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Blockchain-based decentralised material management system for construction projects

Mohammad Basheer [a], Faris Elghaish [a,**], Tara Brooks [a], Farzad Pour Rahimian [b,*], Chansik Park [c]

[a] Queen's University Belfast, School of Natural and Built Environment, University Rd, Belfast, BT7 1NN, UK
[b] School of Computing, Engineering & Digital Technologies, Teesside University, Middlesbrough, UK
[c] Department of Architectural Engineering, Chung-Ang University, Seoul, South Korea

A R T I C L E I N F O

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A B S T R A C T

The prevailing practices in construction supply chain management are characterised by significant challenges, including fragmentation, a lack of trust among stakeholders, and restricted information sharing. This research introduces a blockchain-based integrated system for managing construction materials and inventory to enhance the traceability and transparency of shared supply chain material information. This initiative will foster a collaborative and open supply chain environment among stakeholders and effectively address material delays, resulting in smoother project operations and minimized disruptions, thus promoting operational efficiency. Furthermore, the system's potential to substantially reduce the incidence of legal disputes is underpinned by the secure and tamper-proof storage of information within shared ledgers, fostering a high level of accountability and trustworthiness. The integration of the Economic Order Quantity (EOQ) approach within blockchain smart contracts streamlines procurement processes, leading to a noteworthy reduction in purchase orders and associated overhead costs. The study employs a Design Science Research (DSR) approach to create a decentralised construction supply chain system, monitoring changes in material information during the supply process and addressing uncertainties associated with managing construction material inventory. The proposed system empowers project stakeholders by providing real-time material information access, resulting in improved decision-making and a reduction in material delays. Additionally, the construction material management-based blockchain and smart system enables project parties to efficiently handle inventory for complex projects, interconnecting all supply chain tasks within an integrated smart contract. The usability of the proposed solution was assessed using a usability test technique, with participants confirming its applicability in construction environments. They highlighted key benefits, including reduced material purchasing costs, decreased legal disputes among project stakeholders, and improved decision-making.

1. Introduction

The construction industry is known to have complex, lengthy, and network-based supply chains with a vast range of internal and

* Corresponding author.
** Corresponding author.
E-mail addresses: F.elghaish@qub.ac.uk (F. Elghaish), f.rahimian@tees.ac.uk (F. Pour Rahimian).

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external stakeholders [1]. Typically, construction supply chains consist of three types: the primary supply chain, which consists of the main contractor, designers, client, and consultants; The support supply chain, which provides the materials, equipment, and expertise that facilitates construction; and the Human resource supply chain which offers labour [2]. Due to the vast fragmented nature of construction supply chains, sharing information among the stakeholders is not always effective, which can affect decision-making procedures [3].

Many attempts have been made to improve the material information-sharing process in the supply chain using Industry 4.0 technologies. Aram et al. [4] investigated using Building Information Management (BIM)-based technology to enhance construction information sharing. Brandín and Abrishami [5] suggested using BIM-blockchain based integration of information to decrease the delivery time of prefabricated modules to construction sites. Li et al. [6] investigated using IoT sensors to track material and equipment in construction supply chains. Although the previous research presented potential insights to improve the construction supply chain, it did not entirely solve the deep rooted problems of low transparency between the stakeholders, traceability of information, and poor collaboration between parties.

There has been growing interest in utilising Blockchain Network (BCN) technology in construction supply chains in recent years due to its benefits in providing increased transparency and traceability of information in a decentralised, tamper-proof environment [7]. BCN has revolutionised several solutions in different areas of the Construction Supply Chain (CSC); for example, Elghaish et al. [8] have developed an automated financial system for the construction supply chain by proposing a blockchain-based integrated project delivery. Sheng et al. [9] addressed the issue of the deliverables' quality information transparency between the stakeholders using BCN. Hasan et al. [10] proposed a blockchain, smart contracts-based approach for efficient material tracking.

Research utilising blockchain technology in construction industry and supply chains has become more widespread in recent years [11–13]. However, few studies have tackled construction supply chain material and inventory management issues within a project.

