of Wei may be translated into other Ethereum units, such as Ether, for easy comparison. In this case, it is indicated that 6270082 Wei is equal to 0.00006270082 Ethereum, and the value to US dollars using the current exchange rate is 0.0013140164 US dollars (1 Ethereum = 209.817 US dollar, 13.01.2023). The completion cost for the workpackage (BIMPackage8) is given with the interactions in Figure 4.11

The proposed model demonstrates the use of blockchain in construction projects and

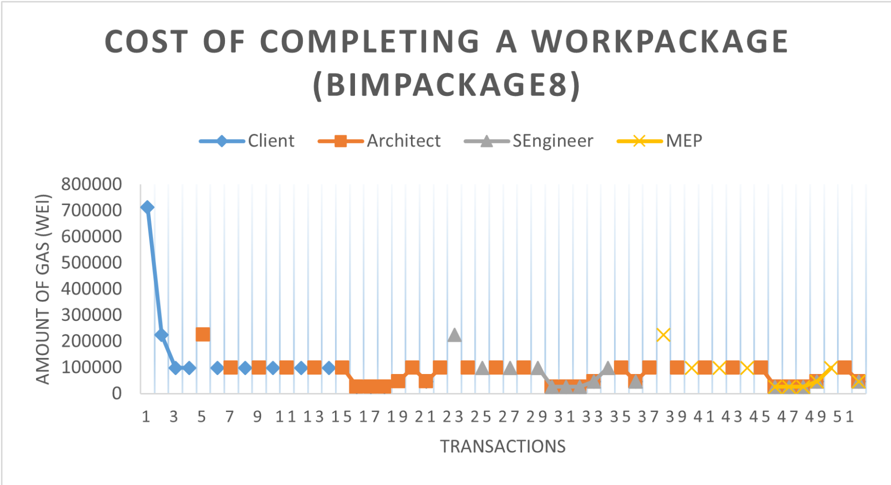


Figure 4.11: Workpackage (BIMPackage8) completion cost

its contribution to BIM-based multidisciplinary collaboration. It provides a framework applicable to the construction industry that addresses payment delays and contract disputes. Smart contracts are utilized throughout the construction process, with tasks created and coded based on these contracts to enhance functionality and automation. With the smart contract and the time stamp registration in the ledger, disputes arising from the contract can be minimised. BIM and blockchain will strengthen collaboration through highly secure interactions between clients, contractors, and subcontractors, and provide reliable information and a BIM data sharing ecosystem. This can further strengthen cooperation between all stakeholders by eliminating third parties and minimising costs.

4.4.3 Scenario 2: Blockchain-Enabled BIM Data Provenance

The assessment was conducted with data and models from the bridge project, which again involved multidisciplinary collaboration for the highway construction project as in Scenario 1. Figure 4.12 depicts the network architecture of the blockchain-based BIM project environment.

The following part introduces a complete BIM model integration based on blockchain throughout the bridge's design phase.

- Discipline A – Architect

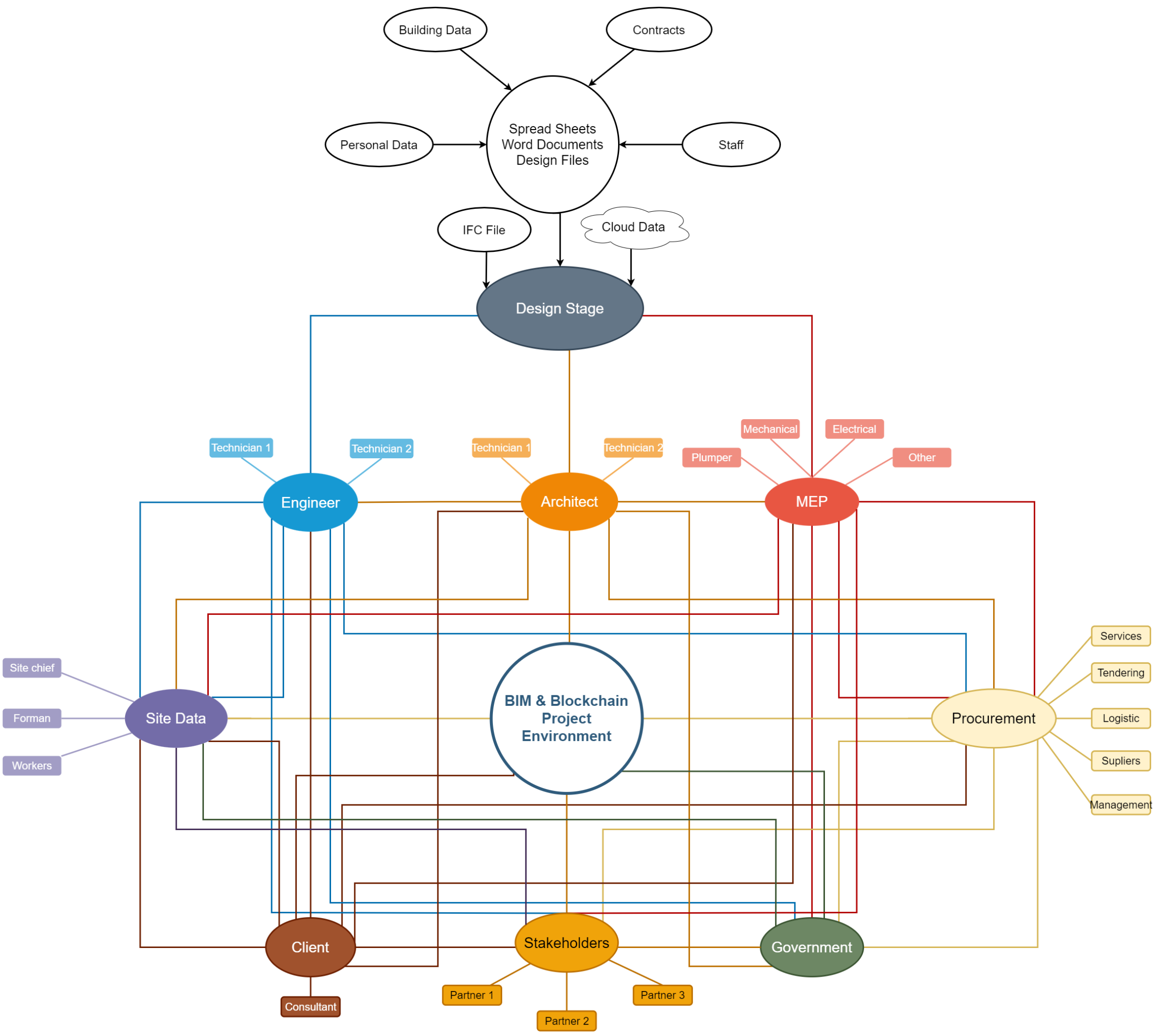


Figure 4.12: Blockchain-based BIM project environment

- Discipline Aa – Architect assistant1
- Discipline Ab – Architect assistant2
- Discipline S - Structural Engineer
- Discipline C - Client
- Discipline M – MEP

Step 0 - "Discipline A," "Discipline S," "Discipline C," and "Discipline M" have been registered into the blockchain system and get their unique blockchain IDs. All changes and activities made to the BIM environment and the model will be recorded on the blockchain. Each discipline, such as “Discipline A”, can have more users, such as “Discipline Aa” and “Discipline Ab”.

Step 1—Discipline C (Client): "Discipline C" has been created for the first block and proceeded with registering the first entity, "Discipline A". Discipline A will create the model "Bridge BIM IFC file" on the blockchain network and continue to record all design changes on the blockchain system.

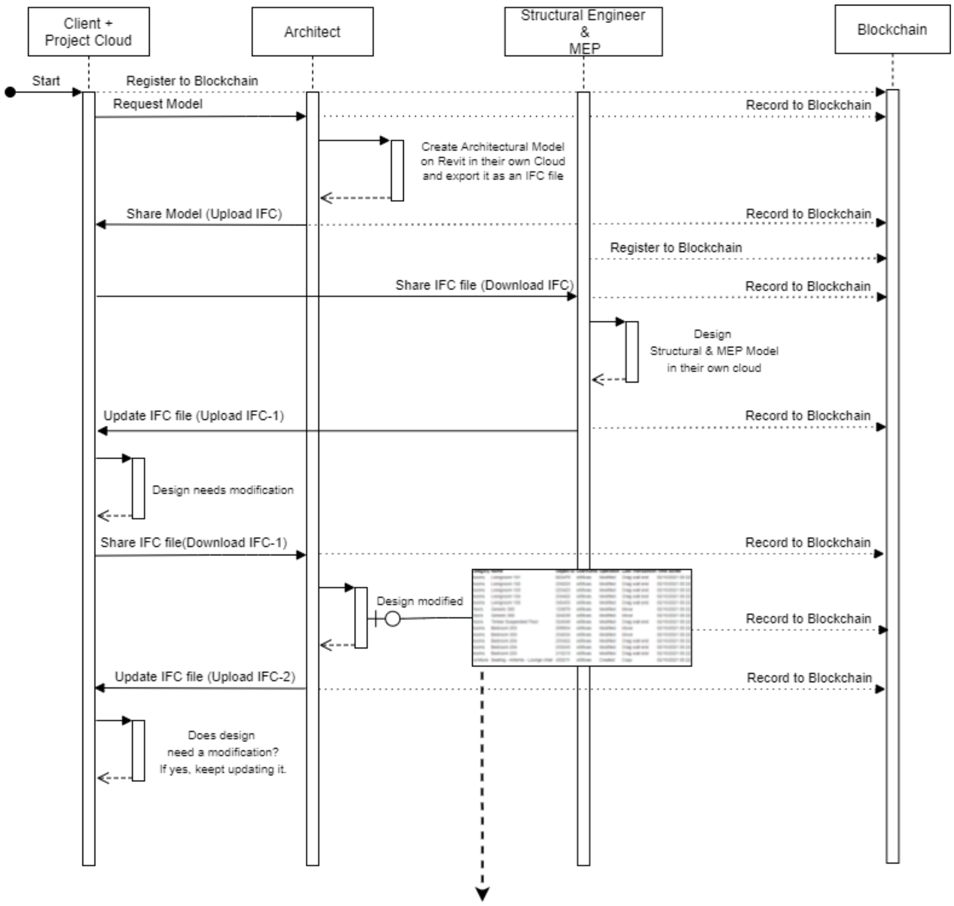
Step 2 - Discipline S (Structural Engineer): The created IFC file (A556-CAP-7000-S06-3D-S-1001.ifc) will be shared with the structural design team by “Discipline A”. The blockchain is configured to keep consistent records on the network. "Discipline S" will start to analyse the architectural drawing and develop the structural design. The IFC file will be shared with "Discipline S", which will start working with the IFC document as a drawing structural design with changes to be recorded in the blockchain network. During all of these stages, every step of the design and file share between design teams is recorded in the blockchain network.

Step 3—Discipline C (Client): When "Discipline A" takes the final design from "Discipline S," "Discipline A" will share it with "Discipline M" (or "Discipline S" will share it with "Discipline M"). The final IFC file from "Discipline A" will be shared with “Discipline C” at the same time to monitor the task process and any data transactions.

Step 4—Discipline A(Architect): “Discipline C” wants to change the electrical box on the drawings at the end of the process using the IFC file. “Discipline C” will send the IFC file to “Discipline A”. “Discipline A” will send the file to “Discipline M”. “Discipline M” will change the box and send it to “Discipline A”, and “Discipline A” will send it to “Discipline C”.

General assumptions involved in the design process

Considering a general project design process, the disciplines involved in the process are first recorded on the blockchain and included in the process. After registration, the disciplines create their design and share it with the client. Any information exchange or activity that occurs with the main "Project" will be recorded directly in the blockchain system. Furthermore, any changes to the IFC file will be stored in the blockchain system, as illustrated in Figure 4.13.



Category	Name	Object ID	Username	Operation	Last Transaction	Time Saved
Structural Column	Column 101	823479	si58vas	Modified	Drag column end	02/10/2021 00:22
Structural Column	Column 102	734223	si58vas	Modified	Drag column end	02/10/2021 00:22
Structural Column	Column 103	564422	si58vas	Modified	Drag column end	02/10/2021 00:22
Structural Column	Column 104	645433	si58vas	Modified	Drag column end	02/10/2021 00:22
Base	Span 1	324123	si58vas	Modified	Move	02/10/2021 00:23
Base	Span 2	321547	si58vas	Modified	Move	02/10/2021 00:23
Base	Girder 1	453265	si58vas	Created	Copy	02/10/2021 00:23

Figure 4.13: The process of provenance records with design discipline

Data Provenance Contracts

The Remix platform is used to facilitate the compilation and deployment of smart contracts. Remix is an Ethereum Solidity development platform that facilitates the development of smart contracts. Dapp is another platform that was used to allow interaction with smart contracts through front-end web pages. To create the front-end web page's interaction, a front-end JavaScript interface to connect the front-end page with the blockchain system was constructed (Appendix C.1). The UI interface allows users to engage with contracts, including deploying new contracts and methods of the contract, such as writing or retrieving blockchain data. The Remix platform is used to deploy a single contract for system testing and smart contract verification. For the testing phase, contracts and transmit transactions across the Kovantest network were installed. Local memory was invoked only on the developer device to verify operations and provide execution results quickly in real time. Before deploying the smart contract on the Ethereum mainnet, its code was tested on a Kovan testnet . Three smart contracts are used to implement the blockchain-based BIM provenance model for the case study presented in this section.

The smart contract for new user/actor/discipline registration: It is considered that each contract is identified with the contract's object number, which is maintained in a mapping connection to the updated contract address. The contract is created or updated for each discipline so that other nodes may see all discipline records by using the `newUser()` function (see Appendix C.1.2).

The smart contract for object or input registration: The contract serves as a means of registering objects and displaying all objects that have been registered. Once other nodes are registered to the system, registered objects can be viewed through the network using the `newObject()` and `Input()` functions (see Appendix C.1.3).

Updating smart contract with users and actors: The object provenance model is implemented via the first contract. Every transaction should be recorded in the contract after the disciplines are recorded on the blockchain platform. With the `updateUser()` and `updateObject()` functions, the final User/Client may see the whole history of transactions for the object in use and may update the role of the users (see Appendix C.1.4).

Implementation Process:

- The smart contract was implemented using the Solidity programming language with the truffle infrastructure and a public blockchain designated Ganache system with truffle console was used to interact with the back-end of the system. After the back-end server was built, the front-end website was developed and deployed to interact with the contract's functions and record the data provenance. The server-side code using Node.JS was implemented with a front-end interface that supports retrieving data provenance from the database rather than the blockchain. Contracts have been installed to allow users to utilise the system for data provenance activities.

Deployment Process:

- The Ethereum public Kovan test network with an existing blockchain Metamask wallet was used in order to deploy the experimental scenarios. Ganache was used to obtain Ether (ETH) for the purpose of testing an application and the address was broadcast on the Kovan testnet. The Solidity integrated development environment (IDE) and Remix are used to develop and deploy smart contracts with a truffle test to validate the existence of the address on the Kovan test network.

Data Provenance Authentication

All disciplines are registered in the network as illustrated in Figure 4.14. The client then requests architectural drawings from the registered architect through the system. The architect shares the file with his design team. Because the file's hash code will be uploaded to the blockchain system, the file activities and provenance are recorded in a provenance database. Following that, the client requests the agreement to be validated using a blockchain query to see whether the requirements of the smart contract are met. The authenticator verifies this process on the blockchain and if the smart contract requirements are met, blockchain verification generates a proof of data by updating the provenance data stored.

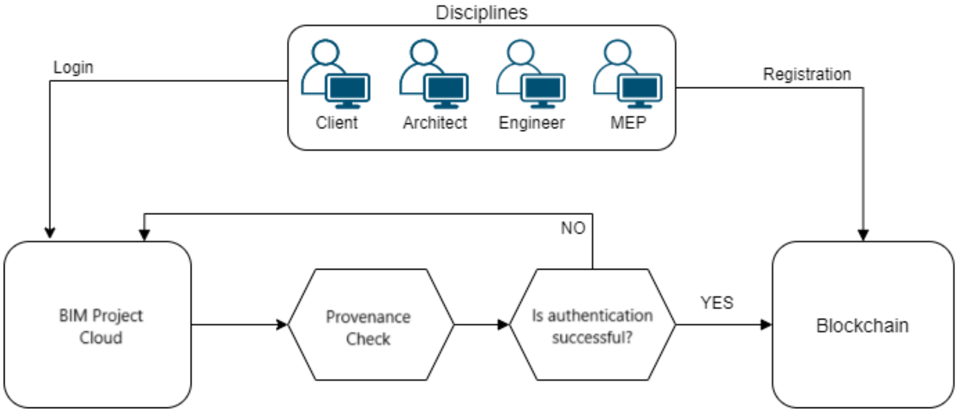


Figure 4.14: The general structure of provenance record to blockchain

Data Provenance Verification

The BIM data associated with the design elements are available chronologically in each version of the model, including where the project was used, who updated it, and when it was modified. This provides the capability to determine which data were requested and shared and whether they were approved. An immutable ledger will be accessed whenever an architect or member of any other discipline makes a modification or performs a task. Disciplines will be able to access object information over the blockchain network by referencing the unique Object ID. This enables information to be accessible throughout the project's duration or at the end of the project. As input, the object's details may be retrieved by inputting the BIM Model ID, the Object ID, and, if requested, the discipline ID allowing access to historical records for the desired object over the blockchain network. Several operations for a BIM object are considered for the verification process, allowing the disciplines to:

- Check the details about an object, operation and time.
- Access specific information on where an object is used in the process, as well as the history of an object throughout the project's life cycle.
- Retrieve the details of an object that was manipulated by one of the disciplines throughout the project life cycle.

4.4.4 Scenario 2: Experimental Results

A prototype was implemented for the framework using an Ethereum blockchain virtual machine, which provides a public blockchain network. Ethereum uses a browser-based compiler called Remix-IDE for writing and compiling smart contracts. The Solidity language has been applied to implement the contracts.

Two smart contracts, named *provenance* and *verification*, are proposed for logging and verifying the information relevant to the disciplines, actors, and objects. The former contract stores the discipline, objects, operations, time of actions, actors, and versions of updates into a blockchain network. The verification contract verifies (i) the objects created/ manipulated by an actor, (ii) the operations of an actor on an object and the time of each operation of an actor on the object, and (iii) the updated versions on an object which actors modify. The deployment costs of both smart contracts are investigated using an Ethereum public blockchain test network (Kovan). The amount of gas used for deploying *provenance* and *verification* contracts are 854979 *wei* and 767248 *wei*, respectively. The transaction costs relevant to the proposed verification depend on the number of involved entities (e.g. objects, actors etc.) that should be investigated within a construction project. To this end, the functions/ transactions of the *verification* contract will be executed and the costs will be evaluated according to various parameters.

Verification of Operations

This experiment investigates the costs required for verifying an actor's executed operation on an object and the exact time when the operation has been executed by changing the number of operations. The assumption is that the number of operations varies from 5 to 30.

The Kovan testnet, a public testnet on the Ethereum blockchain, was used to get the transaction costs and mining time. Kovan is an Ethereum-based PoA blockchain that is publicly accessible. This testnet is the closest to the actual performance of the Ethereum blockchain.Each result was calculated after five executions of the transactions with different parameters to reach an average data. Table 4.5 gives the details about the average verification costs and mining time. When the number of operations increases, the amount of consumed gas increases steadily. To get the average mining time for the verification, the results with different gas price units ranging from 10 to 30 *Gwei* were evaluated.

Table 4.5: Verifying operations and transaction costs

	Number of operations						Mining time
	5	10	15	20	25	30	-
Used gas (wei)	194235	388470	582615	776800	970125	1165410	-
Gas price=10	0.003	0.007	0.01	0.014	0.017	0.02	1477
Gas price=20	0.004	0.008	0.011	0.015	0.019	0.023	294
Gas price=30	0.005	0.011	0.017	0.023	0.029	0.035	25

Given a fixed gas price unit, the verification costs in ETH and mining time in seconds are provided. The visualisation of the mining time with the different gas prices is shown in Figure 4.15. The results indicate that the average mining time decreases sharply when the gas price unit increases. Higher gas price motivates the miners to run the transactions and create the blocks sooner.

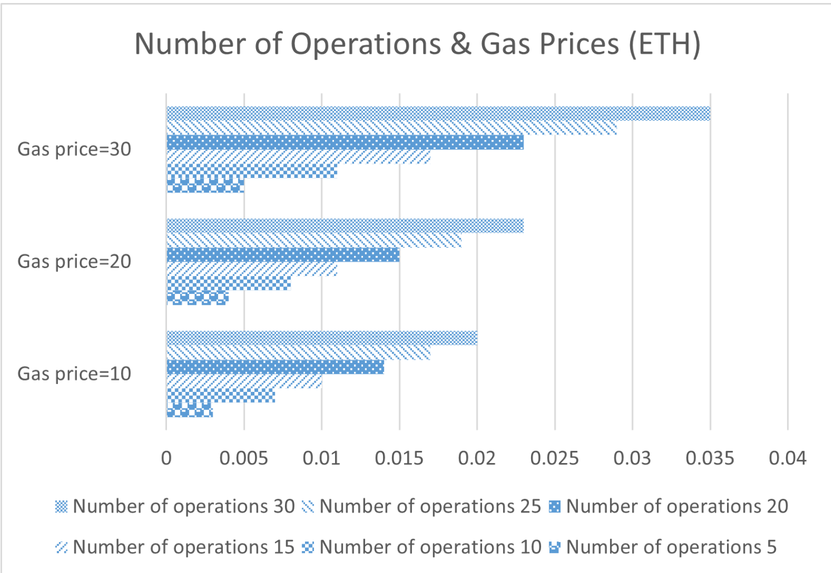


Figure 4.15: Comparison of number of operations & gas prices (ETH)

Verification of an Object's Updates

This experiment verifies an object's history during a project's life cycle. The history shows all the updates of an object that has been modified by the actor(s). By changing the number of updates for an object from 5 to 30, the experiment estimates the amount of gas used for checking the object's history. The rate of the gas price unit is assumed to be 20 Gwei, which is the average rate on the date of the experiment through Ethereum. Table 4.6 shows the experimental results. The amount of gas consumption and the costs of the transactions in both wei and ETH are provided, respectively. As represented, when the number of updates on an object increases, the cost of checking the history of the object increases gradually. It starts from almost 0.002 ETH and reaches nearly 0.005 ETH. The results were obtained after executing the transactions five times in Kovan with various parameters to get the average values. The mining time with the different gas prices is shown in Figure 4.16.

Table 4.6: Verifying an object's updates and transaction costs

Number of updates	5	10	15	20	25	30
Used gas (wei)	48033	62100	78241	93004	103000	121050
Average Cost (ETH)	0.0021	0.0027	0.0032	0.0041	0.0044	0.0053

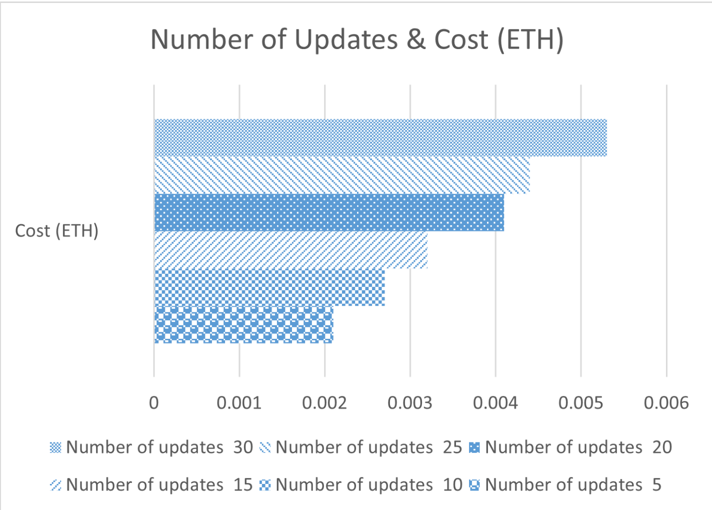


Figure 4.16: Comparison of number of updates & cost (ETH)

Verification of actors

By changing the number of actors working on or manipulating an object, this experiment investigates the costs required for retrieving the actors' details. The assumption is that the number of actors varies from 5 to 30. The gas price unit is 20 Gwei and the transactions are executed and deployed on the Kovan test network. The costs are calculated after execution five times with various parameters to get the average results. Table 4.7 shows the experimental results.

Table 4.7: Verifying actors and transaction costs

Number of actors	5	10	15	20	25	30
Used gas	55251	105920	150680	201902	250032	291230
Average Cost (ETH)	0.0011	0.0021	0.003	0.004	0.005	0.0058

When the number of actors increases, the gas consumed for the verification rises steadily. The table also provides the transaction costs of this verification in ETH. Figures 4.17 and 4.18 show how the gas fluctuates with the number of operations and updates identified in the smart contracts.

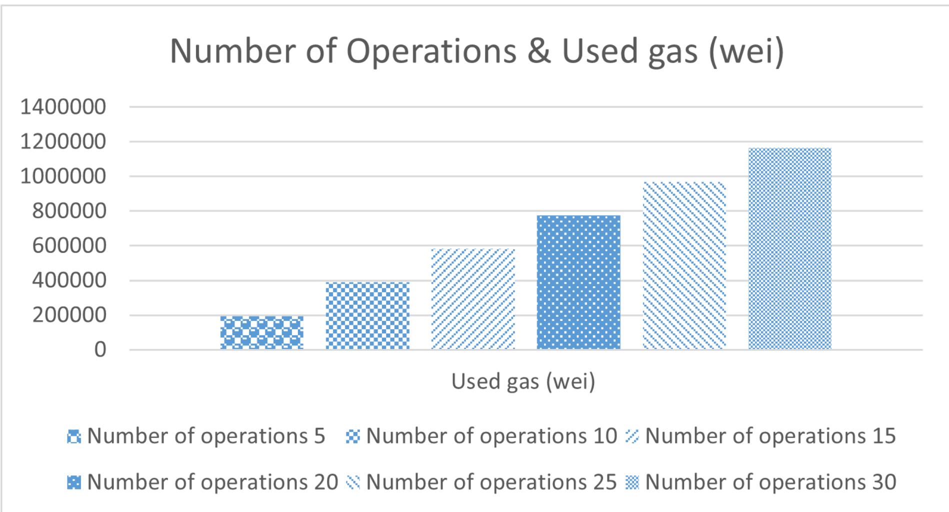


Figure 4.17: Comparing number of operations & gas used (wei)

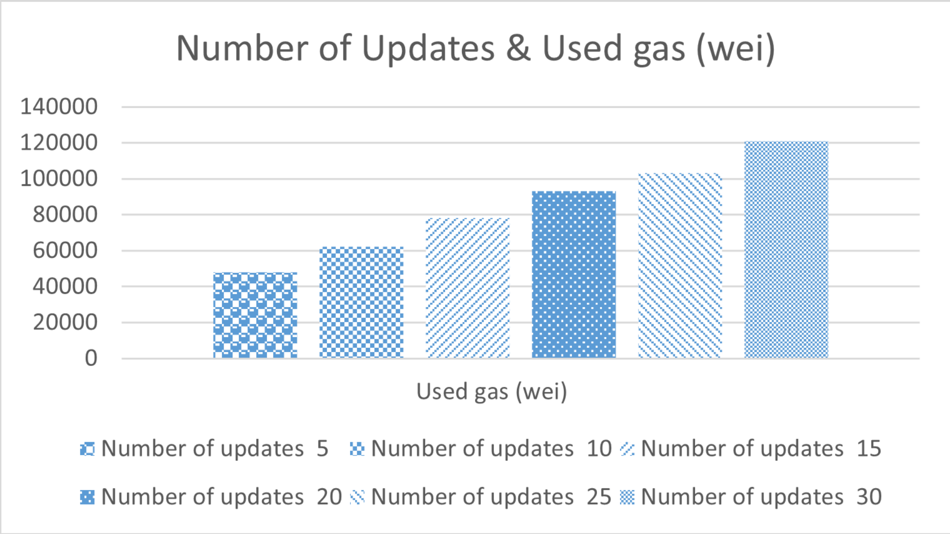


Figure 4.18: Comparing number of updates & gas used (wei)

4.5 Lessons Learned

Blockchain technology presents a single shared framework for construction companies to undertake project tasks along with other relevant financial transactions required to complete a project. Blockchain with associated BIM integration can contribute to market changes, which facilitates the ability to manipulate data between participants, and more reliable issue status and provenance records registered in the chain consistently. Based on the literature survey and trial outcomes, the following key aspects related to construction digitalization are identified:

Efficiency

The integration of blockchain technology into the construction industry, especially in combination with BIM, has led to measurable improvements in efficiency. Key lessons learnt include significantly reducing delays in procurement and development phases. Blockchain's role in reducing conflicts between BIM templates and design contractors has been particularly effective, with fewer inconsistencies and better transitions between project phases. A critical insight is the importance of limiting access to the blockchain environment to registered project participants such as architects, engineers, contractors and clients who can verify and update 'blocks'. This approach increased the general security and reliability of the process while providing traceable, time-stamped records of all design changes. These timestamps allowed stakeholders to monitor and track design updates in real time, preventing errors caused by outdated versions of drawings. This traceability has been a key efficiency metric, improving communication and decision-making timelines. In addition, the decentralised nature of the blockchain contributed to better workflows, particularly in the preparation and modification of drawings. The ability to track design changes in the pre-contract phase and updates in the post-contract phase reduced project delays and minimised regulatory overhead. The reduction of administrative tasks such as documentation and implementation has also become an efficiency advantage.

Data Security

Construction data is usually collected in a central repository and becomes subject to security implications. Sensitive building data must be protected by taking advantage of blockchain's ability to protect data integrity by connecting all pieces of data in the network together through an encrypted signature or private key [124]. Blockchain provides strong policies to protect information with the decentralisation of blocks distributed over a peer-to-peer system [334]. The network's authorisation system ensures that only registered participants can access and interact with the data, while the immutable registration scheme prevents any participant from changing or deleting information once it has been added to the blockchain. This combination strengthens data security and protects the integrity of information by ensuring that all changes are traceable and transparent. As a result, data privacy and security are accessible to all members as they can trust the system to prevent unauthorised changes or breaches.

Transparency and Trustworthiness

Every participant in a construction project can see the sequence of financial and nonfinancial transactions via the blockchain. The blockchain is open to all parties involved in the process, regardless of the nature of the data. The decentralised nature of blockchain encourages users to access the same expertise across systems [335]. As a result, participants have more consistency based on the traceable and immutable record, where users are more willing to enter into a legal smart contract and share their data safely in the BIM environment. Thus, when a blockchain implementation is being used in the construction industry, stakeholders do not need to establish a trust relationship because the automation of a smart contract process reduces trust risks.

Collaboration

Cultural and proximity-related challenges have historically impacted efforts to develop international construction in the modern industry. However, blockchain technology, with its global network of distributed locations and participants, facilitates co-operation between clients, contractors and suppliers in different geographical regions. This eliminates the need for third-party intermediaries, as blockchain provides a stable, reliable and efficient framework for collaboration and often enables such arrangements to be embedded in smart contract terms and regulations.

The integration of BIM and blockchain offers significant benefits, including improved responsiveness, reduced transaction times, lower costs, enhanced reliability and increased transparency, aimed at maximising the efficiency of the construction industry. Also, the existing literature points to a notable gap in the understanding of the importance, development, application and advantages related to the integration of BIM and blockchain and suggests an area for further research and exploration.

Costs

Clients in the building industry conduct business by central intermediaries such as banks and other financial institutions, or through selling real estate through an agent or broker. These third parties require payments to the client in return for supplying services and products. Incorporating blockchain into the construction industry allows customers to eliminate third parties and transaction fees [336]. Smart contracts and direct agreements between design suppliers, manufacturers and main contractors, as well as project clients, can allow for money saving with legislative contract documents [124]. Clients can save money on real estate agent charges by purchasing their properties via the blockchain system. Payment issues associated with conflicts can be minimised, and there would be no delays or nonpayment disputes in the smart contract. In general, blockchain implementation saves time and resources because all processes are automated and transparent [335]. Moreover, implementing blockchain into BIM could lead to more accurate and detailed drawing records, reducing the time needed to develop contract documents. This eliminates the need to deal with incorrect quantities and drawings and optimises the update process during redesign. In addition, blockchain's ability to facilitate precise reconstruction history contributes significantly to the traceability of operations and tasks in construction projects.

Smart contracts allow actions or clear instructions based on terms written in the code on the blockchain to be self-executed through the blockchain. The smart contract has a certain allowance of gas spent depending on the number of actions performed and the gas price of the requested codes. In general, any part of programmable computing (e.g. creating contracts, exchanging messages, accessing resources, and performing financial transactions) would mainly be specified and depending on how many Ethereum virtual machine instructions need to be executed, a request sent to the Ethereum network costs a certain amount of gas. The smart contract has no standard fixed conversion price; determining any gas price depends on the inputs and the codes.

The absence of a fixed price and the fact that any additional changes in the smart contract affect the amount of gas used do not allow us to make a precise price calculation, and hence no exact price has been specified in the trial project. The main focus was on the use of blockchain technology in the BIM process in the construction industry, with emphasis on time efficiency, capability to automate, and collaboration for construction projects. Variable costs in Ethereum have an impact on all businesses because the transaction cost of the smart contract is volatile with fluctuations from low to high costs. The unpredictability of a project cost determined by this price fluctuation may negatively influence decision makers when deciding to incorporate blockchain technology into their systems. On the other hand, Ethereum aims to enhance scalability and optimise the computational effort needed to validate transactions.

The potential of the proposed provenance framework to accelerate the construction process and ensure transparent monitoring and tracking of project tasks across disciplines is highlighted. The findings reveal that the costs associated with implementing smart contracts for provenance can fluctuate depending on the project scale and the number of disciplines involved. In addition, valuable insights are provided on the transformation of supply chain management and the realisation of digital construction, reflecting current areas of interest in this field.

The following sections present both theoretical and practical aspects of this integration.

Theoretical Implications:

The adoption of blockchain in the AEC industry is still in its infancy. However, many applications, journal papers, and site demonstrations are looking to pave the way toward a more feasible and informed adoption. This section aims to promote the integration of blockchain and BIM, making a thorough inventory based on a literature review and assessing implications for practitioners and decision-makers who want to gain an in-depth understanding of this state-of-the-art technology and its application in the construction industry. Because blockchain involves an open and multidisciplinary scope, this section aims to showcase the use of blockchain in a real construction project and disseminate knowledge to researchers and practitioners.

Practical Implications:

On the practical side, a use-case demonstration is created to illustrate the use of blockchain for construction projects, emphasizing usability and efficiency. This involves preparing a general implementation plan for the project lifecycle using the RIBA Plan of Work. Recognizing the need for a deeper understanding of blockchain technology among managers, practitioners, professionals, and decision-makers, a practical example and references are provided to offer an in-depth understanding of blockchain applications. This includes a roadmap for rethinking digitalization strategies in the construction sector. The literature review highlights leading issues in the construction industry, such as task management, information sharing delays, and contract conflicts. Integrating work packages into smart contracts can enhance functionality and time efficiency. BIM and blockchain are argued to strengthen collaboration between clients, contractors, and subcontractors, improving resilience for multi-disciplinary collaboration at various construction stages.

In addition, the traceable and immutable data transfer facilitated by blockchain instils trust among stakeholders, thus enabling informed decision-making during construction. Smart contracts that can manage agreements, operations, and transactions streamline processes and increase reliability, especially when there is data dependency on the project. Leveraging blockchain integration with BIM data provenance supports the creation of more reliable provenance records, which is critical for protecting sensitive construction data that is often centralised.

4.6 Summary

This chapter addresses the integration of blockchain technology and BIM to enhance various aspects of construction projects, including safety, cost-effectiveness, sustainability, and automation. By examining a real-world bridge project, the chapter explores how blockchain technology can be integrated into the construction industry, with a particular focus on simulating the implementation of smart contracts. Leveraging existing academic literature, a blockchain-based BIM environment model is presented, aimed at streamlining construction collaboration processes and promoting secure and transparent transactions while automating project management tasks. The effectiveness of this model is validated through its application in a real construction project, highlighting the potential benefits of integrating blockchain and BIM in creating a collaborative and secure construction environment.

This chapter presents the development of a blockchain-based BIM data provenance model that aims to improve traceability and transparency in construction projects. Through an empirical analysis of a real construction project, the effectiveness of the blockchain data provenance framework is demonstrated, highlighting its ability to continuously track disciplinary actions and build trust through traceable and immutable data exchange. This approach is expected to prevent data loss, streamline data processing, eliminate redundant documentation, and increase transparency, ultimately improving communication, reducing documentation overload, and promoting transparency among stakeholders in the construction ecosystem. Overall, the integration of blockchain technology into the BIM environment promises to drive progress and innovation in the industry, ushering in a more digital and efficient construction ecosystem that is characterised by improved productivity, sustainability, and automation.

Next Chapter: Blockchain for Energy Management in Buildings

The chapter introduces a blockchain based auditable energy sensing and control model, validated through a case study on energy monitoring in an office spaces in Queen's Building at Cardiff University. By analyzing two scenarios, the proposed model demonstrates the cost-effectiveness and transparency for energy sensing of periodically (15 minutes, 2 hours, 6 hours and 12 hours) recording energy data in a blockchain framework.

Chapter 5

Blockchain for Energy Management in Buildings

This chapter addresses the RQ3 research question and its connected objective, exploring how blockchain technology can facilitate technological innovation in building energy management. This chapter presents a blockchain model designed to enhance energy sensing and control, which is demonstrated through a case study of energy monitoring in office spaces and buildings. It discusses the benefits of this innovative approach, including improved energy efficiency and transparency of energy consumption. The case study validates the effectiveness of blockchain-based energy management in real-world building environments, highlighting its potential to advance sustainable energy goals. Through this investigation, this chapter contributes to the development of practical solutions for auditable energy sensing and control systems with blockchain for better energy management practices in construction projects, and offers insights derived from the analysis.

5.1 Context of the Research

The context of the research highlights the importance of sustainability and efficiency in energy management in buildings and highlights the limitations of traditional methodologies in capturing, analysing, and securing energy consumption data. The integration of blockchain technology shows promise in redefining energy data management for buildings by addressing concerns such as data integrity, vulnerabilities, lack of transparency, and real time consideration.

The research objectives include developing an energy sensing and controlling solution using blockchain to prioritise the security and privacy of data, provide real-world proof of feasibility, and address scalability issues. This chapter presents a thorough case study that explores the cost implications associated with the regular recording of energy consumption data in buildings securely stored on blockchain. Two scenarios are explored to demonstrate the transformative potential of blockchain technology in supporting energy management in buildings. The first scenario focuses on improving energy efficiency in a specific building, while the second scenario extends to a city-level context involving multiple buildings in a blockchain network.

The application of blockchain technology in this chapter is based on three main objectives. First, blockchain is used to manage the originality and authenticity of energy data published by IoT devices, covering both light-weight (sensor, actuator) and full nodes (gateway). This ensures that the data generated by these devices remain tamper-proof and trustworthy, which is essential to protect the integrity of the entire system. Second, the integration of blockchain aims to increase transparency within the ecosystem. By leveraging the blockchain, energy control measurements from smart devices are made publicly accessible. This provides stakeholders with real-time access to relevant data, and promotes trust and confidence in the accuracy and reliability of the information shared. Third, the blockchain serves as a reliable mechanism for the verification of data related to energy efficient buildings.

In addition to these goals, the implementation of auditable energy sensing and control systems is another key objective of applying blockchain technology to ensure the authenticity, accuracy and transparency of data within the ecosystem. This process ensures the accuracy of data and creates an accountability mechanism that holds all participants involved in energy management responsible for the information they produce and share.

Smart contracts on the blockchain automate the processes involved in managing sensors, simplifying device management, and reducing the risk of human error. Data collected from various areas of a building are analysed to improve the energy efficiency and comfort of occupants while reducing costs, and the entire process is recorded on blockchain for immutability and transparency. The proposed system securely records energy-related data on blockchain, enabling real-time monitoring and the development of predictive models for future energy consumption pathways based on historical data. This research can be further extended so that ML and AI algorithms can be applied to data recorded by blockchain to generate insights to influence energy use and occupant comfort, enabling more advanced analytics and systems actuation.

5.2 Blockchain Application in Buildings

The integration of blockchain technology into buildings presents significant advantages in increasing data security, privacy and efficiency in energy management systems. By using blockchain, the security of sensitive data related to energy consumption can be significantly increased. Traditional systems may face the risk of data loss due to vulnerabilities such as system failures, cyber-attacks or unauthorised access. In contrast, the decentralised and immutable nature of blockchain reduces these risks by enabling data to be securely distributed across a network of nodes, making it less susceptible to single points of failure or tampering. Moreover, blockchain technology increases the security of actuator signals, ensuring that commands and data transmissions are protected. It also protects the privacy of sensor data in smart building environments. By leveraging these capabilities, blockchain can transform energy management systems by promoting a more secure and efficient approach to managing energy resources.

