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Unveiling Blockchain Technology in Construction Supply Chain Management: The What, When, Who, Where, and How Towards Digitalization

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ABSTRACT

Digitalization and technology disruptions have ushered in the Fourth Industrial Revolution (IR 4.0), which is now required for many sectors. On the other hand, the building sector is seen to be among those that is resistant to change. The possibility of implementing blockchain technology in the building sector has not received much attention. The cryptocurrency space is not new to blockchain technology. In essence, it is a public ledger or distributed database that contains all the executed and shared digital events or transactions between all involved parties. Herein lies the utility of blockchain technology, particularly in the highly transactional construction sector. Blockchain technology records every transaction and arranges all the "blocks" into a "chain," acting as a middleman in every transaction we make to foster trust. In the construction business, supply chain management spans a range of stakeholders, including contractors, manufacturers, consultants, and clients. It also covers numerous construction organization activities, starting with planning, design, construction, and maintenance. Numerous activities lead to a large volume of transactions that impede communication and cooperation between these parties and result in expensive arbitration or lawsuit cases. It has been acknowledged that blockchain technology is one of the cutting-edge innovations that have the potential to revolutionize several sectors. Using blockchain technology has several benefits, such as lower transaction costs, protection against data tampering and falsification, and more flexibility. Because it involves so many transactions between many parties, the construction sector is typically seen as having a lot of potential for using blockchain technology. There aren't many examples of blockchain uses in the construction sector, despite its apparent benefits.

Keywords: Blockchain technology; supply chain management; construction industry; digitalization

INTRODUCTION

The construction industry in Malaysia is determined to be the main driver of economic growth. It ensures and keeps sustainability of the key resources, fuels growth, and protections the arrangement framework for continuous economic and social development. Construction is one of the major industries in Malaysia, that is contributing to construction work that has been completed in the first quarter of 2022 continuously successful at -6.10 percent (Q4 2021: -12.90%) according to A year-on-year source, amounting to RM29.50 billion (Q4 2021: RM27.60 billion), (Strategic Communication and International Division Department of Statistics, Malaysia, 2022)[1]

While manufacturing productivity has nearly doubled and is still rising over the same period, construction productivity has been stagnant for decades (Sveikauskas et al., 2016). Of course, the construction industry is extremely different, but to stay up with the current state of the global economy, more productive businesses are required. One aspect of this growth is digitalization. The many modeling tools and software improve the efficiency of the design process and increase the level of interaction between the project and document control. The usage of Building Information Modelling (BIM) is arguably the biggest development (Kuperberg et al., 2021). According to Dounas et al. (2020), it improves the integration of the design process and aids in creating a digital description of every facet of the constructed asset.

As technology and intelligent systems evolve at a rapid pace, the construction sector must adapt to meet the demands of the Fourth Industrial Revolution, as it has been called. This revolution heralds the arrival of a tangible cyber system that will transform buildings as we know them in the future. To adapt to these changes, it is essential to place a strong focus on using expertise while also developing new skills and knowledge. Crucial to the situation is that, in collaboration with stakeholders in the construction sector, the Ministry of Works, via CIDB, has created a Construction Strategy Plan 4.0 (2021–2050) to support the sector as it adapts to the changes.A five-year CIDB short-term plan called Construction Strategy Plan 4.0 will serve as the foundation for a draft plan framework that will improve the capabilities of the construction sector in the 4.0 sector revolution. The National 4.0 Industry Policy (Industry4WRD), also known as Dasar Industri 4.0 Nasional (Industry4WRD), and the Shared Prosperity Vision 2030, also known as Wawasan Kemakmuran Bersama (WKB) 2030, are being taken into consideration while developing the strategic plan. Additionally, it complements and supports other national policies, such as the Digital Economic Policy (Construction 4.0 Strategy Plan 2021–2025), the Malaysia Smart City Framework, and the National IoT Strategic Roadmap.5. The following four enablers determined the Construction Strategy Plan 4.0:

- Enabler 1- People
- Enabler 2- Integrated Technologies
- Enabler 3- Economy
- Enabler 4- Governance

Together, the four enablers will provide the groundwork for ensuring that the Construction 4.0 transition is implemented and, as a result, building a whole ecosystem to adapt to the changes. The 12 primary technologies—also referred to as "disruptive technologies"—that the Construction Strategy Plan 4.0 has identified as having the potential to transform the construction industry are as follows:

- Pre-fabrication and Modular Construction
- Building Information Modelling (BIM)
- Autonomous Construction
- Augmented Reality & Virtualisation
- Cloud and Realtime Collaboration
- 3D Scanning and Photogrammetry
- Big Data & Predictive Analysis
- Internet of Things (IoT)
- 3D Printing and Additive Manufacturing
- Advanced building materials
- Blockchain
- Artificial Intelligence

Complex and dynamic modifications are required for the Industrial Revolution 4.0 era to keep up with the rate of technological growth that we will encounter in the future. The issue necessitates effective governance and great collaboration among numerous stakeholders, including the government, industry, academics, and society. All play a vital part in ensuring that constant efforts are made to turn the construction sector into strong competitiveness, which will be the greatest contributor to the country's economic growth. Construction projects include a variety of procedures, people, and goods, so it's no surprise that they rarely stick to the plan. The rising complexity of buildings and structures is taxing quality management systems, while the flow of information in the supply chain is frequently diversified and pre-ordered, resulting in communication breakdowns, waste, and lawsuits. Two linked emergent technology streams, the Internet of Things and the "blockchain", were proposed as innovations that may unlock capacities and productivity, much like the inventive socio-technical processes of the past that led to significant gains in global trade and communications (Heiskanen,2017).

Blockchain is one of these disruptive technology categories, as it ensures transparent delivery of information through all system contributors in a way, where no party holds overall control of the information. Information is shared in a predefined way, and cannot be changed, almost all simultaneously. All data distributed and recorded on blockchain systems is unchanged(Behera et al, 2015). Blockchain technology will increase parity, information is difficult to falsify, and information can be digitalized to help ensure sustainability in complex supply chains. By using this Blockchain technology the industry players can verify from where the source material is produced, manufactured, and how it is handled. Public ledger verification systems can increase transparency which can address corruption, child labor, falsified certifications, etc. This in turn can help all buyers in the construction industry to identify the right supplier (Turk et al, 2017).

LITERATURE REVIEW

Evolution of Modern Construction

Construction is said to have predated modern humans and from mud huts and megalithic stones to mega highways and skyscrapers, the evolution of construction reflects mankind's ever-growing mastery of raw materials and technology. The construction scale and scope evolved as more people settled in cities humans built increasingly sophisticated permanent structures whose purpose was to support sedentary living. The resurgence of the construction industry coincided with the rise of modern science and throughout the centuries, construction continued to build upon the economies of scale created during the Industrial Revolution. On the other hand, the construction industry began to expand in Malaysia on the Independence Day. Booming of the construction scene in Malaysia started in the early 1990s in tandem with the Government's Vision 2020 to make the country an industrialized country by that time. Propelling towards that goal the government has highly invested in modernizing the infrastructure which is designed to push forward Malaysia into the digital age and position it as a hub for high-technology businesses in Southeast Asia (Ibrahim, Roy, Ahmed and Imtiaz, 2010).

The present-day construction has shifted and increasingly focused on sustainability. Digital transformation is now here, and the construction industry is picking up where construction forms are adopting technology to improve efficiency and productivity. The future of construction is now here and solving construction's sustainability, and efficiency depends on it. The evolution of modern construction has been marked by significant advancements in technology, materials, and methodologies. Recent innovations have increasingly focused on sustainability and efficiency. In the past few years, the integration of Building Information Modeling (BIM) has revolutionized construction practices by enhancing project planning, coordination, and execution. BIM's capacity for creating detailed 3D models has improved accuracy and reduced errors, leading to more efficient project delivery (Smith, 2021). Additionally, the rise of prefabrication and modular construction techniques has streamlined the building process, allowing for faster assembly and reduced waste. These methods also facilitate better quality control as components are often manufactured in controlled environments (Jones et al., 2022). The adoption of advanced materials, such as self-healing concrete and high-performance insulation, has further contributed to the evolution by enhancing durability and energy efficiency (Lee & Kim, 2023). Moreover, the push towards greener construction practices has been driven by stricter regulations and a growing emphasis on environmental impact. Green building certifications, such as LEED, have become more prevalent, pushing the industry towards sustainable practices and energy-efficient designs (Nguyen, 2024). These advancements reflect a broader shift towards a more technologically sophisticated and environmentally conscious approach to construction.