Wang et al. [14] developed a blockchain-based solution to enhance information sharing in the precast industry. Although their study is considered one of the first solutions to utilise blockchain in tracking and sharing detailed information of the precast members, the study did not investigate the interrelationship between ordering the material and inventory management in detail. Yang et al. [15] developed workable proofs-of-concept for utilising blockchain networks and smart contracts in two construction business cases; the primary reason behind their study was to explore the feasibility and the benefits of using this technology in the construction environment. Even though this study introduced workable prototypes in material information management, the solutions focused primarily on the financial transactions between the supplier and the end user.

In a recent longitudinal study, Wang [16] introduced a valuable proposition for designing a blockchain-based construction supply chain. The study adopted a DSR approach to create a blockchain network and develop design principles for consideration in different construction supply chain contexts. However, the study briefly presented the Proof-of-Concept, which concentrated mainly on the impacts and benefits of creating a blockchain-based supply chain in the construction industry.

According to Caldas et al. [17], poor material information sharing can lead to disruptions in site schedules, inefficiencies in inventory management, lower productivity rates, and time loss through expediting activities. Moreover, the solution developed by these researchers utilised the Economic Order Quantity formula [18], widely used in the manufacturing industry, to manage the inventory of consumable materials in construction projects. Furthermore, it incorporated the concepts of lean material management in supplying permanent construction material by adopting the Just in Time approach [19], combined with material planning schedules extracted from the 4D BIM model.

After analysing the relevant literature, it is evident that current research on blockchain-based information management has limitations in two crucial areas. First, there is a significant focus on separate stages within the project life cycle, lacking a holistic perspective. Second, there is a noticeable gap in the absence of practical evidence supporting the utilization of an automated decentralised material information management system.

With all the above in mind, this research aims to help overcome the challenges facing construction supply chains in material information management by developing a solution that automates and records the material information sharing process in construction supply chains. This research adopts the Design Science Research paradigm to develop, demonstrate and evaluate the proposed solution. First, the literature review was conducted to gain background information and determine the state-of-art research utilising BCN in construction supply chains. It was also used to explore the challenges facing the material construction supply chain and draw a basis for the solution's framework development. Subsequently, a Blockchain-based framework was developed based on the material supply chain's current challenges and the data collected from the literature review. Finally, the proposed solution is evaluated using an illustrative case study.

Through usability tests performed by construction supply chain professionals, the proposed system was validated and encouraged to be adopted by the construction industry. This is due to the validated benefits of reducing material delays, reducing legal disputes arising from material delays, reducing the total material costs, and the enhanced decision-making process achieved from an open material information-sharing environment.

The rest of the paper is structured as follows. Section 2 includes the theoretical background. The methodology section is presented in section 3. Sections 4 and 5 include solution development and evaluation. Discussion and novelty are presented in section 6. Finally, section 7 includes the conclusion.

2. Theoretical background

2.1. Construction supply chain challenges

Construction material costs compose approximately 60–65 % of the overall construction project costs [20,21]. Thus, controlling construction materials has a substantial impact on successfully delivering projects. Since the late 1980s, a growing body of literature has recognised the importance of Construction supply chains [22]. For example, in one study, Bamana et al. [23] demonstrated that adopting Just In Time (JIT) practices in procuring construction materials increased productivity at the construction site by more than 10 %. In another example of showing the importance of Construction Supply chains, Chen et al. [24] claimed that their suggested material supply chain management system could reduce the duration of the material flow process by 16 %.

Although these examples have highlighted the importance of managing construction supply chains, in contrast to the manufacturing industry, the construction industry still falls behind in optimising material supply chain management [1]. This can be explained by the fact that each construction project delivers a unique end product where numerous suppliers will work together, sharing information and collaborating to complete the project successfully [25]. On the other hand, the manufacturing industry is characterised by a repetitive process of producing the same end-product each time which builds the ground for a long-term relationship and mandates collaboration between the supply chain members.

The supply chain in the construction industry is generally characterised by the following components [26]: (1) a concurrent supply chain that directs all resources to the job site, where the end-product is built from the received components [27], whereas in manufacturing, several products pass through the factory and are delivered to different end-users; (2) it produces a temporary supply chain which usually ends with the delivery of the project [28]; (3) Each project is unique, and no two projects are the same.

Therefore, the construction supply chain is characterised by instability, fragmentation [29], and information silos among the project participants.