Beyond the security benefits, blockchain facilitates the creation of a secure and decentralised system for data sharing between sensors, promoting efficient communication and collaboration. This capability enables the system to respond effectively to real-time environmental changes, improving automation and decision-making processes. Additionally, the implementation of smart contracts on the blockchain can automate various processes involved in managing sensors in a smart home environment. For example, smart contracts can automate software updates, device maintenance tasks, and security protocols, thus simplifying device management and reducing the risk of human error. The transparent nature of smart contracts ensures that these processes are executed efficiently and with integrity.

Data collected from different areas of a building, including temperature, humidity and air quality, is analysed to improve occupant efficiency and comfort, and reduce energy costs. These data are securely recorded in a blockchain system, creating a comprehensive record of the building's energy efficiency profile over time. The entire transaction process, from data collection to analysis and management, is recorded on the blockchain, ensuring immutability and transparency. This provides a secure and reliable method for monitoring and controlling energy consumption in buildings, thus promoting increased accountability and optimisation of energy use.

5.3 Energy Management Using Blockchain

Recent advances in building technology have introduced smartness indicators that measure the level of instrumentation and control flexibility in buildings. These indicators enable active demand response (DR) capabilities that allow buildings equipped with appropriate hardware and information and communication technology (ICT) to respond to grid signals and change their power profile accordingly. DR encompasses incentives and price-based schemes that facilitate communication between the grid and consumers to optimise power usage while maintaining occupant comfort. Numerous studies have demonstrated the effectiveness of individual buildings in adjusting their power consumption in response to grid signals while prioritising the needs of the occupants [337].

Building automation systems typically consist of sensors, actuators, controllers, a centralised unit, and a network interface standard. These systems enable communication between internal devices and services in buildings, allowing them to adapt to environmental and grid conditions, and interact with neighbouring buildings to form active microgrids or digital electrical services.

Data collected from various field sensors, such as temperature, humidity, and air quality, within a building are recorded on the blockchain network to create a comprehensive record of the building's energy efficiency profile, as illustrated in Figure 5.1. To capture user behaviour, the system monitors and analyses how the users interact with energy related setpoints. For example, changes in boiler temperature and ventilation settings can be tracked with timestamps that provide temporal context. Smart contracts on the blockchain can be programmed to identify specific behaviours and trigger automated responses based on predefined criteria. Energy data analytics align with the constraints associated with blockchain-based recording of energy parameters and transactions, as well as ensuring the reliability and dependability of sensor-enabled systems. However,

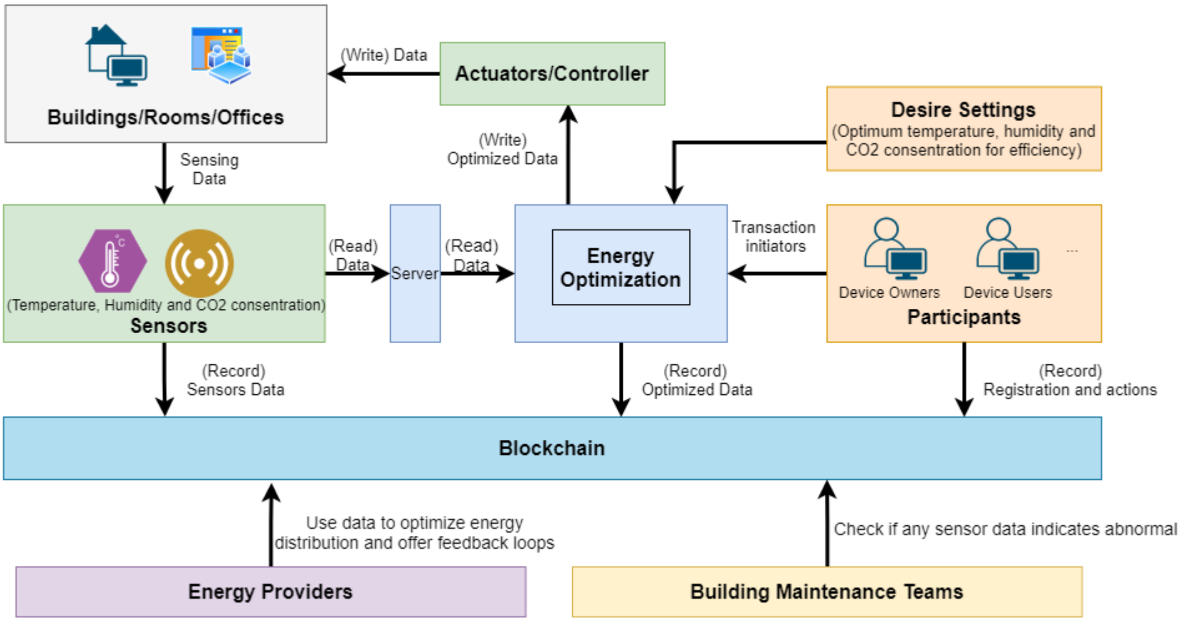


Figure 5.1: Blockchain-based IoT device data recording system

these constraints increase the overall validity and effectiveness of the system by enabling the integration of secure and reliable technologies into the energy management process.

Building maintenance teams can access the blockchain to monitor the health of the system by checking real-time sensor data. In this way, users can detect any anomalies or malfunctions early and make timely interventions such as repairs or system checks, which increases overall operational efficiency and extends the life of the system. Energy providers also benefit from blockchain integration by using energy optimisation data to dynamically adjust power distribution. Thanks to the transparent view of energy consumption offered by the blockchain, energy providers can implement feedback loops based on consumption patterns, promoting more efficient energy use and better decision-making regarding supply and demand.

As part of our efforts to integrate blockchain technology into building management systems, a scalable solution has been developed to meet the needs of both individual buildings and entire networks. The initial focus was on a single building, where a cost analysis was conducted to assess the feasibility of integrating blockchain into the existing infrastructure for periodic data recording. This assessment confirmed the viability of blockchain integration at the individual building level and also provided valuable information to scale to larger building networks. Blockchain implementation in this context is driven by three key objectives. First, it ensures the authenticity and integrity of the sensor data, while maintaining its accuracy at various nodes. Second, this increases transparency and increases trust in shared information by making energy control metrics accessible to stakeholders. Finally, the blockchain acts as a trusted validator for data related to energy-efficient buildings, ensuring originality and accountability of the data. These applications express our effort to transform building management practices by enabling efficiency and trust through blockchain innovation.

5.3.1 Blockchain-based Energy Management for Buildings

Our research focuses on leveraging blockchain technology for energy management in buildings, emphasising the management of energy consumption data. Data collected from sensors, including temperature, humidity, and CO2 concentration, are securely recorded on the blockchain, providing tamper-proof records and enabling reliable monitoring of energy use. Advanced data collection and analysis are facilitated through sensors that allow data transfer and remote management based on consumption data. This enables monitoring of various levels of electricity, water, or gas consumption within the building environment or facilities.

In response to the requirement for efficient energy management and higher accountability in a smart building environment, a scenario was developed utilising existing sensor data from a variety of IoT devices, including lightweight and full nodes, as explained in a later section. As summarised in Table 5.1, a scenario analysis was performed focusing on energy management at the Queen's Building at Cardiff University.

Efforts to develop energy interventions included exploring how energy sensing and control can be integrated with blockchain. The initial analysis focused on a single building and was later expanded to cover a wider network of buildings.

Leveraging the existing sensor infrastructure along with a framework for smart contract development and Remix IDE, blockchain technology was integrated to ensure

Table 5.1: Smart energy management system scenario

Scenario	Energy Management
Description	An example of energy optimisation related to energy consumption reduction based on cooling and ventilation.
Input variables	- Dynamic occupancy of room - Outdoor relative humidity - Indoor relative humidity - Outdoor temperature - Indoor temperature - Supplied air into zone (from outdoors) - CO2 concentrations
Control variables	- Indoor temperature set point - Inlet set point
Outputs	- Thermal energy consumption - Electrical energy consumption
Actors	- BMS - Automation server - Lightweight Node (sensor, actuator) - Full node (gateway) - Interpreter (smartphone/DApp) - Facility technician

data integrity and accountability in an energy management scenario. The scenario involved periodic data collection at 15 minutes, 2 hours, 6 hours and 12 hours from sensors including occupancy, temperature, humidity, CO2 concentration and electricity usage. An instance of scenarios was implemented based on data available in the Forum, a space within the Queen's Building. These data were securely transferred to the framework, where they were subjected to processing and analysis. Smart contracts were developed in Remix IDE, including the implementation of data recording rules to facilitate transparent verification of energy-related data. The blockchain ledger acted as a tamper-proof repository, ensuring the authenticity of energy control metrics published by smart devices and increasing transparency in energy management practices. This scenario demonstrates a pragmatic approach to improving energy efficiency and accountability in a smart building environment using existing sensing infrastructure and blockchain technology integration.

5.3.2 City-level Blockchain-based Energy Management

This experiment aimed to record data and energy transactions for 10 buildings within the blockchain system, providing strong evidence for past energy events and providing the basis for future energy predictions based on the recorded data. Our example demonstrates how blockchain technology can implement and document energy efficiency interventions on a city-scale. On Cardiff University's campus, temperature, humidity, and CO2 concentration were collected for a total of 10 buildings. The data collection process followed a similar procedure to that used for individual buildings, as summarised in Table 5.1.

The collected data was then securely recorded on the blockchain, providing a tamper-proof record of energy use. Transactions affecting building assets are defined in the context of smart contracts, which allow individuals to interact with assets and assign them unique identities across various blockchain networks. Conditions are defined to determine which individuals can participate in each type of action recorded in the distributed ledger of the blockchain. For example, as shown in Table 5.2, only the device owner had access to update the instance of the device entity.

Table 5.2: Example of a transaction definition in the smart contract

Component	Function	Type	Actor	Condition
Data	reading	Transaction	Sensor	Asset = Sensor
Data	writing	Transction	Actuator	Asset = Actuator
Sensors	create	Tansaction	Owner	Participant = owner
Sensors	update	Tansaction	Owner	Participant ID = owner ID in asset
Sensors	delete	Tansaction	Owner	Participant ID = owner ID in asset

Table 5.3 provides an overview of the smart energy management contract and an example of a data record showing the input and output energy parameters involved in the contract. Furthermore, capturing energy data at the city level has the potential to facilitate the creation of a decentralised energy market, reshaping spending patterns toward energy investments in distributed resources. This could lead to a redistribution of energy to new market stakeholders, in contrast to the current centralised distribution and regulation of electricity in smart cities.

Table 5.3: Sample of energy data recording to smart contract

Contract	name
From - to	Sensors_owner_ID
Input	sensor_ID actuator_ID data_values (temperature, humidity and Co2 concentration)
Timestamp	Date & time

5.4 Blockchain for Energy Management

Our focus was to demonstrate adapted and secure energy management at a building level through the use of blockchain. The implemented smart energy method includes a low-cost and low-energy consumption scheme with a system that can alert customers in case of problems caused by overcurrent and reactive energy control. A sensor-assisted blockchain-based system was proposed to enhance the efficiency of the energy system in a building. A schematic overview of the energy management system is shown in Figure 5.2.

Gateway Devices: Gateway devices are important in the energy management system because they act as intermediaries between sensors and the blockchain network. These devices collect data from various sensors, such as temperature, occupancy, and lighting sensors, before securely transmitting it to the blockchain. For example, an IoT gateway installed in a commercial building collects data from multiple sensors distributed in different areas of the building and enables the integration of sensor data into the blockchain network.

Blockchain Network Components: The blockchain network consists of full nodes, light-weight nodes, and smart contracts that work together to facilitate secure and efficient data management and analysis. Full nodes, operated by energy service providers, maintain the integrity of the blockchain ledger by storing a full copy and verifying transactions. The light-weight nodes transmit data to the full nodes. Together, these nodes facilitate real-time data processing and analysis, ensuring the integrity and transparency

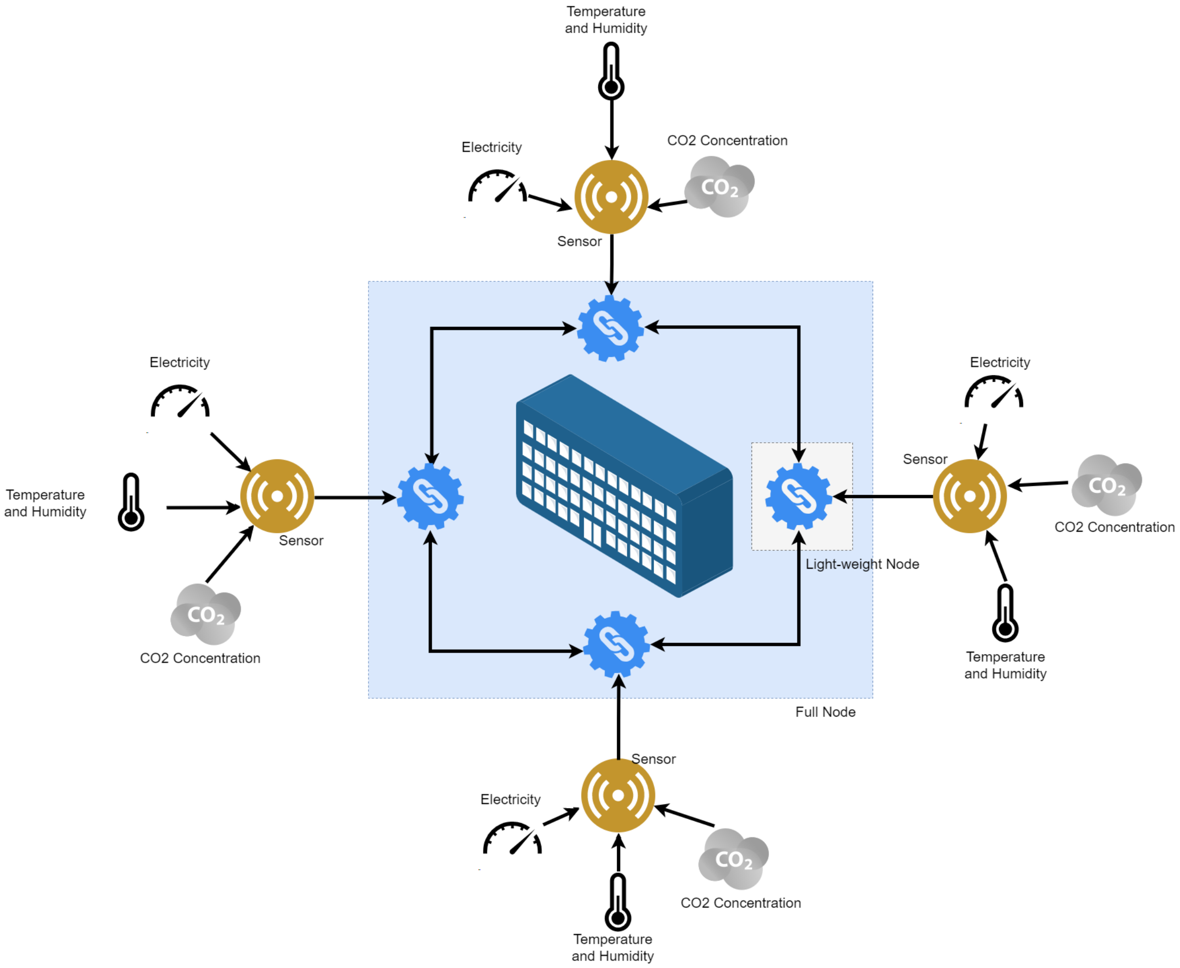


Figure 5.2: Schematic overview of the energy management system.

of the energy analytics system.

Strategic deployment of nodes is essential for capturing, recording and transmitting data from sensors to a blockchain network. These nodes exhibit different functionalities and resource demands, meeting different infrastructure needs. Light-weight nodes designed for data collection or transmission and full nodes that can fulfill both functions are essential components. However, light-weight nodes face challenges when connecting directly to a blockchain network due to resource constraints. To solve this problem, light-weight nodes are connected to full nodes that act as intermediaries. By leveraging the computational resources of full nodes, the transactions of light-weight nodes are monitored and facilitated for registration on the blockchain network. After enrolment, devices and users gain access to smart contracts that ensure data security and integrity. The entities involved in this framework, such as controllers and processors, can operate as full nodes or use platforms integrated into specific full nodes to facilitate the process.

Roles in the System

The following roles are defined in this framework:

- Full Nodes: Within the blockchain network, gateways function as full nodes tasked with collecting energy consumption data. These gateways oversee the deployment and coordination of sensors throughout the building infrastructure, facilitating the transfer of data to the blockchain for analysis. Although both sensors and gateways contribute to the collection of energy consumption data, their roles within the blockchain network are different. Sensors primarily act as data sources capturing real-time information, while gateways manage sensor deployment, maintenance, and data transfer processes, enabling integration with the blockchain.
- Light-weight Nodes: Light-weight nodes consume fewer resources compared to full nodes, making them suitable for devices with limited computing power and storage capacity. The light-weight nodes can be sensors and actuators in the blockchain framework. Strategically placed in a building, these nodes act as primary data sources that continuously collect real-time information about energy consumption.
- Blockchain Managers: Managers control the operation and maintenance of the blockchain network. They manage user access, govern the deployment and configuration of nodes, and ensure the integrity and authenticity of the blockchain infrastructure.

Smart Contract

The energy management system is facilitated by a basic smart contract known as the Reading Contract. This contract provides a framework for energy consumption analysis, serving to enhance both the functionality and security of the system. The Reading Contract is designed to create a secure method for the arbitrator, light-weight node, and full node to access the precise energy consumption data determined by the smart meter. Executed within a private blockchain network, this contract offers the following functions:

Recording Function: This function enables the secure transmission of energy data to the blockchain. The recording function ensures the integrity and immutability of the recorded energy consumption data by utilising cryptographic techniques.

Access Function: Light-weight nodes, full nodes, or arbitrators can initiate the Access function to retrieve specific blocks of information related to the amount of energy consumed. This function facilitates transparent access to energy consumption data, while maintaining data privacy and security measures.

Using the Read Contract, the energy management system strikes a balance between accessibility and security and enables stakeholders to make informed decisions based on accurate and verifiable energy consumption data.

Actualisation of the Model

The protocol is summarised in Figure 5.3.

The realisation of the model sequence diagram describes a systematic protocol for energy management in the framework of blockchain integration. The protocol starts with the light-weight node initiating the procedure by sending a request for energy management to the full node. Upon receipt of the request, the full node proceeds to activate a customised smart contract on the blockchain that is specifically designed for the recording of energy consumption data. This activation of the smart contract is confirmed by the blockchain, which then notifies the full node of its successful initiation. As a result, the full node communicates the activation of the smart contract to the light-weight node, ensuring transparency and effective communication throughout the process. Upon activation of the smart contract, the light-weight node provides the necessary energy consumption data to the full node for analysis. The full node assumes the important responsibility of transferring these data to the blockchain through interaction with the blockchain. Along this procedural trajectory, confirmation messages are

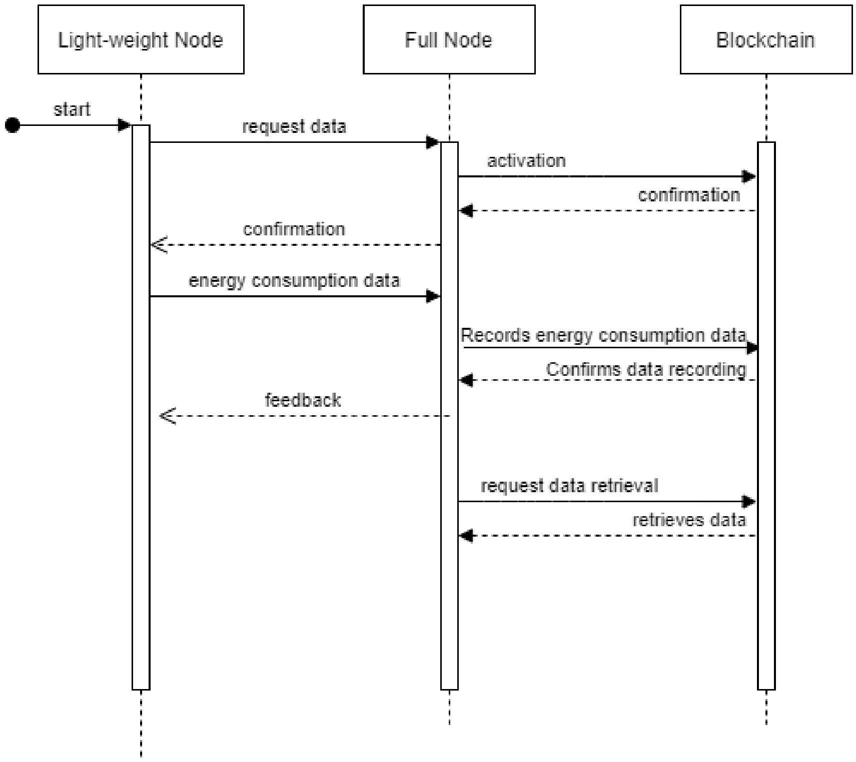


Figure 5.3: The protocol for energy management via a smart contract

exchanged between the full node and the blockchain to verify that the data have been successfully transferred to the blockchain, thus ensuring data integrity and reliability, which are indispensable features of any blockchain-driven system. Then, once the data transcription process is completed, the full node provides feedback to the light-weight node on the status of the process. This feedback mechanism allows all actors to stay informed and monitor the progress of the energy management process. This sequence of actions defines a methodical and transparent protocol for energy management, leveraging the capabilities of blockchain technology to support efficiency and data integrity in energy management efforts.

Protocol on Detection and Notification of Violations

The claimed violation can be automatically reported to an arbitrator for verification and determination if the full node or light-weight node suspects a violation in the energy management process. To report violations based on claims from full nodes or light-weight nodes, the arbitrator, a trusted third party integrated into the blockchain, may require proof of a smart contract. The arbitrator can identify a full node as a violator if it uses the light-weight node's data without authorisation or fails to inform the light-weight node about data access.

The verification procedure begins when the arbitrator initiates the verification agreement. The light-weight node or the full node submits its request to the arbitrator, along with the hash address representing the financial transactions of the light-weight node and the full node. The arbitrator conducts the contract verification procedure by accessing the blockchain ledger and checking the accounts of both the full node and the light-weight node. Verifying the claim involves decrypting the hash address using its private key and voting on the claim, indicating whether a violation has occurred. In addition, the arbitrator can verify the energy data monitoring signals between the full node and the light-weight node by examining the data of the smart metre. By enabling the privacy verification function, the arbitrator monitors transactions recorded by data aggregators on the blockchain to determine whether they have the consent of the light-weight node. By enabling both payment and consent features, the arbitrator accesses existing blockchain records to monitor the full node's access to the light-weight node's data to track the light-weight node's play and report violations.

Protocol for Energy Consumption Data Management

The estimated energy consumption from smart sensors is read and stored in a blockchain. Each participant in this blockchain ecosystem (i.e., light-weight node, full node and arbitrator) has its own account. The light-weight node collects energy data and sends it to the full node for processing. The light-weight node determines the energy usage using the private key and signs the result before transmitting it to other participants in the blockchain. This guarantees that the data have been verified by the light-weight node and provides assurance to all parties involved. According to the reading contract, only authorised parties such as the light-weight node, full node, and arbitrator are allowed to request access to read the energy consumption data.

The sequence diagram in Figure 5.4 shows the interactions between the participants in the process of analysis of energy consumption and recording on blockchain. This sequence of actions defines a systematic and transparent protocol for the calculation and storage of energy consumption data within a blockchain ecosystem, ensuring data integrity and reliability while maintaining confidentiality.

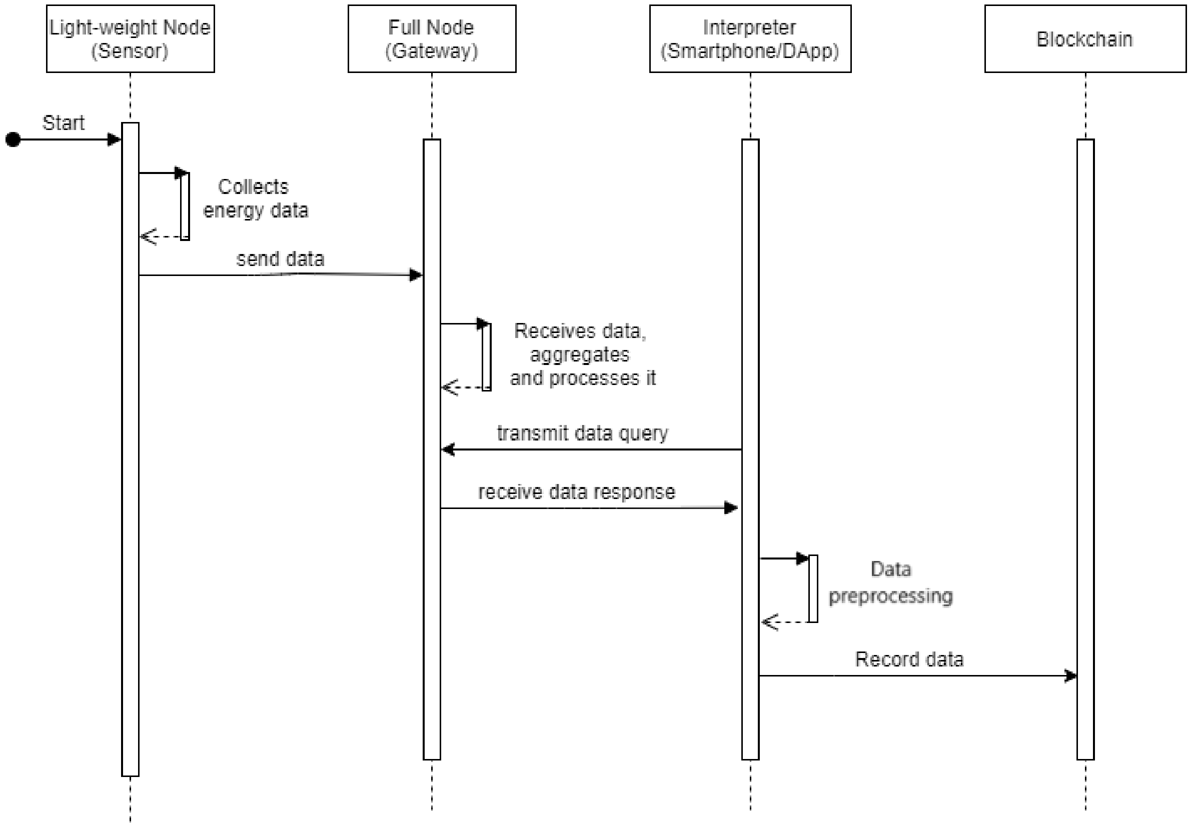


Figure 5.4: The protocol of energy consumption data management

5.4.1 Configuration

Energy management and monitoring use a custom configuration to collect the data necessary for the development of a smart contract. Our focus was on parameters that were readily available from sensors deployed in the Forum in the Queen's Building. These parameters were carefully selected and are detailed in Table 5.4.

This table provides a display of the input data values associated with the identified variables. Our methodology provides a framework to accurately quantify energy consumption trends over time. This enables effective analysis, monitoring, and management of energy data with precision and efficiency.

Table 5.4: Monitoring input

Input	Unit
Monitoring Inputs	
Indoor temperature	$°C$
Humidity	%
CO_2 concentration	ppm
Electricity consumption	kWh
Time	–
Day	–
Month	-
Year	-

5.5 Case Study Analysis

Experiments were conducted using a network of IoT devices, sensors, and actuators in the Queen's Buildings. These devices were used to monitor and regulate energy operations by collecting data such as temperature, humidity, and CO2 concentration.

We present in the following the experimental setup:

- The first step is to determine which sensors or IoT devices will be implemented in the experiment. For this study, the Queen's Building at Cardiff University was evaluated with the 3D model of the building presented in Figure 5.5. Electrical data and devices were selected for the implementation of the energy data blockchain registry. Table 5.5 presents other data inputs from different sensors, including temperature, humidity, CO2 concentration, and electricity.
- In the second step, the Ethereum Remix platform was selected and used in the experiment to build and test smart contracts in a controlled environment.
- The next step is to develop and implement smart contracts used to realise energy monitoring data from sensors to the blockchain. For this, the contract is configured to receive data from devices and sensors, verify it, and then record it on the blockchain.

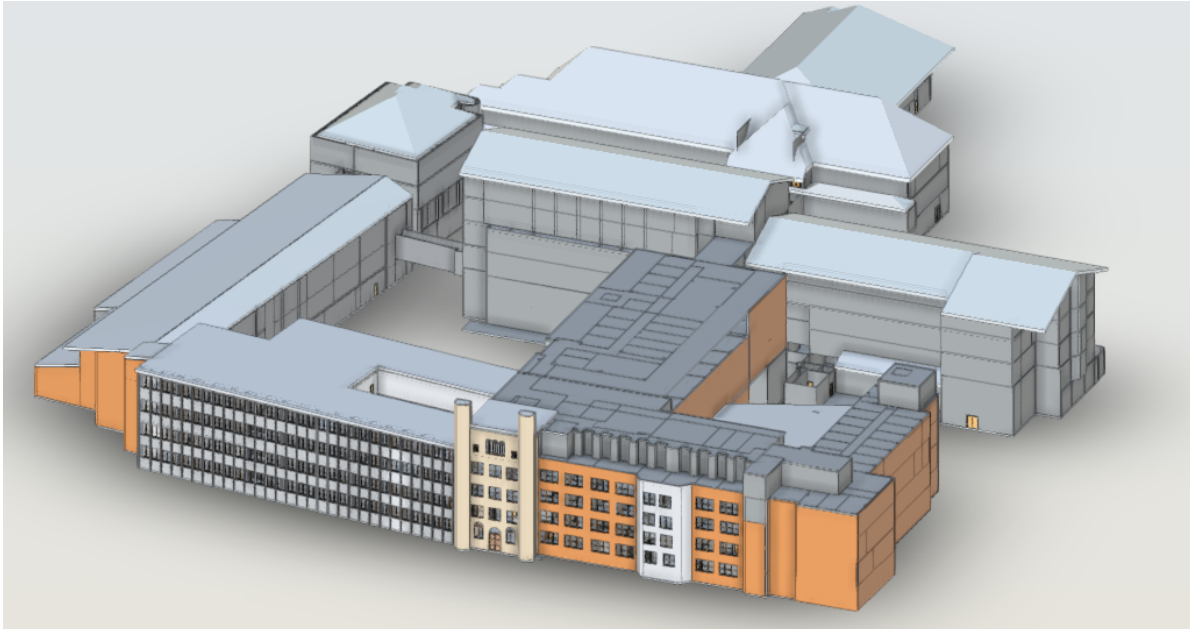


Figure 5.5: 3D model of the Queen's Building

Table 5.5: A sample of the temperature, humidity, CO2 concentration, and electricity consumption data of the Queen's Building at 15 minutes resolutions

Date&Time (15 min.)	Temp ($^{\circ}C$)	Humidity (%)	CO2 (ppm)	Q. West (kWh)
12/10/2016 00:15	18	73	420	18
12/10/2016 00:30	18	73	418	18
12/10/2016 00:45	18	74	421	18
12/10/2016 01:00	17	74	422	19
12/10/2016 01:15	17	74	425	18
12/10/2016 01:30	17	75	426	19
12/10/2016 01:45	17	75	430	18
12/10/2016 02:00	17	74	432	18
12/10/2016 02:15	17	74	430	18
12/10/2016 02:30	18	73	429	20
12/10/2016 02:45	18	73	428	18
...	...	...	...	...

We used Solidity, the programming language of the Ethereal platform, to develop smart contracts. These contracts are designed to receive sensor data and store it on the Ethereum blockchain. Once deployed, smart contracts were activated to read the data provided by sensing devices, verify its authenticity, and record new transactions on the blockchain. Through the functionality of the smart contract, the process of transferring and recording data on the blockchain was automated. The scalability and overall performance of the system were monitored and analyzed by tracking the number of transactions performed and the time required for each transaction. To facilitate the monitoring of energy usage using sensors, Solidity 0.5.16 version was used to create the IoTBC smart contract (see Appendices D.1 and D.2).

Smart contracts are designed to monitor the energy consumption of a building based on sensor data. However, the second smart contract expands on the previous one, including extra input parameters for all parts of the electricity consumption of the Queen's Building. The input variables for the first smart contract consist of data for humidity, temperature, CO2 concentration, and electricity consumption of the Forum space in the Queen's Building. The output variables include data arrays for the inlet temperature setpoint, electrical energy consumption, and thermal energy consumption. The smart contract records the input data using a specified function and produces an output value depending on the input parameters. With the second smart contract, the input variables contain all of the parameters of the first smart contract, in addition to a "struct" for storing electricity consumption data. The struct includes arrays for the types of electricity consumption of the Queen's Building east (QE), west (QW), south (QS), centre (QC), and north (QN). The second smart contract utilises a set function to store input data and produces output values depending on input parameters.

The key difference between the two smart contracts is that the second contract includes input variables to compute electrical energy consumption in addition to thermal energy consumption, which was calculated by the first smart contract. This extra data can be used to better energy consumption and lower the building's total energy expenses. In the study, the first smart contract is referred to as "eight variables", which includes electricity for all parts of the building such as the west, east, south, and north buildings of the Queen's Building (see Appendix D.1.) and the second is referred to as "four variables", which include temperature, humidity, CO2 concentration and electricity consumption of the Forum at the Queen's Building (see Appendix D.2.).

To reduce gas use, smart contracts are created for each data transaction. Several transactions were conducted using the online Remix IDE, which operates distributed contracts. The testnet has two smart contracts: an energy contract and a verification contract. The first provides an opportunity for individuals to combine individual funds to purchase and trade energy resources and information collected by sensors. The second contract includes a method for keeping track of transactions between buyers and sellers, creating an audit trail that may be used to detect violations.

Our experiment demonstrates the effectiveness of using blockchain technology in conjunction with IoT devices for energy monitoring. Securely recording data in a decentralized network enhances system security, efficiency, scalability, and availability. This approach promises to enable new use cases and business models for IoT applications, promoting increased security and transparency in the collection, storage, and exchange of energy data.

5.6 Experimental Results

The smart contract is mainly designed to record energy related data from sensors by storing the day and time, and electricity data. The data is stored securely on the Ethereum blockchain and can be accessed by anyone with permission. It is essential to note that the precise implementation of the smart contract may vary based on the needs of the experiment and the devices used. In addition, security mechanisms such as encryption, authentication, and access control should be established to safeguard the data and devices from unwanted access and modification. Moreover, the smart contract can be placed on the Ethereum blockchain, and sensors can be activated to store data on the blockchain.

5.6.1 Queen's Building: Results by Time Interval

This experiment examines the projected costs of transactions with four energy-related variables on the Ethereum blockchain. Table 5.6 presents the projected costs for transactions with four variables and associated time periods and illustrates the projected costs associated with executing energy records on the Ethereum blockchain at various time intervals and parameter values. Figure 5.6 illustrates the gas used for all transactions.

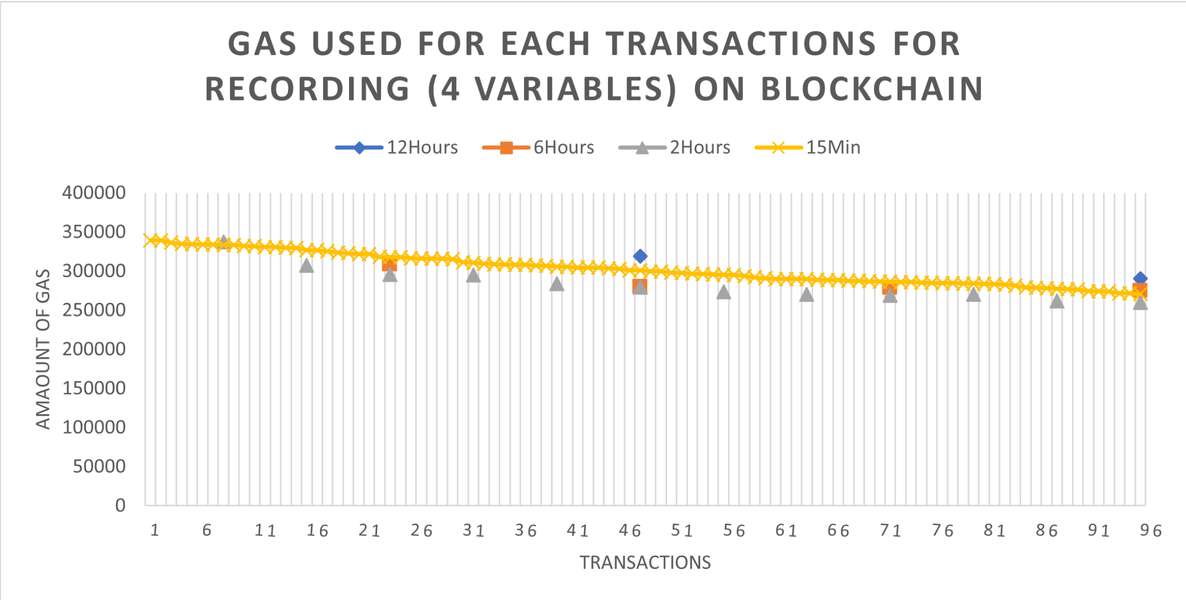


Figure 5.6: The first smart contract execution gas for different time interval energy transactions recorded with four variables

Table 5.6: Transactions costs for the first smart contract at different time intervals with four variables

All transactions cost result for different time intervals with 4 variables				
	15Min	2Hours	6Hours	12Hours
Wei	29047212	3403283	1141795	608893
Ethereum (eth)	0.029047212	0.003403283	0.001141795	0.000608893
Dollars ($)	47.75	5.60	1.88	1.00

The costs are shown in three separate units: Wei (the smallest unit of ether), ether, and US dollars. The results reveal that, regardless of the time period, the projected costs are often lower for energy transactions with four variables compared to eight variables recorded in the smart contract. This is because transactions with four variables use fewer processing resources, and hence have cheaper gas expenses.

When the time interval increases, the predicted cost in Wei decreases due to fewer transactions. The anticipated cost in US dollars shown in Table 5.7 varies from $1.64 to $50.47 for the 15-minute and 12-hour periods, respectively (1eth= $1643.85 - 22.02.2023). This is the result of the second smart contract with an increased number of variables, and the energy transaction cost can be seen in Figure 5.7.

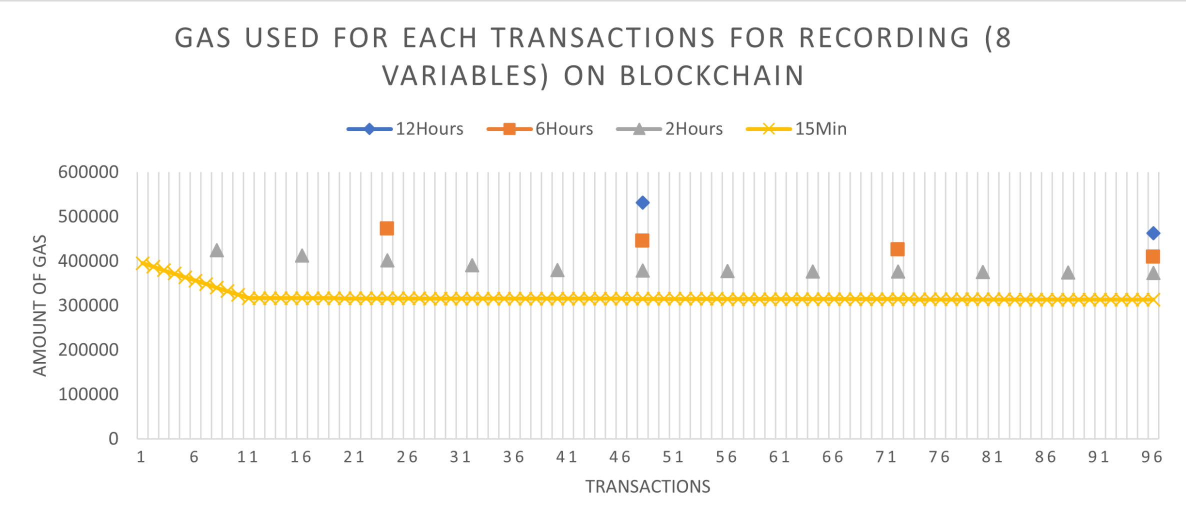


Figure 5.7: The second smart contract execution gas result for the time interval transactions recorded with eight variables

Table 5.7: All transaction costs for the second smart contract at different time intervals with eight variables

All transactions costs at different time intervals with 8 variables				
	15Min	2Hours	6Hours	12Hours
Wei	30702630	4646210	1753839	995576
Ethereum (eth)	0.03070263	0.00464621	0.00153839	0.000995576
Dollars ($)	50.47	7.64	2.88	1.64

The cost comparison in Figure 5.8 between the high and low numbers of variables recorded for each energy transaction shows that energy using four variables can result in lower transaction costs. As shown in the table, energy transactions with four variables result in lower costs in terms of Wei, Ethereum, and dollars for different intervals of granularity for energy (15 minutes, 2 hours, 6 hours, and 12 hours). Therefore, the variables recorded in each transaction can result in cost savings for the parties involved (i.e., facility managers).