Supply Chain Management in the Construction Industry

The idea of the supply chain is a network that aligns firms that bring products or services to market which includes various parties directly or indirectly in fulfilling a customer request (Lambert, Stock, and Ellram (1998); Chopra & Meindl (2007)). Supply chain management in the construction industry involves various

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stakeholders including the client, consultants, contractor, and manufacturer which encompasses different functions of construction organizations that start with planning, design, construction, and maintenance. Construction activity is a process characterized by high levels of fragmentation and where the effective integration, coordination, and management of the chain, from suppliers to final clients, is a necessary condition to obtain good results of adopting supply chain management. Supply chain management can be a useful approach for construction companies to address the management of materials and information flow issues. However, various problems associated with fragmentation in the supply chain network such as isolation of professionals, and lack of coordination between design and construction which is being done sequentially cause further fragmentation (Mohd Nawi et al., 2014). At present, the way the project stakeholders communicate and interact within a construction supply chain network has changed towards collaboration and integration because of technological novelties and new management principles. Construction stakeholders must learn to collaborate for advances to occur. Integration in construction aims to promote a working environment where information is freely exchanged among all the stakeholders (Baiden, Price, and Dainty (2006); Egan & Anumba (2006), Baugh & Khalfan (2002). A study done by Chen et al. (2020) has classified three categories of coordination enablers among construction stakeholders within a construction supply chain network which are (1) contractual enablers, (2) procedural enablers, and (3) technological enablers. With better coordination, disputes among construction stakeholders can be reduced and can improve overall supply chain predictability. There is a review done on a group of Industry 4.0 technologies to improve construction supply chain performance via information visibility and real-time communication among stakeholders (Dallasega et al. (2018a, b). Therefore, there is a need to explore and discover these developments on how different construction supply chain processes can be efficiently coordinated or managed.

Recent developments in Supply Chain Management (SCM) within the construction industry have focused on integrating digital technologies, enhancing sustainability, and improving resilience and collaboration. Digitalization has played a significant role in transforming construction SCM, with tools like Building Information Modelling (BIM), Internet of Things (IoT), artificial intelligence, and blockchain emerging as key enablers of efficiency and transparency. For instance, recent studies highlight how these technologies streamline processes, reduce errors, and foster real-time collaboration among stakeholders, significantly improving supply chain performance in construction (Olanrewaju & Abdul-Aziz, 2021; Li & Guo, 2024).

Sustainability has also become a crucial aspect of SCM in construction. Green supply chain management practices are increasingly adopted to minimize environmental impact and improve resource efficiency. Researchers have critically analyzed these practices, emphasizing the need for more sustainable approaches in material sourcing, waste management, and energy use within the construction supply chain (Darko, Chan, & Huo, 2020; Zhang & Tang, 2022).

The recent global disruptions, particularly the COVID-19 pandemic, have underscored the importance of resilience in construction supply chains. The need for strategies that enhance the ability to withstand and recover from such disruptions has been widely recognized. Studies suggest that building resilience through diversified sourcing, robust risk management practices and flexible supply chain structures is essential for maintaining continuity in the face of global challenges (Ivanov & Dolgui, 2021; Fang & Zhao, 2022).Additionally, the trend towards collaborative models like Integrated Project Delivery (IPD) has gained traction. These models encourage closer partnerships among supply chain participants, aiming to reduce risks, enhance innovation, and improve overall project performance. Recent research, including work published in 2024, points out the benefits of these collaborative approaches, although barriers such as contractual challenges and cultural resistance still need to be addressed for widespread adoption (Love, Matthews, & Zhou, 2020; Rahman & Al-Turki, 2024).

Moving towards Digitalization in the Construction Industry for IR4.0

The adoption of technology in the construction industry has evolved in tandem with the industrial revolutions, culminating in the current Fourth Industrial Revolution (IR4.0). From the First Industrial Revolution (1760-1830), which introduced mechanization and new building materials such as glass, cast iron, and steel, to the Second Industrial Revolution (1870-1914) that brought innovations like mass-produced steel, electricity, and telegraphs, the construction industry has seen significant technological advancements. The Third Industrial Revolution, starting in the 1950s, marked a digital revolution with the advent of the Internet, information technology, and personal computers, enhancing precision and design capabilities through 3D computer-aided design (Naboni & Paoletti, 2015). Today, IR4.0 is characterized by the integration of the Internet of Things (IoT), artificial intelligence (AI), and robotics into construction practices. IoT devices enable real-time site monitoring, improving equipment performance and worker safety (Wang & Zhang, 2021). AI and machine learning algorithms advance predictive maintenance and project management, enhancing forecasting and risk assessment (Brown & Lee, 2022). Robotics and automation, including drones and robotic systems, streamline tasks such as site surveying and material handling, reducing labor and increasing efficiency (Garcia et al., 2023). Digital twins—virtual replicas of physical assets—are becoming vital for managing and optimizing construction projects through simulation and scenario analysis (Miller & Johnson, 2024). The COVID-19 pandemic has accelerated this shift towards IR4.0, highlighting the need for the construction industry to embrace digital technologies for better decision-making, resource management, and overall operational efficiency (Lat et al., 2021; Gilchrist, 2016; Bock, 2015). This ongoing transformation reflects a significant leap towards a more data-driven and automated industry, demonstrating the profound impact of technological advancements on modern construction practices.

Definition of Blockchain Technology

Blockchain technology was first introduced by Satoshi Nakamoto in 2008 as the foundational technology behind Bitcoin, the first cryptocurrency. Nakamoto's innovation was designed to address the need for a decentralized electronic ledger that securely tracks transactions or digital events without the need for a central authority (Nakamoto, 2021). The core concept of blockchain involves grouping transactions into blocks, which are then linked together in chronological order using cryptographic hashes, creating a continuous and immutable chain (Crosby et al., 2016). Each block contains a timestamp and a hash of the previous block, which ensures the integrity and security of the data while maintaining a transparent and tamper-resistant record of all transactions (Swan, 2022). This structure eliminates the need for intermediaries by enabling peer-to-peer transactions that are verifiable and secure (Christidis & Devetsikiotis, 2021). Over the past decade, blockchain technology has expanded beyond cryptocurrency to impact various industries through innovations such as smart contracts—self-executing contracts with terms encoded directly into the blockchain—which automate and enforce agreements without intermediaries (Tapscott & Tapscott, 2020). Additionally, decentralized applications (dApps) and decentralized finance (DeFi) platforms have emerged, leveraging blockchain's capabilities to provide new forms of financial services and applications (Zohar, 2023). Researchers continue to explore and develop blockchain applications across diverse sectors, highlighting its potential to transform industries by enhancing transparency, security, and efficiency (Folkinshteyn & Lennon, 2016).

The Application of Blockchain Technology in the Construction Industry

The blockchain application has the potential to transform the digital world by enabling a distributed consensus in which all online transactions involving digital assets, past and present, may be confirmed at any time in the future. Despite the lack of strong proof of blockchain's applicability in the construction business, it is viewed as beneficial in other industries. Several applications of blockchain use cases across the different industries that apply to the construction industry are i.) creating a peer-to-peer economy and eliminating intermediaries, ii.) decentralizing recordkeeping with all entities in the chain validating transactions and traceable transaction records., iii) in terms of government services provide a more efficient, transparent, and accountable government system (University of Malaya, 2018).

Based on previous research involving blockchain technology in construction some potential applications of blockchain have been found in a variety of applications like loan fraud (Cai and Zhu, 2016), voting systems (Ayed, 2017), agriculture supply chains (Kamble, Gunasekaran and Sharma, 2019), bitcoin (Bohme, Christin, Edelman and Moore, 2015), and energy reserves (Andoni et al., 2019) and many more. Blockchain in the construction industry is still in the introduction concept (Darabseh & Martins, 2020). Blockchain technology can automatically authenticate data in a construction project's extended supply chain, allowing the construction industry players to track work in progress, timeline, cost and payments, and needed resources.