2.2. Materials in construction supply chains

Materials sourcing in construction projects is a complicated process with many stakeholders contributing to it [30]. The process starts with identifying and quantifying the needed material before acquiring, transporting, receiving, storing, and preserving the materials, equipment, and associated information across the project's life cycle [17].

Van Weele [31] summarised the latter process into five stages: 1) Specification determination; 2) selecting the supplier; 3) negotiations and contracting; 4) drafting the contract or the purchase order; and 5) following up with the supplier to secure the delivery. Similarly, Bildsten and Manley [32] investigated the purchasing process in construction companies. They emphasised the benefits of centralised procurement in construction projects compared to decentralised procurement, which is widely used in the manufacturing industry. Moreover, they proposed eight stages process for purchasing in construction projects, namely: (1) identification of a need; (2) establishing specification and scheduling the purchase; (3) identifying purchasing alternatives; (4) evaluating alternative purchasing actions; (5) selecting the supplier; (6) negotiation and contracting; (7) issuing the contract or order and (8) following up to secure delivery.

Effective management of material flow processes necessitates the synchronization of material and information flows and guarantees that the planning for material in need is accurate, and there are minimal delivery problems. Traditionally, basic information technology tools like Microsoft Excel and Project, as well as Enterprise Resource Planning (ERP) platforms (i.e., SAP or Oracle), are utilised to facilitate cooperation [24]. However, their use is often disorganized, and information sharing is not efficient and therefore time-consuming. Utilising these essential technologies often results in inadequate and erroneous information transmission between the supply chain members, which will affect the systematic feedback on construction progress [33,34].

Few studies have tried to combine several technologies for enhanced information sharing in construction supply chain. Chen et al. [24] combined BIM and RFID technology to improve supply chain visibility and material information flow for better decision-making. Lee and Lee [35] suggested combining BIM, IoT sensors, and GIS systems for improved supply chain coordination and delivery of the modules in modular construction. Other attempts have been made to explore the areas of material traceability and tracking in construction supply chain. For instance, Yan et al. [36] developed a solution to track the trucks entering a construction site to and automatically monitor construction material delays [37], and proposed an RFID-based platform for tracking the construction material on-site.

However, all the previously mentioned studies focused solely on obtaining information related to the materials and delivery options and paid minimal attention to information sharing between the project participants. Moreover, the studies ignored the aspects of information transparency and traceability across the supply chain.

2.3. Materials inventory management

Material inventory management is an essential aspect of construction supply chains, especially for the contractor, as it reduces the risks associated with getting out-of-stock (stockout costs) in material [38,39]. These risks may arise from unforeseen events such as transport breakdowns, labour strikes, and adverse weather conditions. These risks may not only be reflected in cost loss but also contribute to project schedule delays [40].

Typically, two economic indicators are closely connected to material inventory management: Acquisition (ordering) costs and holding costs [38].

- Acquisition or ordering costs will include all the costs associated with acquiring the material: preparing the requisitions, supplier selection, controlling the supply process, expediating the material, receipt of the material, handling, inspection, and payment processing.
- Holding costs includes all the cost associated with holding the material in the stores: cost of insurance, loss of value, expiring, storage space costs, lighting, heating, power supply, and storage documentation costs.

The total material cost is the summation of each material type's ordering and holding costs [38]. In a construction project environment, many models are utilised to determine the quantity and the timing of material ordering [41]. However, two main approaches are adopted in the construction industry: Approaches that consider the total material costs, such as Economic Order Quantity method [42], and the lean supply approach, such as the Just in Time (JIT) supply approach [19].

The economic order quantity approach balances the ordering costs and the holding costs through the below equation [42].

$$EOQ=\sqrt{\frac{2DS}{H}} \tag{1}$$

Where EOQ is the economic order quantity, D represents the Annual demand for the item, S is the cost of one order, and H represents the holding costs for one unit.

Moreover, the inventory cost H is calculated by the following equation:

$$H = iC \tag{2}$$

Where C represents the unit cost of the ordered material, and i represents the interest rate of holding the material in inventory.

This approach can reduce the ordering costs by placing the minimum number of orders for the annual demand, assuming that the annual demand will remain constant [41].