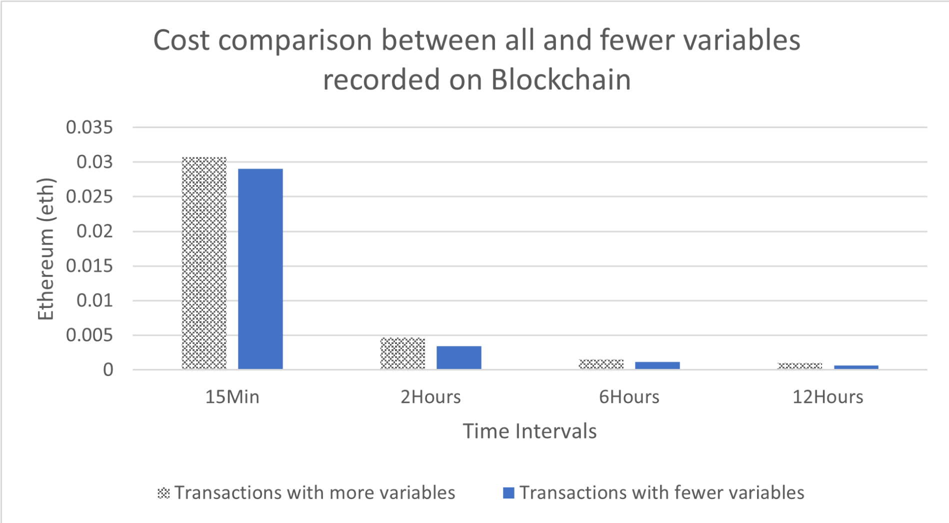


Figure 5.8: Cost comparison for blockchain energy transactions at different intervals

5.6.2 Building-level Cost Results and Comparisons

We examined 10 buildings and collected their data to record in blockchain in two hour time intervals to monitor their gas consumption and associated costs.

Figure 5.9 illustrates the smart contract gas consumption patterns for each building over two hours. Meanwhile, Figure 5.10 provides a comparative analysis of the smart contract gas consumption costs affected by energy management for buildings. To collect a representative sample of energy consumption and expenditure within the confined location, 10 buildings were chosen to obtain a representative sample. Additionally, a sample size of 10 buildings was deemed sufficient based on available resources and data. Selecting this sample aimed to ensure that the study's findings were valid and could be generalized to the larger population of buildings within the study's location. Four variables were also used for all buildings for the input.

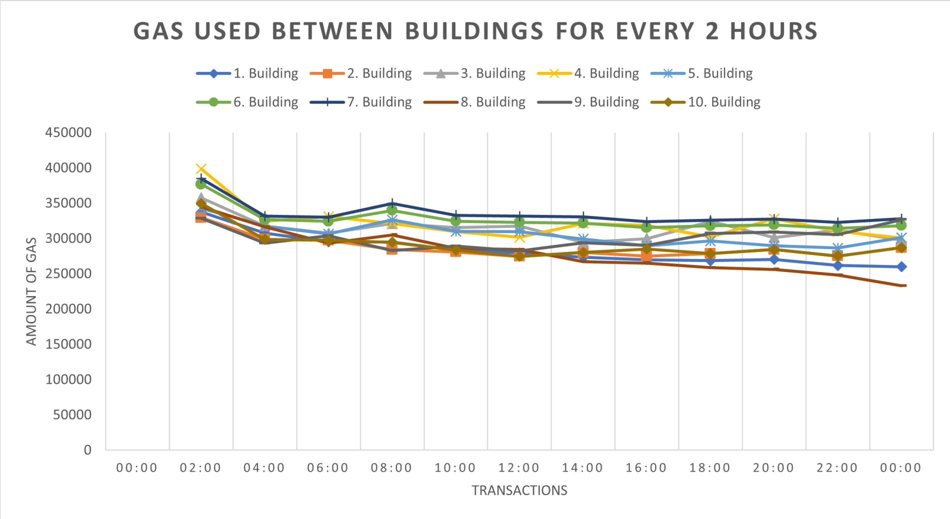


Figure 5.9: Amount of gas used for buildings at 2 hour intervals

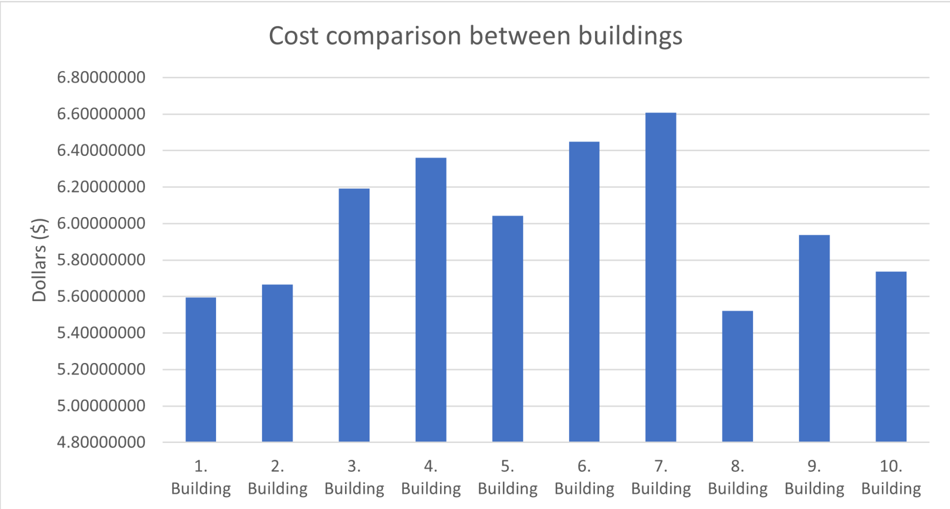


Figure 5.10: Cost comparison for buildings energy transactions at 2 hour intervals

Table 5.8 compares, in US dollars (1eth= $1643.85 - 22.02.2023), the gas consumption for the smart contract of 10 buildings over time, as recorded in blockchain in two hour intervals. The data provide insight into the variance in energy consumption and cost between the 10 buildings. Building 7 had the highest energy consumption costs, while Building 8 had the lowest. The remaining buildings had costs ranging from $5.59 to $6.61. This data can be used by building managers or other interested parties to identify gas consumption patterns, which can then be used to optimise energy usage and reduce costs.

Table 5.8: All transaction costs for different buildings at two hour time intervals

All transactions cost result for different buildings for two hours time intervals										
	1	2	3	4	5	6	7	8	9	10
Wei	3403283	3447223	3767269	3868869	3676213	3922823	4019574	3359343	3612492	3489873
Ethereum (eth)	0.003403	0.003447	0.003767	0.003869	0.003676	0.003923	0.004020	0.003359	0.003612	0.003490
Dollars ($)	5.594487	5.666718	6.192825	6.359840	6.043143	6.448533	6.607576	5.522256	5.938394	5.736828

Differences in gas consumption for the same transactions in different buildings may indicate subtle variations in parameters or potential issues specific to the Remix IDE environment. For example, these differences could be due to variations in the data processed by the smart contract and small variations in the computational workload required for each transaction and mining. Similarly, in a live blockchain network, this gas variance could be influenced by factors such as smart contract complexity, contract state, blockchain network conditions, resource competition, and overall efficiency of the code, all of which could result in observed gas consumption differences between transactions for different buildings.

5.7 Implications

The results of this study highlight the broader implications of integrating blockchain technology and smart contracts into energy management frameworks. By leveraging blockchain to securely record energy data from sensors, this study highlights the potential for improved security, transparency, and efficiency in energy management operations. Smart contracts are emerging as essential tools to automate processes, validate data, and facilitate data sharing among stakeholders, thereby promoting collaboration and trust within the energy management ecosystem. In addition, the decentralised nature of blockchain-based energy management offers scalability and flexibility, reducing the risks associated with centralised control and increasing the reliability of the system.

The implications of this research extend to the critical area of cybersecurity, particularly with regard to protecting the integrity and confidentiality of energy data. By securely integrating blockchain technology, this research ensures that energy consumption data is tamper-proof and emphasises the necessity of strong cybersecurity measures. This underlines the importance of strengthening cybersecurity protocols, especially in the framework of incorporating blockchain into building energy management systems. These findings emphasise the need to mitigate potential risks and strengthen the reliability of energy data, thus increasing the resilience and reliability of building energy management infrastructures.

This chapter presents an exploration of how blockchain technology can provide a foundation for future efforts to support energy efficiency interventions in buildings. Our research reveals the vast potential of blockchain in traditional approaches to energy management and paves the way for future systems. Blockchain's capabilities and applications in building energy optimisation can catalyse innovations in this field. By highlighting the transformative impact of blockchain, our work provides a technological foundation for achieving high levels of energy efficiency and sustainability in buildings.

The integration of sensor-enhanced smart meters with blockchain technology is delivering transformative results for energy monitoring and management in buildings. These advanced meters provide detailed information on energy consumption patterns and environmental conditions, enabling precise analysis and proactive decision-making processes that surpass traditional monitoring methods. Blockchain technology ensures the integrity, transparency, and security of energy data, whether through centralised gateways or decentralised data transmission. This decentralised ledger acts as a tamper-proof repository that is accessible to all stakeholders, increasing trust and enabling more effective energy management practices. The strategic use of sensor-enhanced smart meters in combination with blockchain technology provides real-time visibility into energy usage, which enables stakeholders to make informed decisions and implement targeted energy saving measures.

The implications of this study extend beyond its immediate scope, with resonance in future research, policy development, and industry applications. The adoption of blockchain technology and smart contracts in energy management promises opportunities for new business models, regulatory developments, and sustainable energy transitions. As energy efficiency systems advance, exploring potential synergies between blockchain, IoT, and other emerging technologies could reveal more ways to improve energy efficiency, enable cost reductions, and advance environmental sustainability goals.

The integration of artificial intelligence (AI) and machine learning (ML) with energy data recorded on the blockchain has transformative potential for energy management systems. The blockchain provides data integrity and transparency, creating a stable foundation for AI and ML algorithms to derive insights from energy usage patterns. These algorithms can leverage the data recorded by the blockchain to characterise energy consumption behaviours, predict future energy demands and identify optimisation opportunities. For example, AI algorithms can facilitate proactive energy management strategies by examining historical energy usage data stored on the blockchain to identify trends and anomalies.

Additionally, smart contracts on the blockchain can automate energy management tasks based on AI and machine learning recommendations. These contracts can perform predefined actions such as adjusting thermostat settings or switching between energy sources in response to real-time data analysis performed by AI algorithms. This automation streamlines energy management operations, minimises human intervention and enables immediate response to fluctuating energy needs. Moreover, combining AI and ML with energy data recorded on the blockchain is encouraging the development of adaptive and predictive energy management systems. These systems can continuously learn from new data inputs, optimise energy use in real time and thus increase efficiency, cost-effectiveness and environmental sustainability.

5.8 Summary

This chapter presents a blockchain model that was designed to improve energy detection and control, which is demonstrated through a case study of energy monitoring in office spaces and buildings. The discussion highlights the benefits of this innovative approach, emphasising improved energy efficiency and transparency of energy consumption. This chapter begins by examining the management of energy consumption data in building environments, with a focus on secure storage facilitated by blockchain technology. By analysing two different scenarios, the implications in the context of office and building environments associated with the periodic recording of energy consumption data on a blockchain are demonstrated, demonstrating its cost-effectiveness and transparency. Taking advantage of the inherent security features of blockchain technology, the aim is to provide the sensitive information required for decision making in building management applications. This information is important for developing and implementing effective energy management strategies that are tailored to the specific needs of building operations.

The findings provide insight into the financial implications of recording data on blockchain, and offer actionable insights to improve operational efficiency in building management by leveraging the secure storage capabilities of blockchain technology. As the integration of blockchain technology continues to evolve in the field of energy management, this study serves as a fundamental step towards promoting sustainability and flexibility in building operations. Through a pragmatic approach based on a case study, this research provides insights into the use of blockchain technology for energy efficiency management and interventions in building environments, and supports sustainability efforts.

Next Chapter: Validation through KPIs and Questionnaire

The chapter explores the key role of blockchain in the construction industry aiming to focus on Key Performance Indicators (KPIs) for categorising the benefits of blockchain at various stages of the construction lifecycle. It includes analyses, including return of investment (ROI) calculations, to assess the potential advantages and disadvantages of blockchain. The second section presents findings from a questionnaire detailing demographic data, blockchain knowledge, perceptions of its benefits and challenges, and attitudes towards its implementation in construction. Combining questionnaire findings with practical considerations, the next chapter provides an overview of the implications of blockchain for the construction industry.

Chapter 6

Validation through KPIs and Questionnaire

This chapter focuses on addressing the RQ4 and its corresponding objectives focussing on the impact and assessment of blockchain technology in the construction industry. This includes a review of the benefits and drawbacks identified in the literature and case studies, with a focus on key performance indicators (KPIs) and return-on-investment (ROI) metrics. The inclusion of these metrics enhances the classification of blockchain's impact, offering a quantitative lens to assess potential benefits and drawbacks in construction projects. To capture expert feedback from industry professionals, a questionnaire was conducted, bringing together diverse perspectives and experiences. This enriched the quantitative analysis with qualitative context and valuable real-world assessments. The synergistic combination of quantitative assessment through KPIs and ROI metrics, coupled with qualitative insights from industry experts, aims to provide policymakers and construction professionals with an understanding of the impact and potential value proposition associated with the adoption of blockchain technology.

6.1 Assessing Blockchain's Impacts Through KPIs

KPIs are used to evaluate and measure performance in achieving predetermined objectives, goals, or industry standards. KPIs are essential in the construction industry for monitoring and evaluating project performance, identifying areas for improvement, and determining how well project goals are being achieved. To evaluate the impact of blockchain technology on construction projects, it is essential to determine and design relevant KPIs [338].

KPIs can be used to measure the effectiveness of procurement and delivery strategies, communication, decision making, and employee commitment during the procurement stage. During the design stage, KPIs can be applied to measure project management skills, innovation, quality assurance, and conformity to technical specifications. KPIs can be also used to measure productivity, safety, quality control, cost control, and delivery time during the construction stage. Moreover, KPIs can be used to assess the ability to meet objectives, quality, reliability, flexibility, and the total cost of ownership

[339]. By monitoring KPIs, stakeholders can identify areas for improvement and work to maximise blockchain technology's impact in the construction industry.

A comprehensive approach to assessing the success of blockchain technology in the construction industry is presented. This approach is organised according to four main classifications: project management, cost and schedule performance, quality management, and safety management. The project management category evaluates the efficacy and effectiveness of project management processes and includes KPIs such as project completion time, budget compliance, frequency of change orders, and blockchain-based project documentation. The cost and schedule performance category evaluates the ability of blockchain to enhance project cost and time performance, and includes KPIs such as cost and time savings achieved, variances in project cost and schedule, and on-time project completion rates. The quality management category evaluates the capacity of blockchain to improve quality management processes. This includes KPIs such as the number of defects identified and corrected during construction, the percentage of defects identified during the warranty period, the percentage of construction documents stored on the blockchain, and the percentage of quality control checks performed using blockchain. The final category, safety management, evaluates the capacity of blockchain to improve safety management processes and includes KPIs such as the number of safety incidents on construction sites, documented safety violations, the percentage of workers who have completed safety training, and the percentage of safety incidents recorded on the blockchain. These KPIs can provide a collection of measurements to evaluate the impact of blockchain technology on various aspects of the construction industry, and can inform decisions and improve projects. Figure 6.1 exemplifies the classification of the benefits and drawbacks of blockchain technology.

Some benefits and drawbacks were eliminated from the process for various reasons. Some benefits were considered to be too specific or narrow to be included in the categorisation, while some drawbacks were considered to be too general or unrelated to the construction industry. In addition, it was determined that some benefits or drawbacks were redundant or overlapped with others, so they were combined or eliminated.

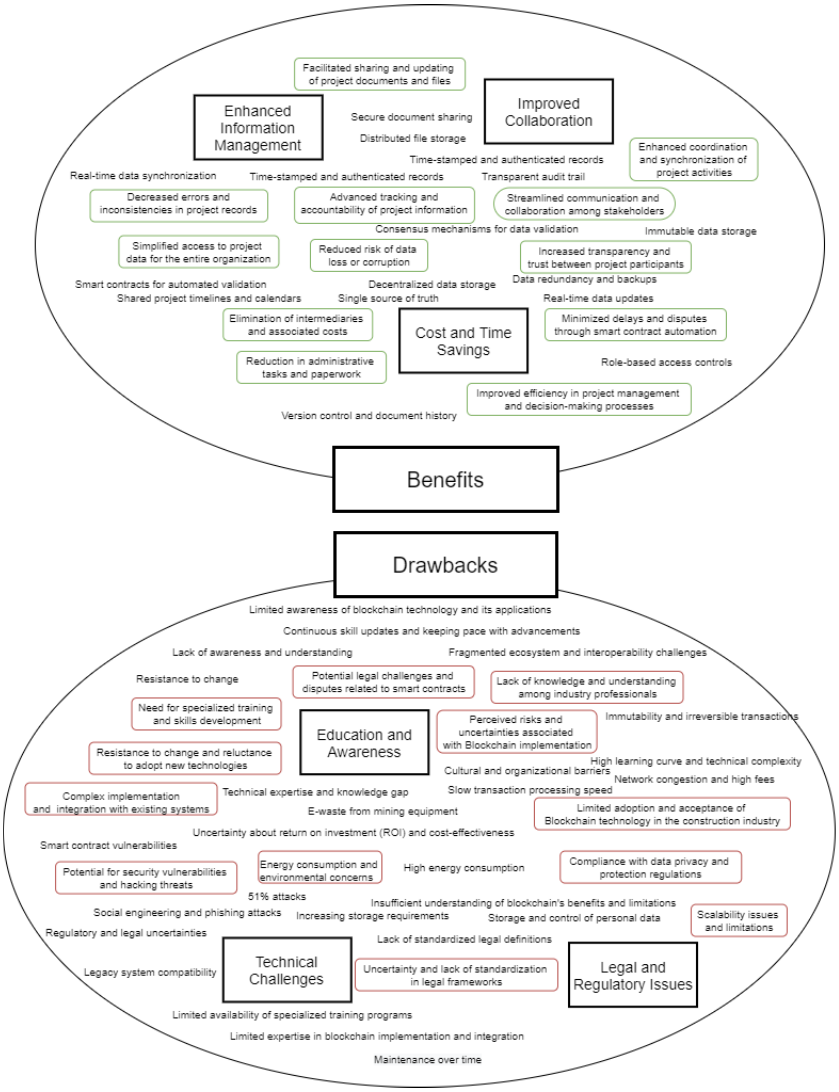


Figure 6.1: The benefits and drawbacks of blockchain technology

6.1.1 Development of the KPI Framework

The analysis of the benefits and drawbacks of blockchain was conducted using NVivo's qualitative data analysis, focusing on both the frequency of mentions and the depth of thematic discussions. This approach ensured that the percentages for each benefit and drawback were based on thoroughly examining thematic prominence and elaboration in a different dataset.

The first step involved importing a large selection of research papers and documents on blockchain in the construction industry into NVivo. Each document was considered as a resource within the software, allowing for systematic categorisation and analysis. A thorough preliminary review of the documents assisted in identifying recurring themes related to the advantages and challenges of blockchain, which were then categorised into different thematic nodes such as 'Improved Data Management' and 'Implementation Challenges'.

The textual data obtained from the sources were coded according to these predefined themes. Each statement relating to a particular benefit or drawback was assigned to the relevant node. For example, references to 'Improved Data Management' were systematically coded to this node, ensuring that each case, whether brief or detailed, was captured. This coding process ensured a comprehensive coverage of the various topics discussed in the literature and allowed for an accurate representation of the thematic content of the dataset.

Following coding, NVivo's query tools were used to analyse the frequency with which each theme appeared in the documents. 'Word Frequency' and 'Text Search' queries were used to count the number of times each benefit or drawback was mentioned throughout the dataset. The analysis also went beyond mere frequency counts to consider the depth of discussion for each theme. NVivo allowed a distinction to be made between brief mentions of a benefit and more detailed discussions that provided detailed insights, examples or case studies. This distinction enabled an understanding of how prominent each theme was in the dataset.

Percentages for each theme were calculated taking into account both the frequency and depth of thematic discussions. In particular, the proportion of detailed discussions was determined by dividing the number of in-depth discussions of a particular benefit by the total number of relevant thematic discussions. For example, if a benefit such as 'Improved Data Management' was discussed in detail in a certain number of cases, this number was compared to the overall number of mentions of blockchain benefits to calculate its percentage. This method ensures that the percentage reflects thematic importance based on how often and how in-depth the benefit or drawback is discussed, rather than just its presence in the dataset.

NVivo's integration of qualitative insights and quantitative data provided a view of thematic emphasis. By combining frequency analysis with an assessment of the depth of discussion, it was possible to create a meaningful representation of the importance of each theme within the dataset.

This approach to thematic analysis, using NVivo's advanced coding, querying and visualisation tools, enabled the accurate calculation of percentages reflecting the importance of each blockchain benefit and drawback. By focusing on both the frequency of mentions and the depth of thematic discussions, the analysis provides a multifaceted and detailed understanding of how these themes are represented within the dataset. This methodology ensures that the resulting percentages also reflect the emergence, prominence and elaboration of each theme in the documents analysed.

Benefits Categorisation of the KPIs

The common benefits of blockchain technology are categorised from the literature review from a detailed analysis using NVivo as follows (in percentage):

- Improved data management and record-keeping (17%): Using a distributed ledger system, blockchain can ensure that all project information is reliable, accurate, and up-to-date, with fewer errors and inconsistencies in project records. This can result in enhanced monitoring and accountability of project data, reduced risk of loss or corruption of data, and streamlined access to project data throughout the organisation.
- Reduced fraud and corruption (15%): Another benefit of blockchain technology, which is often mentioned by increasing the auditability and transparency of financial transactions, is that it can reduce the likelihood of unauthorised changes to financial records, and enhance the capacity to detect and prevent fraudulent activity. This can result in increased stakeholder trust and confidence in the integrity of the project.
- Increased transparency and accountability (16%): By providing enhanced visibility into the project's status and progress, stakeholders can identify and resolve issues

early on, resulting in more efficient project workflows and increased stakeholder confidence in the project's outcomes.

- Faster and more secure payments (13%): By reducing transaction times and costs, enhancing payment accuracy and dependability, and increasing payment security and privacy, blockchain can support faster and more efficient payment processes.
- Increased supply chain efficiency and visibility (17%): Blockchain can improve the efficiency and effectiveness of the construction supply chain by improving the monitoring and tracking of materials and products, enhancing supplier and vendor management, and reducing supply chain delays and disruptions.
- Improved customer trust and loyalty (16%): By improving the customer experience through increased transparency and communication, enhancing data privacy and security protections, and improving customer satisfaction and loyalty, blockchain can facilitate construction companies in strengthening their customer relationships.
- Other benefits (16%): These include increased regulatory compliance, smart asset management for optimised use and maintenance, decentralised project governance structures for streamlined decision-making, and a focus on environmental sustainability through validated sustainable practices. Furthermore, stakeholders can promote innovation and comprehensive solutions by leveraging the integration of blockchain with emerging technologies, such as AI, ML, or IoT. This category underscores the multifaceted nature of blockchain's potential impact by recognising the wide range of benefits that stakeholders can envision based on their individual perspectives and project requirements.

Drawbacks Categorisation of the KPIs

The common disadvantages of blockchain technology obtained from the literature review using NVivo are also categorised as follows (in percentage):

- The first collection of terms is categorised under "Implementation challenges

(31%)", and describes potential implementation and integration costs and complexities associated with blockchain technology in existing systems and processes. These obstacles can make it difficult for organisations to justify the initial investment, and overcoming them may require significant time and resources.

- The second collection of terms under "Technical issues (23%)" identifies potential technical challenges associated with blockchain technology, including system downtime or errors, difficulty scaling to meet rising demand, and security vulnerabilities. These issues can affect the functionality and dependability of blockchain solutions and may necessitate ongoing maintenance and support.
- The third collection of terms is categorised under "Regulatory and legal considerations (21%)", which emphasises the legal and regulatory uncertainties regarding blockchain technology, particularly concerning data privacy and security regulations. Organisations implementing blockchain technology may be found responsible for data breaches and other security incidents, and may be required to conform to complex legal and regulatory frameworks.
- The fourth collection of terms is categorised under "User adoption (15%)", which indicates the potential resistance from employees and stakeholders to adopting new technology and altering established processes. This resistance can impede adoption and may necessitate substantial efforts to overcome the problem through education and training.
- In addition to the previously identified challenges, the category "Other drawbacks (10%)" in blockchain implementation for construction projects can encompass complexities such as energy consumption concerns due to specific consensus mechanisms, potential disruptions from integration with existing legacy systems, the need to adapt to changing regulatory environments, scalability challenges relative to project size, and issues of data ownership and control in decentralised networks.

The categorization of benefits and drawbacks has been organised into the following groups:

- **Improved data management and record-keeping**
  - Improved accuracy and completeness of project data
  - Reduced errors and discrepancies in project records
  - Improved tracking and accountability of project data
  - Reduced risk of data loss or corruption
  - Streamlined access to project data across the organization
- **Reduced fraud and corruption**
  - Improved transparency and auditability of financial transactions
  - Reduced opportunities for unauthorized changes to financial records
  - Increased ability to detect and prevent fraudulent activity
- **Increased transparency and accountability**
  - Improved visibility into project status and progress
  - Increased ability to identify and address issues early on
  - Enhanced stakeholder trust and confidence in project outcomes
- **Faster and more secure payments**
  - Reduced transaction times and costs
  - Improved payment accuracy and reliability
  - Enhanced payment security and privacy
- **Increased supply chain efficiency and visibility**
  - Improved tracking and tracing of materials and products
  - Enhanced supplier and vendor management
  - Reduced supply chain delays and disruptions
- **Improved customer trust and loyalty**
  - Enhanced customer experience through increased transparency and communication
  - Improved data privacy and security protections
  - Increased customer satisfaction and loyalty

- **Implementation challenges**
  - Initial costs associated with implementation and integration of blockchain technology
  - Complexity of implementing and integrating new technology into existing systems and processes
  - Limited availability of skilled personnel to implement and manage blockchain solutions
- **Technical issues**
  - Potential for system downtime or errors
  - Difficulty in scaling blockchain technology to meet increasing demands
  - Risks associated with security vulnerabilities and potential hacking attempts
- **Regulatory and legal considerations**
  - Uncertainty surrounding legal and regulatory frameworks for blockchain technology
  - Compliance with data privacy and security regulations
  - Potential liability for data breaches or other security incidents
- **User adoption**
  - Potential resistance from employees to adopting new technology and changing established processes
  - Need for training and education on the use of blockchain technology
  - Difficulty in convincing stakeholders of the benefits of blockchain technology

6.1.2 Calculation of KPIs

The process is designed to assess, collect, and analyze information about the benefits of blockchain, as outlined in the previous section. The primary focus of the calculation process was on ROI calculations, a commonly used financial metric to determine the effectiveness of an investment. It is a technique to evaluate the efficacy and effectiveness of an investment by comparing the gain or loss generated by the investment towards its cost. ROI is determined by dividing the investment's net profit (or loss) by its initial cost and expressing the result as a percentage. A positive ROI indicates that an investment generated a benefit, whereas a negative ROI indicates that the investment was ineffective.

The ROI formula [340] used in the analysis is given by:

$$ROI = \left(\frac{\text{Gain from Investment} - \text{Cost of Investment}}{\text{Cost of Investment}} \right) \times 100$$

This formula serves as a key metric for evaluating the impact of implementing blockchain technology. The calculations of benefits encompass enhanced data management, fraud reduction, increased transparency, faster payments, improved supply chain efficiency, and heightened customer trust. For instance, improvements in project data accuracy are quantified as $\frac{\text{Errors Before - Errors After}}{\text{Number of Records}}$. Meanwhile, drawbacks, such as implementation challenges and technical issues, are measured in associated costs. This examination provides a quantitative basis for organisations to weigh the advantages and challenges associated with blockchain adoption.

Each subject is analysed with its special formula. Only some formulas are given here as examples; however, detailed formulas for each benefit and drawback category are provided in Table E.1 in Appendix E.1.

Calculation of Benefits

- **Improved Data Management and Record-keeping:**
  - Improved accuracy and completeness of project data.
  - Reduced errors and discrepancies in project records.
  - Improved tracking and accountability of project data.
  - Reduced risk of data loss or corruption.
  - Streamlined access to project data across the organisation.

$$Benefit = \frac{\text{Number of Errors without blockchain - Number of Errors with blockchain}}{\text{Number of Records}}$$

- **Reduced Fraud and Corruption:**
  - Improved transparency and auditability of financial transactions.
  - Reduced opportunities for unauthorised changes to financial records.
  - Increased ability to detect and prevent fraudulent activity.

$$Benefit = \frac{\text{Number of Transaction Errors without blockchain - Number of Transaction Errors with blockchain}}{\text{Total Number of Transactions}}$$

- **Increased Transparency and Accountability:**
  - Improved visibility into project status and progress.
  - Increased ability to identify and address issues early on.
  - Enhanced stakeholder trust and confidence in project outcomes.

$$Benefit = \frac{\text{Value of Increased Trust and Confidence}}{\text{Total Project Cost}} \times 100$$

- **Faster and More Secure Payments:**
  - Reduced transaction times and costs.
  - Improved payment accuracy and reliability.
  - Enhanced payment security and privacy.

$$Benefit = (A \times B \times C)/D$$

where A is the number of payment errors or discrepancies before implementing blockchain technology, B is the average amount of time and resources spent to resolve each payment error or discrepancy before implementing blockchain technology, C is the percentage of payment errors or discrepancies that can be eliminated with blockchain technology, and D is the total number of payments processed before and after implementing blockchain technology

- **Increased Supply Chain Efficiency and Visibility:**

- Improved tracking and tracing of materials and products.
- Enhanced supplier and vendor management.
- Reduced supply chain delays and disruptions.

$$Benefit = \frac{\text{Previous Average Delay Time - New Average Delay Time}}{\text{Previous Average Delay Time}} \times 100\%$$

- **Improved Customer Trust and Loyalty:**

- Enhanced customer experience through increased transparency and communication.
- Improved data privacy and security protections.
- Increased customer satisfaction and loyalty.

$$CustomerExperienceBenefit = (P \times Q) - R$$

where P is the number of customers who benefit from increased transparency and communication, Q is the average increase in the customer satisfaction score due to enhanced transparency and communication, and R is the cost of implementing the blockchain solution to achieve enhanced transparency and communication

Calculations of Drawbacks

- **Implementation Challenges:**
  - Initial costs associated with the implementation and integration of blockchain technology.
  - Complexity of implementing and integrating new technology into existing systems and processes.
  - Limited availability of skilled personnel to implement and manage blockchain solutions.

$$Cost = \text{Implementation Costs} + \text{Integration Costs} + \text{Training Costs}$$

- **Technical Issues:**
  - Potential for system downtime or errors.
  - Difficulty in scaling blockchain technology.
  - Risks associated with security vulnerabilities and potential hacking attempts.

$$Cost = \text{Cost of Addressing Technical Issues} + \text{Cost of Downtime}$$

- **Regulatory and Legal Considerations:**
  - Uncertainty surrounding legal and regulatory frameworks.
  - Compliance with data privacy and security regulations.
  - Potential liability for data breaches or other security incidents.

$$Cost = \text{Legal Compliance Costs} + \text{Data Breach Costs}$$

- **User Adoption:**
  - Potential resistance from employees.
  - Need for training and education.
  - Difficulty in convincing stakeholders of the benefits.

$$Cost = \text{Training Costs} + \text{Productivity Loss Costs}$$

In conclusion, analysing the impact of blockchain technology on issues ranging from project management to supply chain efficiency and customer satisfaction reveals numerous potential benefits. These include improved data accuracy, less fraud, greater transparency and improved operational efficiency. However, it is also important to recognise potential drawbacks, such as implementation challenges, technical issues, regulatory considerations, and user adoption concerns. The ROI formula provides a quantitative measure of the general success of blockchain implementation. The detailed calculation formulas summarised in Appendix E.1 provide an understanding of the potential gains in each specific area.

6.1.3 Calculation Impact

The percentages in Table 6.1 provide a quantitative understanding of the level of achievability. Businesses and organisations may consider these benefits when exploring the adoption of blockchain technology. The analysis of various aspects of blockchain implementation in construction projects presents an active field, which can be changed by new improvements in technology.

Table 6.1: Calculating possible minimum and maximum impact for benefits

Benefit of Blockchain	1	2	3	4	5	Min benefit	Average benefit	Max benefit
1-Improved data management and record-keeping	Improved accuracy and completeness of project data	Reduced errors and discrepancies in project records	Improved tracking and accountability of project data	Reduced risk of data loss or corruption	Streamlined access to project data across the organization			
min	0.0%	0.0%	*9.0%*	9.9%	*86.7%*	0.0%	21.1%	*86.7%*
max	*54.0%*	*54.0%*	*11.5%*	*14.6%*	*99.9%*	*11.5%*	46.8%	*99.9%*
Average	*27.0%*	*27.0%*	*10.3%*	*12.3%*	*93.3%*	*5.8%*	*34.0%*	*93.3%*
2-Reduced fraud and corruption	Improved transparency and auditability of financial transactions	Reduced opportunities for unauthorized changes to financial records	Increased ability to detect and prevent fraudulent activity					
min	0.0%	25.0%	*ND*			0.0%	12.5%	25.0%
max	*9.7%*	*64.0%*	*ND*			*9.7%*	36.9%	*64.0%*
Average	*4.9%*	*44.5%*	*ND*			*4.9%*	*24.7%*	*44.5%*
3-Increased transparency and accountability	Improved visibility into project status and progress	Increased ability to identify and address issues early on	Enhanced stakeholder trust and confidence in project outcomes					
min	0.0%	0.0%	0.0%			0.0%	0.0%	0.0%
max	*3.5%*	*14.3%*	*5.7%*			*3.5%*	7.8%	*14.3%*
Average	*1.8%*	*7.2%*	*2.9%*			*1.8%*	*3.9%*	*7.2%*
4-Faster and more secure payments	Reduced transaction times and costs	Improved payment accuracy and reliability	Enhanced payment security and privacy					
min	25%	0%	0%			0%	8%	25%
max	*75%*	*21.25%*	*100%*			*21.25%*	65%	*100%*
Average	*50.0%*	*10.6%*	*50.0%*			*10.6%*	*36.9%*	*62.5%*
5-Increased supply chain efficiency and visibility	Improved tracking and tracing of materials and products	Enhanced supplier and vendor management	Reduced supply chain delays and disruptions					
min	50%	50%	0%			0%	33%	50%
max	*100%*	*100%*	*60%*			*60%*	87%	*100%*
Average	*75.0%*	*75.0%*	*30.0%*			*30.0%*	*60.0%*	*75.0%*
6-Improved customer trust and loyalty	Enhanced customer experience through increased transparency and communication	Improved data privacy and security protections	Increased customer satisfaction and loyalty					
min	-99%	50%	*ND*			-99%	-25%	50%
max	50%	*100%*	*ND*			50%	75%	*100%*
Average	*50.0%*	*75.0%*	*ND*			*-24.5%*	*25.3%*	*75.0%*

In essence, the results show that organisations can get positive impacts in key areas such as improved data management and record-keeping efficiency (34.0%), reduced fraud and corruption (24.7%), increased transparency and accountability (3.9%), faster and more secure payments (36.9%), and increased supply chain efficiency and visibility (60.0%). However, there are potential barriers to increasing customer trust and loyalty, ranging from -99.0% to 50.0%. These findings highlight the multifaceted nature of blockchain's impact on the construction industry, with overall positive trends revealing increased operational efficiency, transparency, and security.

Improved Data Management and Record Keeping (Figure 6.2):

In the least optimistic scenario, the potential impact ranges from 0.0% to 86.7%, suggesting a minimal improvement. Conversely, the most optimistic scenario indicates a substantial impact of 11.5% to 99.9%. On average, organisations can anticipate a significant positive impact of approximately 34.0%, promising enhanced efficiency, accuracy, and accessibility in data management and record keeping.

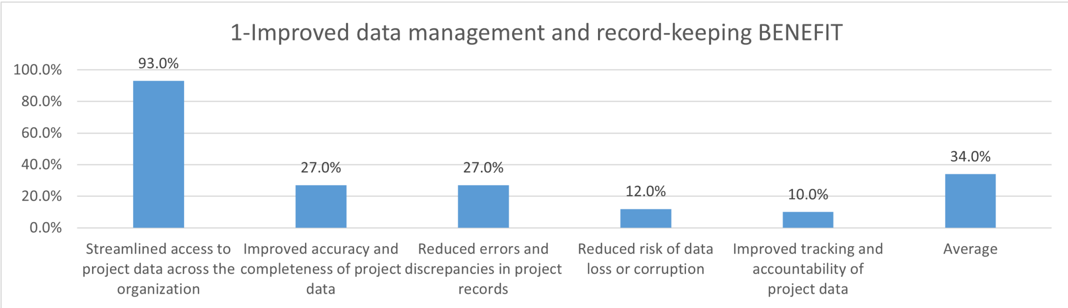


Figure 6.2: Improved data management and record keeping calculation result

Reducing Fraud and Corruption (Figure 6.3):

The least optimistic scenario implies moderate improvements (0.0% to 25.0%), while the most optimistic scenario indicates a notable reduction (9.7% to 64.0%). On average, the impact stands at 24.7%, underscoring a significant and positive influence on financial transaction transparency and security.

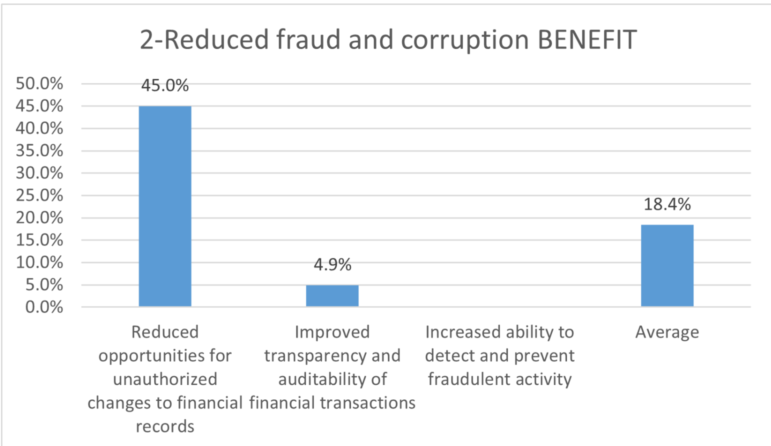


Figure 6.3: Reduced fraud and corruption calculation result

Increased Transparency and Accountability (Figure 6.4):

The least optimistic scenario suggests a small positive impact (0.0% to 0.0%), with the most optimistic scenario implying moderate improvements (3.5% to 14.3%). On average, organisations can expect a modest positive impact of around 3.9%, leading to increased project visibility and stakeholder confidence.

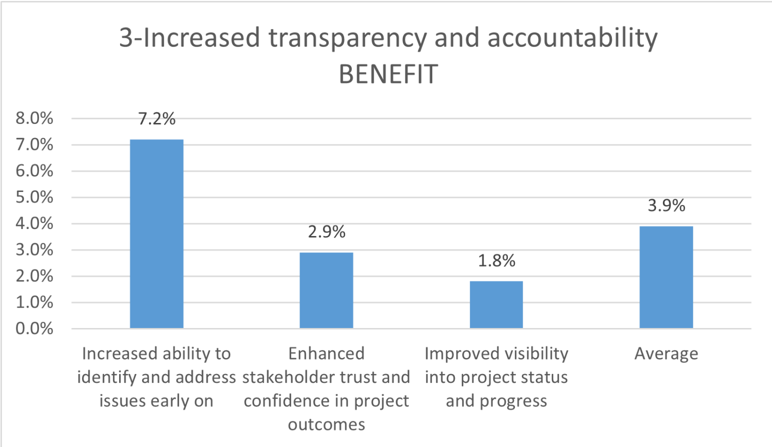


Figure 6.4: Increased transparency and accountability calculation result

Faster and More Secure Payments (Figure 6.5):

The least optimistic scenario suggests moderate improvements (0.0% to 25.0%), while the most optimistic scenario indicates a significant improvement (21.25% to 100.0%). On average, organisations can expect a notable positive impact of around 36.9%, particularly in terms of transaction speed, accuracy, and security.