In the construction industry, the supply chain is a network of many organizational units and interactions (Xue et al., 2007), which includes information flow, material flow, service and product flow, and payment flow between the customer, designer, provider, contractor, and consultant. O'Brien, William J., London, Kerry, and Vrijhoef (2004) established the current construction supply chain (CSC) frameworks to assist construction organizations in reducing waste, improving quality, and creating accurate and predictable project schedules. Vrijhoef & Koskela (2000) highlighted the following two key aspects of CSC structure and function:

- CSC is a converging supply chain that directs all materials to the construction site, the point where the main object is assembled from the incoming materials.
- Most of the time, CSC is a temporary supply chain that produces one-off construction projects through constant organizational changes based on 1) project changes (mainly design-wise), and 2) a constrained timeline for project completion.

Construction Parties Involved in the Blockchain Technology

Figure 1 shows an overview of a typical Construction Supply Chain (CSC), indicating the different types of flow associated with the different parties in the chain.

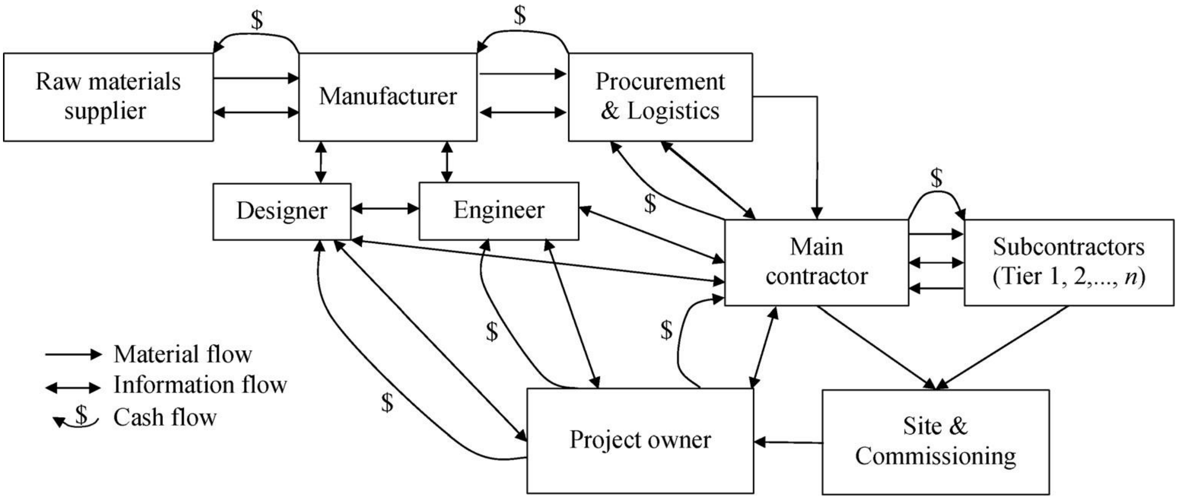

Figure 1: Z

The source of raw materials is at the beginning of the material flow, which runs from left to right. This flow of information can be two-way and can include, but is not limited to, datasheets, standards, and material quality. It also depends on the kind of information being shared. In contrast to materials, currency moves left to right. The primary contractor pays the parties who supply them with the supplies and information needed for the project's execution and completion, and the project owner pays the main contractor as well as any subcontractors. To guarantee an effective flow of supplies and information as well as on-time financial transactions, there must be constant contact between the primary contractor, the project owner, and every other party involved in the chain.

Since information is bidirectional, two persons must send or receive it. Bills (both send and receive), quality specifications of materials (supplier to manufacturer), material specifications/ISO (supplier to manufacturer), material standards (supplier to manufacturer), fabrication specifications (manufacturer to supplier), and storing and shipping specifications (supplier to manufacturer) are all included in this information. Guidelines for production (which the manufacturer forwards to the supplier) and order deadlines (which the manufacturer forwards to the supplier). Payment transactions (cash) move from supply to manufacturer, or from right to left. The company also pays the designer and engineer with cash. Any transportation arrangements are the supplier's obligation in this flow, and the associated payments are part of the cash flow. Materials in the following categories might be sent including the components, services, supplies, and goods.

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The Structure of Blockchain Technology

The first stage, after determining the applicable business case for implementing a blockchain solution, is to determine its applicability, as illustrated in Figure 2. Within a feasibility study, the organization must outline the possible return on investment (ROI), the stakeholders, the key performance indicators (KPI) that they want to enhance with the new system, and the obstacles connected with it. ROI does not only imply financial benefits; it may also be realized through reduced complexity, which reduces risk and improves collaboration and trust. However, some of the intangible advantages, such as improved teamwork and decreased complexity in procurement, can be translated into financial benefits as up to 10-15% savings on project expenses(Kollewe, 2018).

Figure 2: Stages to Move Towards the Implementation of a Blockchain Solution

Source: Penzes, B. (2018)

Furthermore, Odell and Fadzeyeva (2018) suggest that increased productivity, cost savings, and so on might result in an ROI ranging from 43% to 590% for a sample organization. This broad range of possible benefits illustrates two things: first, that this task is quite tough, and each organization must tailor their measurements to their own business, and second, that the potential benefits of new technology may be enormous.

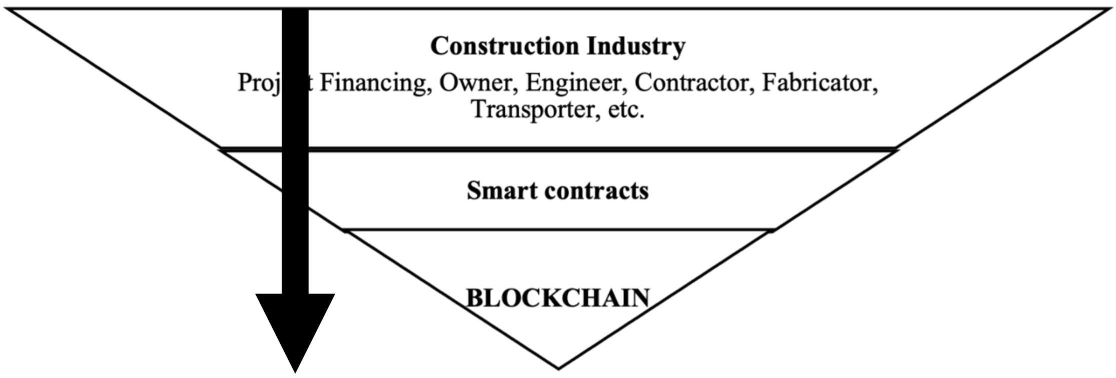

Figure 3: The Structure of Blockchain

Source: Compiled by the authors

Figure 3 explains the structure of blockchain technology in the construction industry where the transfer and distribution of databases starts from the construction industry to the use of smart contracts. Further explanations on this transfer of database are as follows:

1. Construction Payments

Construction companies could receive payments almost instantly after completing a job. This would help them manage their cash flow better and avoid payments being delayed by 30 days or more in the construction industry.

2. Construction Contracts

A smart contract is a digital contract that is stored on the blockchain where contracts are immutable and cannot be deleted or altered. This would help to avoid disputes and make it easier to enforce the contract.

3. Project Management

Blockchain technology makes sure all parties involved in a project can view the digital ledger and see the construction site and contract progress made. This would help to improve communication and coordination between the different parties. Thus, improving project management in construction.

4. Procurement

All stakeholders would be able to view the digital ledger and see the procurement status with blockchain technology for this method can be used to streamline the construction procurement process.

The Benefits of Utilizing Blockchain Technology in the Construction Industry

The efficiency of various flow types at all stages has been questioned due to the complexity of material and information movement over many interactions in the chain. These problems mostly stem from the fixed buyer-supplier connection and a significant degree of fragmentation among the participants, which makes the Construction Supply Chain (CSC) a dynamic, complex network with high-risk opportunities (Aloini et al., 2012).

As it is, though, supply chain management will be revolutionized by Industry Revolution 4.0 (IR 4.0) through digitalization. In addition to enhanced transparency that enables a higher-level view of the supply chain and a real-time reaction on planning and execution levels across all parties involved, Schrauf & Berttram (2016) noted that the digital supply chain will give integrated planning and execution. Digitizing the building supply chain has the advantage of tracking and tracing all node-to-node connections, facilitating effective communication, and making information available to all participants at once. As a result, fewer issues of information flow and, by extension, material and currency flows would arise. According to Bhargava et al. (2019), the digital supply chain would benefit in multiple dimensions: 1) improved productivity, 2) reduced downtime, 3) lower costs, 4) reduced waste, and 5) improved utilization of resources.

Applications of blockchain technology have a lot of promise in the CSC. The primary goals of cost, transparency, security, trust, reliability, speed, risk mitigation, sustainability, and flexibility may all be facilitated by technology. Kshetri (2017). Various research works have been carried out about the categorization of blockchain applications to the CSC.