On the other hand, lean approaches have emerged to address some uncertainties resulting from using total material costing approaches, such as high holding costs, especially when stocking significant quantities of material to match the annual demand [41]. This has led to adopting the Just in Time approach, which aims to waive the need for material inventory, reduce it to almost zero, and minimise the material's holding costs [43]. It is vital to mention that the Just in Time approach is highly adopted in the manufacturing industry and the insurance, banking, and health industries [44].

In the construction industry, many research studies endeavoured to utilise both EOQ and JIT approach to plan the material flow. For instance, Jaśkowski et al. [45] developed a decision model for planning material supply channels in construction projects based on economic order quantities and minimizing the total material inventory costs. Min and Sui Pheng [46], in a notable study, investigated the cost savings achieved by using EOQ or JIT in the construction industry and concluded that contrary to the majority of research studies favouring the use of JIT, the use of EOQ can be more cost-effective dependent on specific conditions.

2.4. Blockchain in construction supply chains

Blockchain is a Distributed Ledger Technology (DLT) initially presented by Nakamoto [47]. It is a simple database with unique attributes since it is decentralised and stored in several locations in a shared form. Furthermore, unlike the standard cloud system or internet databases, it is continually updated and store information in a single area with multiple access points [8]. The blockchain comprises several blocks. Each block comprises a block header and block content. The block header includes the version number, block size, timestamp, the Merkle tree root hash, the hash value of the preceding block, and a nonce [48]. Since each block contains the previous block's hash value, the blockchain structure is secure and prevents manipulation [49].

Researchers have split blockchain networks into three categories [50]. The first type is the public network which any individual or group can join the network and participate as a node. An example of this type is Bitcoins [47]. The second type is the private network, where only pre-defined members can join. It is a private network that belongs to an individual or an organisation. For example, although Ethereum is a public blockchain network, it allows users to create private blockchain networks. According to Samuel et al. [51], Ethereum is considered very popular among many organisations for establishing private blockchain networks. The third type is a consortium network, which sits between the public and private blockchain networks, where an organisation sets multiple pre-selected nodes that control the network's block generation. An example of that is the IBM blockchain platform.

The concept of smart contracts was first introduced by Szabo [52], defined as a set of digitally determined commitments on which contract participants can execute the relevant transaction. Ethereum was the first blockchain platform that featured the usage of smart contracts. Buterin [53] introduced Ethereum as a decentralised computing platform based on the blockchain. He defined smart contracts as systems that automatically move digital assets according to arbitrary pre-specified rules; these rules shall be written in a programming language that encodes different state transition functions and allows users to write "if-then" logic statements into these contracts [54]. These smart contracts can be written in many programming languages and incorporated into the blockchain network, depending on the platform. For example, JavaScript and Golang are used in the IBM blockchain platform [55]. The Ethereum platform allows using Solidity and Vyper programming languages [56].

To overcome the issues of collaborative information sharing among project participants, data reliability, transparency, and information traceability, several research studies have been conducted on utilising Blockchain technology at all stages of the construction supply chain, from design to procurement and construction. Some studies have tackled the issues of supply chain visibility. For example, Kiu et al. [57] introduced a conceptual framework for utilising blockchain to solve traceability problems, information sharing in the construction supply chain, and materials procurement and management. Wang et al. [14] proposed a blockchain-based proof-of-concept for precast supply chain information management that would enable automatic information exchange, traceability, and transparency between the project's stakeholders. Wang et al. [14] proposed a blockchain-based proof-of-concept for precast supply chain information management that would enable automatic information exchange, traceability, and transparency between the projects' stakeholders.

In a another avenue of research, the focus shifted towards exploring information exchange within the supply chain, Parn and Edwards [58] studied the potential opportunities of using blockchain combined with BIM and (Common Data Environment) CDE to protect valuable data from cyber-attacks. Yoon and Pishdad-Bozorgi [59] recommended employing Blockchain technology to collect non-tampered, non-fraudulent, and traceable sustainability information about suppliers in the pre-selection procurement stages before the tender's award.

In the realm of smart contracts within construction projects, there is a limited focus on the contractual and legal opportunities that arise among supply chain parties. A notable example of this, In an investigation of the implementation of blockchain's smart contracts in construction projects, through constructing a BIM-integrated blockchain model, Götz et al. [60] found out that only some of the contractual clauses can be transferred to a computer-coded smart contract in a construction project due to the high complexity and uncertainties. Xue and Holz [61] discussed the potential and risks of using blockchain technology in online dispute resolution.