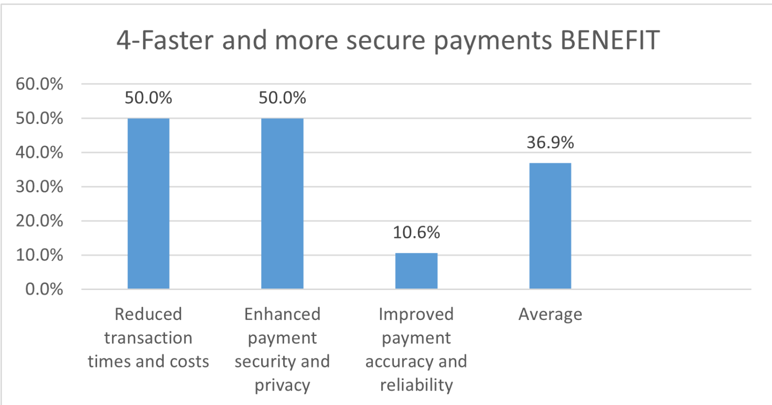


Figure 6.5: Faster and more secure payments calculation result

Increased Supply Chain Efficiency and Visibility (Figure 6.6):

The least optimistic scenario implies moderate improvements (0.0% to 50.0%), while the most optimistic scenario suggests a significant positive impact (60.0% to 100.0%). On average, organisations can anticipate a substantial positive impact of around 60.0%, promising improved supply chain efficiency and visibility.

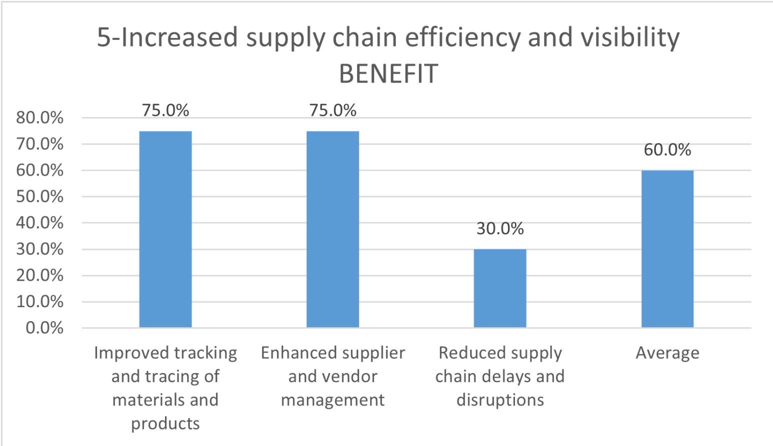


Figure 6.6: Increased supply chain efficiency and visibility calculation result

Improved Customer Trust and Loyalty (Figure 6.7):

The least optimistic scenario indicates potential challenges ranging from -99.0% to 50.0%, while the most optimistic scenario suggests a significant positive impact (50.0% to 100.0%). On average, organisations may face challenges (-24.5%), but successful implementation could result in a notable positive impact of 25.3% on customer trust and loyalty.

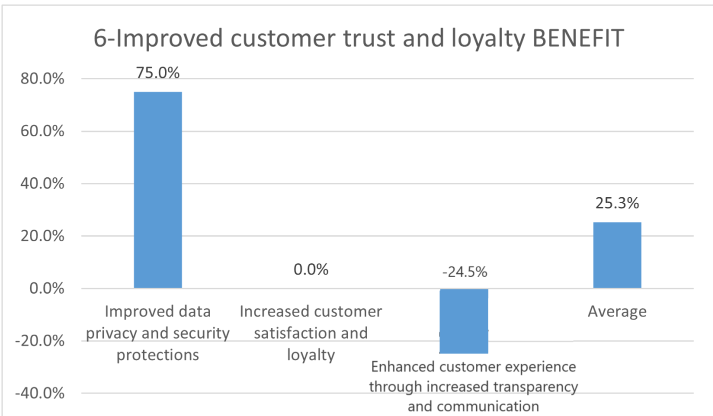


Figure 6.7: Improved customer trust and loyalty calculation result

Table 6.2 provides valuable insight into the challenges and limitations associated with the adoption of blockchain technology in the construction industry. Implementation challenges are highlighted as a significant barrier, particularly with complexities in integrating blockchain into existing systems and the limited availability of skilled personnel.

Table 6.2: Calculating possible minimum and maximum impact for drawbacks

Drawbacks	1	2	3	Min benefit	Average benefit	Max benefit
7- Implementation challenges	Initial costs associated with implementation and integration of blockchain technology	Complexity of implementing and integrating new technology into existing systems and processes	Limited availability of skilled personnel to implement and manage blockchain solutions			
min	0.0%	0.0%	0.0%	-50.0%	0%	-20.0%
max	20.0%	64.6%	50.0%	20.0%	45%	64.6%
Average	10.0%	32.3%	25.0%	-15.0%	22.4%	22.3%
8-Technical issues	Potential for system downtime or errors	Difficulty in scaling blockchain technology to meet increasing demands	Risks associated with security vulnerabilities and potential hacking attempts			
min	0.0%	0.0%	0.0%	-25.0%	0%	0.1%
max	20.0%	50.0%	10.0%	10.0%	27%	50.0%
Average	10.0%	25.0%	5.0%	-7.5%	13.3%	25.1%
9-Regulatory and legal considerations	Uncertainty surrounding legal and regulatory frameworks for blockchain technology	Compliance with data privacy and security regulations	Potential liability for data breaches or other security incidents			
min	0.0%	0.0%	0.0%	0.0%	0%	0.0%
max	72.0%	50.0%	50.0%	50.0%	57%	72.0%
Average	36.0%	25.0%	25.0%	25.0%	28.7%	36.0%
10-User adoption	Potential resistance from employees to adopting new technology and changing established processes	Need for training and education on the use of blockchain technology	Difficulty in convincing stakeholders of the benefits of blockchain technology			
min	0.0%	10.0%	0.0%	0.0%	3%	15.0%
max	50.0%	50.0%	50.0%	50.0%	50%	50.0%
Average	25.0%	30.0%	25.0%	25.0%	26.7%	32.5%

Table 6.2 shows that convincing stakeholders of the benefits and addressing the users' adoption concerns are also notable challenges. Technical issues such as potential system outages, scaling challenges and security risks further emphasise the importance of a robust infrastructure. In addition, the regulatory and legal considerations section highlights the uncertainties surrounding legal frameworks and the need to comply with data privacy and security regulations. Percentages and statistical values provide a quantitative assessment of the rigour of these drawbacks, enabling organisations to make informed decisions when considering implementing blockchain technology.

6.2 Questionnaire Investigation and Findings

This section assesses the understanding, potential benefits, drawbacks, and perceived importance of blockchain for the industry's future success. This research aims to contribute to existing knowledge by providing empirical evidence from a questionnaire that captures the expert opinions of the European Construction Technology Platform (ECTP). All of the results are provided in Appendix E.2.

6.2.1 Context of the Questionnaire

In this research, the perspectives of 48 participants from different professional backgrounds in the construction industry were examined. The respondents were composed of architects, engineers, academics, BIM experts, and other professionals associated with the ECTP, and played an important role in providing insight into the industry's perceptions and knowledge of blockchain. In addition, as members of the ECTP community, these respondents have a direct interest in advancing technological innovations in the construction industry. Their responses reflect not only their perspectives but also broader trends and priorities in the industry with regard to adopting new technologies such as blockchain in construction. In addition, the responses of the ECTP participants are important because of their representativeness, expertise, and potential influence in shaping the future direction of technology adoption in the European construction industry.

Among the different sectors of the respondents in the questionnaire, as shown in Figure 6.8, the education sector emerges as dominant with 42.6% of the respondents representing academia. The industrial sector identifies 29.8%, while the commercial sector shows representation with 27.7% of the professionals questioned.

When the professional roles are analysed, as presented in Figure 6.9, engineers include 25% of the respondents. Project managers represent 20.8%, educators and academics contribute 22.9%, and architects contribute 8.3%. Other various roles 10.4% are professions related to BIM.

When the experience of the respondents is investigated in Figure 6.10, 2.1% had the least resonance, which is less than 1 year of experience. Meanwhile, 25% of respondents had less than 5 years of experience, 22.9% had 5-10 years of experience, and 50% had more than 10 years of experience in the construction industry or technology. Although there is no direct indication from the questionnaire about blockchain experience-based understanding it can be concluded that a significant proportion of respondents (50%) have a significant career in the industry, which may be associated with a deeper understanding of the technology.

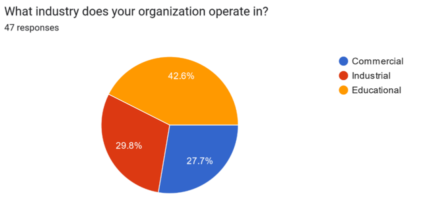


Figure 6.8: Types of organisation

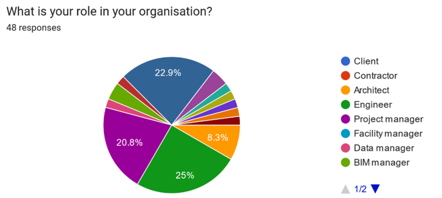


Figure 6.9: Roles in organisation

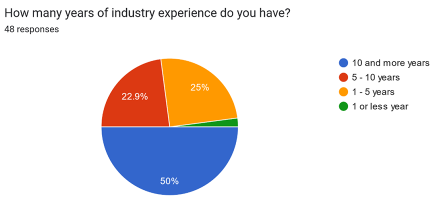


Figure 6.10: Industry experience

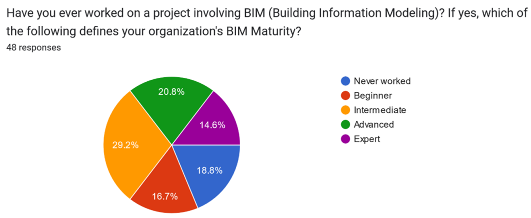


Figure 6.11: Organisation BIM maturity

Regarding the participation of the respondents shown in Figure 6.11, a significant proportion of the respondents are in the intermediate category (29.2%), indicating the level of experience. Advanced practitioners have a percentage of 20.8%, indicating a few professionals with a high level of expertise in BIM. Beginners have a proportion of 16.7%, reflecting active participation in the initial stages of BIM implementation. In particular, 14.6% consider themselves experts in BIM and show an advanced level of competence. In contrast, 18.8% of the respondents have not yet worked on a BIM project, emphasising a segment that has not yet fully adopted BIM applications.

6.2.2 Participants' Knowledge and Familiarity with Blockchain

The questionnaire provides insight into the levels of familiarity of the respondents with the blockchain, as illustrated in Figure 6.12. A quarter of the respondents are well familiar with blockchain, having heard of blockchain technology, indicating a basic understanding, although they have not studied the topic in depth. A further 12.5% of the respondents have researched blockchain and have a medium level of familiarity, indicating a better understanding of its principles and applications. However, the highest proportion of 43.8% show limited familiarity, having heard of blockchain but have done minimal study or research, indicating the need for further instruction. The remaining percentage indicates that they are unfamiliar with the blockchain, highlighting a significant segment that is completely unaware of the technology and its potential implications.

Figure 6.13 shows the level of self-assessed knowledge of blockchain technology of the respondents, revealing a diverse understanding of blockchain. Although the respondents report limited or no knowledge of blockchain (10.4%), the majority exhibit varying degrees of awareness and understanding. The largest segment reported basic knowledge at 31.3%, followed by intermediate at 33.3%, advanced at 18.8%, and expert at 6.3%.

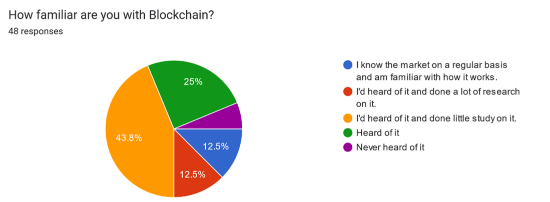


Figure 6.12: Familiarity of the participants with blockchain

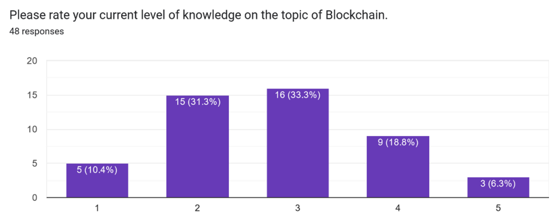


Figure 6.13: Knowledge of the participants about blockchain

6.2.3 Evidencing Challenges in the Construction Industry

The questionnaire reveals that there is a consensus among the respondents on the transformative possibilities of blockchain technology in the construction industry, as presented in Figure 6.14. The responses confirm a widespread interest in the use of blockchain, with supply chain management (62.2%) and data management (66.7%) emerging as the leading areas of consideration. This alignment underscores blockchain's perceived capacity to increase transparency and operational efficiency, particularly in critical areas such as supply chain logistics and data governance. Identity certification (57.8%) and Digital Document Management (53.3%) also received notable support. The acknowledgement of blockchain's potential to create secure identities and optimise document-related processes demonstrates recognition of its value in addressing the security and procedural challenges inherent in the construction industry.

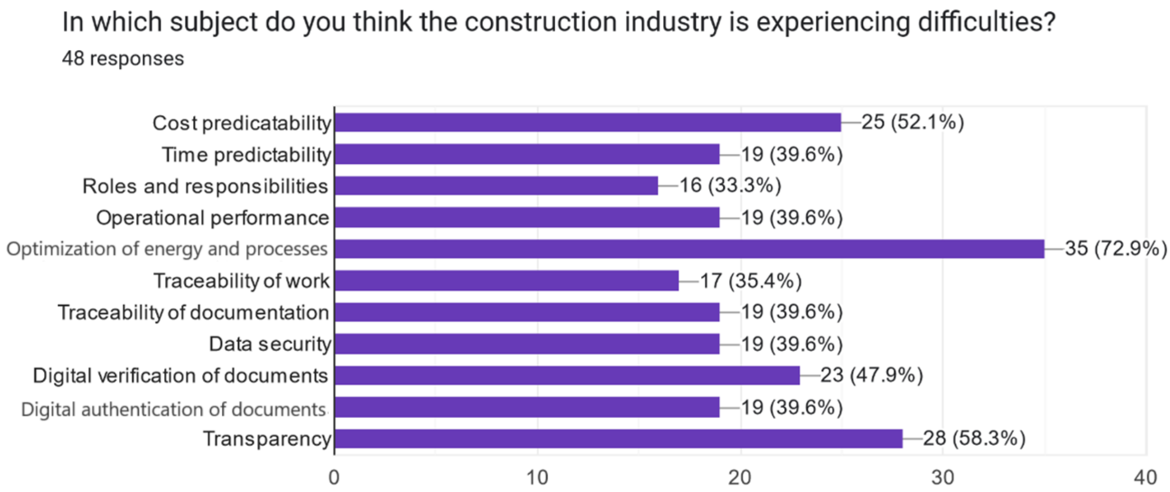


Figure 6.14: Identifying difficulties in the construction industry

The results are described using the correlation coefficients (Pearson's r) method in order to examine the strength and direction of the linear relationship between pairs of variables. Question 6 was selected for comprehensiveness and analysed with SPSS software. The findings are analysed as presented in Table 6.3:

Some key findings and their implications for construction management follow:

Data/Information Security and Collaborative Design: The strong positive correlation (Pearson's $r = 0.981$) indicates that there is a highly positive linear relationship between data/information security and collaborative design. This means that as one variable increases, the other tends to increase. In the context of construction management, this

Table 6.3: Analysis of Q6 on SPSS: Correlation

Correlation

		1	2	3	4	5	6	7	8	9	10	11	12
1	Collaborative design	1											
2	Coordination in activities	.322*	1										
3	Real time monitoring	.503**	.83	1									
4	Data/Information security	.981**	.330*	.511**	1								
5	Secure database	.404**	.067	.358*	.346*	1							
6	Cost-effective solutions	.278	.343*	.041	.246	.179	1						
7	Data quality	.255	.273	.286	.254	.480**	.132	1					
8	Preventing work delay	.101	.116	.312*	.149	.120	.055	.259	1				
9	Preventing payment delay	.103	.029	.238	.103	.490**	.078	.400**	.491**	1			
10	Contract disputes	-.079	.183	-.017	-.104	.514**	-.041	.541**	.334*	.639**	1		
11	Transparency	.276	.380*	.207	.299*	.347*	.013	.377*	.363*	.366*	.503**	1	
12	Automation	.187	.273	.323*	.201	.428**	.115	.282	.068	.091	.230	.351*	1

*. Correlation is significant at the 0.05 level (2-tailed).

**. Correlation is significant at the 0.01 level (2-tailed).

could mean that a focus on data/information security is closely linked to collaborative design efforts.

Real-time Monitoring and Related Variables: The positive correlations (Pearson's r = 0.503, 0.511) between real-time monitoring of data/information security, secure database contract disputes, data quality contract disputes, and contract dispute transparency suggest that these variables tend to move in the same direction. For example, an improvement in real time monitoring is associated with an improvement in data/information security and a reduction in contract disputes. These relationships provide insight into the interconnected nature of these elements in the construction sector.

Contract Disputes and Related Variables: The positive correlations between secure database contract disputes, data quality contract disputes, and contract dispute transparency (Pearson's r = 0.514, 0.541, 0.503) suggest that addressing issues related to secure databases, data quality, and transparency can have a positive impact on reducing contract disputes in construction projects.

Understanding these relationships in construction management is important to making informed decisions and optimising processes. For example, if the focus is on reducing contract disputes, the findings suggest that attention should be delivered to factors such as secure databases, data quality, and transparency. Similarly, the realisation of the connection between data/information security and collaborative design highlights the importance of addressing both aspects simultaneously for effective construction project management.

6.2.4 Evidencing Challenges in the BIM Environment

The challenges faced by experts and working in the same BIM environment while sharing data across multiple disciplines during the design or construction phases is a common concern, as seen in Figure 6.15. The responses show that 31.8% of respondents "always" and 43.2% "usually" face challenges. This highlights the urgent need to improve collaboration tools and practices with implications for the integration of innovative solutions, such as blockchain.

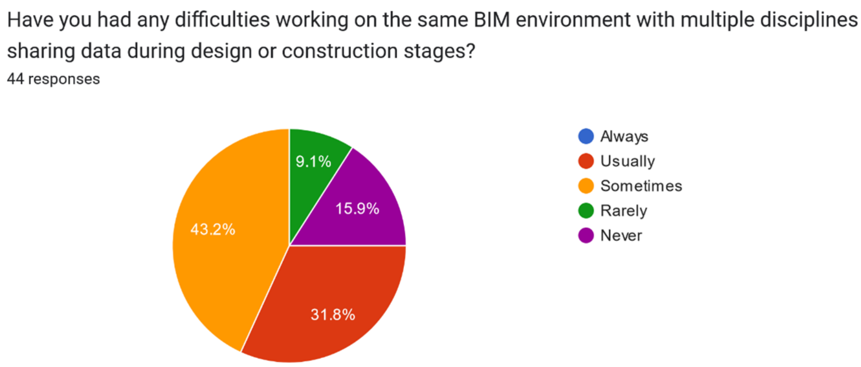


Figure 6.15: Data sharing difficulties in the BIM environment

6.2.5 Evidencing the Needs for a Sustainable Construction

A positive perspective from the participants on the integration of BIM and blockchain to advance the transition to a sustainable and carbon neutral construction industry is presented in Figure 6.16. The results show that integrating BIM and blockchain with digital twins of buildings and infrastructure systems can positively contribute

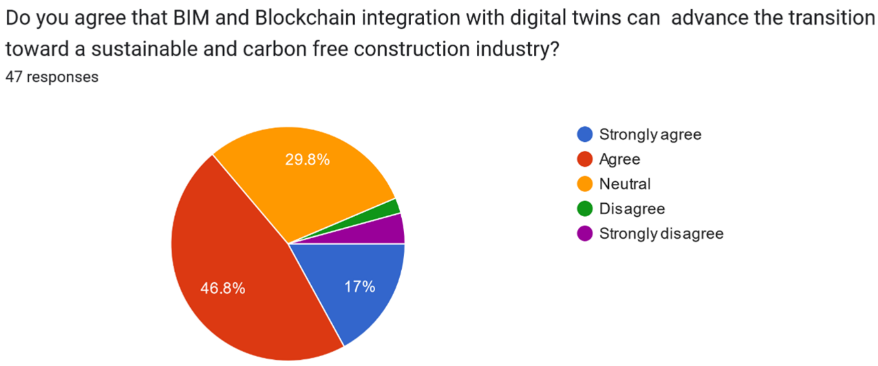


Figure 6.16: Determining the need for a carbon neutral and sustainable construction industry

to sustainability and carbon emission reduction targets in the construction industry. Through the use of digital twins, real-time data on energy consumption, resource use and operational performance can be captured and analysed. This integration enables more accurate simulations and proactive management of building systems, resulting in optimised energy efficiency, reduced waste and lower carbon emissions throughout the building's lifecycle. The combined percentage of "strongly agree" (17%) and "agree" (46.8%) responses is significant and indicates that the majority of respondents see potential benefits in this integration. The 29.8% "undecided" response indicates that a significant number of respondents are undecided or would welcome more information. The percentages of "disagree" (2.1%) and "strongly disagree" (4.3%) responses are relatively low, indicating that only a small minority are sceptical or opposed to the idea. Evidence of support and interest in adopting new blockchain tools can be seen in the questionnaire findings presented in Figure 6.17.

The most demanding field is the sustainable energy skills register in the construction industry (74.4%), indicating a push for recognition and certification of energy efficiency capabilities. There is interest in collaborations (46.5%) and policy incentives (25.6%), emphasising that their importance is recognised. There is also considerable interest in the use of technology (37.2%) and building new partnerships (41.9%) to improve energy efficiency practices.

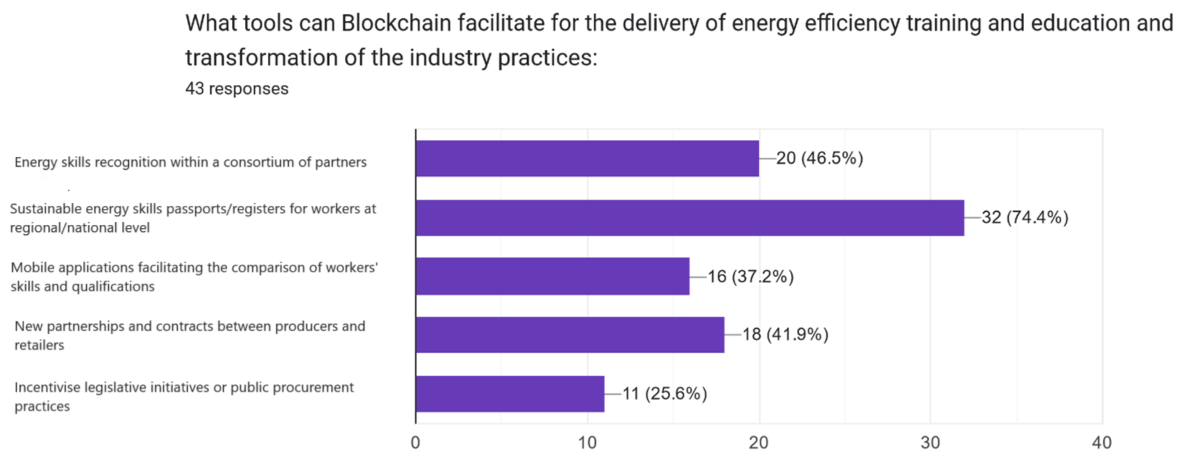


Figure 6.17: Provision of a new energy efficiency tool

6.2.6 Determining the Potential Applications of Blockchain

The questionnaire highlights different perceptions about the feasibility of blockchain in overcoming specific challenges and optimising various aspects of the construction industry, as shown in Figure 6.18. The respondents recognise the potential of blockchain in data management (66.7%) and highlight its ability to ensure the integrity and availability of critical project data. Supply chain management (62.2%) and digital document management (53.3%) also received notable support.

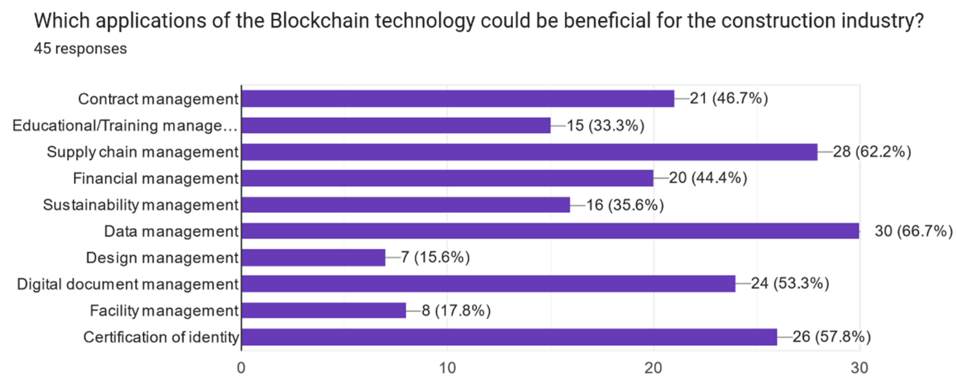


Figure 6.18: Possible application fields of blockchain

This points to the consensus on the technology's ability to increase transparency and traceability in construction processes. Identity certification has emerged as a strong area of interest (57.8%). This reflects the industry's need to securely and transparently verify people and organisations involved in construction projects. Contract management, financial management and education/training management received moderate recognition, while some practices such as design management and facilities management showed relatively lower levels of recognition, suggesting potential areas for further research and development.

6.2.7 Determining Possible BIM and Blockchain Integration

The respondents expressed considerable optimism about the transformative potential of integrating BIM and blockchain into the construction industry, as shown in Figure 6.19. The results reflect a potential positive impact of the integration of BIM and blockchain and collective optimism about the future of construction practice. There is strong support for improved management throughout the life cycle phases (66.7%), indicating a belief in the integration's ability to improve general project efficiency. The provenance of the model and the traceability of the BIM data also attracted significant support at 54.8%, highlighting the perceived importance of transparent and traceable data in BIM workflows.

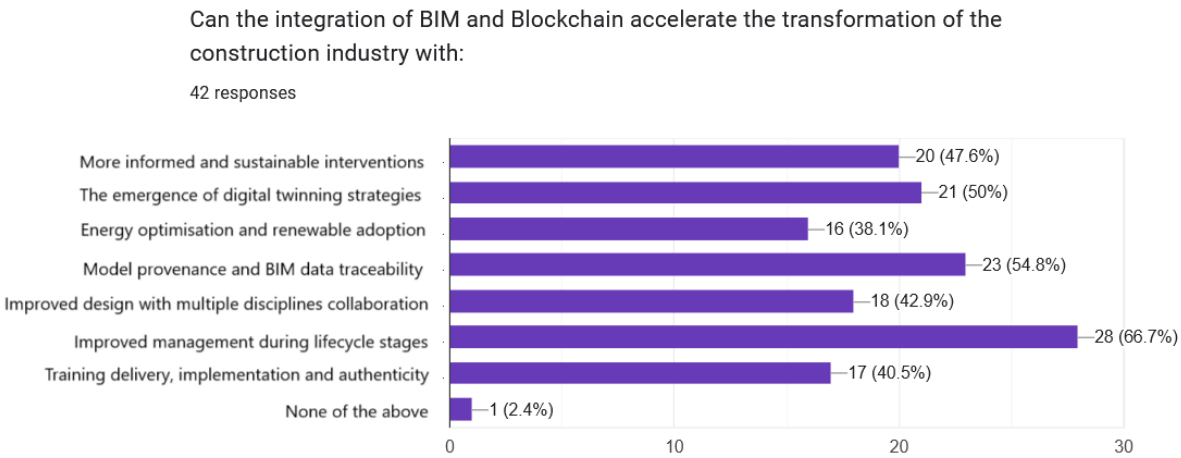


Figure 6.19: The transformative potential of integrating BIM and blockchain

The positive outlook extends to various areas such as the emergence of digital twin strategies (50%), more informed and sustainable interventions (47.6%), improved design collaboration (42.9%), and educational delivery and authenticity (40.5%). The low proportion of respondents who selected "none of the above" (2.4%) shows that there is widespread consensus that integration has promise in addressing challenges in the construction industry and enabling innovation in different dimensions.

6.2.8 Interest in Emerging Technologies

The findings of the questionnaire shown in Figure 6.20 reveal different perceptions about the beneficial impact of emerging technologies on the digitalisation process in the construction industry. Blockchain/smart contract technology received considerable support, with 37.5% rating it important and 29.2% rating it moderate, indicating significant recognition of its potential. Similarly, both IoT and cloud computing received significant support, with 41.7% and 35.4% rating them as important, respectively, indicating their perceived importance in advancing digitalisation. Augmented Reality and AI received more mixed responses, with ratings ranging from moderate, important and major, indicating a different perspective on their potential impact.

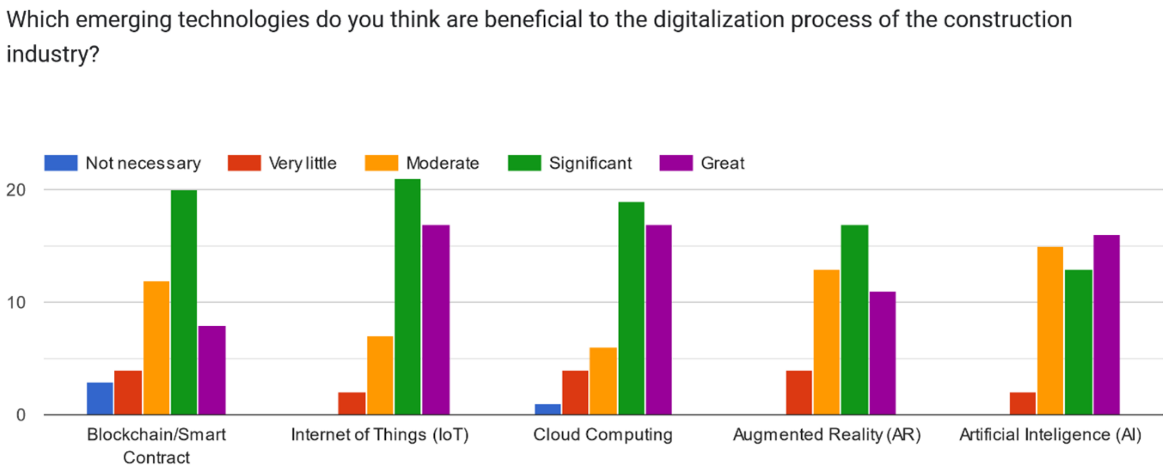


Figure 6.20: Technology perspectives in digitalisation in construction

The results of the questionnaire also indicate that there is a moderate to high level of interest among respondents in adopting blockchain, as shown in Figure 6.21 for future projects in the construction industry, with 42.2% showing considerable interest and an additional 20% showing moderate interest.

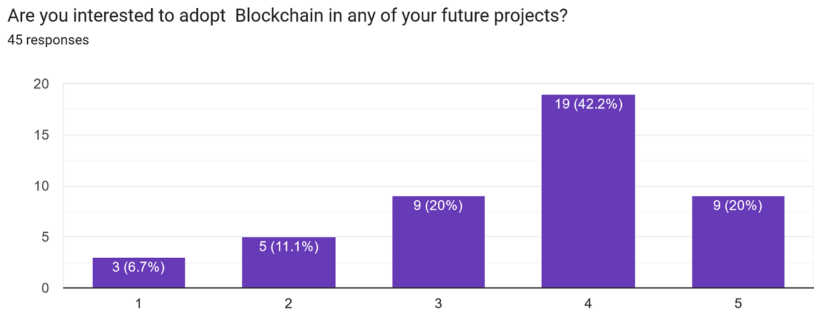


Figure 6.21: Perspectives to adopt blockchain in respondent's future projects

In contrast, a minority of respondents showed limited interest: 6.7% showed very little interest and 11.1% showed marginal interest. These findings suggest that there is significant potential for the adoption of blockchain in construction projects.

6.2.9 Questionnaire Comments

In an open-ended question, responses from stakeholders in the construction industry reflect a range of perspectives on the potential adoption of blockchain technology, particularly in project management, energy efficiency, and training applications. While some respondents are enthusiastic about blockchain's capabilities, advocating for extensive change management processes and pilot projects to showcase its advantages, others perceive blockchain as a problem-seeking technology, expressing concerns about its practicality and energy consumption. The recognition of blockchain's potential benefits in improving record-keeping, traceability, and stakeholder coordination is significant. In addition, recommendations for the establishment of regulatory frameworks and the implementation of stakeholder demonstrations underline a collective desire for a clearer understanding and pragmatic use of blockchain within the industry. These insights serve to develop a methodology and implementation strategy to effectively integrate blockchain technology into construction industry applications. These results provide a useful perspective to understand the needs and considerations, and thus contribute to the academic narrative on the need for blockchain integration in the construction industry. In general, the results show that although there are different perspectives on the integration of blockchain among construction industry professionals, the majority are positive about the integration of blockchain technology.

6.3 Summary

This chapter presents evidence of the fundamental role of blockchain and the needs of the construction industry to build a value proposition for blockchain integration. The first part of the chapter, on KPIs, confirms the utility of blockchain and categorises its benefits for different aspects of the construction life cycle. The analysis adopts a categorisation of KPIs that reflects an understanding of the common benefits and challenges faced by the construction industry. Various analyses are provided to assess the potential advantages and disadvantages of blockchain integration, including potential ROI calculations. In the second part of this chapter, the results of the questionnaire are reported in terms of demographic information, knowledge of blockchain, perceptions of the potential benefits, limitations and challenges of blockchain, and attitudes towards blockchain implementation in the construction industry. By combining questionnaire analysis with practical calculations, this chapter provides an overview of the implications of blockchain in the construction industry.

Next Chapter: Conclusions & Future Work

The next chapter synthesizes the findings in alignment with the overall objectives of the thesis, and research questions. It also describes the thesis contributions and limitations alongside future research directions.

Chapter 7

Conclusions & Future Work

The previous chapters have studied the integration of blockchain technology at various stages of the construction life cycle to improve safety, efficiency, and sustainability in construction projects. With our general thesis objectives, this chapter synthesises the findings from the chapters, with a specific focus on the three research questions. The contributions and limitations of the thesis are presented, along with insights for future research in this field.

7.1 Revisiting Research Questions

This chapter will address the research questions stated in Chapter One and explain our work by revisiting each question.

7.1.1 Life-cycle Integration

The first research question focuses on integrating and applying BIM and blockchain. A model is proposed that integrates blockchain with BIM to enhance the construction collaboration process. This integration model has the potential to automate processes, eliminate the need for intermediaries, and minimise delays in the construction life cycle by providing secure, transparent, and traceable transactions.

> ***RQ1:*** *"Can BIM and blockchain be integrated and applied in construction life-cycle stages to improve safety, cost-efficiency and sustainability of construction projects?"*

Chapter 4 investigates the analysis of the integration of blockchain and BIM technologies within the construction life cycle and supply chain. This chapter introduces innovative frameworks and models that facilitate the evaluation and implementation of blockchain-based BIM in practical scenarios. This research contributes to the automation of construction life cycle management, showing the process of smart contract deployment and execution within the supply chain. This research also contributes to the academic literature by publishing one article and a conference paper. The article is titled "Integration of BIM and Blockchain into Construction Life Cycle and Supply Chains", and the conference paper is titled "Circular Economy and Construction Supply Chains".

This research proposes a model that integrates blockchain and BIM, highlighting the importance of security, transparency, collaboration, and traceability within the BIM environment. A case study is conducted to validate the effectiveness of the proposed model, demonstrating its ability to increase stakeholder trust, reduce project delays, and mitigate conflicts. A guide for implementing blockchain in the construction industry, this thesis also highlights the benefits of integrating blockchain and BIM systems in data management and process performance.

The research conducted in these chapters contributes to advancing the application of blockchain in construction management and supply chain operations. Integrating blockchain and BIM provides many benefits, including enhanced security, automation, and improved traceability. This integration can potentially enable a more digitised and optimised construction ecosystem. Furthermore, examining blockchain in the context of construction supply chains highlights its ability to support sustainability initiatives.

7.1.2 BIM Data Provenance

RQ2: *"Can a blockchain-based BIM provenance model be developed to ensure traceability and transparency of BIM data in a construction project?"*

The second research question focuses on the integration of blockchain and BIM to establish a secure and reliable BIM data provenance for construction projects. This research is addressed in Chapter 4, where integration and its consequences are investigated. The published paper, "Blockchain-supported BIM Data Provenance for Construction Projects", serves as evidence of the contribution of this research to the academic literature.

This chapter's main objective is to explore how blockchain can be integrated with BIM to create a system that ensures secure and immutable data exchange within construction projects. The proposed model provides documentation of all activities and transactions in a construction project, and demonstrates procedures for integrating BIM data provenance with blockchain using construction data. The results highlight the advantages of using an integrated blockchain system, including traceable and immutable data exchange. Among the key benefits of this integration are improved contract enforcement, operations, transactions, and evaluation. The use of blockchain-based BIM data provenance enables continuous monitoring of disciplinary activities, as demonstrated by an empirical case study presented in this chapter. The integration of provenance data and blockchain in construction projects prevents data loss by permanently recording the entire project record within the blockchain system. Moreover, using smart contracts eliminates the need for repetitive documentation and digitally records the BIM process within the blockchain framework. This accelerates data processing and reduces the burden of document management. The proposed approach also improves communication and collaboration among project stakeholders, promoting transparency and improving project management. The inclusion of drawing records as a data source is another significant aspect of the proposed method. It allows for the reconfiguration of various activities based on the tasks involved in a given project, further enhancing flexibility and adaptability.

7.1.3 Energy Efficiency Applications

RQ3: *"How can blockchain technology be applied to energy management systems to improve operational performance and ensure sustainable building practices?"*

Chapters 5 focus on exploring the use of blockchain in energy management in the construction industry. This chapters contributes to the academic literature, with one paper currently under review.

Chapter 5 explores the use of a blockchain-based system for energy management in building infrastructures. This chapter underlines the importance of increasing data privacy, transparency, and efficiency in energy management processes. Through the presentation of a case study, this chapter validates the effectiveness of the proposed system and evaluates its performance in practical contexts. It also demonstrates the applicability of blockchain technology in both office and building environments, revealing its potential to revolutionise energy analytics applications. This analysis emphasises blockchain's transformative capacity to innovate energy management systems while preparing the ground for future applications of ML and AI. These advanced methodologies promise to leverage data patterns and behaviours to optimise energy consumption, improve operational efficiency, and elevate occupant comfort levels. In conclusion, this chapter aims to highlight the benefits of integrating blockchain into energy management systems, while providing insights for implementation and operational improvements.

In summary, the use of blockchain in energy management has significant potential to improve performance, security, and accountability. Blockchain enhances the data analysis process and strengthens data integrity, providing advantages to energy management fields. Continued advances in these technologies have the potential to contribute to a more sustainable and technologically sophisticated direction by driving future innovations and developments in these fields.

7.1.4 KPIs & Questionaire

RQ4: *"What are the key benefits and drawbacks of the blockchain application for the construction industry?"*

Chapter 6 presented impact calculations and a questionnaire to address the research question on the integration of blockchain technology into the construction sector. The first chapter focused on key performance indicators (KPIs) categorising the benefits and drawbacks of blockchain at various stages of the construction lifecycle. This analysis provided potential ROI impact calculations and insights into the industry's common benefits and challenges. The second part of the chapter presents questionnaire results detailing demographics, blockchain knowledge levels and stakeholder perceptions of potential benefits, limitations and challenges. The impacts of blockchain integration in the construction industry are demonstrated by integrating the questionnaire findings with practical calculations. In conclusion, this chapter highlights the advantages of adopting blockchain technology and underlines the need for ongoing research and implementation efforts to realise its full potential to enhance construction processes.

7.1.5 Revisiting the Hypothesis

Based on the previously mentioned responses to the research questions, it is now possible to confirm the following hypothesis:

"The integration of blockchain technology into various processes within the construction industry—such as design, construction and energy management can lead to significant improvements enabling workflow automation, enhancing collaboration between stakeholders, improving data integrity, security and monitoring, and supporting informed decision-making. These developments encourage the implementation of more efficient and optimized practices in project management and the construction lifecycle. "

7.2 Reflections on Research Findings

In this research, our objective is to examine our research findings and explore their implications and contributions to the academic field. Navigating discoveries involves examining their significance, assessing their impact, and maintaining a commitment to the methodological rigor that forms the foundation of the work. This analysis highlights the transformative potential of the research and reveals previously unexplored directions in the construction industry.