METHODOLOGY

The purpose of this study is to investigate the applications of blockchain technology to supply chain management in the building sector. The findings of the far more comprehensive investigation, which took a reasonable and analytical approach, were considered while assessing the possible advantages of implementing blockchain technology in Malaysia's construction sector to move towards digitalization. The steps that yielded the results guided the systematic literature review (García-Mireles et al., 2012; Keele University, 2007; Strech& Sofaer, 2012):

- formulate the review question and eligibility criteria,
- identify all the literature that meets the eligibility criteria,
- extract and synthesize data, and
- derive and present data

Formulating the review questions and eligibility criteria

The primary goal of the research is to determine whether blockchain technology can be used to improve supply chain management in Malaysia's construction sector. The potential for blockchain technology to be applied by companies in the construction sector to enhance present processes has been brought to light by the questions raised by the technological advancements brought about by the Industrial Revolution 4.0 (IR4.0). As a result, the criteria that might help with the conceptual framework's construction are the analysis of many keywords. The eligibility criteria are described in Table 1.

Identifying the related literature that meets the eligibility criteria

A comprehensive evaluation was conducted on textbooks and a selection of journals published by reputable publishers, including Emerald, Elsevier, Wiley, Blackwell Publishing, and Springer, both in hard copy and online. The most recent research from 2000 to 2022, as well as articles published in several reputable journals, This comprehensive review includes the Journal of Quality in Maintenance Engineering, Journal of Building Maintenance, World Journal of Engineering and Technology, Journal of Facilities Management, Property Management, Construction and Building Materials, Procedia Environmental Sciences, Procedia Engineering, Journal of Building Appraisal, Journal of Performance of Constructed Facilities, and Construction Management and Economics.

Table 1: The eligibility criteria for blockchain technology

Questions on Blockchain	**Eligibility Criteria**
What is Blockchain Technology?	• Core concepts • Types of Blockchain • Applications of Blockchain
When to implement Blockchain in Construction Supply Chains?	• Identifying key moments for implementation • Timing considerations
Who are the Key Stakeholders?	• Primary stakeholders in construction supply chains • Roles and responsibilities
Where to apply Blockchain Technology?	• Critical areas in construction Supply Chains • Case studies and examples
How to implement Blockchain Technology?	• Steps for successfulimplementation

Extracting and synthesizing data from the literature

To make the process of combining data easier to handle, the data were removed followingsome predetermined eligibility criteria and tabulated. To be more concentrated, just the primary characteristics of the qualifying requirements were considered.

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Deriving and presenting the results

The data were then presented in a tabulation form based on the eligibility criteria.

RESULTS AND FINDINGS

All the results based on the eligibility criteria are tabulated. Table 2 to Table 7summarises the eligibility criteria provided in the literature.

What is Blockchain Technology?

One of the most important advantages of blockchain technology is frequently emphasized as being its capacity to improve supply chain transparency and traceability. Blockchain technology gives everyone involved in the supply chain access to real-time information on the flow of resources and commodities through the creation of a decentralized, unchangeable ledger. For sectors like food safety, medicines, and luxury goods—where responsibility and trust are critical—transparency is essential. Tracing a product's origin and path may lower fraud risk, enhance product recalls, and boost consumer confidence. Blockchain does increase openness, but it is not a solution to every problem with the supply chain. The technology's effectiveness depends on the accuracy of the data entered into the blockchain. If initial data is flawed or fraudulent, blockchain merely perpetuates these inaccuracies. Therefore, while blockchain enhances transparency, it must be integrated with other technologies, such as IoT devices, to ensure the reliability of data inputs (Tian, 2016). Table 2 shows the aspects related to blockchain technology including its core concepts, types of blockchain, and applications in supply chains.

Blockchain's cryptographic security measures make it highly resistant to tampering and fraud. Every transaction recorded on the blockchain is encrypted and linked to the previous transaction, making it nearly impossible to alter without detection. This feature is particularly valuable in industries prone to counterfeiting and fraud, such as electronics, luxury goods, and pharmaceuticals. While blockchain significantly improves security, it is not entirely immune to attacks. For instance, 51% of attacks, where a group of miners controls more than half of the network's mining power, could potentially manipulate the blockchain. Although this is more likely in smaller blockchain networks, it remains a theoretical risk. Moreover, the reliance on cryptographic keys means that if these keys are lost or compromised, access to the blockchain could be permanently lost, posing a significant security risk (Conti et al., 2018).

Table 2: What is Blockchain Technology?

Aspects	**Description**	**Sources**
Core Concepts	Distributed Ledger Technology (DLT): A decentralized database managed by multiple participants. Smart Contracts: Self-executing contracts with the terms of the agreement directly written into code. Cryptographic Security: Ensures data integrity and security through cryptographic methods.	Tapscott & Tapscott, 2016; Christidis&Devetsikiotis, 2016; Narayanan et al., 2016; Casino et al., 2019; Singh et al., 2020; Qasse et al., 2023; Hassan & De Filippi, 2023
Types of Blockchain	**Public Blockchains**: Open and decentralized networks where anyone can participate and validate transactions (e.g., Bitcoin, Ethereum). **Private Blockchains**: Restricted networks, controlled by a single organization (e.g.,	Pilkington, 2016; Buterin, 2015; Cachin, 2016; Xu et al., 2021; Zamani &Babajide, 2023; Makhdoom et al., 2024

	Hyperledger). **Permissioned Blockchains**: Hybrid models where only authorized participants can validate transactions (e.g., Ripple).	
Applications in Supply Chains	**Traceability and Transparency**: Enables real-time tracking of products and materials. **Fraud Prevention and Security**: Reduces the risk of tampering and counterfeiting. **Efficiency and Cost Reduction**: Streamlines processes and reduces administrative costs.	Saberi et al., 2019; Kshetri, 2018; Francisco & Swanson, 2018; Queiroz et al., 2020; Pournader et al., 2020; Ghobakhloo et al., 2023; Min & Zhou, 2024

Blockchain can streamline operations in supply chains by automating processes such as payments, contract execution, and inventory management. Smart contracts, which automatically execute when predefined conditions are met, reduce the need for intermediaries, speed up transactions, and lower administrative costs. In global trade, where time and cost efficiency are critical, blockchain's ability to reduce delays and lower transaction costs is highly beneficial. Despite its potential to enhance efficiency, blockchain's current scalability limitations could undermine its cost-effectiveness in large-scale supply chains. Public blockchains can be slow and expensive to operate due to their reliance on resource-intensive consensus mechanisms like Proof of Work. Moreover, the initial cost of implementing blockchain, including the need for technological infrastructure and staff training, can be prohibitive for smaller companies, limiting its widespread adoption (Yli-Huumo et al., 2016).

While the potential benefits of blockchain are significant, the technology faces several challenges that must be addressed for it to be fully effective in supply chains. These include scalability issues, energy consumption, regulatory uncertainty, and the need for industry-wide standards. The scalability of blockchain remains a significant hurdle. As the number of transactions increases, public blockchains can become slower and more expensive to operate. This is a particular concern for global supply chains that require the processing of large volumes of transactions in real time. Additionally, the energy consumption of some blockchain networks, particularly those using Proof of Work, is a critical environmental concern. These challenges suggest that while blockchain holds great promise, its implementation must be carefully managed to avoid unintended consequences (Zheng et al., 2017).

When to Implement Blockchain in Construction Supply Chains?

Determining the optimal timing for implementing blockchain technology in construction supply chains is crucial for maximizing its benefits and minimizing potential disruptions. As the construction industry grapples with inefficiencies such as lack of transparency, slow processes, and data inaccuracies, blockchain offers promising solutions. However, successful integration requires careful consideration of the right moment to adopt this technology. Table 3 shows the key moments for implementing the blockchain in the construction supply chain.