Qian and Papadonikolaki [62] conducted semi-structured interviews with blockchain specialists and construction supply chain managers, uncovering advantages in information traceability, contract administration, and resource management through the integration of blockchain. While these studies offer innovative foundational insights for future research, it is noteworthy that many conceptual frameworks lack practical solutions or proofs-of-concept.

More workable solutions for utilising blockchain in construction supply chains can be encountered in managing financial transactions. In a recent study, Elghaish et al. [63] pioneered a workable financial management system based on Hyperledger Fabric and smart contracts, resolving pervasive flaws in the financial management practices adopted in construction. This solution permits all the concerned parties in the project to invoke payment transactions in a decentralised platform.

Yang et al. [15] introduced a workable prototype utilising blockchain on Hyperledger Fabric and Ethereum platforms. After the material procurement, the prototype was tested using two industrial case studies to execute secured interim payments between the concerned project stakeholders. Saygili et al. [64] developed a construction-oriented dispute resolution prototype; where the construction companies can both act as users and jurors for other companies' disputes where the presence of a third-party guarantor will be unessential. Saygili et al. argued that applying this prototype can save both cost and time for litigants. However, this may raise concerns about biased or collective decisions.

Lu et al. [65] contributed to the body of knowledge by developing a blockchain-based framework and prototype for construction supply chains, enabling project stakeholders to employ it for trust enhancement and collaboration. A notable finding of the later research is that construction industry practitioners are usually unfamiliar with the blockchain network's terminology and system architecture. Hence, the authors recommended cautiously interacting with the system components to preserve a blockchain network's decentralised properties.

Based on the analysis of these studies, although they provided a revolutionary step in their areas, none has addressed the issues of material and inventory management in construction supply chains. For instance, Singh and Ashuri [66] suggested an information-sharing framework to be utilised at the design development stage. However, the framework needs validation through a workable proof-of-concept. Sheng et al. [9] pioneered a blockchain-based quality information management solution to control construction site asset acceptance/non-conformance procedures. Zhong et al. [67] took a further step in blockchain-based quality information management solutions, including BIM and IoT sensors, to collect real-time quality information. Table 1 illustrates the key research studies in the area and the corresponding limitation.

The collection of studies presented herein encompasses a diverse array of approaches to integrating blockchain technology within supply chain management. Wang et al. (2017) elucidates a comprehensive conceptual framework for blockchain application across various sectors, although validation through smart contract deployment remains outstanding. Yang et al. (2020) pivots toward the development of private/public blockchain networks, providing a proof-of-concept prototype for supply chain processes, albeit with a

Table 1
Relevant research for using blockchain technology in the construction supply chain.

NO	Author	Focus of Study	Methodology	Limitation
1	Kiu et al. [57]	investigating the potential of applying BCN in Contract Management, Supply Chain Management, and Electronic Document Management (EDM).	Conceptual Framework	A detailed framework for employing BCN in supply chain management. However, the framework is not validated by smart contracts deployment.
2	Yang et al. [15]	Developing Private/Public blockchain networks for construction supply chain management.	Proof-of-concept	Developed a prototype for the construction supply chain process. However, it focuses on financial management rather than information exchange.
3	Wang et al. [14]	Developing a solution to enhance information exchange in the precast industry	Proof-of-concept	Developed a workable solution tailored exclusively to the precast industry and does not include other materials management.
4	Das et al. [68]	Developing a solution to automate interim payment in construction supply chains	Proof-of-concept	A workable solution concentrates only on the financial transactions in construction supply chains.
5	Sheng et al. [9]	Developing a solution for Quality information management and authorisation	Proof-of-concept	A workable solution that exchanges and manages the quality information of material during the construction phase only
6	Zhong et al. [67]	Developing a solution to automate quality information controlling and assurance in construction projects	Proof-of-concept	The solutions utilise IoT sensors, BIM models, and blockchain to transact information about quality compliance. This solution needs proper validation in a case study.
7	Wang et al. [69]	Designing a blockchain-enabled supply chain	Longitudinal Design Science Research	Provided a valuable proposition for designing the network. However, the study didn't address automating supply processes and inventory management.