7.2.1 Significance

This thesis represents a pioneering initiative that evidences that the use of blockchain in the construction industry can advance sustainable construction practices and technological innovation. This research explores potential synergies between blockchain and BIM, addressing issues faced by the construction industry such as operational inefficiencies, lack of transparency, and environmental impact. This research offers practical solutions and contributes to a wider narrative on leveraging new technologies for sustainable development. This research also conceptualises construction projects with an emphasis on transparency, collaboration, efficiency, and sustainability. Pioneering new frameworks, this research develops a model for future innovations and best practices in the construction industry.

The transformative potential of blockchain technology in the construction industry has been explored in several areas. Each chapter contributes to advancing knowledge, informing practice, and shaping the future trajectory of construction management and technology. This thesis explores how blockchain technology can revolutionise the construction industry through a series of discussions. Emphasising the urgent need for enhanced transparency and accountability, illustrated by the blockchain-based BIM data provenance that ensures data integrity, reduces disputes and increases trust between stakeholders. Asset management emerges as another focus area, demonstrating how blockchain optimises asset life-cycle management, improves operational efficiency, minimises downtime and ultimately leads to cost savings. Moreover, the integration of blockchain into energy efficiency initiatives demonstrates its capacity to promote sustainable construction practices by monitoring energy utilisation. Collectively, the findings emphasise the transformative potential of blockchain technology in the construction industry. By addressing key challenges and opportunities in areas ranging from BIM data provenance to asset management and energy efficiency, this research contributes to advancing knowledge and informing practices in the construction industry.

Furthermore, this research demonstrates the feasibility and benefits of blockchain-BIM integration for the construction industry's policy-making and regulatory frameworks, providing a model for the adoption of sustainable practices. This can lead to changes in the planning, execution, and monitoring of construction projects, focusing on environmental management and social responsibility. This also contributes to the advancement of interdisciplinary collaboration and knowledge exchange, bridging technology, sustainability, and industry practice, and promoting a more integrated approach to addressing challenges, such as data security and trust between stakeholders. This interdisciplinary approach increases a collaborative environment where different perspectives are considered and integrated. Ultimately, this research has the potential to accelerate the digital transformation of the construction industry with a transformative effect. Leveraging the power of blockchain and BIM leads into a future where construction projects are more efficient and transparent, as well as environmentally sustainable.

7.2.2 Rigor

The research shows methodological sensitivity by adopting a mixed method approach to validate theoretical and practical knowledge throughout the construction project. This includes the process of data collection, analysis, and interpretation, and results in a practical perspective. The introduction of new concepts and the implementation of case studies and statistical analysis for the questionnaire ensured that the results obtained were based on analysis and contributed to the applicability of the research to a wider community.

The literature review process was evaluated using a systematic approach to assess and analyze the available information. Extensive searches were conducted in numerous databases and sources covering a wide range of scientific studies relevant to the research topic. The quality and relevance of the literature were assessed and focused on identifying gaps, contradictions, and emerging trends in the literature. The findings from the literature were synthesised and logically organised to provide a strong foundation for the analysis. All sources are cited and previous work is represented to maintain academic integrity. Importantly, the implications of the literature for the current research are considered and reflections on how the research contributes to new insights or perspectives to the field are presented.

In addition to the theoretical foundation, this research utilises empirical research. Real-world case studies from various construction projects are developed and analysed to provide practical insights into the implementation of blockchain-BIM integration. In conducting the case studies, attention was given to defining precise objectives and scopes, and ensuring that these were aligned with the research objectives. A diverse and representative selection of cases was chosen to reflect a variety of perspectives and experiences in the construction industry. Triangulation of evidence through the use of multiple sources, such as data, documents, and observations, provided depth and rigour to the analysis process. Furthermore, transparency was maintained throughout the case studies by carefully documenting data collection and analysis processes, thereby enhancing the credibility of the findings. These case studies validate theoretical frameworks and enhance scientific understanding of the practical implications of integrated technologies in real-world environments.

The questionnaire design and implementation process also contributed to the rigour of the research. The questions were sensitively formulated to reflect the research objectives. The survey was conducted according to best practices and utilised appropriate approaches to increase response rates and ensure data quality.

In general, this research establishes a scientific model for future research efforts investigating blockchain-BIM integration and sustainable construction practices to contribute to the advance of knowledge in the construction industry. Participation in case studies, questionnaires, and literature review processes highlights the credibility and reliability of findings that enrich the literature and provide a basis for informed decision making in the construction industry.

7.2.3 Impact

The purpose of this research is to contribute to the fields of engineering, architecture, and information technology, enhancing existing knowledge and providing insights for future research efforts in the construction industry. By investigating the practical implications of integrating blockchain and BIM, this research expands the scientific literature and opens new directions for new research.

This research contributes to academic knowledge by addressing gaps and expanding the discourse surrounding the adoption of blockchain in construction. Through empirical evidence and theoretical insights, this research enriches the academic literature by shedding light on the potential benefits and challenges of blockchain implementation in combination with BIM.

This research also aims to provide benefits to practitioners, policymakers, and stakeholders in the construction industry. Through the presentation of case studies and the introduction of innovative concepts, this research provides stakeholders with practical strategies to effectively incorporate blockchain and BIM technologies into construction processes. This research underscores the transformative potential of blockchain technology in construction project management and supply chain operations, emphasising its potential for improved efficiency, transparency, automation, and risk mitigation. This development has the potential to catalyse the digitalisation of the construction industry and the adoption of sustainable practices, ultimately resulting in cost reduction and improved project outcomes.

Furthermore, this research explores the cost implications of blockchain-BIM integration, providing case studies and practical applications adapted to the construction industry. Thus, it is expected to empower industry stakeholders to make informed decisions, and promote a more informed and progressive outlook in the construction industry.

7.3 Contributions

The contributions of the thesis are presented in this section.

Contribution 1: This research contributes to examining the integration of blockchain technology into the construction industry, focusing on construction management and life-cycle stages, aiming to enhance automation, data management, transparency, traceability, and efficiency within the construction life cycle. A blockchain model is proposed to demonstrate the feasibility and effectiveness of this integration through a case study.

Contribution 2: This research contributes to developing a BIM data provenance model by leveraging blockchain technology to improve data reliability and authenticity in construction projects. A real bridge construction case study is used to demonstrate the effectiveness of the provenance model and its integration with the project BIM data.

Contribution 3: This research contributes to proposing a blockchain capability that can support improved energy management based on auditable energy sensing and control policies in buildings. By developing and validating a blockchain-based model, the study demonstrates the potential of blockchain to improve data accuracy, transparency, and efficiency in energy management for buildings.

Contribution 4: This research contributes to providing empirical support for our findings by applying an evaluation framework that includes KPIs with associated impact calculations and a questionnaire that evidences the significance of the research and improved the scientific understanding of the field while providing a foundation for future research efforts.

7.4 Limitations

Despite the potential to integrate blockchain into various fields, it is essential to recognise and address certain limitations that require careful consideration. Several limitations have been observed in the process of integrating blockchain into the construction industry.

This research faced limitations due to *the difficulty and cost associated with simulating a real blockchain system*. Working in a live blockchain environment created challenges and imposed significant costs that hindered testing and development processes. While the use of testnet environments and virtual simulations attempted to solve this problem, the emerging nature of blockchain technology was an obstacle to extensive experimentation. As a result, the inability to replicate real-world conditions exactly may affect the generalisability of the research findings. Moreover, when considering the integration of blockchain, *scalability challenges* have emerged. As the number of participants and transactions in a blockchain network increases, concerns about performance and rising costs have emerged as potential limitations that require careful consideration and resolution. Furthermore, *the need for high-end computing resources* was another challenge for us. Meeting these system requirements and ensuring optimal performance became obstacles in the implementation process. In addition, the complexity of blockchain interoperability with existing systems and the requirement for specialised knowledge posed further limitations that had to be taken into account.

Ethereum price volatility prevented the direct application of blockchain in real-world scenarios. This uncertainty instructed this research to prefer an alternative Remix IDE platform approach. Our decision to use Remix IDE for certain aspects of development and testing is driven by its cost-effectiveness, time efficiency, enhanced control, privacy and security provisions, flexibility, collaborative development features, fast feedback loop, and simplified deployment process. However, using the Remix IDE for blockchain development presents limitations, such as a lack of real-world interactions, scalability challenges, limited testing capabilities, and a lack of consensus mechanisms. These limitations require careful consideration and adaptation to ensure the effective implementation of blockchain solutions.

The early stage of *blockchain's technological maturity* has impacted our work throughout the process. The continuous evolution and ongoing developments in blockchain have raised uncertainties regarding its maturity and stability, which has had an impact on its applicability in our specific area of work.

Data confidentiality and privacy are important considerations when implementing blockchain publicly. While blockchain is known for its transparency and immutability, protecting sensitive information becomes challenging when publicly shared. Achieving a balance between transparency and data privacy while at the same time implementing strong security measures is essential for a successful blockchain implementation. *In addition, the limited observation period and data collection* in our case study may not have accurately captured the long-term impact or potential changes over time. A longer study period and a more comprehensive data collection process could have provided more powerful insights.

7.5 Future Work

This section explores future research directions in the field of blockchain with the intention to overcome limitations and improve the scalability, energy efficiency, regulatory compliance, user experience, and overall effectiveness of blockchain systems. Key focus areas include integrating blockchain with BIM, life-cycle assessment (LCA), IoT, AI / ML, empirical research, standardisation for material passports, privacy advancements, blockchain integration in IoT, and decentralised governance for smart cities.

7.5.1 Life-cycle Assessment

In the field of LCA, future research could be conducted to study the environmental consequences of applying blockchain in construction projects. Such efforts require a comprehensive assessment of the entire life cycle, covering all stages from raw material extraction to disposal while taking into account relevant factors such as energy consumption, emissions, and resource utilisation.

More specifically, LCA studies can be conducted to assess the environmental impacts resulting from the use of blockchain-enabled processes, such as material tracking, supply chain management, and project documentation in construction. Comparative analyses with traditional systems or alternative technologies will provide invaluable insights into the ecological footprint of blockchain applications. Furthermore, exploring the integration of blockchain with BIM, IoT, AI, and ML from an environmental perspective can promote understanding of sustainability within digital construction practices.

The potential environmental benefits and drawbacks of blockchain integration in smart cities, especially related to decentralised governance frameworks and citizen engagement, can be explored through LCA methodologies. This approach facilitates examining the ecological consequences accompanying the widespread adoption of blockchain in urban planning and governance.

In summary, incorporating LCAs into future research efforts will provide a holistic understanding of the environmental consequences associated with blockchain applications, thereby supporting the goals of sustainability, efficiency, and transparency in various industries, especially in the context of construction and smart cities.

7.5.2 Beyond Artificial Intelligence and Machine Learning

In the area of future exploration, the integration of AI and ML with blockchain stands as a pivotal frontier, especially tailored to the unique challenges and opportunities in the construction industry. Emphasis should be placed on predictive analytics for energy efficiency by leveraging advanced algorithms to analyse historical data and predict future energy demands. This integration has the potential to revolutionise sustainability efforts and resource management practices in the industry. Another critical area for future research is optimising resource allocation through AI and ML applications. This requires developing intelligent systems that use online (real-time) learning and dynamic programming to dynamically plan tasks, predict equipment maintenance needs and make real-time adjustments based on evolving project variables. These systems continuously learn from new data inputs, allowing them to adapt to changing conditions and optimise decisions as projects progress. The ultimate goal is to increase efficiency and reduce resource waste through data-driven decision-making processes that respond instantly to project developments, ensure optimal resource allocation and minimise downtime.

The future of construction envisions generative AI, blockchain, and BIM converging to unlock a multitude of opportunities. Generative AI has the potential to streamline design processes by automatically generating building plans that conform to project specifications, while blockchain ensures the integrity and security of these plans. AI algorithms can optimise supply chains by predicting material requirements, and blockchain provides a secure and transparent system for tracking materials throughout the construction process. Inspection procedures can be enhanced through AI-driven defect detection using BIM data, and blockchain guarantees the accuracy and reliability of inspection reports. Smart contracts embedded in blockchain automate construction agreements and AI plays a pivotal role in their creation and enforcement. Furthermore, AI analysis of BIM data can improve predictive maintenance and energy efficiency, while blockchain acts as a secure ledger to store relevant information. This integration promises to promote more efficiency, transparency, and sustainability in construction projects.

In addition, integrating AI and ML into BIM systems maintains security for advanced data analysis. Automated pattern recognition, anomaly detection, and data-driven insights improve decision support mechanisms by offering a more sophisticated and intelligent approach to processing complex construction data. Furthermore, addressing privacy and security concerns related to blockchain implementation requires innovative AI-driven solutions. Future research should explore the development of AI-powered encryption algorithms, anomaly detection mechanisms, and intelligent access controls to strengthen data protection in construction projects.

7.5.3 Exploring Smart City Applications

The integration of blockchain technology offers promising possibilities for smart cities, especially in the area of data coordination and documentation, and the development of interdisciplinary collaboration. This approach can reduce delays and costs, while monitoring and trusting changes in the digital environment facilitates informed decision-making in smart cities. The development of smart city applications requires innovative research to take advantage of the latest technologies and promote collaboration in this field. One possible solution is the integration of blockchain into intelligent transportation systems (ITS) as a method to improve data management in smart cities. In particular, the use of blockchain in ITS aims to improve data coordination, documentation, and security. A book chapter titled "Intelligent Transport Systems Applications: Security and Transfer of Big Transport Data" was published to serve as a practical reference in this context. Future research may evaluate strategies that leverage blockchain to improve security, while addressing big data challenges in transportation. Although cloud technology is widely used for data processing, it carries security risks.

Innovative developments in smart city applications can be realised through the integration of cybersecurity measures facilitated by blockchain technology. By leveraging blockchain's secure and decentralised architecture, cities can build formidable defences against cyber threats. Implementing blockchain-driven authentication and access control mechanisms strengthens the protection of smart city systems, ensuring that only authorised entities have access. In addition, blockchain's immutable transaction log and audit trails ensure transparency and accountability, discouraging data tampering and manipulation. Furthermore, the integration of advanced encryption techniques with blockchain strengthens overall cybersecurity in smart city environments by protecting data transfer and storage confidentiality. This strategic combination of cybersecurity measures with blockchain technology enhances data protection and increases trust in smart city infrastructure, contributing to resilience and sustainability in urban development initiatives. In addition, incentivising secure practices through blockchain-based reward mechanisms can actively engage stakeholders in the protection of smart city systems.

7.5.4 Digital Twinning

Digital Twin technology has significant potential to enhance digitalisation in various sectors, including urban planning, construction, and manufacturing. These digital replicas, from entire cities to individual buildings and machines, constantly evolve with technological advances. This evolution is further supported by emerging technologies such as blockchain. A paper titled "Leveraging BIM and Blockchain for Digital Twins" has been published to show the integration and importance of blockchain in this context.

In the BIM and blockchain integration field, the incorporation of cross-chain technology may be a promising avenue for future research. This innovative approach aims to address critical challenges related to interoperability and data exchange between different blockchain networks, thereby promoting a more interconnected and comprehensive digital representation of construction projects. Through the integration of cross-chain capabilities, the transfer and synchronisation of data and transactions between the various blockchain networks involved in the BIM process can be facilitated. Consequently, this integration has the potential to create a more cohesive digital twin model by enhancing the interoperability of information stored on different blockchain platforms. Future research efforts could focus on identifying standards and protocols that enable secure and efficient communication between various blockchain networks. By creating a framework that leverages cross-chain solutions to enhance the functionality and connectivity of digital twins in the construction industry, a pioneering step towards an integrated and collaborative future for construction project management can be taken.

Furthermore, this exploration encompasses critical areas for future research, including tokenisation mechanisms, scalability, and regulatory considerations. An in-depth examination of these dimensions provides valuable insight into how the convergence of BIM and blockchain can redefine data management, enhance stakeholder engagement, and address critical concerns related to scalability and ethical governance. Understanding and addressing these issues will impact the implementation of BIM and blockchain integration in the construction industry and advance it toward a more efficient and transparent future.

7.5.5 Circularity in Construction

Future initiatives in the construction industry focus on leveraging blockchain technology to drive circularity in supply chains. Integrating blockchain into material tracking systems has the potential to revolutionise the way in which materials are managed, reused, and recycled. A paper entitled "Circular Economy and Construction Supply Chains" has been published with a vision of potential integration in this context.

One direction for future work is the development of material passport systems. These digital records can provide information on a material's origin, composition, and life-cycle stages. By integrating blockchain, these passports can become immutable, transparent ledgers that track the movement and transformation of materials throughout their life cycle. This can improve traceability and enable stakeholders to make more informed decisions about the reuse and recycling of materials.

Future work should also focus on interoperability and standardisation. The development of common protocols and data formats will facilitate communication between different blockchain platforms and supply chain systems. This interoperability is necessary to create a harmonised ecosystem where stakeholders can exchange information and collaborate effectively to promote circularity. In addition, ethical provenance in the supply chain is essential. The transparency of blockchain can be used to verify the origin and authenticity of materials, ensuring that resources are sourced responsibly and ethically, further contributing to sustainability and compliance with ethical standards.

There is also a need for research into new applications of the blockchain in the practice of circular construction. For example, smart contracts could be used to automate processes such as material procurement, ensuring that sustainability criteria are met at every stage of the supply chain. Similarly, tokenisation of materials could encourage recycling and reuse by creating a market for secondary raw materials.

Bibliography

[1] J. Doerr. *Speed & Scale: An Action Plan for Solving Our Climate Crisis Now*. Penguin Business, 2021.

[2] Cara A Horowitz. Paris agreement. *International Legal Materials*, Vol. 55(4):pp. 740–755, 2016. doi: 10.1017/S0020782900004253.

[3] s Ho and Liang Liu. Analytical model for analyzing construction claims and opportunistic bidding. *Journal of Construction Engineering and Management*, Vol. 130:pp. 94–104, 02 2004. doi: 10.1061/(ASCE)0733-9364(2004)130:1(94).

[4] Eric Thomas, Peter Schott, Jay Bowman, Jay Snyder, and Natalie Spare. Construction disconnected. Technical report, PlanGrid and FMI, 2018. URL http://pg.plangrid.com/rs/572-JSV-775/images/Construction_Disconnected.pdf.

[5] Faith Tangara. 7 causes of construction rework: Evercam, Sep 2022. URL https://evercam.uk/blog/7-causes-of-construction-rework.

[6] Filipe Barbosa, Jonathan Woetzel, Jan Mischke, Mari J; Joao Ribeirinho, Mukund Sridhar, Matthew Parsons, Nick Bertram, and Stephanie Brown. Reinventing construction through a productivity revolution, 2017. URL https://www.mckinsey.com/capabilities/operations/our-insights/reinventing-construction-through-a-productivity-revolution.

[7] Faith Tangara. Causes of delays in construction and impact of evercam technology, Sep 2022. URL https://evercam.io/blog/causes-of-delays-in-construction-and-impact-of-evercam-technology/.

[8] Propeller Aero. 10 construction cost overrun statistics you need to hear, Aug 2023. URL https://www.propelleraero.com/blog/10-construction-project-cost-overrun-statistics-you-need-to-hear/.

[9] Richard Waterhouse et al. Nbs international bim report. 2019. *Disponible à l'adresse: https://www.thenbs.com/knowledge/national-bim-report-2019*, 2019.

[10] Ioan Petri, Tom Beach, Yacine Rezgui, Ian E. Wilson, and Haijiang Li. Engaging construction stakeholders with sustainability through a knowledge harvesting platform. *Computers in Industry*, Vol. 65:pp. 449 – 469, 2014. ISSN 0166-3615. doi: 10.1016/j.compind.2014.01.008. ICT for Sustainability in Industry.

[11] Jian Li, Lei Hou, Xiangyu Wang, Jun Wang, Jun Guo, Shaohua Zhang, and Yi Jiao. A project-based quantification of bim benefits. *International Journal of Advanced Robotic Systems*, Vol. 11(8):pp. 123, 2014. doi: 10.5772/58448.

[12] Andres Pedroza-SN. Potentials of blockchain application in bim: An effective solution to complex data management and reliability of information on big aec projects. *University College London*, 2019.

[13] Benjamin Teisserenc and Samad Sepasgozar. Adoption of blockchain technology through digital twins in the construction industry 4.0: A pestels approach. *Buildings*, Vol. 11(12), 2021. ISSN 2075-5309. doi: 10.3390/buildings11120670.

[14] Erika A Parn and David Edwards. Cyber threats confronting the digital built environment. *Engineering, Construction and Architectural Management*, Vol. 26:pp. 245–266, 2019. doi: 10.1108/ECAM-03-2018-0101.

[15] Liviu-Adrian Hirtan, Ciprian Dobre, and Horacio Gonzalez-Velez. Blockchain-based reputation for intelligent transportation systems. *Sensors*, Vol. 20(3), 2020. ISSN 1424-8220. doi: 10.3390/s20030791.

[16] Ayyoub Lamssaggad, Nabil Benamar, Abdelhakim Senhaji Hafid, and Mounira Msahli. A survey on the current security landscape of intelligent transportation

systems. *IEEE Access*, Vol. 9:pp. 9180–9208, 2021. doi: 10.1109/ACCESS.2021.3050038.

[17] Paul Chynoweth, Sharon Christensen, Judith McNamara, and Kathryn O'Shea. Legal and contracting issues in electronic project administration in the construction industry. *Structural Survey*, Vol. 25:pp. 191–203, 2007. doi: 10.1108/02630800710772791.

[18] Yong Yuan and Fei-Yue Wang. Towards blockchain-based intelligent transportation systems. In *2016 IEEE 19th International Conference on Intelligent Transportation Systems (ITSC)*, pages Vol. 2663–2668, 2016. doi: 10.1109/ITSC.2016.7795984.

[19] Hany F Atlam, Ahmed Alenezi, Madini O Alassafi, and Gary Wills. Blockchain with internet of things: Benefits, challenges, and future directions. *International Journal of Intelligent Systems and Applications*, Vol. 10(6):pp. 40–48, 2018. doi: 10.1109/COMST.2020.3009103.

[20] Nawari O Nawari and Shriraam Ravindran. Blockchain technologies in bim workflow environment. In *Computing in Civil Engineering 2019: Visualization, Information Modeling, and Simulation*, pages pp. 343–352. American Society of Civil Engineers Reston, 2019. doi: 10.1061/9780784482421.044.

[21] Sudeep Tanwar, Qasim Bhatia, Pruthvi Patel, Aparna Kumari, Pradeep Kumar Singh, and Wei-Chiang Hong. Machine learning adoption in blockchain-based smart applications: The challenges, and a way forward. *IEEE Access*, Vol. 8:pp. 474–488, 2020. doi: 10.1109/ACCESS.2019.2961372.

[22] Victoria Pancoast, Kevin McIve, Paul Mullen, Jordi Recan, and Gary Kitt. 2022 global construction disputes report. URL https://www.arcadis.com/en/knowledge-hub/perspectives/global/global-construction-disputes-report.

[23] Chapter twenty-two - transportation system. In Shubhani Aggarwal, Neeraj Kumar, and Pethuru Raj, editors, *The Blockchain Technology for Secure and Smart Applications across Industry Verticals*, volume Vol. 121 of *Advances in Computers*, pages pp. 431–454. Elsevier, 2021. doi: 10.1016/bs.adcom.2020.08.022.

[24] Piotr F. Borowski. Digitization, digital twins, blockchain, and industry 4.0 as elements of management process in enterprises in the energy sector. *Energies*, Vol. 14(7), 2021. ISSN 1996-1073. doi: 10.3390/en14071885.

[25] Hanh Tran and David G Carmichael. Contractor's financial estimation based on owner payment histories. *Organization, technology & management in construction: an international journal*, Vol. 4:pp. 481–489, 2012. doi: 10.5592/otmcj.2012.2.4.

[26] Z Ren, C.J Anumba, and O.O Ugwu. The development of a multi-agent system for construction claims negotiation. *Advances in Engineering Software*, Vol. 34: pp. 683–696, 2003. ISSN 0965-9978. doi: 10.1016/S0965-9978(03)00107-8.

[27] Janakiram Karlapudi, Karsten Menzel, Seppo Törmä, Andriy Hryshchenko, and Prathap Valluru. Enhancement of bim data representation in product-process modelling for building renovation. pages pp. 738–752. Springer, 2020. doi: 10.1007/978-3-030-62807-9_58.

[28] Izabella V. Lokshina, Michal GreguÅ¡, and Wade L. Thomas. Application of integrated building information modeling, iot and blockchain technologies in system design of a smart building. *Procedia Computer Science*, Vol. 160:pp. 497–502, 2019. ISSN 1877-0509. doi: 10.1016/j.procs.2019.11.058. The 10th International Conference on Emerging Ubiquitous Systems and Pervasive Networks (EUSPN-2019) / The 9th International Conference on Current and Future Trends of Information and Communication Technologies in Healthcare (ICTH-2019) / Affiliated Workshops.

[29] Gökhan Arslan, Mustafa Tuncan, M. Talat Birgonul, and Irem Dikmen. E-bidding

proposal preparation system for construction projects. *Building and Environment*, Vol. 41:pp. 1406–1413, 2006. ISSN 0360-1323. doi: 10.1016/j.buildenv.2005.05.024.

[30] Tien-Hsiang Chuang, Bo-Cing Lee, and I-Chen Wu. Applying cloud computing technology to bim visualization and manipulation. In *28th International Symposium on Automation and Robotics in Construction*, volume Vol. 201, pages pp. 144–149, 2011. doi: 10.22260/ISARC2011/0023.

[31] Nawari O Nawari and Shriraam Ravindran. Blockchain and the built environment: Potentials and limitations. *Journal of Building Engineering*, Vol. 25:pp. 100832, 2019. doi: 10.1016/j.jobe.2019.100832.

[32] Nawari Nawari. Blockchain technologies: Hyperledger fabric in bim work processes. pages pp. 813–823, 2021. doi: 10.1007/978-3-030-51295-8_56.

[33] Jong Han Yoon, Xinghua Gao, and Pardis Pishdad-Bozorgi. Blockchain: Technologies for facilitating cyber-physical security in smart built environment. pages pp. 164–189, 04 2021. doi: 10.1201/9781003017547-7.

[34] Amer A Hijazi, Srinath Perera, Ali Alashwal, and Rodrigo N Calheiros. Blockchain adoption in construction supply chain: A review of studies across multiple sectors. In *Constructing Smart Cities: Proceedings of the 22nd CIB World Building Congress (CIB2019), 17-21 June 2019, The Hong Kong Polytechnic University, Hong Kong, China*, 2019. URL `https://researchdirect.westernsydney.edu.au/islandora/object/uws%3A55406`.

[35] Anas Bataw, Richard Kirkham, and Eric Lou. The issues and considerations associated with bim integration. *MATEC Web of Conferences*, Vol. 66:pp. 00005, 01 2016. doi: 10.1051/matecconf/20166600005.

[36] Gabriella Hastig and Manmohan Sodhi. Blockchain for supply chain traceability: Business requirements and critical success factors. *Production and Operations Management*, Vol. 29, 2019. doi: 10.1111/poms.13147.

[37] Sohail Jabbar, Huw Lloyd, Mohammad Hammoudeh, Bamidele Adebisi, and Umar Raza. Blockchain-enabled supply chain: analysis, challenges, and future directions. *Multimedia Systems*, pages pp. 1–20, 2020. doi: 10.1007/s00530-020-00687-0.

[38] Ragib Hasan, Radu Sion, and Marianne Winslett. Preventing history forgery with secure provenance. *ACM Transactions on Storage*, Vol. 5, 2009. doi: 10.1145/1629080.1629082.

[39] Wenbo Du, Xiaozhi Ma, Hongping Yuan, and Yue Zhu. Blockchain technology-based sustainable management research: The status quo and a general framework for future application. *Environmental Science and Pollution Research*, Vol. 29(39):pp. 58648–58663, 2022. doi: 10.1007/s11356-022-21761-2.

[40] Suruchi Dhingra. The use of smart buildings solutions can reduce total global energy consumption by 3-5 URL `https://transformainsights.com/blog/smart-buildings-reduce-global-energy#`.

[41] Anil Sawhney, Michael Riley, and Javier Irizarry. *Construction 4.0: An innovation platform for the built environment*. Routledge, 2020. doi: 10.1201/9780429398100.

[42] Raihan Maskuriy, Ali Selamat, Petra Maresova, Ondrej Krejcar, and Oladipo Olalekan David. Industry 4.0 for the construction industry: Review of management perspective. *Economies*, Vol. 7(3), 2019. ISSN 2227-7099. doi: 10.3390/economies7030068.

[43] Mario Hermann, Tobias Pentek, and Boris Otto. Design principles for industrie 4.0 scenarios. In *2016 49th Hawaii International Conference on System Sciences (HICSS)*, pages pp. 3928–3937, 2016. doi: 10.1109/HICSS.2016.488.

[44] FathyElsayed Youssef Abdelmajied. Industry 4.0 and its implications: Concept, opportunities, and future directions. In Tamas Banyai, Agota Banyai,

and Ireneusz Kaczmar, editors, *Supply Chain*, chapter 1. IntechOpen, Rijeka, 2022. doi: 10.5772/intechopen.102520.

[45] Orsolya Nagy, Ilona Papp, and Roland Zsolt SzabÃ³. Construction 4.0 organisational level challenges and solutions. *Sustainability*, Vol. 13(pp. 21), 2021. ISSN 2071-1050. doi: 10.3390/su132112321.

[46] Wesam Salah Alaloul, M.S. Liew, Noor Amila Wan Abdullah Zawawi, and Ickx Baldwin Kennedy. Industrial revolution 4.0 in the construction industry: Challenges and opportunities for stakeholders. *Ain Shams Engineering Journal*, Vol. 11(1):pp. 225–230, 2020. ISSN 2090-4479. doi: 10.1016/j.asej.2019.08.010.

[47] Wesam S. Alaloul, Mohd Shahir Liew, and Noor Amila BWA Zawawi. A framework for coordination process into construction projects. *MATEC Web of Conferences*, Vol. 66:pp. 00079, 2016. doi: 10.1051/matecconf/20166600079.

[48] Rafael Sacks, Ioannis Brilakis, Ergo Pikas, Haiyan Sally Xie, and Mark Girolami. Construction with digital twin information systems. *Data-Centric Engineering*, 1:e14, 2020. doi: 10.1017/dce.2020.16.

[49] Markus Krämer and Zsuzsa Besenyői. Towards digitalization of building operations with bim. *IOP Conference Series: Materials Science and Engineering*, Vol. 365:pp. 022067, 06 2018. doi: 10.1088/1757-899X/365/2/022067.

[50] Qiuchen Lu, Ajith Kumar Parlikad, Philip Woodall, Xiang Xie, Zhenglin Liang, Eirini Konstantinou, James Heaton, and Jennifer Schooling. Developing a dynamic digital twin at building and city levels: A case study of the west cambridge campus. *Journal of Management in Engineering*, Vol. 36, 10 2019. doi: 10.1061/(ASCE)ME.1943-5479.0000763.

[51] Malachy Mathews, Dan Robles, and Brian J. Bowe. Bim+blockchain: A solution to the trust problem in collaboration? 2017. doi: 10.21427/D73N5K.

[52] Md Aslam Hossain and Abid Nadeem. Towards digitizing the construction industry: State of the art of construction 4.0. In *Proceedings of the ISEC*, volume Vol. 10, pages pp. 1–6, 2019. doi: 10.14455/ISEC.res.2019.184.

[53] Building information modelling (bim) uptake: Clear benefits, understanding its implementation, risks and challenges. *Renewable and Sustainable Energy Reviews*, Vol. 75:pp. 1046–1053, 2017. ISSN 1364-0321. doi: 10.1016/j.rser.2016.11.083.

[54] Mohsen Attaran. Digital technology enablers and their implications for supply chain management. *Supply Chain Forum: An International Journal*, Vol. 21(3): pp. 158–172, 2020. doi: 10.1080/16258312.2020.1751568.

[55] Hui Deng, Yiwen Xu, Yichuan Deng, and Jiarui Lin. Transforming knowledge management in the construction industry through information and communications technology: A 15-year review. *Automation in Construction*, Vol. 142:pp. 104530, 2022. doi: 10.1016/j.autcon.2022.104530.

[56] Sofiat O. Abioye, Lukumon O. Oyedele, Lukman Akanbi, Anuoluwapo Ajayi, Juan Manuel Davila Delgado, Muhammad Bilal, Olugbenga O. Akinade, and Ashraf Ahmed. Artificial intelligence in the construction industry: A review of present status, opportunities and future challenges. *Journal of Building Engineering*, Vol. 44:pp. 103299, 2021. ISSN 2352-7102. doi: 10.1016/j.jobe.2021.103299.

[57] Sreejith Balasubramanian, Vinaya Shukla, Nazrul Islam, and Shalini Manghat. Construction industry 4.0 and sustainability: An enabling framework. *IEEE Transactions on Engineering Management*, pages pp. 1–19, 2021. doi: 10.1109/TEM.2021.3110427.

[58] The strategic role of logistics in the industry 4.0 era. *Transportation Research Part E: Logistics and Transportation Review*, Vol. 129:pp. 1–11, 2019. ISSN 1366-5545. doi: 10.1016/j.tre.2019.06.004.

[59] Faris Elghaish, M. Reza Hosseini, Sandra Matarneh, Saeed Talebi, Song Wu, Igor Martek, Mani Poshdar, and Nariman Ghodrati. Blockchain and the â€˜internet of things' for the construction industry: research trends and opportunities. *Automation in Construction*, Vol. 132:pp. 103942, 2021. ISSN 0926-5805. doi: 10.1016/j.autcon.2021.103942.

[60] Calin Boje, Annie Guerriero, Sylvain Kubicki, and Yacine Rezgui. Towards a semantic construction digital twin: Directions for future research. *Automation in Construction*, Vol. 114:pp. 103179, 2020. ISSN 0926-5805. doi: 10.1016/j.autcon.2020.103179.

[61] Ning Gu and Kerry London. Understanding and facilitating bim adoption in the aec industry. *Automation in Construction*, Vol. 19(8):pp. 988–999, 2010. ISSN 0926-5805. doi: 10.1016/j.autcon.2010.09.002.

[62] Ruoyu Jin, Tong Yang, Poorang Piroozfar, Byung-Gyoo Kang, Dariusz Wanatowski, Craig Matthew Hancock, and Llewellyn Tang. Project-based pedagogy in interdisciplinary building design adopting bim. *Engineering, Construction and Architectural Management*, 2018. doi: 10.1108/ECAM-07-2017-0119.

[63] Rongyue Zheng, Jianlin Jiang, Xiaohan Hao, Wei Ren, Feng Xiong, and Yi Ren. bcbim: A blockchain-based big data model for bim modification audit and provenance in mobile cloud. *Mathematical Problems in Engineering*, Vol. 2019, 2019. doi: 10.1155/2019/5349538.

[64] Dena Mahmudnia, Mehrdad Arashpour, and Rebecca Yang. Blockchain in construction management: Applications, advantages and limitations. *Automation in Construction*, 140:104379, 2022. doi: 10.1016/j.autcon.2022.104379.

[65] Marcel Matthess, Stefanie Kunkel, Bing Xue, and Grischa Beier. Supplier sustainability assessment in the age of industry 4.0 â€“ insights from the electronics industry. *Cleaner Logistics and Supply Chain*, Vol. 4:pp. 100038, 2022. ISSN 2772-3909. doi: 10.1016/j.clscn.2022.100038.

[66] Alan J. McNamara and Samad M.E. Sepasgozar. Intelligent contract adoption in the construction industry: Concept development. *Automation in Construction*, Vol. 122:pp. 103452, 2021. ISSN 0926-5805. doi: 10.1016/j.autcon.2020.103452.

[67] Dongmin Lee, Sang Hyun Lee, Neda Masoud, M.S. Krishnan, and Victor C. Li. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in Construction*, Vol. 127:pp. 103688, 2021. doi: 10.1016/j.autcon.2021.103688.

[68] Xiaofeng Xu and Yangyang He. Blockchain application in modern logistics information sharing: a review and case study analysis. *Production Planning & Control*, pages pp. 1–15, 2022. doi: 10.1080/09537287.2022.2058997.

[69] Liupengfei Wu, Weisheng Lu, Rui Zhao, Jinying Xu, Xiao Li, and Fan Xue. Using blockchain to improve information sharing accuracy in the onsite assembly of modular construction. *Journal of Management in Engineering*, Vol. 38(3), 2022. doi: 10.1061/(asce)me.1943-5479.0001029.

[70] Xiao Li, Weisheng Lu, Fan Xue, Liupengfei Wu, Rui Zhao, Jinfeng Lou, and Jinying Xu. Blockchain-enabled iot-bim platform for supply chain management in modular construction. *Journal of Construction Engineering and Management*, Vol. 148(2), 2022. doi: 10.1061/(asce)co.1943-7862.0002229.

[71] Denis J. Scott, Tim Broyd, and Ling Ma. Exploratory literature review of blockchain in the construction industry. *Automation in Construction*, Vol. 132: pp. 103914, 2021. ISSN 0926-5805. doi: 10.1016/j.autcon.2021.103914.

[72] Goran Strbac. Demand side management: Benefits and challenges. *Energy Policy*, Vol. 36(12):pp. 4419–4426, 2008. ISSN 0301-4215. doi: 10.1016/j.enpol.2008.09.030. Foresight Sustainable Energy Management and the Built Environment Project.

[73] Poljansek M. Building information modelling (bim) standardization. (KJ-NA-28977-EN-N), 2017. ISSN 1831-9424. doi: 10.2760/36471.

[74] Massimo Regona, Tan Yigitcanlar, Bo Xia, and Rita Yi Man Li. Opportunities and adoption challenges of ai in the construction industry: A prisma review. *Journal of Open Innovation: Technology, Market, and Complexity*, Vol. 8(1):pp. 45, 2022. ISSN 2199-8531. doi: 10.3390/joitmc8010045.

[75] Beliz Ozorhon and Ugur Karahan. Critical success factors of building information modeling implementation. *Journal of Management in Engineering*, Vol. 33(3), 2017. doi: 10.1061/(asce)me.1943-5479.0000505.

[76] Chengshuang Sun, Shaohua Jiang, Miroslaw J. Skibniewski, Qingpeng Man, and Liyin Shen. A literature review of the factors limiting the application of bim in the construction industry. *Technological and Economic Development of Economy*, Vol. 23(5):pp. 764–779, 2017. doi: 10.3846/20294913.2015.1087071.

[77] Maria Christina Georgiadou. An overview of benefits and challenges of building information modelling (bim) adoption in uk residential projects. *Construction Innovation*, Vol. 19(3):pp. 298–320, 2019. doi: 10.1108/ci-04-2017-0030.

[78] Chris Newman, David Edwards, Igor Martek, Joseph Lai, Wellington Didibhuku Thwala, and Iain Rillie. Industry 4.0 deployment in the construction industry: A bibliometric literature review and uk-based case study. *Smart and Sustainable Built Environment*, Vol. 10(4):pp. 557–580, 2020. doi: 10.1108/sasbe-02-2020-0016.

[79] Sevilay Demirkesen and Algan Tezel. Investigating major challenges for industry 4.0 adoption among construction companies. *Engineering, Construction and Architectural Management*, 2021. doi: 10.1108/ecam-12-2020-1059.

[80] Shohin Aheleroff, Xun Xu, Ray Y. Zhong, and Yuqian Lu. Digital twin as a service (dtaas) in industry 4.0: An architecture reference model. *Advanced Engineering*

Informatics, Vol. 47:pp. 101225, 2021. ISSN 1474-0346. doi: 10.1016/j.aei.2020.101225.

[81] Danda B. Rawat, Ronald Doku, and Moses Garuba. Cybersecurity in big data era: From securing big data to data-driven security. *IEEE Transactions on Services Computing*, Vol. 14(6):pp. 2055–2072, 2021. doi: 10.1109/TSC.2019.2907247.

[82] Zibin Zheng, Shaoan Xie, Hong-Ning Dai, Weili Chen, Xiangping Chen, Jian Weng, and Muhammad Imran. An overview on smart contracts: Challenges, advances and platforms. *Future Generation Computer Systems*, Vol. 105:pp. 475–491, 2020. ISSN 0167-739X. doi: 10.1016/j.future.2019.12.019.

[83] Fran Casino, Thomas K. Dasaklis, and Constantinos Patsakis. A systematic literature review of blockchain-based applications: Current status, classification and open issues. *Telematics and Informatics*, Vol. 36:pp. 55–81, 2019. ISSN issn 0736-5853. doi: 10.1016/j.tele.2018.11.006.