Table 3: Key Moments for Implementation of Blockchain

Key Moment for Implementation	**Description**	**Sources**
Project initiation and planning phases	Blockchain is crucial during the project initiation and planning phases for establishing transparent records. Smart contracts automate agreements, ensuring adherence to	Chong et al., 2021; Li et al., 2022; Turk

	timelines and budgets.	&Klinc, 2020
Procurement and contracting stages	At the procurement and contracting stages, blockchain ensures transparency in bidding and contracting. It prevents fraud by providing an immutable record of all transactions and certifications.	Ding et al., 2021; Li et al., 2023; Turk &Klinc, 2020
Construction and post-construction phases	Blockchain aids in tracking the progress of construction projects in real-time, ensuring accountability. Post-construction, it helps with maintenance by providing a permanent record of all activities.	Chong et al., 2021; Ding et al., 2021

Blockchain technology's application during the project initiation and planning phases offers significant potential for improving transparency and accountability. The use of blockchain in creating immutable records of agreements, roles, and responsibilities can mitigate the risks of miscommunication and ensure that all parties are aligned from the start. Smart contracts, which automatically enforce terms and conditions, further enhance this process by eliminating the need for intermediaries and reducing delays (Chong et al., 2021; Li et al., 2022). However, while these benefits are clear, the integration of blockchain in these early stages requires substantial initial investment and a deep understanding of the technology, which could be a barrier to adoption for smaller firms or less technologically advanced regions (Turk & Klinc, 2020).

In the procurement and contracting stages, blockchain's ability to create a secure and transparent environment for transactions can significantly reduce the risk of fraud and enhance trust among stakeholders. By ensuring that all supplier information and material certifications are verifiable and immutable, blockchain helps to prevent the introduction of counterfeit materials and ensures that only compliant suppliers are engaged (Ding et al., 2021; Li et al., 2023). However, the effectiveness of blockchain in this stage is highly dependent on the willingness of all parties to participate in the blockchain network, which can be a challenge given the traditional resistance to change in the construction industry (Turk & Klinc, 2020). Moreover, the technology's complexity may require additional training and adaptation, which could slow down its implementation.

During the construction and post-construction phases, blockchain's capability to track materials and project progress in real-time offers unparalleled transparency and accountability. This real-time tracking can reduce delays, prevent disputes, and ensure that construction quality meets contractual standards. Furthermore, in the post-construction phase, the permanent records maintained on the blockchain can be invaluable for future maintenance, repairs, and renovations (Chong et al., 2021; Ding et al., 2021). Despite these advantages, the adoption of blockchain in these later stages might still face resistance due to the perceived rigidity of smart contracts, which could limit flexibility in responding to on-the-ground challenges (Li et al., 2022). Additionally, the need for all stakeholders to have consistent access to and understanding of blockchain technology remains a significant hurdle.

Timing is a crucial factor in the successful implementation of blockchain technology, particularly in construction supply chains. As blockchain presents opportunities to enhance transparency, improve data accuracy, and streamline processes, understanding when to adopt this technology is essential. Table 4 describes the timing considerations for implementing the blockchain.

Table 4: Timing Consideration for Implementation of Blockchain

Timing Considerations	**Description**	**Sources**
Technological readiness and infrastructure	The adoption of blockchain in construction supply chains hinges on the availability of robust technological infrastructure. This includes sufficient computing power, secure digital storage, and integration with existing construction software and	Li et al., 2023; Turk &Klinc, 2020; Kshetri, 2021; Zhao et al., 2022

	systems.	
Regulatory environment and compliance	The regulatory landscape is crucial when considering blockchain implementation. Companies must ensure that their use of blockchain complies with local and international regulations, which can vary significantly. Regulatory clarity can either accelerate or hinder the adoption process.	Li et al., 2022; Chong et al., 2021; Perera et al., 2020; Hughes et al., 2021
Market readiness and stakeholder acceptance	Market readiness and stakeholder acceptance are critical for the successful implementation of blockchain. This involves educating stakeholders, ensuring that all parties are on board, and addressing any resistance to change. The perceived benefits must outweigh the costs for widespread adoption.	Ding et al., 2021; Li et al., 2023; Turk &Klinc, 2020; Wang et al., 2021; Shashank et al., 2022

The timing considerations for implementing blockchain in construction supply chains are multifaceted and interdependent. Technological readiness, regulatory compliance, and market acceptance must align to enable successful adoption. While blockchain holds significant potential to transform construction supply chains, these factors highlight the challenges that must be addressed before widespread adoption can occur. The industry needs to focus on building the necessary infrastructure, navigating the regulatory landscape, and fostering stakeholder engagement to fully realize the benefits of blockchain technology. Without these critical elements in place, the adoption of blockchain may remain limited, and its transformative potential may not be fully realized.

The successful implementation of blockchain in construction supply chains is heavily dependent on the readiness of the technological infrastructure. Blockchain technology requires advanced computing power, secure digital storage, and seamless integration with existing systems, which are not always readily available in the construction industry. While the potential benefits of blockchain, such as enhanced transparency and security, are widely recognized, the technological maturity of the industry is still a significant hurdle (Li et al., 2023; Kshetri, 2021). This challenge is exacerbated by the often-fragmented nature of construction projects, which involve multiple stakeholders with varying levels of technological capability. As a result, the industry must first invest in upgrading its infrastructure and ensuring that all parties involved have access to the necessary technology (Turk & Klinc, 2020; Zhao et al., 2022). Without this foundation, the implementation of blockchain may result in inefficiencies and integration issues, undermining its potential benefits.

The regulatory environment plays a crucial role in the adoption of blockchain technology in construction supply chains. The current regulatory landscape is complex and varies significantly across regions, which can create uncertainty and hinder blockchain adoption. Companies must navigate these regulations to ensure that their use of blockchain complies with local and international laws, which is particularly challenging given the novelty of the technology (Li et al., 2022; Hughes et al., 2021). Regulatory clarity is essential to provide companies with the confidence to invest in blockchain technologies. However, the lack of comprehensive and consistent guidelines can slow down the adoption process, especially in highly regulated sectors like construction (Perera et al., 2020). Moreover, the risk of non-compliance and potential legal repercussions may deter companies from embracing blockchain, despite its potential to streamline operations and enhance transparency.

Market readiness and stakeholder acceptance are perhaps the most critical factors for the successful implementation of blockchain in construction supply chains. While the technology offers clear advantages, such as improved traceability and reduced fraud, its adoption requires a fundamental shift in how the industry operates (Ding et al., 2021; Li et al., 2023). This shift involves not only technological changes but also significant cultural and organizational changes. Stakeholders must be educated about the benefits of blockchain and persuaded to accept and support its implementation (Wang et al., 2021). However, resistance to change is a common challenge in the construction industry, which is often characterized by traditional practices and skepticism towards new technologies (Shashank et al., 2022). Therefore, achieving stakeholder buy-in is crucial, and this requires clear communication of the benefits, as well as addressing concerns about the costs and complexity of implementing blockchain.

Who are the Key Stakeholders?

As the primary executors of construction projects, construction companies, and contractors are pivotal in ensuring that projects meet their design specifications, timelines, and budgets. Their role is multifaceted, encompassing project management, resource allocation, and the integration of new technologies like BIM and Construction 4.0. Construction companies and contractors rely heavily on suppliers for timely and quality materials and on subcontractors for specialized tasks. They also depend on clear directives from clients and project owners. The integration of advanced technologies (e.g., Construction 4.0) is transforming the industry by enhancing efficiency and reducing errors, but it also requires significant investment in training and infrastructure. Failure to adapt could lead to inefficiencies and increased project risks.

Suppliers and subcontractors are critical to the supply chain as they provide the materials and specialized labor necessary for construction projects. Their role is often underestimated but is essential for maintaining project timelines and quality.

Their success is closely linked to the construction companies and contractors they work with. Any delays or quality issues on their part can have cascading effects on the entire project. Additionally, the effectiveness of suppliers and subcontractors often depends on clear communication and coordination with the main contractors. Efficient coordination between suppliers, subcontractors, and contractors can significantly reduce costs and time overruns. However, poor communication and lack of integration in the supply chain can lead to delays, increased costs, and compromised quality.

As the financiers and ultimate decision-makers, clients and project owners play a crucial role in setting the project's scope, budget, and timeline. Their involvement is key to ensuring that the project aligns with their vision and objectives. Clients rely on contractors to deliver the project according to their specifications. They also depend on timely and accurate reporting from contractors to make informed decisions throughout the project lifecycle. Active client involvement is often linked to project success, as it ensures that the project remains aligned with the client's objectives. However, over-involvement or lack of clear directives can lead to project delays and increased costs.

Table 5 highlights the complex web of interdependencies among various stakeholders in the construction supply chain. Each stakeholder plays a critical role, and their actions or inactions can have significant ripple effects throughout the entire project lifecycle. The success of construction projects heavily depends on effective collaboration and communication among all stakeholders. Breakdowns in communication can lead to project delays, cost overruns, and compromised quality.