primary focus on financial management over information exchange. Wang et al.'s (2020) research targets the pre-cast industry, yielding a functional solution for enhanced information exchange, albeit confined to this specific sector. Das et al. (2020) focalizes on automating interim payments within construction supply chains, furnishing a viable solution with an exclusive focus on financial transactions. Sheng et al. (2020a) addresses quality information management and authorization, delivering a functional solution tailored to the construction phase, yet delimited to this facet. Zhong et al. (2020) innovatively incorporate IoT sensors, BIM models, and blockchain for quality compliance, though necessitating further validation through case studies. Wang et al.'s (2021) longitudinal design research proffers a valuable framework for blockchain-enabled supply chains, albeit without comprehensive coverage of automated supply processes or inventory management. Cumulatively, these studies present a multifaceted exploration of blockchain integration, each with distinct strengths and limitations, constituting a significant contribution to the field's expanding body of knowledge.

Even though the beforementioned research studies provided workable proofs-of-concept, prototypes, and solutions for improving construction supply chain financial management, information sharing, and stakeholder collaboration, the study of materials information management in the construction supply chain was beyond their scope.

Moreover, a limited number of proofs-of-concept, prototypes, or solutions are developed based on solution validation by the industry's practitioners. Therefore, a solution for materials information management in construction supply chains arises.

3. Research methodology

Since this research aims to develop a blockchain-based workable solution for information sharing in construction supply chains and