[84] Edward Meinert, Abrar Alturkistani, Kimberly Foley, Tasnime Osama, Josip Car, Azeem Majeed, Michelle Van Velthoven, Glenn Wells, and David Brindley. Blockchain implementation in health care: Protocol for a systematic review. 2018. doi: 10.2196/10994.

[85] Usama Ahmed, Ioan Petri, Omer Rana, Imran Raza, and Syed Asad Hussain. Federating cloud systems for collaborative construction and engineering. *IEEE Access*, Vol. 8:pp. 79908–79919, 2020. doi: 10.1109/ACCESS.2020.2990233.

[86] Yan Chen and Cristiano Bellavitis. Blockchain disruption and decentralized finance: The rise of decentralized business models. *Journal of Business Venturing Insights*, Vol. 13:pp. e00151, 2020. ISSN 2352-6734. doi: 10.1016/j.jbvi.2019.e00151.

[87] Fei Tao, Yongping Zhang, Ying Cheng, Jiawei Ren, Dongxu Wang, Qinglin Qi, and Pei Li. Digital twin and blockchain enhanced smart manufacturing service

collaboration and management. *Journal of Manufacturing Systems*, 2020. doi: 10.1016/j.jmsy.2020.11.008.

[88] Ibrar Yaqoob, Khaled Salah, Mueen Uddin, Raja Jayaraman, Mohammed Omar, and Muhammad Imran. Blockchain for digital twins: Recent advances and future research challenges. *IEEE Network*, Vol. 34(5):pp. 290–298, 2020. doi: 10.1109/MNET.001.1900661.

[89] Asad Siyal, Aisha Junejo, Muhammad Zawish, Kainat Ahmed, Aiman Khalil, and Georgia Soursou. Applications of blockchain technology in medicine and healthcare: Challenges and future perspectives. *Cryptography*, Vol. 3:pp. 3, 2019. doi: 10.3390/cryptography3010003.

[90] Lee Dongmin, Sang Lee, Neda Masoud, M.S. Krishnan, and Victor Li. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in Construction*, Vol. 127:pp. 103688, 2021. doi: 10.1016/j.autcon.2021.103688.

[91] Jannis Angelis and Elias Ribeiro da Silva. Blockchain adoption: A value driver perspective. *Business Horizons*, Vol. 62(3):pp. 307–314, 2019. ISSN 0007-6813. doi: 10.1016/j.bushor.2018.12.001.

[92] Daqiang Guo, Shiquan Ling, Hao Li, Di Ao, Tongda Zhang, Yiming Rong, and George Q. Huang. A framework for personalized production based on digital twin, blockchain and additive manufacturing in the context of industry 4.0. In *2020 IEEE 16th International Conference on Automation Science and Engineering (CASE)*, pages pp. 1181–1186, 2020. doi: 10.1109/CASE48305.2020.9216732.

[93] Azad Madni, Carla Madni, and Don Lucero. Leveraging digital twin technology in model-based systems engineering. *Systems*, Vol. 7:pp. 7, 2019. doi: 10.3390/systems7010007.

[94] Keqi Wang, Wei Xie, Bo Wang, Jinxiang Pei, Wencen Wu, Mike Baker, and Qi Zhou. Simulation-based digital twin development for blockchain enabled end-

to-end industrial hemp supply chain risk management. In *2020 Winter Simulation Conference (WSC)*, pages pp. 3200–3211, 2020. doi: 10.1109/WSC48552.2020.9384115.

[95] Huawei Huang, Wei Kong, Sicong Zhou, Zibin Zheng, and Song Guo. A survey of state-of-the-art on blockchains: Theories, modelings, and tools. *ACM Comput. Surv.*, Vol. 54(2), 2021. ISSN 0360-0300. doi: 10.1145/3441692.

[96] Marco Macchi, Irene Roda, Elisa Negri, and Luca Fumagalli. Exploring the role of digital twin for asset lifecycle management. *IFAC-PapersOnLine*, Vol. 51(11): pp. 790–795, 2018. ISSN 2405-8963. doi: 10.1016/j.ifacol.2018.08.415.

[97] Kendrik Yan Hong Lim, Pai Zheng, and Chun-Hsien Chen. A state-of-the-art survey of digital twin: techniques, engineering product lifecycle management and business innovation perspectives. *Journal of Intelligent Manufacturing*, 2020. doi: 10.1007/s10845-019-01512-w.

[98] Jing Kang. Convergence analysis of bim & blockchain technology in construction industry informatization. In *2022 4th International Conference on Smart Systems and Inventive Technology (ICSSIT)*, pages pp. 256–259, 2022. doi: 10.1109/ICSSIT53264.2022.9716352.

[99] Salman Azhar, Malik Khalfan, and Tayyab Maqsood. Building information modelling (bim): Now and beyond. *Construction Economics and Building*, Vol. 12 (4):pp. 15–28, 2015. doi: 10.5130/ajceb.v12i4.3032.

[100] Vishal Singh, Ning Gu, and Xiangyu Wang. A theoretical framework of a bim-based multi-disciplinary collaboration platform. *Automation in Construction*, Vol. 20:pp. 134–144, 2011. ISSN 0926-5805. doi: 10.1016/j.autcon.2010.09.011.

[101] Robert Eadie, Mike Browne, Henry Odeyinka, Clare McKeown, and Sean McNiff. Bim implementation throughout the uk construction project lifecycle: An analysis. *Automation in Construction*, Vol. 36:pp. 145–151, 2013. ISSN 0926-5805. doi: 10.1016/j.autcon.2013.09.001.

[102] Sandra T. Matarneh, Mark Danso-Amoako, Salam Al-Bizri, Mark Gaterell, and Rana T. Matarneh. Bim for fm. *Facilities*, Vol. 38(5/6):pp. 378–394, 2019. doi: 10.1108/f-07-2018-0084.

[103] Peter E.D. Love, Jane Matthews, Ian Simpson, Andrew Hill, and Oluwole A. Olatunji. A benefits realization management building information modeling framework for asset owners. *Automation in Construction*, Vol. 37:pp. 1–10, 2014. ISSN 0926-5805. doi: 10.1016/j.autcon.2013.09.007.

[104] Temidayo Oluwasola Osunsanmi, Clinton Ohis Aigbavboa, Ayodeji Emmanuel Oke, and Muredini Liphadzi. Appraisal of stakeholders' willingness to adopt construction 4.0 technologies for construction projects. *Built Environment Project and Asset Management*, Vol. 10(4):pp. 547–565, 2020. doi: 10.1108/BEPAM-12-2018-0159.

[105] Jennifer Li, David Greenwood, and Mohamad Kassem. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction*, Vol. 102:pp. 288–307, 2019. ISSN 0926-5805. doi: 10.1016/j.autcon.2019.02.005.

[106] Anastasia Nikologianni, Mohammad Mayouf, and Silvia Gullino. Building information modelling (bim) and the impact on landscape: A systematic review of evolvements, shortfalls and future opportunities. *Cleaner Production Letters*, Vol. 3:pp. 100016, 2022. doi: 10.1016/j.clpl.2022.100016.

[107] Liupengfei Wu, Weisheng Lu, Ziyu Peng, and Chris Webster. A blockchain non-fungible token-enabled 'passport' for construction waste material cross-jurisdictional trading. *Automation in Construction*, Vol. 149:pp. 104783, 2023. ISSN 0926-5805. doi: 10.1016/j.autcon.2023.104783.

[108] Shrinivas Baldawa, Lakshmisudha Kondaka, R Shobhana Iyer, and Divyalaxmi Thiruganan. Blockchain-based construction management system. In *2023 7th*

International Conference on Trends in Electronics and Informatics (ICOEI), pages pp. 597–603, 2023. doi: 10.1109/ICOEI56765.2023.10125997.

[109] Yishuo Jiang, Xinlai Liu, Zicheng Wang, Ming Li, Ray Y. Zhong, and George Q. Huang. Blockchain-enabled digital twin collaboration platform for fit-out operations in modular integrated construction. *Automation in Construction*, Vol. 148: pp. 104747, 2023. ISSN 0926-5805. doi: 10.1016/j.autcon.2023.104747.

[110] Binh Minh Nguyen, Thanh Dao, and Ba Lam Do. Towards a blockchain-based certificate authentication system in vietnam. *PeerJ Computer Science*, 03 2020. doi: 10.7717/peerj-cs.266.

[111] Sloane Brakeville and Bhargav Perepa. Blockchain basics: Introduction to distributed ledgers, Jun 2019. URL https://developer.ibm.com/tutorials/cl-blockchain-basics-intro-bluemix-trs/.

[112] Žiga Turk and Robert Klinc. Potentials of blockchain technology for construction management. *Procedia Engineering*, Vol. 196:pp. 638–645, 2017. ISSN 1877-7058. doi: 10.1016/j.proeng.2017.08.052.

[113] Kevin Delmolino, Mitchell Arnett, Ahmed Kosba, Andrew Miller, and Elaine Shi. Step by step towards creating a safe smart contract: Lessons and insights from a cryptocurrency lab. volume Vol. 9604, pages pp. 79–94, 02 2016. ISBN 978-3-662-53356-7. doi: 10.1007/978-3-662-53357-4_6.

[114] Helder Cardeira. *The benefits of integrating Smart Contracts and BIM using an XML protocol*. The New Wave annual conference., 2017.

[115] Jeremy Barnett. Blockchain for bim: Smart contracts lawyer, Sep 2016. URL http://www.jeremybarnett.co.uk/legal-software/blochain-for-bim-smart-contracts-lawyer.

[116] Smart Contracts Alliance. Smart contracts: 12 use cases for business & beyond. *Chamber of Digital Commerce*, Vol. 56:

pp. 1–53, 2016. URL http://digitalchamber.org/assets/smart-contracts-12-use-cases-for-business-and-beyond.pdf.

[117] Vincent Hargaden, Nikolaos Papakostas, Anthony Newell, Adam Khavia, and Adam Scanlon. The role of blockchain technologies in construction engineering project management. In *2019 IEEE International Conference on Engineering, Technology and Innovation (ICE/ITMC)*, pages pp. 1–6, 2019. doi: 10.1109/ICE.2019.8792582.

[118] AS Erri Pradeep, TW Yiu, and R Amor. Leveraging blockchain technology in a bim workflow: A literature review. In *International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving data-informed decision-making*, pages pp. 371–380, 2019. doi: 10.1680/icsic.64669.371.

[119] Srinath Perera, Samudaya Nanayakkara, M.N.N. Rodrigo, Sepani Senaratne, and Ralf Weinand. Blockchain technology: Is it hype or real in the construction industry? *Journal of Industrial Information Integration*, Vol. 17:pp. 100125, 2020. ISSN 2452-414X. doi: 10.1016/j.jii.2020.100125.

[120] Algan Tezel, Eleni Papadonikolaki, Ibrahim Yitmen, and Per Hilletofth. Preparing construction supply chains for blockchain: an exploratory analysis. In *CIB World Building Congress 2019 Constructing Smart Cities, Hong Kong SAR, China, 17–21 June 2019*, volume Vol. 6, 2019. URL https://discovery.ucl.ac.uk/id/eprint/10076425.

[121] Borja García de Soto, Isolda Agustí-Juan, Jens Hunhevicz, Samuel Joss, Konrad Graser, Guillaume Habert, and Bryan Adey. Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall. *Automation in Construction*, Vol. 92, 2018. doi: 10.1016/j.autcon.2018.04.004.

[122] Kiu Mee San, Chia Fah Choy, and Wong Phui Fung. The potentials and impacts of blockchain technology in construction industry: A literature review. In *IOP*

Conference Series: Materials Science and Engineering, volume Vol. 495, page pp. 012005. IOP Publishing, 2019. doi: 10.1088/1757-899X/495/1/012005.

[123] Dermott McMeel and Alexandra Sims. *Chip of the new block (chain): blockchain and the construction sector*. BRANZ, 2021. URL https://d39d3mj7qio96p.cloudfront.net/media/documents/ER62_Blockchain_and_the_construction_sector_LR10482.pdf.

[124] Kiu Mee San, Chia Fah Choy, and Wong Phui Fung. The potentials and impacts of blockchain technology in construction industry: A literature review. In *IOP conference series: materials science and engineering*, volume Vol. 495, page pp. 012005. IOP Publishing, 2019. doi: 10.1088/1757-899X/495/1/012005.

[125] Weisheng Lu, Xiao Li, Fan Xue, Rui Zhao, Liupengfei Wu, and Anthony G.O. Yeh. Exploring smart construction objects as blockchain oracles in construction supply chain management. *Automation in Construction*, Vol. 129:pp. 103816, 2021. doi: 10.1016/j.autcon.2021.103816.

[126] Applications of distributed ledger technology (dlt) and blockchain-enabled smart contracts in construction. *Automation in Construction*, Vol. 132:pp. 103955, 2021. ISSN 0926-5805. doi: 10.1016/j.autcon.2021.103955.

[127] Digitalised circular construction supply chain: An integrated bim-blockchain solution. *Automation in Construction*, Vol. 148:104746, 2023. ISSN 0926-5805. doi: 10.1016/j.autcon.2023.104746.

[128] Zhen Liu, Ziyuan Chi, Mohamed Osmani, and Peter Demian. Blockchain and building information management (bim) for sustainable building development within the context of smart cities. *Sustainability*, Vol. 13, 2021. doi: doi.org/10.3390/su13042090.

[129] Han Luo, Moumita Das, Jun Wang, and Jack CP Cheng. Construction payment automation through smart contract-based blockchain framework. In *ISARC.*

Proceedings of the International Symposium on Automation and Robotics in Construction, volume Vol. 36, pages pp. 1254–1260. IAARC Publications, 2019.

[130] Hesam Hamledari and Martin Fischer. Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. *Automation in Construction*, Vol. 132:pp. 103926, 2021. doi: 10.1016/j.autcon.2021.103926.

[131] Moumita Das, Han Luo, and Jack Cheng. Securing interim payments in construction projects through a blockchain-based framework. *Automation in Construction*, Vol. 118:pp. 103284, 2020. doi: 10.1016/j.autcon.2020.103284.

[132] V. Ciotta, G. Mariniello, D. Asprone, A. Botta, and G. Manfredi. Integration of blockchains and smart contracts into construction information flows: Proof-of-concept. *Automation in Construction*, Vol. 132:pp. 103925, 2021. ISSN 0926-5805. doi: 10.1016/j.autcon.2021.103925.

[133] Muhammad Fariq Abdul Hamid and Zulhasni Abdul Rahim. Construction 4.0 readiness and challenges for construction skills training institutions in malaysia. In *Advances on Intelligent Informatics and Computing: Health Informatics, Intelligent Systems, Data Science and Smart Computing*, pages pp. 697–706. Springer, 2022. doi: 10.1007/978-3-030-98741-1_58.

[134] Jameela Al-Jaroodi and Nader Mohamed. Blockchain in industries: A survey. *IEEE Access*, Vol. 7:pp. 36500–36515, 2019. doi: 10.1109/ACCESS.2019.2903554.

[135] Claudio Mandolla, Antonio Messeni Petruzzelli, Gianluca Percoco, and Andrea Urbinati. Building a digital twin for additive manufacturing through the exploitation of blockchain: A case analysis of the aircraft industry. *Computers in Industry*, Vol. 109:pp. 134–152, 2019. ISSN 0166-3615. doi: 10.1016/j.compind.2019.04.011.

[136] Haitao Wu, Botao Zhong, Heng Li, Jiadong Guo, and Yuhang Wang. On-site construction quality inspection using blockchain and smart contracts. *Journal of Management in Engineering*, Vol. 37(6):pp. 04021065, 2021. doi: 10.1061/(ASCE)ME.1943-5479.0000967.

[137] Samudaya Nanayakkara, Srinath Perera, Dilum Bandara, Thilini Weerasuriya, and Jason Ayoub. Blockchain technology and its potential for the construction industry. 11 2019. doi: 10.6084/m9.figshare.10315331.v3.

[138] Da Sheng, Lieyun Ding, Botao Zhong, Hanbin Luo, and Jiageng Chen. Construction quality information management with blockchains. *Automation in Construction*, Vol. 120:pp. 103373, 2020. doi: 10.1016/j.autcon.2020.103373.

[139] Mohita Gangwar Sharma and Sunil Kumar. The implication of blockchain as a disruptive technology for construction industry. *IIM Kozhikode Society & Management Review*, Vol. 9(2):pp. 177–188, 2020. doi: 10.1177/2277975220932343.

[140] Awsan Mohammed, Ahmad Almousa, Ahmed Ghaithan, and Laith A. Hadidi. The role of blockchain in improving the processes and workflows in construction projects. *Applied Sciences*, Vol. 11(19), 2021. ISSN 2076-3417. doi: 10.3390/app11198835.

[141] Zhaojing Wang, Tengyu Wang, Hao Hu, Jie Gong, Xu Ren, and Qiying Xiao. Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. *Automation in Construction*, Vol. 111, 2019. doi: 10.1016/j.autcon.2019.103063.

[142] Vincent Hargaden, Nikolaos Papakostas, Anthony Newell, Adam Khavia, and Adam Scanlon. The role of blockchain technologies in construction engineering project management. In *2019 IEEE international conference on engineering, technology and innovation (ICE/ITMC)*, pages pp. 1–6. IEEE, 2019.

[143] Kai Kang, Xinlai Liu, Yishuo Jiang, Kam Lee, Sean Wan, George Q. Huang, and Ray Zhong. Blockchain opportunities for construction industry in hong kong: a case study of risc and site diary. *Construction Innovation*, 2022. doi: 10.1108/CI-08-2021-0153.

[144] Alireza Shojaei. Exploring applications of blockchain technology in the construction industry. *Proceedings of International Structural Engineering and Construction*, Vol. 6, 2019. doi: 10.14455/ISEC.res.2019.78.

[145] Rosanna Cole, Mark Stevenson, and James Aitken. Blockchain technology: Implications for operations and supply chain management. *Supply Chain Management: An International Journal*, 24(4):469–483, 2019. doi: 10.1108/scm-09-2018-0309.

[146] Alireza Shojaei. Exploring applications of blockchain technology in the construction industry. *Edited by Didem Ozevin, Hossein Ataei, Mehdi Modares, Asli Pelin Gurgun, Siamak Yazdani, and Amarjit Singh. Proceedings of International Structural Engineering and Construction*, Vol. 6, 2019.

[147] Xiangyu WANG Wenchi SHOU Jun WANG, Peng WU. The outlook of blockchain technology for construction engineering management. *Frontiers of Engineering Management*, Vol. 4:67, 2017. doi: 10.15302/J-FEM-2017006. URL https://journal.hep.com.cn/fem/EN/abstract/article_19503.shtml.

[148] Samudaya Nanayakkara, Srinath Perera, Dilum Bandara, Thilini Weerasuriya, and Jason Ayoub. Blockchain technology and its potential for the construction industry. 11 2019. doi: 10.6084/m9.figshare.10315331.v3.

[149] MNN Rodrigo, Srinath Perera, Sepani Senaratne, and Xiaohua Jin. Blockchain for construction supply chains: a literature synthesis. In *Proceedings of ICEC-PAQS Conference 2018*, 2018. URL https://researchdirect.westernsydney.edu.au/islandora/object/uws:49027.

[150] Kyeongbaek Kim, Gayeoun Lee, and Sangbum Kim. A study on the application of blockchain technology in the construction industry. *KSCE journal of civil engineering*, Vol. 24(9):pp. 2561–2571, 2020.

[151] Mohammed S. Alnahari and Samuel T. Ariaratnam. The application of blockchain technology to smart city infrastructure. *Smart Cities*, Vol. 5(3):pp. 979–993, 2022. ISSN 2624-6511. doi: 10.3390/smartcities5030049.

[152] Lee Dongmin, Sang Lee, Neda Masoud, M.S. Krishnan, and Victor Li. Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. *Automation in Construction*, Vol. 127:pp. 103688, 2021. doi: 10.1016/j.autcon.2021.103688.

[153] Iris Belle. The architecture, engineering and construction industry and blockchain technology. *Digital Culture*, Vol. 2017:pp. 279–284, 2017.

[154] Suitability analysis of consensus protocols for blockchain-based applications in the construction industry. *Automation in Construction*, Vol. 145:104638, 2023. ISSN 0926-5805. doi: 10.1016/j.autcon.2022.104638.

[155] M. S. Kiu, F. C. Chia, and P. F. Wong. Exploring the potentials of blockchain application in construction industry: a systematic review. *International Journal of Construction Management*, Vol. 22(15):pp. 2931–2940, 2022. doi: 10.1080/15623599.2020.1833436.

[156] Abhinaw Sai Erri Pradeep, Tak Wing Yiu, Yang Zou, and Robert Amor. Blockchain-aided information exchange records for design liability control and improved security. *Automation in Construction*, Vol. 126:pp. 103667, 2021. doi: 10.1016/j.autcon.2021.103667.

[157] Abel Maciel. Use of blockchain for enabling construction 4.0. In *Construction 4.0*, pages pp. 395–418. Routledge, 2020. doi: 10.1201/9780429398100-20.

[158] Luisanna Cocco, Roberto Tonelli, and Michele Marchesi. A system proposal for information management in building sector based on bim, ssi, iot and blockchain. *Future Internet*, Vol. 14, 2022. doi: 10.3390/fi14050140.

[159] Steven Graham. Implementation of blockchain technology in the construction industry. 2019. URL https://digitalcommons.calpoly.edu/cmsp/190.

[160] Rebecca Yang, Ron Wakefield, Sainan Lyu, Sajani Jayasuriya, Fengling Han, Xun Yi, Xuechao Yang, Gayashan Amarasinghe, and Shiping Chen. Public and private blockchain in construction business process and information integration. *Automation in Construction*, Vol. 118:pp. 103276, 2020. ISSN 0926-5805. doi: 10.1016/j.autcon.2020.103276.

[161] Mahtab Kouhizadeh, Qingyun Zhu, and Joseph Sarkis. Blockchain and the circular economy: potential tensions and critical reflections from practice. *Production Planning & Control*, Vol. 31:pp. 950–966, 2020. doi: 10.1080/09537287.2019.1695925.

[162] Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction*, Vol. 102:pp. 288–307, 2019. ISSN 0926-5805. doi: 10.1016/j.autcon.2019.02.005.

[163] Sara Saberi, Mahtab Kouhizadeh, Joseph Sarkis, and Lejia Shen. Blockchain technology and its relationships to sustainable supply chain management. *International Journal of Production Research*, Vol. 57(7):pp. 2117–2135, 2019. doi: 10.1080/00207543.2018.1533261.

[164] Žiga Turk and Robert Klinc. Potentials of blockchain technology for construction management. *Procedia Engineering*, Vol. 196:pp. 638–645, 2017. ISSN 1877-7058. doi: 10.1016/j.proeng.2017.08.052.

[165] Rongyue Zheng, Jianlin Jiang, Xiaohan Hao, Wei Ren, Feng Xiong, and Yi Ren. bcbim: A blockchain-based big data model for bim modification audit and prove-

nance in mobile cloud. *Mathematical Problems in Engineering*, Vol. 2019:pp. 1–13, 2019. doi: 10.1155/2019/5349538.

[166] Alan McNamara and SM Sepasgozar. Barriers and drivers of intelligent contract implementation in construction. *n: 42nd Australasian Universities Building Education Association Conference,*, Vol. 143: pp. 281–93, 2018. URL https://docs.wixstatic.com/ugd/94be57_f3778ad853e8419f8028861fac33bcba.pdf.

[167] Fan Xue and Weisheng Lu. A semantic differential transaction approach to minimizing information redundancy for bim and blockchain integration. *Automation in Construction*, Vol. 118:pp. 103270, 2020. doi: 10.1016/j.autcon.2020.103270.

[168] Theodoros Dounas, Davide Lombardi, and Wassim Jabi. Framework for decentralised architectural design, bim and blockchain integration. *International Journal of Architectural Computing*, Vol. 19, 2020. doi: 10.1177/1478077120963376.

[169] Xingyu Tao, Moumita Das, Yuhan Liu, and Jack Cheng. Distributed common data environment using blockchain and interplanetary file system for secure bim-based collaborative design. *Automation in Construction*, Vol. 130:pp. 103851, 2021. doi: 10.1016/j.autcon.2021.103851.

[170] Minju Kim, Xianxiang Zhao, Yong-Woo Kim, and Byong-Duk Rhee. Blockchain-enabled supply chain coordination for off-site construction using bayesian theory for plan reliability. *Automation in Construction*, Vol. 155:pp. 105061, 2023. ISSN 0926-5805. doi: 10.1016/j.autcon.2023.105061.

[171] Brad Hardin and Dave McCool. *BIM and construction management: proven tools, methods, and workflows*. John Wiley & Sons, 2015. URL https://classes.engr.oregonstate.edu/cce/spring2019/cce203/BIM_HardingMcCool_reading/BIM%20&%20Construction%20Management.pdf.

[172] Faris Elghaish, Sepehr Abrishami, and M. Reza Hosseini. Integrated project delivery with blockchain: An automated financial system. *Automation in Construction*, Vol. 114:pp. 103182, 2020. ISSN 0926-5805. doi: 10.1016/j.autcon.2020.103182.

[173] Thuy Duong Oesterreich and Frank Teuteberg. Understanding the implications of digitisation and automation in the context of industry 4.0: A triangulation approach and elements of a research agenda for the construction industry. *Computers in Industry*, Vol. 83:pp. 121–139, 2016. ISSN 0166-3615. doi: 10.1016/j.compind.2016.09.006.

[174] Umit Isikdag. Design patterns for bim-based service-oriented architectures. *Automation in Construction*, Vol. 25:pp. 59–71, 2012. doi: doi.org/10.1016/j.autcon.2012.04.013.

[175] Qiuchen Lu, Xiang Xie, Ajith Kumar Parlikad, James Heaton, and Jennifer Schooling. From bim towards digital twin: Strategy and future development for smart asset management. 2019. doi: 10.17863/CAM.40565.

[176] Ersin Namli, Umit Isikdag, and Mustafa Kocakaya. Building information management (bim), a new approach to project management. *Journal of Sustainable Construction Materials and Technologies*, Vol. 4:pp. 323–332, 2019. doi: 10.29187/jscmt.2019.36.

[177] Moumita Das, Xingyu Tao, and Jack CP Cheng. Bim security: A critical review and recommendations using encryption strategy and blockchain. *Automation in construction*, Vol. 126:pp. 103682, 2021.

[178] R. Honti and J. Erdelyi. Possibilities of bim data exchange. In *18th International Multidisciplinary Scientific GeoConference SGEM 2018*, volume Vol. 18, pages pp. 923–930, 2018. doi: 10.5593/sgem2018/2.2/S09.117.

[179] Fan Xue and Weisheng Lu. A semantic differential transaction approach to min-

imizing information redundancy for bim and blockchain integration. *Automation in construction*, Vol. 118:pp. 103270, 2020. doi: 10.1016/j.autcon.2020.103270.

[180] Assam Hammi and Abdelaziz Bouras. Towards safe-bim curricula based on the integration of cybersecurity and blockchains features. pages pp. 2380–2388, 03 2018. doi: 10.21125/inted.2018.0453.

[181] Sathyan Munirathinam. Chapter six - industry 4.0: Industrial internet of things (iiot). In Pethuru Raj and Preetha Evangeline, editors, *The Digital Twin Paradigm for Smarter Systems and Environments: The Industry Use Cases*, volume Vol. 117 of *Advances in Computers*, pages pp. 129–164. Elsevier, 2020. doi: 10.1016/bs.adcom.2019.10.010.

[182] Patrick Dallasega, Erwin Rauch, and Christian Linder. Industry 4.0 as an enabler of proximity for construction supply chains: A systematic literature review. *Computers in Industry*, Vol. 99:pp. 205–225, 2018. ISSN 0166-3615. doi: 10.1016/j.compind.2018.03.039.

[183] NI Wei LIU Ren-ping GUO Ying-jie NIU Xin-xin ZHENG Kang-feng ZHA Xuan, WANG Xu. Blockchain for iot: the tradeoff between consistency and capacity. *Chinese Journal on Internet of Things*, Vol. 1(1):21, 2017. doi: 10.11959/j.issn.2096-3750.2017.00004.

[184] De-Graft Joe Opoku, Srinath Perera, Robert Osei-Kyei, and Maria Rashidi. Digital twin application in the construction industry: A literature review. *Journal of Building Engineering*, Vol. 40:pp. 102726, 2021. ISSN 2352-7102. doi: 10.1016/j.jobe.2021.102726.

[185] Arzoo Miglani, Neeraj Kumar, Vinay Chamola, and Sherali Zeadally. Blockchain for internet of energy management: Review, solutions, and challenges. *Computer Communications*, Vol. 151:pp. 395–418, 2020. doi: 10.1016/j.comcom.2020.01.014.

[186] Sarwar Sayeed and Hector Marco-Gisbert. Proof of adjourn (poaj): A novel approach to mitigate blockchain attacks. *Applied Sciences*, Vol. 10(18), 2020. ISSN 2076-3417. doi: 10.3390/app10186607.

[187] Nick Szabo. Smart contracts, 1994. URL http://www.fon.hum.uva.nl/rob/Courses/InformationInSpeech/CDROM/Literature/LOTwinterschool2006/szabo.best.vwh.net/smart.contracts.html.

[188] Hesam Hamledari and Martin Fischer. Role of blockchain-enabled smart contracts in automating construction progress payments. *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, Vol. 13:pp. 04520038, 10 2020. doi: 10.1061/(ASCE)LA.1943-4170.0000442.

[189] Bhabendu Kumar Mohanta, Soumyashree S Panda, and Debasish Jena. An overview of smart contract and use cases in blockchain technology. 2018. doi: 10.1109/ICCCNT.2018.8494045.

[190] Theodoros Dounas, Davide Lombardi, and Wassim Jabi. Framework for decentralised architectural design, bim and blockchain integration. *International Journal of Architectural Computing*, Vol. 19, 2020. doi: 10.1177/1478077120963376.

[191] Xueyan Zhang, Tingting Liu, Anisur Rahman, and Lingzhong Zhou. Blockchain applications for construction contract management: A systematic literature review. *Journal of Construction Engineering and Management*, Vol. 149(1):pp. 03122011, 2023. doi: 10.1061/(ASCE)CO.1943-7862.0002428.

[192] Jin Hong Tan, Siaw-Chuing Loo, Nurshuhada Zainon, Nur Mardhiyah Aziz, and Faizul Azli Mohd Rahim. Potential functionality and workability of blockchain within a building information modelling (bim) environment. *Journal of Facilities Management*, Vol. 21(4):pp. 490–510, 2022. doi: 10.1108/jfm-10-2021-0131.

[193] Yongqi Wang, Vimal Kumar Thangasamy, Zhaoqi Hou, Robert L.K. Tiong, and Limao Zhang. Collaborative relationship discovery in bim project delivery: A

social network analysis approach. *Automation in Construction*, Vol. 114:pp. 103147, 2020. ISSN 0926-5805. doi: 10.1016/j.autcon.2020.103147.

[194] Eissa Alreshidi, Monjur Mourshed, and Yacine Rezgui. Requirements for cloud-based bim governance solutions to facilitate team collaboration in construction projects. *Requirements Engineering*, 23:1–31, 03 2018. doi: 10.1007/s00766-016-0254-6.

[195] Burcin Becerik-Gerber, AM ASCE, Kihong Ku, and Farrokh Jazizadeh. Bim-enabled virtual and collaborative construction engineering and management. *Journal of professional issues in engineering education and practice*, Vol. 138 (3):pp. 234–245, 2012. doi: 10.1061/(ASCE)EI.1943-5541.0000098.

[196] Alastair Watson. Digital buildings â€“ challenges and opportunities. *Advanced Engineering Informatics*, Vol. 25(4):pp. 573–581, 2011. ISSN 1474-0346. doi: 10.1016/j.aei.2011.07.003. Special Section: Advances and Challenges in Computing in Civil and Building Engineering.

[197] Rafael Sacks, Charles Eastman, Ghang Lee, and Paul Teicholz. *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*. 2018. ISBN 9781119287537. doi: 10.1002/9781119287568.

[198] Gökhan Demirdöğen, Zeynep Işık, Yusuf Arayici, and Hande Aladağ. Interoperability and emerging smart technologies. In *BIM Teaching and Learning Handbook*, pages pp. 199–220. Routledge, 2021. doi: 10.1201/9780367855192-16.

[199] Rafael Sacks, Charles Eastman, Ghang Lee, and Paul Teicholz. *BIM Handbook: A Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers*. 2018. ISBN 9781119287537. doi: 10.1002/9781119287568.

[200] Yan Liu, Sander van Nederveen, and Marcel Hertogh. Understanding effects of bim on collaborative design and construction: An empirical study in china.

International Journal of Project Management, Vol. 35(4):pp. 686–698, 2017. ISSN 0263-7863. doi: 10.1016/j.ijproman.2016.06.007.

[201] Fredrik Svalestuen, Vegard Knotten, Ola Lædre, Frode Drevland, and Jardar Lohne. Using building information model (bim) devices to improve information flow and collaboration on construction sites. 2017. URL http://www.itcon.org/2017/11.

[202] Sepehr Alizadehsalehi, Ahmad Hadavi, and Joseph Chuenhuei Huang. From bim to extended reality in aec industry. *Automation in Construction*, Vol. 116:pp. 103254, 2020. ISSN 0926-5805. doi: 10.1016/j.autcon.2020.103254.

[203] Jennifer Li, David Greenwood, and Mohamad Kassem. Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. *Automation in Construction*, Vol. 102:pp. 288–307, 2019. ISSN 0926-5805. doi: 10.1016/j.autcon.2019.02.005.

[204] Riccardo Patriarca, Johan Bergström, Giulio Di Gravio, and Francesco Costantino. Resilience engineering: current status of the research and future challenges. *Safety Science*, Vol. 102, 2018. doi: 10.1016/j.ssci.2017.10.005.

[205] Basak Keskin, Baris Salman, and Beliz Ozorhon. Airport project delivery within bim-centric construction technology ecosystems. *Engineering, Construction and Architectural Management*, ahead-of-print, 2020. doi: 10.1108/ECAM-11-2019-0625.

[206] Konstantinos Christidis and Michael Devetsikiotis. Blockchains and smart contracts for the internet of things. *IEEE Access*, Vol. 4:pp. 1–1, 2016. doi: 10.1109/ACCESS.2016.2566339.

[207] Nir Kshetri and Jeffrey Voas. Blockchain in developing countries. *IT Professional*, Vol. 20:pp. 11–14, 2018. doi: 10.1109/MITP.2018.021921645.

[208] Alan McNamara and Samad Sepasgozar. Intelligent contract adoption in the construction industry: Concept development. *Automation in Construction*, Vol. 122, 2021. doi: 10.1016/j.autcon.2020.103452.

[209] Xingyu Tao, Yuhan Liu, Peter Kok-Yiu Wong, Keyu Chen, Moumita Das, and Jack Cheng. Confidentiality-minded framework for blockchain-based bim design collaboration. *Automation in Construction*, Vol. 136:pp. 104172, 2022. doi: 10.1016/j.autcon.2022.104172.

[210] Dale Sinclair. *RIBA Plan of Work 2013 Overview*, 2013. URL `https://www.ucl.ac.uk/estates/sites/estates/files/riba_plan_of_work_2013_-_overview.pdf`.

[211] Ali Alhamami, Ioan Petri, Yacine Rezgui, and Sylvain Kubicki. Promoting energy efficiency in the built environment through adapted bim training and education. *Energies*, Vol. 13(9):pp. 2308, 2020. doi: 10.3390/en13092308.

[212] Payman Ahi and Cory Searcy. An analysis of metrics used to measure performance in green and sustainable supply chains. *Journal of Cleaner Production*, Vol. 86:pp. 360–377, 01 2015. doi: 10.1016/j.jclepro.2014.08.005.

[213] Mohsen Varsei, Claudine Soosay, Behnam Fahimnia, and Joseph Sarkis. Framing sustainability performance of supply chains with multidimensional indicators. *Supply Chain Management*, Vol. 19:pp. 242 – 257, 07 2014. doi: 10.1108/SCM-12-2013-0436.

[214] Dmitry Ivanov, Alexandre Dolgui, and Boris Sokolov. The impact of digital technology and industry 4.0 on the ripple effect and supply chain risk analytics. *International Journal of Production Research*, Vol. 57:pp. 829–846, 2019. doi: 10.1080/00207543.2018.1488086.

[215] Arun Kumar, Sharad Sharma, Nitin Goyal, Aman Singh, Xiaochun Cheng, and Parminder Singh. Secure and energy-efficient smart building architecture with

emerging technology iot. *Computer Communications*, Vol. 176:pp. 207–217, 2021. doi: 10.1016/j.comcom.2021.06.003.

[216] Hyperledger Foundation. Case study: How walmart brought unprecedented transparency to the food supply chain with hyperledger fabric. https://www.hyperledger.org/learn/publications/walmart-case-study, 2022.

[217] IBM Food Trust. Join the power of ibm food trust with walmart. https://www.ibm.com/blockchain/solutions/food-trust/get-started, 2018.

[218] Ian Hamilton, Oliver Rapf, Dr Judit Kockat, Dr Sheikh Zuhaib, Thibaut Abergel, Michael Oppermann, Martina Otto, Sophie Loran, Irene Fagotto, Nora Steurer, et al. Global status report for buildings and construction. *United Nations Environmental Programme: Nairobi, Kenya*, 2020.

[219] Aapo Huovila, Hanne Siikavirta, Carmen Antuña Rozado, Jyri Rökman, Pekka Tuominen, Satu Paiho, Åsa Hedman, and Peter Ylén. Carbon-neutral cities: Critical review of theory and practice. *Journal of Cleaner Production*, Vol. 341: pp. 130912, 2022. ISSN 0959-6526. doi: 10.1016/j.jclepro.2022.130912.

[220] Haiying Ma, Elmo X. Huang, and Kwok-Yan Lam. Blockchain-based mechanism for fine-grained authorization in data crowdsourcing. *Future Generation Computer Systems*, Vol. 106:pp. 121–134, 2020. doi: 10.1016/j.future.2019.12.037.

[221] Elham Anaam, Mohammad Kamrul Hasan, Taher M. Ghazal, Su-Cheng Haw, Haitham M. Alzoubi, and Muhammad Turki Alshurideh. How private blockchain technology secure iot data record. In *2023 IEEE 2nd International Conference on AI in Cybersecurity (ICAIC)*, pages pp. 1–6, 2023. doi: 10.1109/ICAIC57335.2023.10044178.

[222] Horst Treiblmaier, Abderahman Rejeb, and Andreas Strebinger. Blockchain as a driver for smart city development: Application fields and a comprehensive research agenda. *Smart Cities*, Vol. 3:pp. 853–872, 2020. doi: 10.3390/smartcities3030044.

[223] Rajat Chaudhary, Anish Jindal, Gagangeet Singh Aujla, Shubhani Aggarwal, Neeraj Kumar, and Kim-Kwang Raymond Choo. Best: Blockchain-based secure energy trading in sdn-enabled intelligent transportation system. *Computers & Security*, Vol. 85:pp. 288–299, 2019. doi: 10.1016/j.cose.2019.05.006.

[224] J Kadir, A Hanafi, A Shareef, H Khatib, T Baharin, K Sulaima, Ala Hasan, Hassam Rehman, Jahangir Hossain, Aida Kadir, Ainain Hanafi, Hussain Shareef, Tamer Khatib, Kyairul Baharin, and Mohamad Fani Sulaima. Citation: A review on optimal energy management in commercial buildings. *Energies*, 16:1609, 02 2023. doi: 10.3390/en16041609.

[225] Pedro Ponce, Therese Peffer, Juana Isabel Mendez Garduno, Ursula Eicker, Arturo Molina, Troy McDaniel, Edgard D Musafiri Mimo, Ramanunni Parakkal Menon, Kathryn Kaspar, and Sadam Hussain. Demand side management and transactive energy strategies for smart cities. In *Data and AI Driving Smart Cities*, pages pp. 193–227. Springer, 2023.

[226] Mohamed G. Moh Almihat, M. T. E. Kahn, Khaled Aboalez, and Ali M. Almaktoof. Energy and sustainable development in smart cities: An overview. *Smart Cities*, Vol. 5(4):pp. 1389–1408, 2022. doi: 10.3390/smartcities5040071.

[227] Hossein Omrany, Karam M. Al-Obaidi, Amreen Husain, and Amirhosein Ghaffarianhoseini. Digital twins in the construction industry: A comprehensive review of current implementations, enabling technologies, and future directions. *Sustainability*, Vol. 15(14), 2023. doi: 10.3390/su151410908.

[228] Christos Korkas, Asimina Dimara, Iakovos Michailidis, Stelios Krinidis, Rafael Marin-Perez, Ana Isabel Martínez García, Antonio Skarmeta, Konstantinos Kitsikoudis, Elias Kosmatopoulos, Christos-Nikolaos Anagnostopoulos, and Dimitrios Tzovaras. Integration and verification of plug-n-harvest ict platform for intelligent management of buildings. *Energies*, Vol. 15(7), 2022. doi: 10.3390/en15072610.