With the advent of blockchain technology, these stakeholders are becoming increasingly important in ensuring transparency, security, and efficiency in the construction supply chain. Their role is to develop and implement systems that can track materials, payments, and contracts in a secure and immutable manner. The effectiveness of blockchain systems depends on their adoption by all stakeholders in the supply chain, including contractors, suppliers, and regulatory bodies. There is also a need for collaboration with regulatory bodies to ensure that blockchain systems comply with legal and industry standards.

Regulatory bodies and industry association sensure that the construction industry operates within legal and ethical boundaries. They also promote best practices and the adoption of innovative technologies, such as sustainability initiatives and advanced construction methods.

Regulatory bodies depend on compliance from all stakeholders, particularly construction companies and contractors. Industry associations often work closely with regulatory bodies to develop guidelines and standards that benefit the entire industry. The role of regulatory bodies is increasingly important as the industry moves toward greater sustainability and technological innovation. However, overly stringent regulations can stifle innovation, while too lenient regulations can lead to quality and safety issues.

Table 5: Roles and responsibilities of stakeholders in the supply chain

Stakeholders	Roles and responsibilities	Sources
Construction Companies and Contractors	• Manage and execute construction projects. • Ensure adherence to design specifications, timelines, and budgets. • Integrate new technologies (e.g., BIM, Construction 4.0) to enhance productivity and project management.	Sacks, R., & Barak, R. (2019) Dainty, A. R. J., Ison, S. G., & Briscoe, G. (2017)
Suppliers and Subcontractors	• Provide essential materials and equipment. • Perform specialized tasks or trades. • Focus on collaboration and coordination with main contractors to enhance efficiency.	Forcada, N., & Valls, V. (2020) Olsson, N., & Aase, K. (2021)
Clients and Project Owners	• Commission and fund the construction project. • Define project requirements, budget, and scope. • Engage in project oversight and ensure project objectives are met.	Hwang, B.-G., & Ng, W. J. (2018) Yoon, H., & Lee, S. (2022)
Blockchain Developers and IT Teams	• Develop secure and transparent systems for construction supply chain management. • Implement blockchain technology to enhance traceability, reduce fraud, and improve supply chain efficiency.	Li, J., Greenwood, D., & Kassem, M. (2019) Penzes, B. (2018)
Regulatory Bodies and Industry Associations	• Ensure compliance with industry standards and legal requirements. • Promote the adoption of innovative technologies and sustainable practices in the construction industry.	Wright, K. (2021). Zhou, L., & Sun, L. (2020)
End Users and Beneficiaries	• The ultimate recipients of the construction project. • Evaluate project success based on usability, quality, and satisfaction. • Increased focus on sustainability, energy efficiency, and smart technology integration.	Hoppe, T., & van Bueren, E. (2015) Mahmud, S., & Kassem, M. (2023)

End users are the ultimate recipients of the construction project, and their satisfaction is a key measure of the project's success. They have a growing influence on project design and execution, particularly with increasing demand for sustainable and smart buildings. End users rely on the entire construction supply chain to deliver a product that meets their needs and expectations. They also influence the direction of future projects through their feedback and demand for specific features (e.g., energy efficiency, and smart technology). The focus on end-user satisfaction is driving the industry toward more user-centered design and construction practices. However, balancing cost, quality, and user expectations remains a significant challenge for all stakeholders in the supply chain.

Where to Apply Blockchain Technology?

Identifying the most effective areas to apply blockchain technology is essential for maximizing its benefits. Blockchain offers potential solutions for various challenges, such as enhancing transparency, improving data security, and streamlining processes. By focusing on the most relevant applications, organizations can better harness blockchain's capabilities to address specific needs and drive digital transformation. Table 6 demonstrates the critical areas in construction supply chains.

Table 6: Critical Areas in Construction Supply Chains

Critical Area	Significance	Sources
Procurement and Supply Chain Logistics	• Central to ensuring the timely availability of materials and resources for construction projects. • Involves strategic sourcing, supplier selection, and logistics management to reduce costs and improve efficiency. • Technological advancements such as AI, IoT, and blockchain are increasingly being integrated to enhance transparency and efficiency.	Osipova, E., & Eriksson, P. E. (2019) Sadeghi, H., & Azar, A. (2021) Gbadamosi, A., Oyedele, L., & Okorie, U. (2022) Wang, G., Zhang, X., & Zhang, W. (2018)
Contract Management and Execution	• Essential for defining the legal and operational framework of construction projects. • Involves managing contracts to ensure that all parties meet their obligations, timelines, and quality standards. • The use of smart contracts and digital tools is becoming more prevalent to enhance contract execution and reduce disputes.	Chan, A. P. C., & Owusu, E. K. (2017) Chong, H.-Y., &Preece, C. (2019) Hughes, W., Champion, R., & Murdoch, J. (2020) Mason, J. B. (2021)
Quality Control and Assurance	• Critical to ensuring that construction projects meet specified standards and regulatory requirements. • Involves systematic inspection, testing, and validation of materials, processes, and final outputs. • Increasingly, data-driven approaches and real-time monitoring systems are being used to enhance quality assurance in construction.	Love, P. E. D., & Edwards, D. J. (2017) Polat, G., & Ballard, G. (2020) Forster, A. M., & Kayan, B. (2016) Kaliba, C., & Mulenga, D. (2022)

The construction industry is undergoing significant transformations in its supply chain management, driven by advancements in technology and the need for enhanced efficiency. Procurement and supply chain logistics, traditionally the backbone of construction operations, are now increasingly influenced by digital tools such as

AI, IoT, and blockchain, which offer improved transparency and cost savings. However, while these technologies present opportunities, they also demand substantial investment in digital infrastructure and training, which can be a barrier for some firms. Contract management, another critical area, is experiencing a shift towards smart contracts that promise to streamline execution and reduce disputes.

Despite their potential, the adoption of smart contracts is hindered by legal and regulatory challenges, and the industry’s slow pace in embracing these innovations. Quality control and assurance remain central to project success, with data-driven approaches and real-time monitoring systems becoming more prevalent. These innovations enhance precision and reduce the likelihood of defects, yet they require a robust commitment to technological adoption and workforce upskilling. Collectively, while these advancements offer significant improvements, they also introduce new complexities and necessitate a careful balancing of investment, risk, and potential benefits. The industry's future competitiveness will likely hinge on its ability to integrate these technologies effectively, overcoming both financial and regulatory obstacles.

How to implement Blockchain technology?

Implementing blockchain technology in the construction industry involves a structured approach that critically examines the industry's unique challenges and tailors the technology to meet these needs. The process begins with a thorough needs assessment and feasibility study, where companies evaluate whether blockchain's core features—such as transparency, immutability, and decentralization—are suitable for addressing key issues like project delays, payment disputes, and supply chain inefficiencies. This step is crucial as it determines whether the benefits of blockchain outweigh its costs and challenges, which include integration complexity and compliance with industry regulations (Kshetri, 2017).Once feasibility is established, the next step is to design a blockchain solution specifically for the construction industry. This involves defining precise use cases—such as contract management and supply chain tracking—and selecting the appropriate blockchain platform that aligns with these needs. The development of smart contracts plays a pivotal role here, automating critical processes like payment releases and ensuring data integrity without the need for intermediaries (Li et al., 2019). Privacy and data security are also key considerations, especially given the sensitive nature of construction data, necessitating the design of robust security protocols within the blockchain framework (Zheng et al., 2020).

The final critical phase is integrating blockchain with existing systems and processes. This involves ensuring seamless interoperability between the blockchain solution and current construction management tools, which can be a complex task given the decentralized nature of blockchain. Moreover, aligning existing processes with the new blockchain framework requires careful change management and employee training to facilitate adoption. Pilot testing is essential at this stage to identify potential issues and refine the solution before full-scale implementation (Penzes, 2018). This structured approach, grounded in critical evaluation at each stage, ensures that the implementation of blockchain in the construction industry is both effective and sustainable.Table 7 shows the process of how the blockchain can be implemented in the construction supply chain.