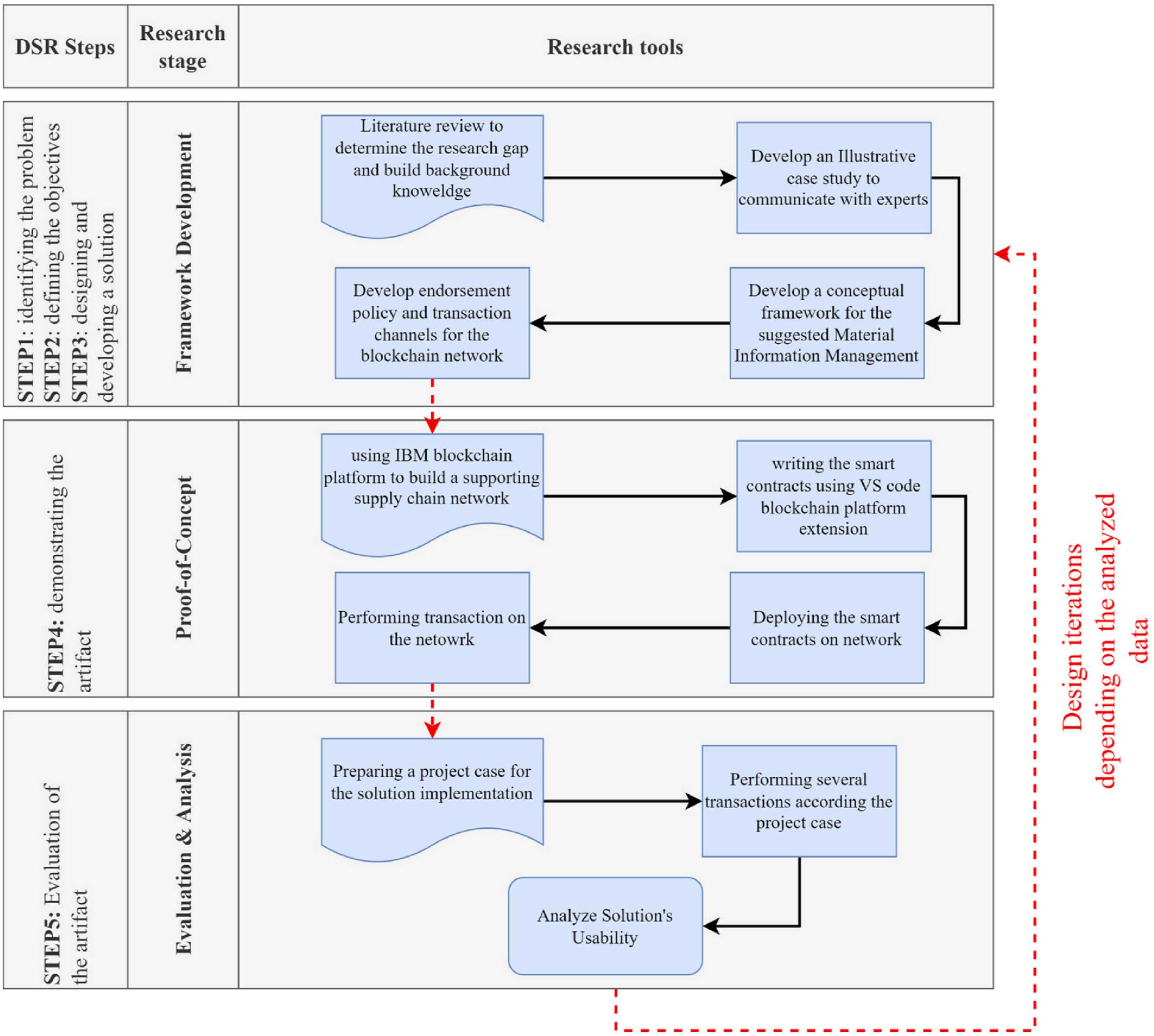

Fig. 1. Research Design and tools.

test its applicability in a real-life scenario, many external factors and organisational procedures would affect the developed solution. In other words, this research is directly affected by the context surrounding it. According to Yin [70], Case Study research is an "empirical inquiry that investigates a contemporary phenomenon in depth and in its real-life context when the boundaries between the context and phenomenon are not clear", where a case can refer to a person, group, organisation, event or a process.

This research adopted a Design Science Research (DSR) paradigm. This approach describes a structured process of artefact development, where an artefact can refer to models, frameworks, methods, or instantiations [71]. This research paradigm is highly adopted by construction industry scholars when developing a solution using Information Technologies. For instance, Lu et al. [65] used this paradigm to develop and validate a blockchain-based framework for enhancing trust in construction supply chains. Elghaish et al. [72] used the same method to develop and validate an AI-based voice assistant for BIM data management. The DSR approach involves six steps to achieve its aims: identifying the problem, defining the objectives, designing and developing a solution, demonstrating the artefact, evaluating the artefact, and communicating [73]. The first two steps: identifying the problem and defining the objectives, were approached by reviewing the existing literature on the construction supply chains. The third step: designing and developing a solution. This was addressed by reviewing the state-of-art literature on blockchain network development. The fourth step: demonstrating the artefact; this was approached by developing a proof-of-concept blockchain network using Hyperledger Fabric API. The fifth step: Evaluating the solution; this was approached by testing the solution on a real-life project case, and the sixth step: communicating the solution; this was addressed by submitting this paper, as shown in Fig. 1.

4. Solution development

In the proposed solution, real-time material information will be accessible to all project stakeholders, allowing them to closely monitor material status updates and compare them with the initial information specified in the issued Purchase Order. The supporting supply chain network will comprise five primary, unchanging network members: the client, the supply chain manager, inventory manager, quality control inspector, and quantity surveyor. Additionally, pre-approved suppliers and logistics providers can be