[229] Larissa Statsenko, Aparna Samaraweera, Javad Bakhshi, and Nicholas Chileshe. Construction 4.0 technologies and applications: A systematic literature review of trends and potential areas for development. *Construction Innovation*, Vol. 23 (5):pp. 961–993, 2023. doi: 10.1108/CI-07-2021-0135.

[230] Umit Cali, Berhane Darsene Dimd, Parisa Hajialigol, Amin Moazami, Sri Nikhil Gupta Gourisetti, Gabriele Lobaccaro, and Mohammadreza Aghaei. Digital twins: Shaping the future of energy systems and smart cities through cybersecurity, efficiency, and sustainability. In *2023 International Conference on Future Energy Solutions (FES)*, pages pp. 1–6, 2023. doi: 10.1109/FES57669.2023.10182868.

[231] Zeyu Wang and Ravi S. Srinivasan. A review of artificial intelligence based building energy use prediction: Contrasting the capabilities of single and ensemble prediction models. *Renewable and Sustainable Energy Reviews*, Vol. 75:pp. 796–808, 2017. ISSN 1364-0321. doi: 10.1016/j.rser.2016.10.079.

[232] AV Ghoshchi, R Zahedi, ZM Pour, and A Ahmadi. Machine learning theory in building energy modeling and optimization: A bibliometric analysis. *J Mod Green Energy*, Vol. 1(4), 2022. doi: 10.53964/jmge.2022004.

[233] Kamanashis Biswas and Vallipuram Muthukkumarasamy. Securing smart cities using blockchain technology. In *2016 IEEE 18th International Conference on High Performance Computing and Communications; IEEE 14th International Conference on Smart City; IEEE 2nd International Conference on Data Science and Systems (HPCC/SmartCity/DSS)*, pages pp. 1392–1393, 2016. doi: 10.1109/HPCC-SmartCity-DSS.2016.0198.

[234] Longfei Wu, Xiaojiang Du, Wei Wang, and Bin Lin. An out-of-band authentication scheme for internet of things using blockchain technology. In *2018 International Conference on Computing, Networking and Communications (ICNC)*, pages pp. 769–773, 2018. doi: 10.1109/ICCNC.2018.8390280.

[235] Pietro Danzi, Anders Ellersgaard Kalor, Cedomir Stefanovic, and Petar Popovski. Analysis of the communication traffic for blockchain synchronization of iot devices. In *2018 IEEE International Conference on Communications (ICC)*, pages pp. 1–7, 2018. doi: 10.1109/ICC.2018.8422485.

[236] Sidique Gawusu, Xiaobing Zhang, Abubakari Ahmed, Seidu Abdulai Jamatutu, Elvis Djam Miensah, Ayesha Algade Amadu, and Frimpong Atta Junior Osei. Renewable energy sources from the perspective of blockchain integration: From theory to application. *Sustainable Energy Technologies and Assessments*, Vol. 52:pp. 102108, 2022. ISSN 2213-1388. doi: 10.1016/j.seta.2022.102108.

[237] PK Preetha, Manjula G Nair, et al. Smart contract based energy trading-an overview. In *2022 IEEE 19th India Council International Conference (INDICON)*, pages pp. 1–7. IEEE, 2022. doi: 10.1109/INDICON56171.2022.10039697.

[238] Franklin L Quilumba, Wei-Jen Lee, Heng Huang, David Y Wang, and Robert L Szabados. Using smart meter data to improve the accuracy of intraday load forecasting considering customer behavior similarities. *IEEE Transactions on Smart Grid*, Vol. 6(2):pp. 911–918, 2014. doi: 10.1109/TSG.2014.2364233.

[239] Adia Khalid, Nadeem Javaid, Abdul Mateen, Manzoor Ilahi, Tanzila Saba, and Amjad Rehman. Enhanced time-of-use electricity price rate using game theory. *Electronics*, Vol. 8(1):pp. 48, 2019. doi: doi.org/10.3390/electronics8010048.

[240] Asma Khatoon, Piyush Verma, Jo Southernwood, Beth Massey, and Peter Corcoran. Blockchain in energy efficiency: Potential applications and benefits. *Energies*, Vol. 12:pp. 3317, 2019. doi: 10.3390/en12173317.

[241] Elarbi Badidi. Edge ai and blockchain for smart sustainable cities: Promise and potential. *Sustainability*, Vol. 14:pp. 7609, 2022. doi: 10.3390/su14137609.

[242] Nazir Ullah, Waleed Alnumay, Waleed Al-Rahmi, Ahmed Alzahrani, and Hosam Al-Samarraie. Modeling cost saving and innovativeness for blockchain technology

adoption by energy management. *Energies*, Vol. 13, 09 2020. doi: 10.3390/en13184783.

[243] Yongping Zhang, Xiwei Xu, Ang Liu, Qinghua Lu, Lida Xu, and Fei Tao. Blockchain-based trust mechanism for iot-based smart manufacturing system. *IEEE Transactions on Computational Social Systems*, Vol. 6(6):pp. 1386–1394, 2019. doi: 10.1109/TCSS.2019.2918467.

[244] Amjad Qashlan, Priyadarsi Nanda, Xiangjian He, and Manoranjan Mohanty. Privacy-preserving mechanism in smart home using blockchain. *IEEE Access*, Vol. 9:pp. 103651–103669, 2021. doi: 10.1109/ACCESS.2021.3098795.

[245] Zibin Zheng, Shaoan Xie, Hongning Dai, Xiangping Chen, and Huaimin Wang. An overview of blockchain technology: Architecture, consensus, and future trends. In *2017 IEEE International Congress on Big Data (BigData Congress)*, pages pp. 557–564, 2017. doi: 10.1109/BigDataCongress.2017.85.

[246] Mike Schulze, Henrik Nehler, Mikael Ottosson, and Patrik Thollander. Energy management in industry – a systematic review of previous findings and an integrative conceptual framework. *Journal of Cleaner Production*, Vol. 112:pp. 3692–3708, 2016. ISSN 0959-6526. doi: 10.1016/j.jclepro.2015.06.060.

[247] Robert Cohen and Bill Bordass. Mandating transparency about building energy performance in use. *Building Research & Information*, Vol. 43(4):pp. 534–552, 2015. doi: 10.1080/09613218.2015.1017416.

[248] Luisa F. Cabeza, Lídia Rincón, Virginia Vilariño, Gabriel Pérez, and Albert Castell. Life cycle assessment (lca) and life cycle energy analysis (lcea) of buildings and the building sector: A review. *Renewable and Sustainable Energy Reviews*, Vol. 29:pp. 394–416, 2014. ISSN 1364-0321. doi: 10.1016/j.rser.2013.08.037.

[249] Tobias Junne, Mengzhu Xiao, Lei Xu, Zongfei Wang, Patrick Jochem, and Thomas Pregger. How to assess the quality and transparency of energy sce-

narios: Results of a case study. *Energy Strategy Reviews*, Vol. 26:pp. 100380, 2019. ISSN 2211-467X. doi: 10.1016/j.esr.2019.100380.

[250] Marina Sofos, Jared T. Langevin, Michael Deru, Erika Gupta, Kyle S. Benne, David Blum, Ted Bohn, Robert Fares, Nick Fernandez, Glenn Fink, Steven Frank, Jennifer Gerbi, Jessica Granderson, Dale Hoffmeyer, Tianzhen Hong, Amy Jiron, Stephanie Johnson, Srinivas Katipamula, Teja Kuruganti, Jared Langevin, William C Livingood, Ralph Muehleisen, Monica Neukomm, Valerie Nubbe, Patrick Phelan, MaryAnn Piette, Janet Reyna, Amir Roth, Aven Satre-Meloy, Michael Specian, Draguna Vrabie, Michael Wetter, and Steve Widergren. Innovations in sensors and controls for building energy management: Research and development opportunities report for emerging technologies. 2020. doi: 10.2172/1601591.

[251] Tarik Himdi, Mohammed Ishaque, and Muhammed Jawad Ikram. Cyber security challenges in distributed energy resources for smart cities. In *2022 9th International Conference on Computing for Sustainable Global Development (INDIACom)*, pages pp. 788–792, 2022. doi: 10.23919/INDIACom54597.2022.9763107.

[252] Wei Yu, Panos Patros, Brent Young, Elsa Klinac, and Timothy Gordon Walmsley. Energy digital twin technology for industrial energy management: Classification, challenges and future. *Renewable and Sustainable Energy Reviews*, Vol. 161:pp. 112407, 2022. ISSN 1364-0321. doi: 10.1016/j.rser.2022.112407.

[253] Arzoo Miglani, Neeraj Kumar, Vinay Chamola, and Sherali Zeadally. Blockchain for internet of energy management: Review, solutions, and challenges. *Computer Communications*, Vol. 151:pp. 395–418, 2020. ISSN 0140-3664. doi: 10.1016/j.comcom.2020.01.014.

[254] X.J. Luo and Lukumon O. Oyedele. Forecasting building energy consumption: Adaptive long-short term memory neural networks driven by genetic algorithm.

Advanced Engineering Informatics, Vol. 50:pp. 101357, 2021. ISSN 1474-0346. doi: 10.1016/j.aei.2021.101357.

[255] Kadir Amasyali and Nora M. El-Gohary. A review of data-driven building energy consumption prediction studies. *Renewable and Sustainable Energy Reviews*, Vol. 81:pp. 1192–1205, 2018. ISSN 1364-0321. doi: 10.1016/j.rser.2017.04.095.

[256] Yinan Li, Wentao Yang, Ping He, Chang Chen, and Xiaonan Wang. Design and management of a distributed hybrid energy system through smart contract and blockchain. *Applied Energy*, Vol. 248:pp. 390–405, 2019. ISSN 0306-2619. doi: 10.1016/j.apenergy.2019.04.132.

[257] Bassam Zafar and Sami Ben Slama. Energy internet opportunities in distributed peer-to-peer energy trading reveal by blockchain for future smart grid 2.0. *Sensors*, Vol. 22(21), 2022. doi: 10.3390/s22218397.

[258] Marcella Atzori. Blockchain technology and decentralized governance: Is the state still necessary? *Journal of Governance and Regulation*, Vol. 6, 03 2017. doi: 10.22495/jgr_v6_i1_p5.

[259] Nir Kshetri. Will blockchain emerge as a tool to break the poverty chain in the global south? *Third World Quarterly*, Vol. 38:pp. 1710–1732, 2017. doi: 10.1080/01436597.2017.1298438.

[260] Christopher Kinnaird, Matthias Geipel, and Mark Bew MBE. Blockchain technology. URL `https://www.arup.com/perspectives/publications/research/section/blockchain-technology`.

[261] Steph Blundell. Blockchain and smart contracts: Binary solutions in a non-binary industry?, 2022. URL `https://www.pbctoday.co.uk/news/digital-construction-news/blockchain-and-smart-contracts-binary-solutions-in-a-non-binary-indust` `39349/`.

[262] Amritraj Singh, Reza Parizi, Meng Han, Ali Dehghantanha, Hadis Karimipour, and Kim-Kwang Raymond Choo. *Public Blockchains Scalability: An Examination of Sharding and Segregated Witness*, pages pp. 203–232. 03 2020. ISBN 978-3-030-38180-6. doi: 10.1007/978-3-030-38181-3_11.

[263] Weiqin Zou, David Lo, Pavneet Singh Kochhar, Xuan Bach D Le, Xin Xia, Yang Feng, Zhenyu Chen, and Baowen Xu. Smart contract development: Challenges and opportunities. *IEEE Transactions on Software Engineering*, Vol. PP:pp. 1–1, 09 2019. doi: 10.1109/TSE.2019.2942301.

[264] Mounir El Khatib, Asma Al Mulla, and Wadha Al Ketbi. The role of blockchain in e-governance and decision-making in project and program management. *Advances in Internet of Things*, 12(3):88–109, 2022. doi: 10.4236/ait.2022.123006.

[265] Kyleen W Prewett, Gregory L Prescott, and Kirk Phillips. Blockchain adoption is inevitable—barriers and risks remain. *Journal of Corporate accounting & finance*, 31(2):21–28, 2020. doi: 10.1002/jcaf.22415.

[266] Bhargavi K Chauhan and Dhirenbhai B Patel. A systematic review of blockchain technology to find current scalability issues and solutions. In *Proceedings of Second Doctoral Symposium on Computational Intelligence*, pages 15–29. Springer, 2022. doi: 10.1007/978-981-16-3346-1_2.

[267] Chunhao Li, Yuqian Zhang, and Yongshun Xu. Factors influencing the adoption of blockchain in the construction industry: A hybrid approach using pls-sem and fsqca. *Buildings*, Vol. 12(9), 2022. ISSN 2075-5309. doi: 10.3390/buildings12091349.

[268] Abderahman Rejeb, Karim Rejeb, John G. Keogh, and Suhaiza Zailani. Barriers to blockchain adoption in the circular economy: A fuzzy delphi and best-worst approach. *Sustainability*, Vol. 14(6), 2022. ISSN 2071-1050. doi: 10.3390/su14063611.

[269] Nusi Drljevic, Daniel Arias Aranda, and Vladimir Stantchev. Perspectives on risks and standards that affect the requirements engineering of blockchain technology. *Computer Standards & Interfaces*, 69:103409, 2020. doi: 10.1016/j.csi.2019.103409.

[270] AS Erri Pradeep, TW Yiu, and R Amor. Leveraging blockchain technology in a bim workflow: A literature review. In *International Conference on Smart Infrastructure and Construction 2019 (ICSIC) Driving data-informed decision-making*, pages pp. 371–380. ICE Publishing, 2019.

[271] Yue Pan and Limao Zhang. Integrating bim and ai for smart construction management: Current status and future directions. *Archives of Computational Methods in Engineering*, Vol. 30(2):pp. 1081–1110, 2022. doi: 10.1007/s11831-022-09830-8.

[272] Ibrahim Yitmen, Sepehr Alizadehsalehi, Ä°lknur AkÄ±ner, and Muhammed Ernur AkÄ±ner. An adapted model of cognitive digital twins for building lifecycle management. *Applied Sciences*, Vol. 11(9), 2021. ISSN 2076-3417. doi: 10.3390/app11094276.

[273] Satoshi Nakamoto. Bitcoin: A peer-to-peer electronic cash system. 2008. doi: 10.2139/ssrn.3440802.

[274] Asger B Pedersen, Marten Risius, Roman Beck, et al. A ten-step decision path to determine when to use blockchain technologies. *MIS Quarterly Executive*, Vol. 18(2):pp. 99–115, 2019.

[275] Petri Helo and A.H.M. Shamsuzzoha. Real-time supply chainâ€"a blockchain architecture for project deliveries. *Robotics and Computer-Integrated Manufacturing*, Vol. 63:pp. 101909, 2020. ISSN 0736-5845. doi: 10.1016/j.rcim.2019.101909.

[276] Arun Sekar Rajasekaran, Maria Azees, and Fadi Al-Turjman. A comprehensive survey on blockchain technology. *Sustainable Energy Technologies and Assess-*

ments, Vol. 52:pp. 102039, 2022. ISSN 2213-1388. doi: 10.1016/j.seta.2022.102039.

[277] Chris Dannen. *Introducing Ethereum and solidity*, volume Vol. 1. Springer, 2017. doi: 10.1007/978-1-4842-2535-6.

[278] Remix. 2022. URL https://remix-ide.readthedocs.io/en/latest/. (accessed: 04.07.2022).

[279] Shanto Roy, Md Ashaduzzaman, Mehedi Hassan, and Arnab Rahman Chowdhury. Blockchain for iot security and management: Current prospects, challenges and future directions. In *2018 5th International Conference on Networking, Systems and Security (NSysS)*, pages pp. 1–9. IEEE, 2018.

[280] Stephanie Lo and J Christina Wang. Bitcoin as money? *Federal Reserve Bank of Boston*, 2014. URL https://www.bostonfed.org/publications/current-policy-perspectives/2014/bitcoin-as-money.aspx.

[281] Rosario Girasa. *Regulation of cryptocurrencies and blockchain technologies: national and international perspectives*. Springer, 2018. doi: 10.1007/978-3-319-78509-7.

[282] Israa Abu-elezz, Asma Hassan, Anjanarani Nazeemudeen, Mowafa Househ, and Alaa Abd-alrazaq. The benefits and threats of blockchain technology in healthcare: A scoping review. *International Journal of Medical Informatics*, Vol. 142:104246, 2020. ISSN 1386-5056. doi: 10.1016/j.ijmedinf.2020.104246.

[283] Nicole Radziwill. Blockchain revolution: How the technology behind bitcoin is changing money, business, and the world. *Quality Management Journal*, Vol. 25:pp. 64–65, 2018. doi: 10.1080/10686967.2018.1404373.

[284] Francisco Ferreira Santana, Miguel Mira da Silva, and Florbela Galvão da Cunha. Blockchain for real estate: A systematic literature review. 2021. URL https://aisel.aisnet.org/isd2014/proceedings2021/currenttopics/6/.

[285] Hongyu Luo, Moumita Das, Jun Wang, and JCP Cheng. Construction payment automation through smart contract-based blockchain framework. In *ISARC. Proceedings of the International Symposium on Automation and Robotics in Construction*, volume Vol. 36, pages pp. 1254–1260. IAARC Publications, 2019. doi: 10.22260/ISARC2019/0168.

[286] Marco Iansit and Karim R Lakhani. The truth about blockchain, Aug 2019. URL https://hbr.org/2017/01/the-truth-about-blockchain.

[287] Tommy Koens and Erik Poll. What blockchain alternative do you need? In *Data Privacy Management, Cryptocurrencies and Blockchain Technology*, pages pp. 113–129. Springer, 2018. doi: 10.1007/978-3-030-00305-0_9.

[288] Melanie Swan. *Blockchain: Blueprint for a new economy*. " O'Reilly Media, Inc.", 2015. ISBN 1491920491. URL https://dl.acm.org/doi/10.5555/3006358.

[289] Don Tapscott and Alex Tapscott. *Blockchain revolution: how the technology behind Bitcoin is changing money, business and the world*. Portfolio Penguin, 2018. URL https://dl.acm.org/doi/10.5555/3051781.

[290] Claus Pahl, Nabil El Ioini, and Sven Helmer. A decision framework for blockchain platforms for iot and edge computing. 03 2018. doi: 10.5220/0006688601050113.

[291] William J Gordon and Christian Catalini. Blockchain technology for healthcare: facilitating the transition to patient-driven interoperability. *Computational and structural biotechnology journal*, 16:224–230, 2018. doi: 10.1016/j.csbj.2018.06.003.

[292] Mohsen Attaran and Angappa Gunasekaran. Applications of blockchain technology in business: Challenges and opportunities. 01 2019. doi: 10.1007/978-3-030-27798-7.

[293] Rebecca Yang, Ron Wakefield, Sainan Lyu, Sajani Jayasuriya, Fengling Han, Xun Yi, Xuechao Yang, Gayashan Amarasinghe, and Shiping Chen. Public and

private blockchain in construction business process and information integration. *Automation in Construction*, Vol. 118:pp. 103276, 2020. ISSN 0926-5805. doi: 10.1016/j.autcon.2020.103276.

[294] Enis Karaarslan and E. Konacakli. Data storage in the decentralized world: Blockchain and derivatives. *CoRR*, 2020. URL https://arxiv.org/abs/2012.10253.

[295] Chaoxia Qin, Bing Guo, Yan Shen, Tao Li, Yun Zhang, and Zhen Zhang. A secure and effective construction scheme for blockchain networks. *Security and Communication Networks*, Vol. 2020:pp. 1–20, 2020.

[296] Harald Vranken. Sustainability of bitcoin and blockchains. *Current Opinion in Environmental Sustainability*, Vol. 28:pp. 1–9, 10 2017. doi: 10.1016/j.cosust.2017.04.011.

[297] Dylan Yaga, Peter Mell, Nik Roby, and Karen Scarfone. Blockchain technology overview. Technical report, 2018. URL https://arxiv.org/abs/1906.11078.

[298] Marlene Kuhn, Felix Funk, Guanlai Zhang, and Jorg Franke. Blockchain-based application for the traceability of complex assembly structures. *Journal of Manufacturing Systems*, Vol. 59:pp. 617–630, 04 2021. doi: 10.1016/j.jmsy.2021.04.013.

[299] Ana Reyna, Cristian MartÃn, Jaime Chen, Enrique Soler, and Manuel DÃaz. On blockchain and its integration with iot. challenges and opportunities. *Future Generation Computer Systems*, Vol. 88:pp. 173–190, 2018. ISSN 0167-739X. doi: 10.1016/j.future.2018.05.046.

[300] Wenbo Wang, Dinh Thai Hoang, Peizhao Hu, Zehui Xiong, Dusit Niyato, Ping Wang, Yonggang Wen, and Dong In Kim. A survey on consensus mechanisms and mining strategy management in blockchain networks. *IEEE Access*, Vol. 7: pp. 22328–22370, 2019. doi: 10.1109/ACCESS.2019.2896108.

[301] Xueping Liang, Sachin Shetty, Deepak Tosh, Juan Zhao, Danyi Li, and Jihong Liu. A reliable data provenance and privacy preservation architecture for business-driven cyber-physical systems using blockchain. *International Journal of Information Security and Privacy*, Vol. 12:pp. 68–81, 2018. doi: 10.4018/IJISP.2018100105.

[302] Anand Prakash and Sudhir Ambekar. Digital transformation using blockchain technology in the construction industry. *Journal of Information Technology Case and Application Research*, Vol. 22(4):pp. 256–278, 2020. doi: 10.1080/15228053.2021.1880245.

[303] Andreas Kamilaris, Agusti Fonts, and Francesc X Prenafeta-Boldŭ. The rise of blockchain technology in agriculture and food supply chains. *Trends in Food Science & Technology*, Vol. 91:pp. 640–652, 2019.

[304] Johannes Sedlmeir, Hans Ulrich Buhl, Gilbert Fridgen, and Robert Keller. The energy consumption of blockchain technology: Beyond myth. *Business & Information Systems Engineering*, Vol. 62(6):pp. 599–608, 2020.

[305] Jennifer Li, Mohamad Kassem, Angelo Ciribini, and Marzia Bolpagni. A proposed approach integrating dlt, bim, iot and smart contracts: Demonstration using a simulated installation task. 07 2019. doi: 10.1680/icsic.64669.275.

[306] Diego Romano and Giovanni Schmid. Beyond bitcoin: A critical look at blockchain-based systems. *Cryptography*, Vol. 1:pp. 15, 2017. doi: 10.3390/cryptography1020015.

[307] Julapa Jagtiani, Michael Papaioannou, George Tsetsekos, Erik Dolson, and Dan Milo. *Cryptocurrencies: Regulatory Perspectives and Implications for Investors*, pages pp. 161–186. Springer International Publishing, Cham, 2021. ISBN 978-3-030-65117-6. doi: 10.1007/978-3-030-65117-6_7.

[308] Valentina Gatteschi, Fabrizio Lamberti, Claudio Demartini, Chiara Pranteda, and VÃctor SantamarÃa. Blockchain and smart contracts for insurance: Is the

technology mature enough? *Future Internet*, Vol. 10(2), 2018. ISSN 1999-5903. doi: 10.3390/fi10020020.

[309] Dominik Heber, Marco Groll, et al. Towards a digital twin: How the blockchain can foster e/e-traceability in consideration of model-based systems engineering. In *DS 87-3 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 3: Product, Services and Systems Design, Vancouver, Canada, 21-25.08. 2017*, pages pp. 321–330, 2017.

[310] Manuel Ganter and Thomas Lützkendorf. Information management throughout the life cycle of buildings – basics and new approaches such as blockchain. volume Vol. 323, page pp. 012110, 2019. doi: 10.1088/1755-1315/323/1/012110.

[311] Karoline Figueiredo, Ahmed WA Hammad, Assed Haddad, and Vivian WY Tam. Assessing the usability of blockchain for sustainability: Extending key themes to the construction industry. *Journal of Cleaner Production*, page 131047, 2022.

[312] Faris Elghaish, Sepehr Abrishami, and M. Reza Hosseini. Integrated project delivery with blockchain: An automated financial system. *Automation in Construction*, Vol. 114:pp. 103182, 2020. ISSN 0926-5805. doi: 10.1016/j.autcon.2020.103182.

[313] Zakaria Dakhli, Zoubeir Lafhaj, and Alan Mossman. The potential of blockchain in building construction. *Buildings*, Vol. 9:pp. 77, 04 2019. doi: 10.3390/buildings9040077.

[314] Steven Graham and Jason D. Hailer. 2019. URL `https://digitalcommons.calpoly.edu/cmsp/190`.

[315] Iris Belle. The architecture, engineering and construction industry and blockchain technology. *Digital Culture, Conference on Digital Technologies in Architectural Education and DADA 2017 International Conference on Digital Architecture, China Architecture Industry, Nanjing, China*, pages pp. 279–284, 2017.

[316] Michael Kuperberg and Matthias Geipel. Blockchain and bim (building information modeling): Progress in academia and industry. 2021. doi: doi.org/10.48550/arXiv.2104.00547.

[317] Tamima S. Elbashbishy, Gasser G. Ali, and Islam H. El-adaway. Blockchain technology in the construction industry: mapping current research trends using social network analysis and clustering. *Construction Management and Economics*, Vol. 40:pp. 406–427, 2022. doi: 10.1080/01446193.2022.2056216.

[318] Moumita Das, Xingyu Tao, and Jack C.P. Cheng. Bim security: A critical review and recommendations using encryption strategy and blockchain. *Automation in Construction*, Vol. 126:pp. 103682, 2021. doi: 10.1016/j.autcon.2021.103682.

[319] Aarni Heiskanen. The technology of trust: How the internet of things and blockchain could usher in a new era of construction productivity. *Construction Research and Innovation*, Vol. 8:pp. 66–70, 2017. doi: 10.1080/20450249.2017.1337349.

[320] Mengyuan Cheng, Guoliang Liu, Yongshun Xu, and Ming Chi. When blockchain meets the aec industry: Present status, benefits, challenges, and future research opportunities. *Buildings*, Vol. 11:pp. 340, 2021. doi: 10.3390/buildings11080340.

[321] Yongshun Xu, Heap-Yih Chong, and Ming Chi. Blockchain in the aeco industry: Current status, key topics, and future research agenda. *Automation in Construction*, Vol. 134:pp. 104101, 2022. doi: 10.1016/j.autcon.2021.104101.

[322] Karoline Figueiredo, Ahmed W.A. Hammad, Assed Haddad, and Vivian W.Y. Tam. Assessing the usability of blockchain for sustainability: Extending key themes to the construction industry. *Journal of Cleaner Production*, Vol. 343:pp. 131047, 2022. doi: 10.1016/j.jclepro.2022.131047.

[323] Amer Hijazi, Srinath Perera, Rodrigo Calheiros, and Ali Alashwal. Rationale for the integration of bim and blockchain for the construction supply chain data

delivery: A systematic literature review and validation through focus group. *Journal of Construction Engineering and Management*, Vol. 147, 2021. doi: 10.1061/(ASCE)CO.1943-7862.0002142.

[324] Hexu Liu, SangHyeok Han, and Zhenhua Zhu. Blockchain technology toward smart construction: Review and future directions. *Journal of Construction Engineering and Management*, Vol. 149(3):pp. 03123002, 2023. doi: 10.1061/JCEMD4.COENG-11929.

[325] Yanling Ni, Baolin Sun, and Yucai Wang. Blockchain-based bim digital project management mechanism research. *IEEE Access*, Vol. 9:pp. 161342–161351, 2021. doi: 10.1109/ACCESS.2021.3130270.

[326] Kasey Panetta. The cio's guide to blockchain, 2019. URL https://www.gartner.com/smarterwithgartner/the-cios-guide-to-blockchain/.

[327] Sina Rafati Niya, Florian Schüpfer, Thomas Bocek, and Burkhard Stiller. A peer-to-peer purchase and rental smart contract-based application (pursca). *it - Information Technology*, Vol. 60:pp. 307–320, 2018. doi: 10.1515/itit-2017-0036.

[328] Nawari O. Nawari. Blockchain technologies: Hyperledger fabric in bim work processes. In Eduardo Toledo Santos and Sergio Scheer, editors, *Proceedings of the 18th International Conference on Computing in Civil and Building Engineering*, pages 813–823, Cham, 2021. Springer International Publishing. ISBN 978-3-030-51295-8.

[329] Milad Baghalzadeh Shishehgarkhaneh, Robert C. Moehler, and Sina Fard Moradinia. Blockchain in the construction industry between 2016 and 2022: A review, bibliometric, and network analysis. *Smart Cities*, Vol. 6(2):pp. 819–845, 2023. ISSN 2624-6511. doi: 10.3390/smartcities6020040.

[330] Rabiah Muhammad and Abdur Rehman Nasir. Integrating bim in construction dispute resolution: Development of a contractual framework. *Buildings*, Vol. 12 (11), 2022. ISSN 2075-5309. doi: 10.3390/buildings12111828.

[331] Mark Saunders and Philip Lewis. *Doing research in business and management: An essential guide to planning your project*. Pearson Education, 2012. doi: 10.1080/14767333.2012.687917.

[332] Hans Kristian Grani. What is ifc and what do you need to know about it?, 2016. URL https://blog.areo.io/what-is-ifc/. (accessed: 04.07.2022).

[333] Ioan Petri, Omer F Rana, Tom Beach, and Yacine Rezgui. Performance analysis of multi-institutional data sharing in the clouds4coordination system. *Computers and Electrical Engineering*, Vol. 58:pp. 227–240, 2017. doi: 10.1016/j.compeleceng.2017.02.015.

[334] Karl Wüst and Arthur Gervais. Do you need a blockchain? In *2018 Crypto Valley Conference on Blockchain Technology (CVCBT)*, pages pp. 45–54. IEEE, 2018. URL https://eprint.iacr.org/2017/375.pdf.

[335] Jun Wang, Peng Wu, Xiangyu Wang, and Wenchi Shou. The outlook of blockchain technology for construction engineering management. *Frontiers of engineering management*, pages pp. 67–75, 2017. URL https://journal.hep.com.cn/fem/EN/10.15302/J-FEM-2017006.

[336] Col Vincent Alcazar. Data you can trust. *Air and Space Power Journal*, Vol. 31:pp. 91–101, 2017. URL https://ammo.ncms.org/wp-content/uploads/V-Alcazar.pdf.

[337] Olivier Van Cutsem, David Ho Dac, Pol Boudou, and Maher Kayal. Cooperative energy management of a community of smart-buildings: A blockchain approach. *International Journal of Electrical Power & Energy Systems*, Vol. 117:pp. 105643, 2020. doi: 10.1016/j.ijepes.2019.105643.

[338] Jian Cai, Xiangdong Liu, Zhihui Xiao, and Jin Liu. Improving supply chain performance management: A systematic approach to analyzing iterative kpi accomplishment. *Decision Support Systems*, Vol. 46(2):pp. 512–521, 2009. ISSN 0167-9236. doi: 10.1016/j.dss.2008.09.004.

[339] Angappa Gunasekaran and Bulent Kobu. Performance measures and metrics in logistics and supply chain management: a review of recent literature (1995–2004) for research and applications. *International Journal of Production Research*, Vol. 45(12):pp. 2819–2840, 2007. doi: 10.1080/00207540600806513.

[340] Jason Fernando. Return on investment (roi): How to calculate it and what it means. URL https://www.investopedia.com/terms/r/returnoninvestment.asp.

[341] Amin Mahmoudi, Mahsa Sadeghi, and Leila Moslemi Naeni. Blockchain and supply chain finance for sustainable construction industry: Ensemble ranking using ordinal priority approach. *Operations Management Research*, 2023. doi: 10.1007/s12063-023-00374-z.

[342] Pan Zhang, Haitao Wu, Heng Li, Botao Zhong, Ivan W.H. Fung, and Yiu Yin Raymond Lee. Exploring the adoption of blockchain in modular integrated construction projects: A game theory-based analysis. *Journal of Cleaner Production*, Vol. 408:pp. 137115, 2023. ISSN 0959-6526. doi: 10.1016/j.jclepro.2023.137115.

[343] Botao Zhong, Xing Pan, Lieyun Ding, Qiang Chen, and Xiaowei Hu. Blockchain-driven integration technology for the aec industry. *Automation in Construction*, Vol. 150:pp. 104791, 2023. ISSN 0926-5805. doi: 10.1016/j.autcon.2023.104791.

[344] Ahsan Waqar, Abdul Hannan Qureshi, Idris Othman, Noha Saad, and Marc Azab. Exploration of challenges to deployment of blockchain in small construction projects. *Ain Shams Engineering Journal*, page pp. 102362, 2023. ISSN 2090-4479. doi: 10.1016/j.asej.2023.102362. URL https://www.sciencedirect.com/science/article/pii/S2090447923002514.

[345] Eleni Papadonikolaki, Algan Tezel, Ibrahim Yitmen, and Per Hilletofth. Blockchain innovation ecosystems orchestration in construction. *Industrial*

Management amp;amp; Data Systems, Vol. 123(2):pp. 672–694, 2022. doi: 10.1108/imds-03-2022-0134.

[346] Gao Shang, Low Sui Pheng, and Roderick Low Zhong Xia. Adoption of smart contracts in the construction industry: An institutional analysis of drivers and barriers. *Construction Innovation*, 2023. doi: 10.1108/ci-03-2022-0066.

[347] Kriengsakand Henry Michael Wulandary, Kartikaand Panuwatwanich. Readiness and potential application of smart contracts in the indonesian construction industry. In Xudongand Poh Leong Hienand Pang-Sze Dai Geng, Guoqingand Qian, editor, *Proceedings of The 17th East Asian-Pacific Conference on Structural Engineering and Construction, 2022*, pages pp. 249–263, Singapore, 2023. Springer Nature Singapore. ISBN 978-981-19-7331-4.

[348] Alvina Ekua Ntefua Saah and Jae ho Choi. Blockchain technology in the aec industry: Scientometric analysis of research activities. *Journal of Building Engineering*, Vol. 72:pp. 106609, 2023. ISSN 2352-7102. doi: 10.1016/j.jobe.2023.106609.

[349] Haitao Wu, Pan Zhang, Heng Li, Botao Zhong, Ivan W. H. Fung, and Yiu Yin Raymond Lee. Blockchain technology in the construction industry: Current status, challenges, and future directions. *Journal of Construction Engineering and Management*, Vol. 148(10):pp. 03122007, 2022. doi: 10.1061/(ASCE)CO.1943-7862.0002380.

[350] Jiyang Yu, Hua Zhong, and Marzia Bolpagni. Integrating blockchain with building information modelling (bim): A systematic review based on a sociotechnical system perspective. *Construction Innovation*, 2023. doi: 10.1108/ci-04-2023-0082.

[351] M. S. Kiu, F. C. Chia, and P. F. Wong. Exploring the potentials of blockchain application in construction industry: A systematic review. *International Journal of Construction Management*, Vol. 22(15):pp. 2931–2940, 2020. doi: 10.1080/15623599.2020.1833436.

[352] Naif Al Azmi, Ghaleb Sweis, Rateb Sweis, and Farouq Sammour. Exploring implementation of blockchain for the supply chain resilience and sustainability of the construction industry in saudi arabia. *Sustainability*, Vol. 14(11), 2022. ISSN 2071-1050. doi: 10.3390/su14116427.

[353] Hanan Suliman Eissa Mohammed and Walaa Jamal Salem Alharthi. Blockchain technology and the future of construction industry in the arab region :applications, challenges, and future opportunities. *Engineering Research Journal*, 173 (0):pp. 411–441, 2022. doi: 10.21608/erj.2022.223618.

[354] Mengyuan Cheng and Heap-Yih Chong. Understanding the determinants of blockchain adoption in the engineering-construction industry: Multi-stakeholders' analyses. *IEEE Access*, Vol. 10:pp. 108307–108319, 2022. doi: 10.1109/ACCESS.2022.3213714.

[355] Mushtaq Ahmad Shah and Furquan Uddin. Leveraging blockchain technology in the construction industry. *Building Secure Business Models Through Blockchain Technology*, page 50–65, 2023. doi: 10.4018/978-1-6684-7808-0.ch004.

[356] Atul Kumar Singh, Varadhaiya Gounder Kumar, Jin Hu, and Muhammad Irfan. Investigation of barriers and mitigation strategies to blockchain technology implementation in construction industry: An interpretive structural modeling approach. *Environmental Science and Pollution Research*, Vol. 30(38):pp. 89889–89909, 2023. doi: 10.1007/s11356-023-28749-6.

[357] Purva Gupta and Kumar Neeraj Jha. A decentralized and automated contracting system using a blockchain-enabled network of stakeholders in construction megaprojects. *Journal of Management in Engineering*, Vol. 39(4):pp. 04023021, 2023. doi: 10.1061/JMENEA.MEENG-5366.

[358] Zhou Xinyuan. Feasibility of blockchain technology in project and construction management, 2023. URL https://scholarbank.nus.edu.sg/handle/10635/242486.

[359] Taofeek Tunde Okanlawon, Luqman Oyekunle Oyewobi, and Richard Ajayi Jimoh. Evaluation of the drivers to the implementation of blockchain technology in the construction supply chain management in nigeria. *Journal of Financial Management of Property and Construction*, 2023. doi: 10.1108/jfmpc-11-2022-0058.

[360] Theodoros Dounas, Davide Lombardi, and Wassim Jabi. Towards blockchains for architectural design consensus mechanisms for collaboration in bim. pages pp. 267–274, 2019. doi: 10.5151/proceedings-ecaadesigradi2019_296.

[361] Jim Mason. Bim fork: Are smart contracts in construction more likely to prosper with or without bim? *Journal of Legal Affairs and Dispute Resolution in Engineering and Construction*, Vol. 11:pp. 02519002, 2019. doi: 10.1061/(ASCE)LA.1943-4170.0000316.

[362] Alireza Shojaei, Ian Flood, Hashem Izadi Moud, Mohsen Hatami, and Xun Zhang. *An Implementation of Smart Contracts by Integrating BIM and Blockchain*, pages pp. 519–527. 2019. doi: 10.1007/978-3-030-32523-7_36.

[363] Marijana Sreckovic, Goran Sibenik, Dominik Breitfuss, and Thomas Preindl. Analysis of design phase processes with bim for blockchain implementation. 2020. doi: 10.2139/ssrn.3577529.

[364] Jennifer Li, Mohamad Kassem, and Richard Watson. A blockchain and smart contract-based framework to inrease traceability of built assets. pages pp. 347–362, 2020. doi: 10.46421/2706-6568.37.2020.paper025.

[365] Widya Suliyanti and Riri Sari. Blockchain-based implementation of building information modeling information using hyperledger composer. *Sustainability*, Vol. 13:pp. 321, 2020. doi: 10.3390/su13010321.

[366] Xiao Li, Weisheng Lu, Fan Xue, Liupengfei Wu, Rui Zhao, Jinfeng Lou, and Jinying Xu. Blockchain-enabled iot-bim platform for supply chain management

in modular construction. *Journal of Construction Engineering and Management*, Vol. 148:pp. 04021195, 2022. doi: 10.1061/(ASCE)CO.1943-7862.0002229.

[367] Rifat Sonmez, Salar Ahmadisheykhsarmast, and Aslı Akçamete Güngör. Bim integrated smart contract for construction project progress payment administration. *Automation in Construction*, Vol. 139:pp. 104294, 2022. doi: 10.1016/j.autcon.2022.104294.

[368] Soumaya Bachtobji, Djamel Eddine Kouicem, and Mouna Ben Mabrouk. Towards blockchain based architecture for building information modelling (bim). In *2022 5th Conference on Cloud and Internet of Things (CIoT)*, pages pp. 53–59, 2022. doi: 10.1109/CIoT53061.2022.9766540.

[369] Mohamed A. Kamel, Emad S. Bakhoum, and Mohamed M. Marzouk. A framework for smart construction contracts using bim and blockchain. *Scientific Reports*, Vol. 13(1), 2023. doi: 10.1038/s41598-023-37353-0.

[370] Shishu Ding, Hao Hu, Lei Dai, and Wen Wang. Blockchain adoption among multi-stakeholders under government subsidy: From the technology diffusion perspective. *Journal of Construction Engineering and Management*, Vol. 149 (5):pp. 04023016, 2023. doi: 10.1061/JCEMD4.COENG-12637.

[371] Ensuring construction material provenance using internet of things and blockchain: Learning from the food industry. *Journal of Industrial Information Integration*, Vol. 33:pp. 100455, 2023. ISSN 2452-414X. doi: 10.1016/j.jii.2023.100455.