Table 7: The suggested steps for implementing blockchain in the construction supply chain

Step	Key Activities	Critical Considerations	Source
1. Conduct Needs Assessment & Feasibility Study	a) Identify pain points in construction (e.g., delays, payment disputes, supply chain inefficiencies) b) Evaluate blockchain's suitability for addressing these issues c) Conduct feasibility analysis, including costs, ROI, and regulatory compliance	a) Ensure that blockchain’s features align with industry needs b) Assess economic and technical feasibility	Kshetri, N. (2017)
2. Design a	a) Define specific use cases (e.g.,	a) Select a platform	Li, J.,

Blockchain Solution Tailored to Construction Industry	contract management, supply chain tracking) b) Choose the appropriate blockchain platform (e.g., Ethereum, Hyperledger) c) Develop smart contracts to automate key processes d) Ensure robust data security and privacy protocols	that supports scalability and integration b) Focus on automating processes that add significant value	Greenwood, D., & Kassem, M. (2019)
3. Integrate Blockchain with Existing Systems & Processes	a) Integrate blockchain with current construction management software and ERP systems b) Align existing processes with the new blockchain framework c) Provide employee training and manage change effectively d) Conduct pilot testing and iterate based on feedback	a) Ensure seamless data flow between blockchain and existing systems b) Prepare for potential resistance and ensure smooth adoption	Penzes, B. (2018).
4. Full Implementation	Scale the blockchain solution across the organization based on successful pilot results	Monitor ongoing performance and adjust as necessary	Zheng, Z., Xie, S., Dai, H. N., Chen, X., & Wang, H. (2020)

DISCUSSIONS

In the construction industry, supply chains are intricate and involve numerous stakeholders, from contractors and suppliers to clients and regulatory bodies. Managing these complex networks efficiently has always been a significant challenge, often hampered by issues like lack of transparency, inefficiencies, and trust barriers. Recent technological advancements, particularly blockchain, offer promising solutions to these enduring problems. Blockchain technology, with its decentralized and secure nature, is being increasingly recognized for its potential to revolutionize how construction supply chains operate. This introduction provides an overview of the key benefits of blockchain, including enhanced transparency and traceability, improved efficiency and cost savings, and increased collaboration and trust among all parties involved in construction projects. By exploring these benefits, this discussion highlights how blockchain could transform construction supply chains, addressing critical challenges and fostering more effective project management.

Benefits of Blockchain in Construction Supply Chains

a) Enhanced transparency and traceability

Blockchain technology is renowned for its ability to provide enhanced transparency and traceability across supply chains. In the construction industry, where multiple stakeholders—such as contractors, suppliers, and clients—are involved, blockchain offers an immutable ledger that records every transaction and change in realtime. This ensures that all parties have access to the same information, reducing the likelihood of disputes and increasing accountability (Li et al., 2019).

The transparency afforded by blockchain can also mitigate the risks associated with fraud and mismanagement. By providing a clear, unalterable record of all transactions, blockchain can help to ensure that materials are sourced ethically and that subcontractors adhere to the agreed terms (Turk &Klinc, 2017). However, while the technology promises to revolutionize transparency, its implementation can be challenging, particularly in industries like construction that are traditionally resistant to change and have complex regulatory environments.

b) Improved efficiency and cost savings

Blockchain technology can significantly improve efficiency and reduce costs in construction supply chains by automating and streamlining processes. Smart contracts, a key feature of blockchain, automatically enforce the terms of contracts once the pre-set conditions are met, eliminating the need for intermediaries and reducing administrative overheads (Zheng et al., 2019). This automation can lead to faster project execution, as payments and approvals can be processed in real-time, reducing delays that are common in traditional construction projects.

Furthermore, blockchain's ability to provide accurate, real-time data on the supply chain can enhance decision-making, leading to better resource allocation and minimizing waste. However, the cost of implementing blockchain technology and integrating it with existing systems can be prohibitive, especially for smaller firms. The return on investment (ROI) can be significant, but it is not immediate, which may deter some companies from adopting the technology (Mathews, Robles & Bowe, 2017).

c) Increased collaboration and trust

One of the most transformative benefits of blockchain in construction supply chains is the potential for increased collaboration and trust among stakeholders. Blockchain's decentralized nature ensures that no single party controls the data, which fosters a collaborative environment where all parties can work together transparently (Perera et al., 2020). This trust is further enhanced by blockchain's ability to provide verifiable proof of work, ensuring that all contributions are recognized and appropriately rewarded.

Moreover, by providing a shared, immutable record of all transactions and agreements, blockchain can help prevent conflicts and reduce the time spent on dispute resolution, which is often a significant issue in construction projects. However, while blockchain can enhance collaboration, it also requires a cultural shift within organizations. The construction industry, known for its siloed nature and resistance to change, may find it challenging to adapt to this new, more collaborative approach (Alashwal, Al-Sabri, & Mohammed, 2021).

While the benefits of blockchain in construction supply chains are compelling, its adoption is not without challenges. Enhanced transparency and traceability can significantly reduce fraud and increase accountability, yet the resistance to change in the construction industry and the complexities of existing regulatory frameworks may slow down its implementation. Improved efficiency and cost savings through smart contracts and automation are promising, but the high initial costs and integration difficulties pose significant barriers, particularly for smaller firms. Additionally, while blockchain can increase collaboration and trust among stakeholders, achieving the cultural shift required to fully leverage these benefits will be challenging in an industry that is traditionally fragmented and hierarchical. Therefore, while blockchain holds great potential to revolutionize construction supply chains, realizing these benefits will require overcoming substantial financial, technical, and cultural hurdles.

Future Trends and Development

Blockchain technology has emerged as a transformative force across various sectors, offering enhanced security, transparency, and decentralization. As the technology continues to evolve, it intersects with several other emerging technologies that complement and extend its capabilities. This intersection not only enhances the functionality of blockchain but also opens new avenues for innovation and application. Understanding these complementary technologies and their prospects is crucial for grasping the full potential of blockchain and its role in shaping future technological landscapes.

a) Emerging Technologies Complementing Blockchain

The integration of blockchain with various emerging technologies is significantly enhancing its capabilities and applications. Artificial Intelligence (AI) boosts blockchain's effectiveness by improving data analysis,

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detecting fraud, optimizing smart contracts, and predicting market trends (Pedersen, 2022). Additionally, AI-driven systems offer real-time monitoring and security analysis to protect blockchain networks (Nguyen & Lee, 2023). The Internet of Things (IoT) leverages blockchain to secure and verify data from connected devices, ensuring data integrity and automating processes through smart contracts (Johnson & Roberts, 2023; Wang & Zhang, 2024). Edge computing complements blockchain by enabling data processing closer to the source, which reduces latency and bandwidth usage, thus enhancing scalability (Adams, 2022; Patel, 2023). Finally, quantum computing presents both challenges and opportunities for blockchain. While it threatens traditional cryptographic security, it also drives the development of quantum-resistant algorithms to safeguard blockchain technology against future threats (White & Kim, 2024; Lee & Green, 2023).

b) Prospects and opportunities

Looking ahead, blockchain technology is poised for significant advancements and opportunities. Enhanced interoperability between blockchain networks is a key focus, with projects like Polkadot and Cosmos working to create a decentralized network of blockchains that can seamlessly share and communicate data (Morgan & Singh, 2024). Standardization efforts will also play a crucial role in ensuring compatibility and integration across different blockchain platforms as the technology evolves (Davis & Turner, 2023). The expansion of Decentralized Finance (DeFi) is expected to continue, with innovations in financial products and services that leverage blockchain for lending, borrowing, and trading. As DeFi platforms become more user-friendly, their widespread adoption could disrupt traditional financial systems (Brooks, 2024; Cooper & Thompson, 2024). In governance and voting, blockchain could transform electoral systems by providing transparent, tamper-proof voting records, thereby enhancing trust and reducing fraud (Robinson & Fisher, 2023). Additionally, blockchain has the potential to facilitate new forms of decentralized governance, where decisions are made through consensus rather than centralized authorities (Walker & Martinez, 2024). Addressing sustainability concerns, there will be a push towards more energy-efficient consensus mechanisms, such as proof-of-stake, and blockchain technology can be used to track and verify environmentally friendly practices in supply chains (Evans & Hayes, 2024; Wilson & Clark, 2023).

The construction supply chain, traditionally characterized by fragmented processes and manual management, stands to gain significantly from blockchain integration. Currently, the planning and design phase involves architects and engineers developing project blueprints, often resulting in siloed data and inefficient communication. Blockchain can enhance this stage by providing a decentralized platform for storing and managing project documentation, ensuring a single, immutable source of truth accessible to all stakeholders, thereby improving transparency and collaboration (Swan, 2022). During procurement, the current system relies heavily on manual processes for issuing orders and managing contracts, which can lead to delays and errors. Blockchain can streamline procurement through smart contracts, which automatically execute and enforce agreements based on predefined conditions, ensuring accurate and timely processing of orders and payments while verifying material authenticity (Brown & Lee, 2022).

The illustration how a construction supply chain in its traditional format and how it could be enhanced with blockchain technology for greater efficiency and transparency can be seen in Table 7.

Table 7: The traditional construction supply chain versus future construction supply chain with blockchain

Stages	Traditional construction supply chain	Future Representation with Blockchain
Material procurement	Raw materials are sourced from suppliers. Each supplier maintains its own records, which may not be fully transparent to other parties.	Suppliers register their materials on a blockchain, creating a transparent and immutable record of the source, quality, and quantity. Smart contracts could automatically trigger orders when stock levels fall below a certain threshold
Logistics and	Materials are transported to the construction	As materials move through the supply chain,

transportation	site, often passing through several hands. Tracking these shipments can be challenging due to fragmented systems.	each transaction is recorded on the blockchain. This allows all parties to track shipments in real-time, reducing the risk of loss or delay. Any change in the status of the shipment is immediately updated and visible to all stakeholders.
Construction and assembly	Contractors and subcontractors receive materials and use them for construction. Documentation, such as delivery notes and invoices, is often paper based, leading to delays and potential discrepancies.	Materials are logged upon arrival at the construction site, with their usage recorded on the blockchain. This ensures that there is a clear, real-time record of what materials were used, where, and by whom. Smart contracts can also automate the release of payments as work is completed and verified.
Inspection and quality control	Inspections are conducted at various stages, but the results may not be immediately accessible to all parties involved.	Inspection results are recorded on the blockchain, providing immediate access to quality control data for all parties. This enhances transparency and accountability, ensuring that any issues are quickly identified and addressed.
Payment processing	Payments are made upon completion of certain milestones. Delays can occur due to the time it takes to verify the completion and process the necessary paperwork.	Payments are automated through smart contracts, which release funds once predefined conditions are met (e.g., successful delivery of materials, completion of work milestones). This reduces the time and administrative burden involved in payment processing.

In the construction phase, blockchain can be employed to track real-time progress and manage subcontractor performance using IoT devices, which record and store construction data on the blockchain. This enhances efficiency by providing a transparent and secure record of activities and improving coordination between contractors and subcontractors (Wang & Zhang, 2021).

For quality control and compliance, blockchain technology can simplify the inspection process by recording results and compliance documentation on an immutable ledger. This ensures accurate and accessible records of inspections and regulatory adherence, reducing errors and maintaining a comprehensive compliance history (Christidis & Devetsikiotis, 2021).

Finally, in the delivery and handover phase, the blockchain can manage the final documentation, including inspections, warranties, and client approvals, by securely recording these details on the blockchain. This ensures all contractual obligations are met and facilitates a smooth handover process, with a transparent and verifiable record of all final transactions and documents (Tapscott & Tapscott, 2020). By addressing specific challenges at each stage of the construction supply chain, blockchain technology can significantly enhance efficiency, transparency, and security across the industry.

By integrating blockchain into the construction supply chain, companies can achieve greater transparency, real-time tracking of materials, and automated processes through smart contracts. This technology has the potential to address many of the inefficiencies inherent in traditional supply chains by providing a single, immutable source of truth accessible to all stakeholders. The result is a more resilient, efficient, and trustworthy supply chain that can significantly enhance the delivery of construction projects.

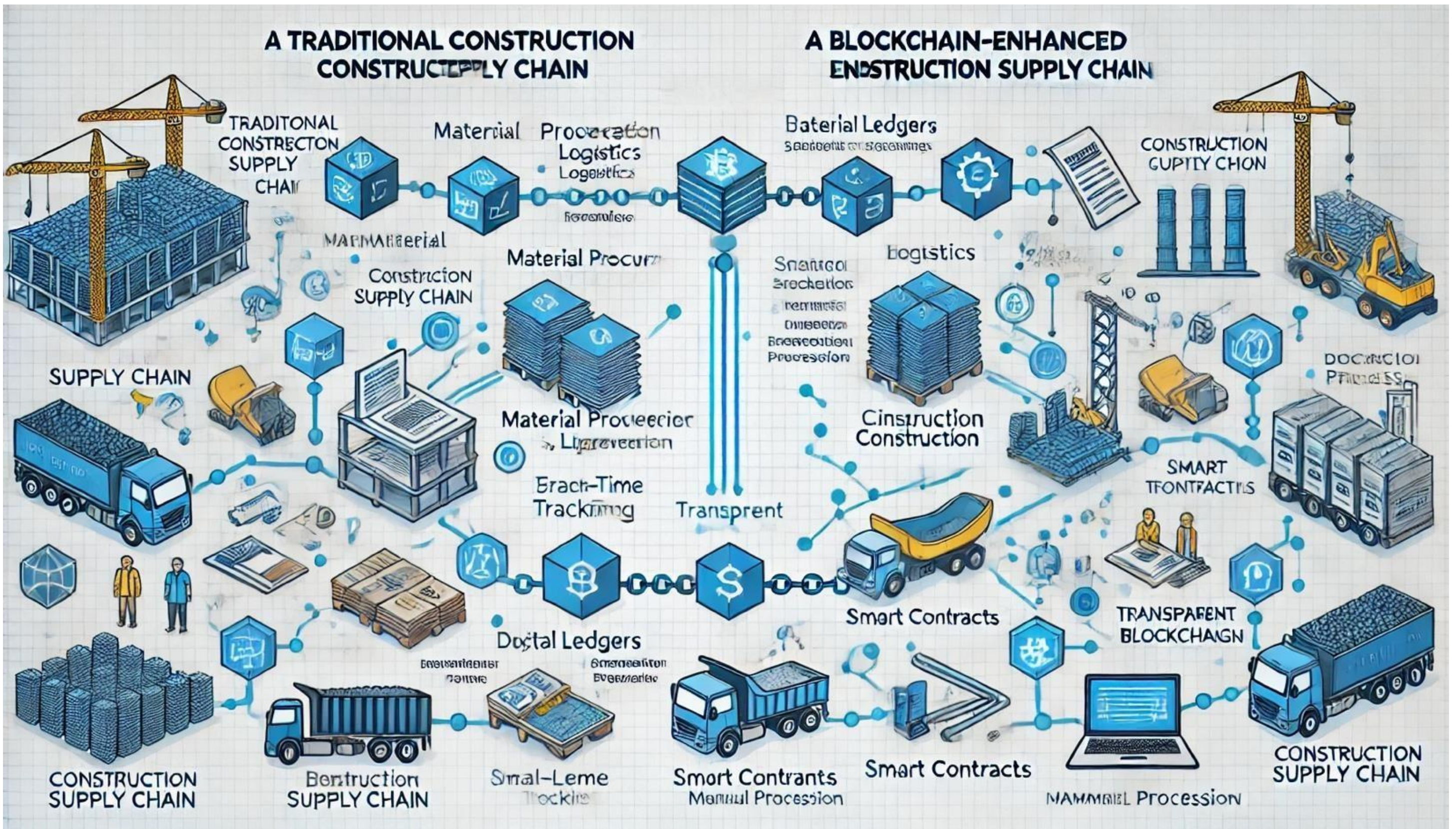

Figure 4: The differences between a traditional construction supply chain and one enhanced with blockchain technology (authors' visualization using DALL-E)

CONCLUSION

This paper has synthesized a comprehensive literature review on the criteria relevant to blockchain technology, particularly focusing on its application within supply chain management in the construction industry. The insights gathered underscore blockchain's potential to revolutionize supply chain processes by enhancing transparency, security, and efficiency. By identifying key criteria for blockchain implementation, this paper contributes to a deeper understanding of the technology's capabilities and its implications for the construction sector. However, while the findings offer valuable preliminary insights, they also highlight the need for further validation. The criteria proposed require additional empirical evidence through more extensive literature reviews and scientific methods, such as surveys, to strengthen their reliability and applicability.

This paper aims to pave the way for future research by establishing a foundation upon which additional criteria can be explored and validated. It is anticipated that subsequent studies will build upon these findings, offering a more nuanced and comprehensive evaluation of blockchain's potential in various industrial contexts.

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DISCLOSURE STATEMENT

The author declares that they have no known competing financial interest or personal relationship that could have appeared to influence the work reported in this article.

DATA AVAILABILITY STATEMENT

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

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