[372] Atul Kumar Singh, V.R. Prasath Kumar, Muhammad Shoaib, Towiwa Sunday Adebayo, and Muhammad Irfan. A strategic roadmap to overcome blockchain technology barriers for sustainable construction: A deep learning-based dual-stage sem-ann approach. *Technological Forecasting and Social Change*, Vol. 194:pp. 122716, 2023. ISSN 0040-1625. doi: 10.1016/j.techfore.2023.122716.

[373] Liupengfei Wu Weisheng Lu and Rui Zhao. Rebuilding trust in the construction industry: a blockchain-based deployment framework. *International Journal of Construction Management*, Vol. 23(8):pp. 1405–1416, 2023. doi: 10.1080/15623599.2021.1974683.

[374] Luca Spalazzi, Francesco Spegni, Alessandra Corneli, and Berardo Naticchia. Blockchain based choreographies: The construction industry case study. *Concurrency and Computation: Practice and Experience*, Vol. 35(16), 2021. doi: 10.1002/cpe.6740.

[375] Rui Zhao, Zhe Chen, and Fan Xue. A blockchain 3.0 paradigm for digital twins in construction project management. *Automation in Construction*, Vol. 145:pp. 104645, 2023. ISSN 0926-5805. doi: 10.1016/j.autcon.2022.104645.

[376] George Blumberg and Maurizio Sibilla. A carbon accounting and trading platform for the uk construction industry. *Energies*, Vol. 16(4), 2023. ISSN 1996-1073. doi: 10.3390/en16041566.

[377] Haitao Wu, Heng Li, Xiaochun Luo, and Shan Jiang. Blockchain-based on-site activity management for smart construction process quality traceability. *IEEE Internet of Things Journal*, pages pp. 1–1, 2023. doi: 10.1109/JIOT.2023.3300076.

AppendixA

Appendix A

A.1 Common and Specific Findings from Research Articles

Table A.1: Common and specific findings from research articles

Authors	Specific findings	Common findings
[34] [164] [118] [315] [319] [203] [144] [122] [310] [149] [119] [148] [318] [316] [317] [143] [320] [321] [322] [323] [325] [156] [329] [341] [342] [191] [343] [344] [345] [346] [347] [348] [349] [350] [351] [64] [324] [352] [353] [354] [355] [356] [357] [358] [359]	Review of Blockchain and subsequent applications.	Provide research on where and how to use this technology in the construction industry.
[312]	The study shows how to design a system that supports the use of Blockchain technology. The system allows project team members to conduct financial transactions automatically by coding the costs charged, benefits, and cost savings of IPD projects.	The study describes Blockchain technology, provides general information about how it works and its potential, and explains possible technical limitations.

Continued on next page

Table A.1 – continued from previous page

Authors	Specific findings	Common findings
[31] [20]	This article explores the potential application of Blockchain technology in the development of an automation system for the Blockchain compliance test process. Hyperledger Fabric is used to address most current issues such as data security, track changes and control of permissions arising from the use of central BIM work processes.	Discover the consequences, challenges and applications of Blockchain technology for process improvement and find areas for future research on Blockchain applications in construction.
[305]	As a conceptual proof, a simulated setup activity is used to verify the conceptual relationships included in the proposed framework. The simulation shows how to implement a mini smart contract within the proposed strategy and how to automate payments when the project execution is combined with machine-readable BIM specifications and contract terms.	Blockchain's main strength is its ability to offer a better solution to the problem of trust.
[166]	It seeks to evaluate if BIM offers an accurate platform for implementing smart contracts in the construction industry.	
[360]	It offers a Blockchain collaboration platform for optimisation issues among distributed stakeholders working with the tool for building information modeling.	Explore the effects, risks, and practices of Blockchain technology to improve data flow in the end-to-end design and construction process.
[165]	Introduced to facilitate BIM data audits for historical modification using blockchain in mobile cloud and big data sharing.	
[285]	It proposes a methodology for automating the construction payments by formalising them as smart contracts and implementing them on a system based on Blockchain.	Demonstrates the advantage of BIM work process integration with Blockchain by providing change tracking and data ownership.
[180]	The paper discusses the integration of new patterns in information technologies such as cybersecurity and Blockchain features into a typical university BIM curriculum.	Improves data storage and permissions management reliability.

Continued on next page

Table A.1 – continued from previous page

Authors	Specific findings	Common findings
[117]	It explores the feasibility of integrating smart contract applications and technology with building information modeling and information management.	
[51]	This article proposes a "new value proposition" for consumers and the AEC practitioners who now benefit from collaboration and have a variety of collaboration tools to allow this to happen in real-time.	Researchers show that Blockchain is a permanent, unchangeable and stable network capable of removing intermediates and automating processes due to its prominent disintermediation, accountability and consistency characteristics.
[313]	A case study examines the potential cost savings of a real estate company using Blockchain. The study tests possible cost savings scenarios from the use of Blockchain (one results shows that potential cost savings from the implementation of Blockchain at 8.3 % of overall residential construction costs, with a standard deviation of 1.26 %).	Executes and releases transaction when conditions have been completed.
[162]	Taking into account the social and technological dimensions, it proposes a multi-dimensional framework that emerged for the adoption of DLT in the construction industry.	Encourages a collaborative decentralised building environment.
[314]	The articles demonstrates the emergence of Blockchain, highlighting the adoption and the progress of construction companies using this technology	
[188]	It examines the conceptual basis for the design of an automated payment system and assesses the role of smart contracts in allowing cash flow to be efficiently and autonomously conditioned on the status of product flow.	Increases both the level of traceability and the level of tracking in real time.
[361]	The article reports on the applicability of using smart contracts with BIM in the construction sector.	Overcoming file redundancy challenges and securing the file storage system.

Continued on next page

Table A.1 – continued from previous page

Authors	Specific findings	Common findings
[167]	Introduces a unique semantic differential transaction (SDT) technique for minimising redundancy in the emerging area of BIM and Blockchain integration.	Records of information cannot be modified based on a consensus.
[362]	A Hyperledger fabric-based Blockchain network is proposed and validated to control a sample building project.	
[363]	Integrate design theory, configuration theory, and task-technology fit into a conceptual framework for a Blockchain based design process.	Ensures accountability, transparency, and trust.
[364]	A framework is presented to integrate various technological systems into an ecosystem that promotes digitalization and enables traceability, improved information management, and regulatory and standard compliance.	Blockchain consensus mechanisms ensure data quality.
[130]	Provides a system based on smart contracts for the autonomous administration of building progress payments. The approach is used to make payments to seven subcontractors for two commercial building projects with monitored progress.	Improve efficiency by automating project management and operations.
[365]	Investigate the exchange of BIM data between many parties utilising a Blockchain platform in a safe way across the whole building lifecycle.	
[128]	In the framework of CIM/Smart Cities, investigate the possible effect of integrating Blockchain and BIM in a smart city setting on the sustainability of buildings.	Eliminates the requirement for a middleman in a transaction.
[168]	Presents a framework for decentralised architectural design.	

Continued on next page

Table A.1 – continued from previous page

Authors	Specific findings	Common findings
[169]	Presents a distributed common data environment (DCDE) architecture for BIM-based design using Blockchain and Interplanetary File System (IPFS).	Using a time stamping technology, Blockchain prevents data manipulation.
[125]	Demonstrates a different approach that utilises smart construction objects (SCOs), and develops a framework for SCOs-enabled Blockchain oracles (SCOs-BOs).	
[67]	Virtual location information from a prefabricated brick is transferred to a digital counterpart in near real-time and stored on the Blockchain with time stamps.	The use of blockchain technology ensures the confidentiality and integrity of transactions.
[366]	Proposes permissioned Blockchain with IBP and presents Blockchain-enabled IoT-BIM platform (BIBP) for DIK-driven supply chain operations in modular construction.	
[209]	Introduces a framework (CMF) for Blockchain-based design cooperation that prioritises secrecy.	Blockchain is a single source of truth.
[158]	Presents a Self Sovereign Identity-based system proposal to highlight how Blockchain, BIM, IoT devices, and Self Sovereign Identity may enable building digitalization, assuring compliance standards and technical requirements.	
[367]	Presents a new BIM-integrated smart contract progress payment system.	Enhances the security of the network.
[368]	Propose a hierarchical design with IoT, fog, and cloud layers that integrates Blockchain to secure Building Management Systems (BMS).	
[369]	Proposed a framework for payment automation using Blockchain in construction projects. Demonstrated the potential for instant payments and secure records.	

Continued on next page

Table A.1 – continued from previous page

Authors	Specific findings	Common findings
[370]	Proposed a game-based system dynamics (EG-SD) model for BT adoption in construction - evaluated diffusion performance under different scenarios.	
[371]	Developed a framework for material provenance tracing and tracking using IoT and blockchain.	
[170]	Developed a blockchain-enabled supply chain coordination system. Used Bayesian updating, which framework is to make predictions about new measurements based on the current measurements, to align stakeholder decisions. The theoretical concept of measuring plan trustworthiness, blockchain and smart contracts has been evaluated.	
[372]	Identified significant barriers to blockchain adoption in India's sustainable construction industry. Developed a roadmap for overcoming barriers.	
[373]	Proposed a deployment framework for blockchain-based trust-building in construction. Articulated a trust-building spectrum and positioned blockchain in it.	
[374]	Developed a set of tools for transparency, accountability, and compliance in the business process modeling notation (BPMN) choreographies using blockchain. Applied the techniques to a construction industry case study.	

Continued on next page

Table A.1 – continued from previous page

Authors	Specific findings	Common findings
[375]	Introduction of ChainPM as a Blockchain 3.0 paradigm for Construction project management (CPM) digital twins, emphasizing indexing key CPM data, combinatorial query, digital authorship, and fast response. Significant reduction in information synchronization latency.	
[127]	Proposal of a solution to address the disconnected nature of blockchain adoption in construction procedures. Support for the upstream circular economy design and fostering collaboration among stakeholders. Development of "a bank of reusable BIM families" to encourage designers to use them.	
[376]	Proposal of a carbon accounting and trading platform using blockchain technology. Synchronization of taxation with the building's life cycle and tracking of hazardous products/materials. The need for computer-based systems for emissions recording and carbon offsets purchase.	
[377]	Introduction of a blockchain-based framework for traceability of on-site construction activities. Use of deep learning algorithms for information extraction from surveillance videos. Application of consortium blockchain to record activity information and maintain transparency.	

APPENDIXB

Appendix B

B.1 Code of the Smart Contract Used for the Workpackage

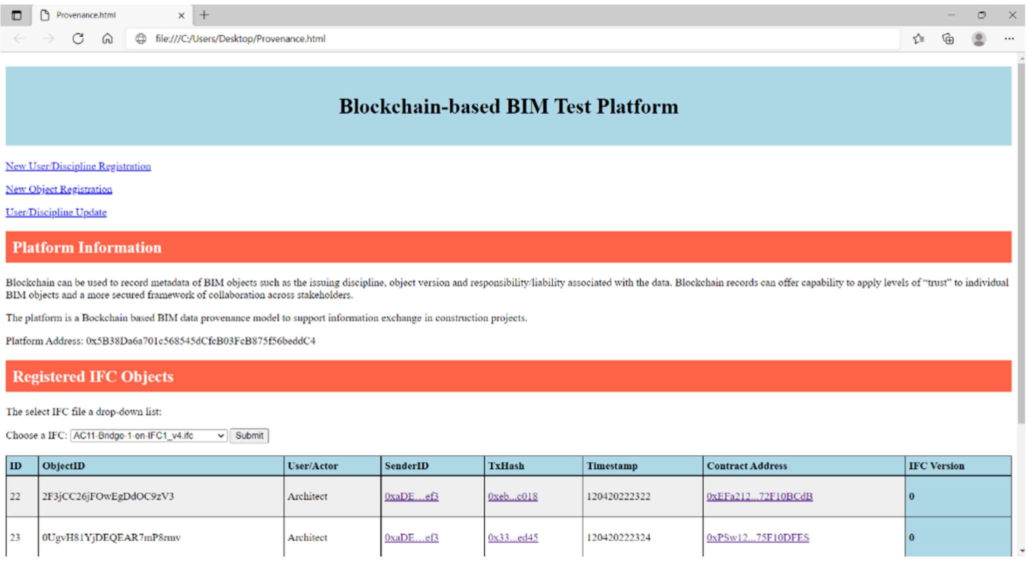
```
pragma solidity ^0.8.0;

contract WorkPackage {
    // Structure to hold information about a work package
    struct Package {
        string sender;
        string receiver;
        string name;
        uint amount;
        string projectFile;
        bool completed;
    }
```

```
    // Mapping to store all work packages
    mapping (address => Package) packages;

    // Events for package completion and due date execution
    event PackageCompleted(address indexed packageAddress,
        string packageName);
    event PackageDueDateExecuted(address indexed packageAddress,
        string packageName);

    // Function to add a new work package
    function addPackage(string memory _sender, string memory _receiver,
        string memory _name, uint _amount, string memory _projectFile)
        public {
        packages[msg.sender] = Package(_sender, _receiver, _name,
        _amount, _projectFile, false);
    }

    // Function to mark a work package as completed
    function completePackage(address _packageAddress) public {
        require(packages[_packageAddress].completed == false,
        "Package already completed");
        packages[_packageAddress].completed = true;
        emit PackageCompleted(_packageAddress, packages[_packageAddress].name)
    }

    // Function to execute a package when its due date is reached
    function executeDueDate(address _packageAddress) public {
        require(packages[_packageAddress].completed == false,
     "Package already completed");
        emit PackageDueDateExecuted(_packageAddress,
            packages[_packageAddress].name);
    }
}
```

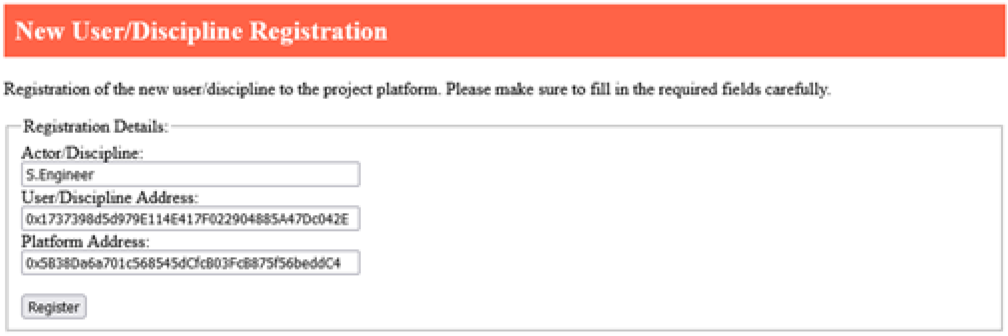
Appendix C

C.1 Blockchain-based BIM Test Platform

C.1.1 Main Page and General Information of the Platform

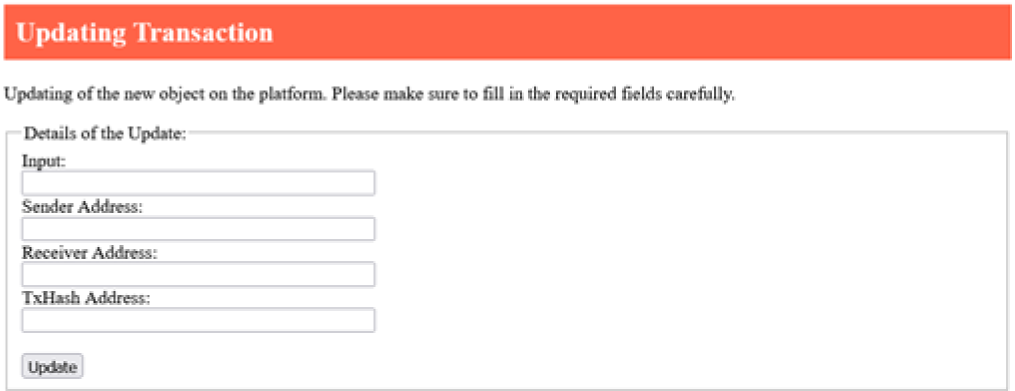


C.1.2 New Discipline Registration



C.1.3 New Object or Input Registration

C.1.4 Updating Transaction



C.1.5 Visualising Model Transactions

Getting Details

The select Project and User from a drop-down list:

Choose a Project's IFC File : AC11-Bridge-1-en-IFC1_v4.ifc

Choose an User/Actor for tracking: Architect Submit Query

User/Actor	SenderID	Receiver	Block No	TxHash	BxHash	Timestamp
Architect	0x43…e32d	0x5B...ddC4	3	0xeb...c018	0x34..as24	120420221922
Architect	0x43…e32d	0x5B...ddC4	4	0x33...ed45	0x8e…23s1	120420221922
Architect	0x43…e32d	0x5B...ddC4	5	0x12...d101	0x38…4eq3	120420221923
Architect	0x43…e32d	0x5B...ddC4	7	0xea...b803	0x14…3esa	120420221923
Architect	0x43…e32d	0x5B...ddC4	8	0xer…567u	0x2v…1o76	120420221925
Architect	0x43…e32d	0x5B...ddC4	10	0xer…3456	0x4d…2s21	120420221927

APPENDIX D

Appendix D

D.1 Smart Contract Code for the Energy Data Record to Blockchain with All Variables (Eight Variables):

```
pragma solidity ^0.5.16;

contract IoTBC {

    // Input variables
    string[] public day;
    uint[] public temperature;
    uint[] public humidity;
    uint[] public co2;

    // ElectricityInput variables for the buildings
    struct ElectricityInput {
        uint[] QE;
        uint[] QW;
        uint[] QS;
```

```
        uint[] QC;
        uint[] QN;
    }

    ElectricityInput electricityInput;

    // Output variables
    uint[] public indoorTemperatureSetpoint;
    uint[] public inletSetpoint;
    uint[] public electricalEnergyConsumption;
    uint[] public thermalEnergyConsumption;


    // Event to log execution time
    event ExecutionTime(uint256 time);

    // Input function
    function set(string memory _day, uint _humidity, uint _temperature, uint _co2,
        uint[] memory _QE, uint[] memory _QW, uint[] memory _QS, uint[] memory _QC,
        uint[] memory _QN, uint _indoorTemperatureSetpoint, uint _inletSetpoint) public returns (uint)
        uint256 startTime = now; // Record start time

        day.push(_day);
        humidity.push(_humidity);
        temperature.push(_temperature);
        co2.push(_co2);

        electricityInput.QE = _QE;
        electricityInput.QW = _QW;
        electricityInput.QS = _QS;
        electricityInput.QC = _QC;
        electricityInput.QN = _QN;

        // Perform calculations to get optimized values
        // ...

        // optimized value for indoor temperature set point
        indoorTemperatureSetpoint.push(_indoorTemperatureSetpoint);
        // optimized value for inlet consumption
        inletSetpoint.push(_inletSetpoint);
        // optimized value for electrical energy consumption
        uint _electricalEnergyConsumption = 0;
        // optimized value for thermal energy consumption
        uint _thermalEnergyConsumption = 0;
```

```
        electricalEnergyConsumption.push(_electricalEnergyConsumption);
        thermalEnergyConsumption.push(_thermalEnergyConsumption);

        // Log execution time
        uint256 executionTime = now - startTime;
        emit ExecutionTime(executionTime);

        // Return an appropriate value
        return 0;
    }

    // Output functions
    function getIndoorTemperatureSetpoint(uint index) public view returns (uint) {
        return indoorTemperatureSetpoint[index];
    }

    function getInletSetpoint(uint index) public view returns (uint) {
        return inletSetpoint[index];
    }

    function getElectricalEnergyConsumption(uint index) public view returns (uint) {
        return electricalEnergyConsumption[index];
    }

    function getThermalEnergyConsumption(uint index) public view returns (uint) {
        return thermalEnergyConsumption[index];
    }

}
```

D.2 Smart Contract Code for the Energy Data Record to Blockchain with Fewer Variables (Four Variables):

```
pragma solidity ^0.5.16;

contract IoTBC {
    // Input variables
    string[] public day;
    uint[] public temperature;
    uint[] public humidity;
    uint[] public co2;
```

```
uint[] public electricity;

// Control variables
uint[] public indoorTemperatureSetpoint;
uint[] public inletSetpoint;

// Output variables
uint[] public electricalEnergyConsumption;
uint[] public thermalEnergyConsumption;

// Event to log execution time
event ExecutionTime(uint256 time);

// Input functions
function set(
    string memory _day,
    uint _humidity,
    uint _temperature,
    uint _co2,
    uint _electricity,
    uint _indoorTemperatureSetpoint,
    uint _inletSetpoint
) public returns (uint) {
    uint256 startTime = now; // Record start time

    day.push(_day);
    humidity.push(_humidity);
    temperature.push(_temperature);
    co2.push(_co2);
    electricity.push(_electricity);

    // Perform calculations to get optimized values
    // optimized value for inlet consumption
    inletSetpoint.push(_inletSetpoint);

    // optimized value for electrical energy consumption
    uint _electricalEnergyConsumption = 0;

    // optimized value for thermal energy consumption
    uint _thermalEnergyConsumption = 0;

    // optimized value for indoor temperature set point
    indoorTemperatureSetpoint.push(_indoorTemperatureSetpoint);

    electricalEnergyConsumption.push(_electricalEnergyConsumption);
```

```
            thermalEnergyConsumption.push(_thermalEnergyConsumption);

            // Log execution time
            uint256 executionTime = now - startTime;
            emit ExecutionTime(executionTime);

            return 0;
        }

        // Output functions
        function getInletSetpoint(uint index) public view returns (uint) {
            return inletSetpoint[index];
        }

        function getElectricalEnergyConsumption(uint index) public view returns (uint) {
            return electricalEnergyConsumption[index];
        }

        function getThermalEnergyConsumption(uint index) public view returns (uint) {
            return thermalEnergyConsumption[index];
        }

        function getIndoorTemperatureSetpoint(uint index) public view returns (uint) {
            return indoorTemperatureSetpoint[index];
        }
    }


    %In the first contract, the control variables for indoor temperature set point and inlet set
```

APPENDIXE

Appendix E

E.1 Blockchain KPI Table with Formulas

Table E.1: Benefits and Drawbacks of Blockchain ROI Formulas

BENEFITS						
Improved data management and record-keeping		Improved accuracy and completeness of project data	Reduced errors and discrepancies in project records	Improved tracking and accountability of project data	Reduced risk of data loss or corruption	Streamlined access to project data across the organization
	Formula	Benefit = (Number of Errors/Discrepancies in Project Data Before Blockchain Implementation - Number of Errors/Discrepancies in Project Data After Blockchain Implementation) / Number of Records	Benefit = (Number of Errors/Discrepancies in Project Data Before Blockchain Implementation - Number of Errors/Discrepancies in Project Data After Blockchain Implementation) / Number of Records	Benefit = (Number of Missed Deadlines or Milestones Before Blockchain Implementation - Number of Missed Deadlines or Milestones After Blockchain Implementation) / Total Number of Deadlines or Milestones	Benefit = (Number of Data Loss or Corruption Incidents Before Blockchain Implementation - Number of Data Loss or Corruption Incidents After Blockchain Implementation) / Total Number of Data Records	Benefit = (Time Spent Searching for Project Data Before Blockchain Implementation - Time Spent Searching for Project Data After Blockchain Implementation) / Total Time Spent Searching for Project Data
Reduced fraud and corruption		Improved transparency and auditability of financial transactions	Reduced opportunities for unauthorized changes to financial records	Increased ability to detect and prevent fraudulent activity		
		Benefit = (Number of Financial Transaction Errors or Discrepancies Before Blockchain Implementation - Number of Financial Transaction Errors or Discrepancies After Blockchain Implementation) / Total Number of Financial Transactions	Benefit = (Number of Unauthorized Changes to Financial Records Before Blockchain Implementation - Number of Unauthorized Changes to Financial Records After Blockchain Implementation) / Total Number of Financial Records	Benefit = (Value of Fraudulent Activity Detected and Prevented After Blockchain Implementation - Value of Fraudulent Activity Detected and Prevented Before Blockchain Implementation) / Total Value of Financial Transactions		
Increased transparency and accountability		Improved visibility into project status and progress	Increased ability to identify and address issues early on	Enhanced stakeholder trust and confidence in project outcomes		

Continued on next page

Table E.1 – continued from previous page

		Benefit = (Value of Time Saved by Improved Visibility into Project Status and Progress / Total Value of Project Time) x 100	Benefit = (Value of Issues Prevented or Mitigated / Total Value of Project Cost) x 100	Benefit = (Value of Increased Stakeholder Trust and Confidence / Total Project Cost) x 100		
Faster and more secure payments		Reduced transaction times and costs	Improved payment accuracy and reliability	Enhanced payment security and privacy		
		Benefit = (Number of Transactions * Average Time per Transaction * Cost per Transaction) - (Number of Transactions * Average Time per Transaction * Cost per Transaction * Reduction Percentage)	Improved payment accuracy and reliability = (A * B * C) / D where: A = Number of payment errors or discrepancies before implementing blockchain technology B = Average amount of time and resources spent to resolve each payment error or discrepancy before implementing blockchain technology C = Percentage of payment errors or discrepancies that can be eliminated with blockchain technology D = Total number of payments processed before and after implementing blockchain technology	1. Reduction in fraud Benefit = (Total fraud cases before - Total fraud cases after) / Total fraud cases before 2. Improved privacy Benefit = (Number of privacy breaches before - Number of privacy breaches after) / Number of privacy breaches before 3. Decreased dependency on intermediaries Benefit = (Total fees paid to intermediaries before - Total fees paid to intermediaries after) / Total fees paid to intermediaries before 4. Increased trust and confidence Benefit = (Total number of disputes before - Total number of disputes after) / Total number of disputes before		
Increased supply chain efficiency and visibility		Improved tracking and tracing of materials and products	Enhanced supplier and vendor management	Reduced supply chain delays and disruptions		

Continued on next page

Table E.1 – continued from previous page

		1. Improved accuracy and completeness of tracking data: Higher accuracy and completeness of tracking data after blockchain implementation compared to before. 2. Reduced errors and discrepancies in tracking data: Fewer errors and discrepancies in tracking data after blockchain implementation compared to before. 3. Improved tracking and accountability of data: Enhanced tracking and accountability of data after blockchain implementation compared to before. 4. Reduced risk of data loss or corruption: Decreased incidents of data loss or corruption after blockchain implementation compared to before. 5. Streamlined access to tracking data: Faster access to tracking data across the organization after blockchain implementation compared to before.	1. Improved supply chain transparency and accountability: Higher transparency and accountability in the supply chain after implementation compared to before. 2. Streamlined procurement and purchasing processes: Faster procurement and purchasing processes after implementation compared to before. 3. Improved supplier performance tracking: Enhanced tracking of supplier performance after implementation compared to before. 4. Increased collaboration and communication with suppliers and vendors: Improved collaboration and communication with suppliers and vendors after implementation compared to before.			
Improved customer trust and loyalty		Enhanced customer experience through increased transparency and communication	Improved data privacy and security protections	Increased customer satisfaction and loyalty		
		Customer Experience Benefit = (P * Q) - R where: P is the number of customers who benefit from increased transparency and communication. Q is the average increase in customer satisfaction score due to enhanced transparency and communication. R is the cost of implementing the blockchain solution to achieve the enhanced transparency and communication	1. Reduced risk of data breaches and cyberattacks 2. Increased protection of sensitive information 3. Improved compliance with data privacy regulations Benefit percentage = (Overall benefit score / Maximum possible score) x 100%	1. Repeat business or customer retention rates 2. Positive customer feedback and reviews 3. Increased referrals and recommendations from satisfied customers 4. Reduced customer complaints or disputes 5. Higher sales revenue and profitability due to customer loyalty		

Continued on next page

Table E.1 – continued from previous page

DRAWBACKS						
Implementation challenges		Initial costs associated with implementation and integration of blockchain technology,	Complexity of implementing and integrating new technology into existing systems and processes,	Limited availability of skilled personnel to implement and manage blockchain solutions		
		1. Software development costs Benefit Formula: (Cost Before - Cost After) / Cost Before 2. Hardware costs Benefit Formula: (Cost Before - Cost After) / Cost Before 3. Infrastructure costs Benefit Formula: (Cost Before - Cost After) / Cost Before 4. Integration costs Benefit Formula: (Cost Before - Cost After) / Cost Before 5. Training and education costs Benefit Formula: (Cost Before - Cost After) / Cost Before 6. Consulting costs Benefit Formula: (Cost Before - Cost After) / Cost Before 7. Legal and regulatory costs Benefit Formula: (Cost Before - Cost After) / Cost Before 8. Maintenance costs Benefit Formula: (Cost Before - Cost After) / Cost Before	1. System requirements (Hours Before - Hours After) / Hours Before 2. Training and education (Cost Before - Cost After) / Cost Before 3. Data migration (Cost Before - Cost After) / Cost Before 4. Integration with existing systems (Time Before - Time After) / Time Before 5. Technical expertise (Cost Before - Cost After) / Cost Before	1. Difficulty in finding qualified personnel (Percentage Before - Percentage After) / Percentage Before 2. Cost of hiring and training (Cost Before - Cost After) / Cost Before 3. Competition for talent (Percentage Before - Percentage After) / Percentage Before		
Technical issues		Potential for system downtime or errors	Difficulty in scaling blockchain technology to meet increasing demands	Risks associated with security vulnerabilities and potential hacking attempts		

Continued on next page

Table E.1 – continued from previous page

		Potential for system downtime or errors = (P * T * R) Where: • P = Probability of system downtime or errors occurring • T = Time period during which the system is expected to operate) • R = Impact or cost of system downtime or errors	1. Estimate the current demand for the blockchain application or network (in transactions per second or other relevant metric). 2. Determine the maximum capacity of the current blockchain system to handle demand (in transactions per second or other relevant metric). 3. Calculate the gap between current demand and the maximum capacity of the system. 4. Estimate the projected future demand for the blockchain application or network over the desired timeframe. 5. Determine the maximum capacity of the current blockchain system in the future timeframe to handle demand. 6. Calculate the gap between projected future demand and the maximum capacity of the system in the future timeframe. 7. Consider any technological advancements or upgrades that may improve the capacity of the blockchain system and adjust the calculations accordingly. 8. Assess the impact of the difficulty in scaling on the overall benefit of the blockchain solution for the organization. 9. Factor in the cost of implementing any necessary upgrades or changes to the blockchain system to improve scalability. 10. Compare the costs and benefits to determine whether the organization should pursue scaling efforts, invest in alternative solutions, or maintain the current level of blockchain technology.	1. Identify the potential security vulnerabilities and their likelihood of occurrence (A). 2. Estimate the potential impact of a security breach or hacking attempt, including potential financial losses and reputational damage (B). 3. Multiply the likelihood of occurrence (A) by the potential impact (B) to calculate the expected value of a security breach (C = A * B). 4. Identify the potential costs associated with mitigating security vulnerabilities and preventing hacking attempts (D). 5. Subtract the potential costs of mitigation (D) from the expected value of a security breach (C) to calculate the net risk of security vulnerabilities and potential hacking attempts (E = C - D).		

Continued on next page

Table E.1 – continued from previous page

Regulatory and legal considerations		Uncertainty surrounding legal and regulatory frameworks for blockchain technology	Compliance with data privacy and security regulations,	Potential liability for data breaches or other security incidents		
		1. Compliance costs 2. Reputation damage 3. Limited investment 4. Limited adoption 5. Legal risks		Potential Liability = (Estimated Cost of Data Breaches) + (Lost Revenue/Business Opportunities) + (Damage to Reputation) + (Cost of Additional Security Measures)		
User adoption		Potential resistance from employees to adopting new technology and changing established processes,	Need for training and education on the use of blockchain technology,	Difficulty in convincing stakeholders of the benefits of blockchain technology		
		One approach could be to use a Likert scale to assess employee attitudes towards the new technology, asking questions	1. Employee time and resources required for training 2. Disruption to regular workflow 3. Effectiveness of training 4. Cost of training 5. Resistance to change	One possible way to calculate the difficulty in convincing stakeholders of the benefits of blockchain technology could be: 1. Determine the number of stakeholders who need to be convinced: N 2. Assign a score to each stakeholder's current level of understanding and acceptance of blockchain technology, on a scale from 1 to 10: S1, S2, S3, ..., SN 3. Assign a score to the expected level of resistance from each stakeholder, on a scale from 1 to 10: R1, R2, R3, ..., RN 4. Assign a weight to each stakeholder based on their level of influence and importance to the project: W1, W2, W3, ..., WN (the weights should add up to 1) 5. Calculate the average score of stakeholders understanding and acceptance: SA = (S1 + S2 + S3 + ... + SN) / N		

E.2 Chapter 8: Questionnaire

Q1:

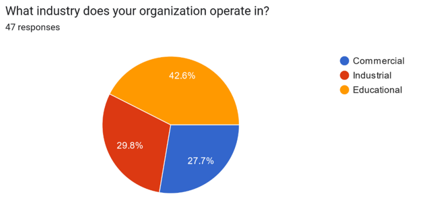


Figure E.1: Question 1

Q2:

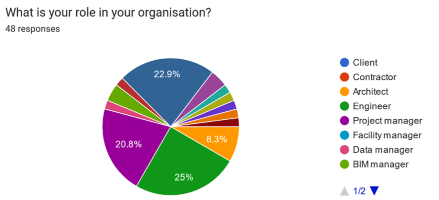


Figure E.2: Question 2

Q3:

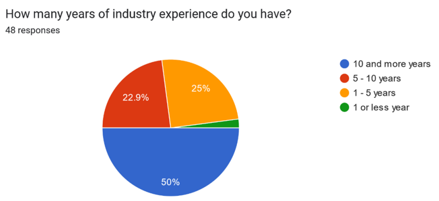


Figure E.3: Question 3

Q4:

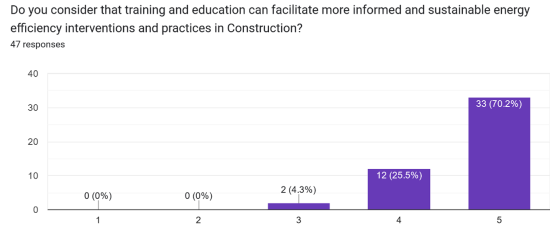


Figure E.4: Question 4

Q5:

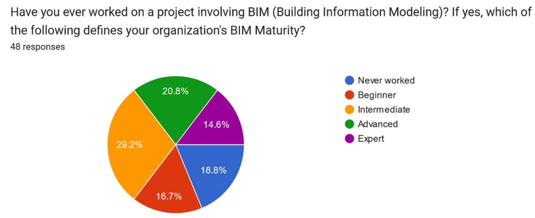


Figure E.5: Question 5

Q6:

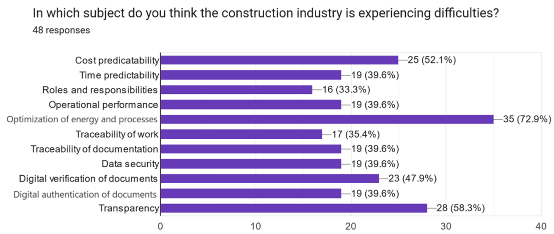


Figure E.6: Question 6

Q7:

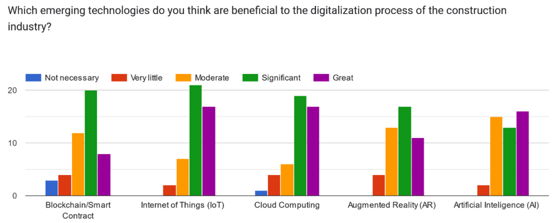


Figure E.7: Question 7

Q8:

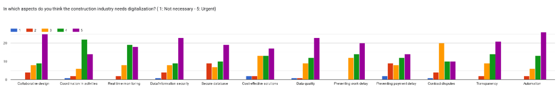


Figure E.8: Question 8

Q9:

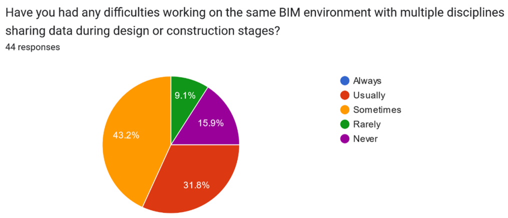


Figure E.9: Question 9

Q10:

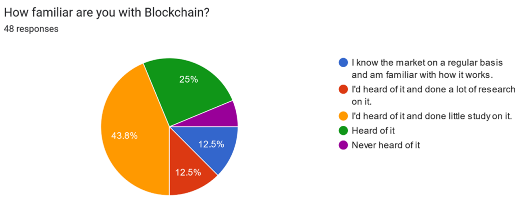


Figure E.10: Question 10

Q11:

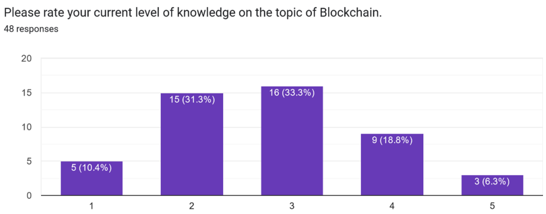


Figure E.11: Question 11

Q12:

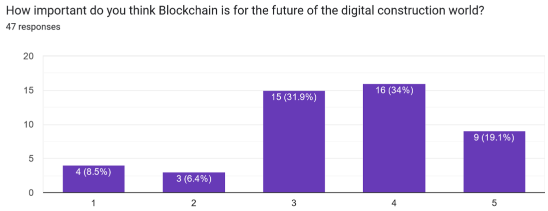


Figure E.12: Question 12

Q13:

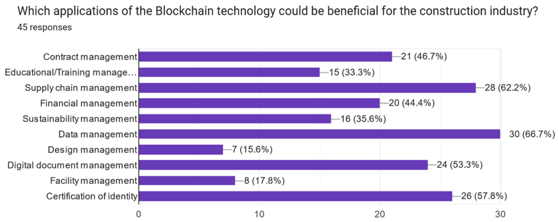


Figure E.13: Question 13

Q14:

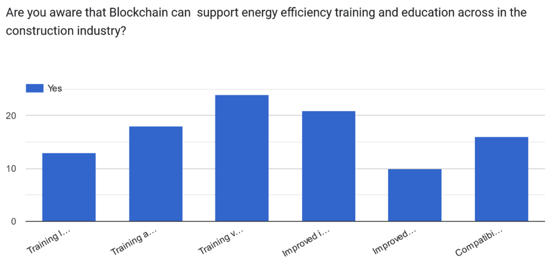


Figure E.14: Question 14

Q15:

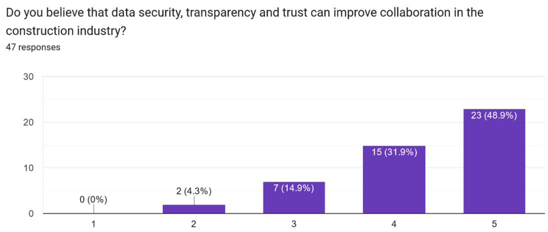


Figure E.15: Question 15

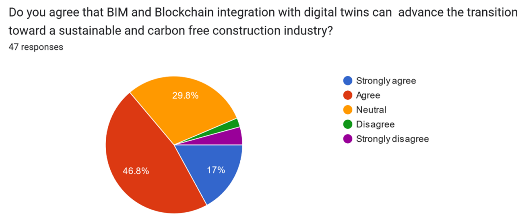
Q16: 

Figure E.16: Question 16

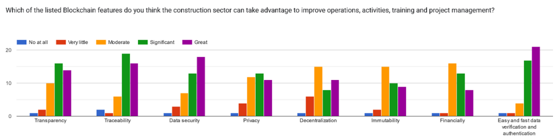
Q17: 

Figure E.17: Question 17

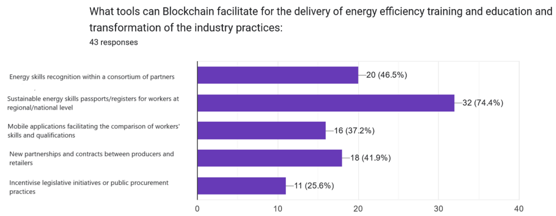
Q18: 

Figure E.18: Question 18

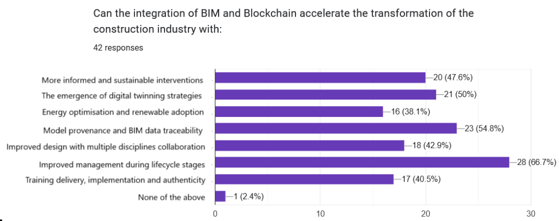
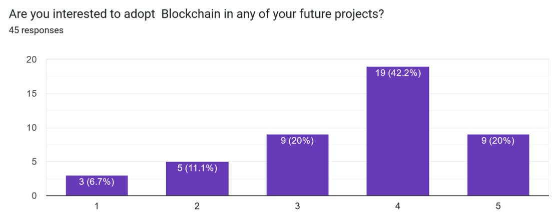
Q19: 

Figure E.19: Question 19



Q20:

Figure E.20: Question 20