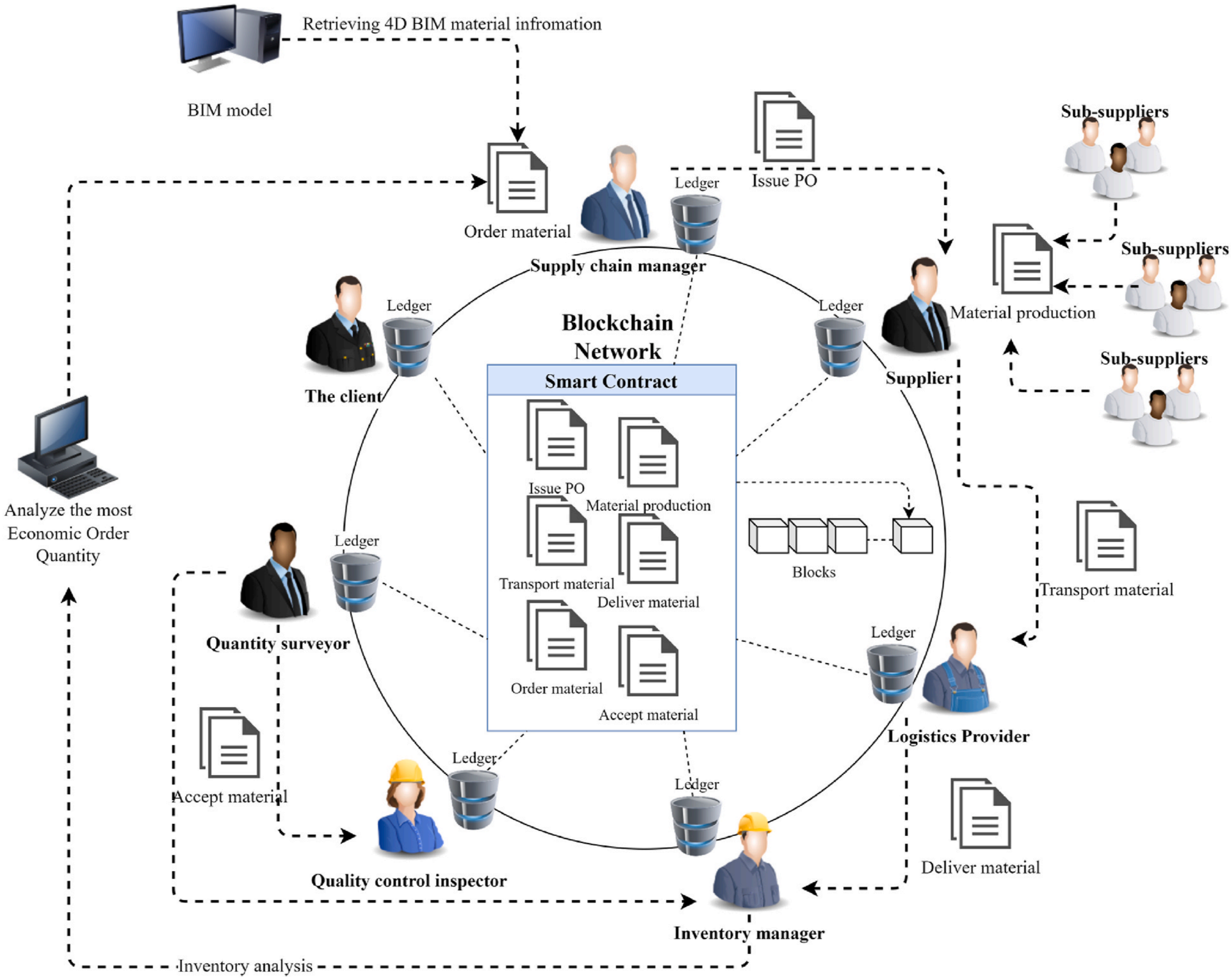

Fig. 2. Blockchain-based Framework for Material Information Management in Construction Supply chains.

seamlessly added to the network through a separate channel, as illustrated in Fig. 2.

As depicted in the figure above, each network member possesses a copy of the ledger, granting them access to material information pertaining to both past and ongoing purchase orders. Within this established network, the ordered material serves as the primary asset, and transactions are indicative of various operations related to the material. These operations encompass issuing purchase orders, material production/acquisition, transportation, material delivery, acceptance, and payment processing.

It is crucial to emphasize that the corresponding client peer initiates each operation, and consensus among endorsing peers for a given transaction is imperative for its processing. The material operations will be meticulously defined as functions within the smart contract's chaincode, a topic further elucidated in the subsequent sections. This meticulous framework ensures the integrity and reliability of the material-related transactions within the supply chain network.

4.1. Structure of the material management chaincode functions

The different transactions in the developed framework will assume a Hyperledger Fabric environment, as previously explained in the literature review. This type of consortium network provides the flexibility to quickly add "suppliers and Logistic companies" to the network and define their roles and communication channel. Fig. 3 presents the structure of the proposed chaincode, which includes three primary categories that branch into eight functions. The three categories are issuing and tracking purchase orders, managing inventory, and retrieving purchase order information.

4.2. Formulation of transaction-based hyperledger fabric smart contract

Adopting blockchain in materials supply management requires close observation of the existing practices in the industry and enhancing them through incorporating logical statements and optimising mathematical equations. Fig. 4 presents all the parameters of the smart contract's functions. Each corresponding function user enters this information.

The following section will present in detail the above transaction flow of information as follow.

4.2.1. Issue and track purchase orders

This process is concerned with issuing and automatically tracking the purchase orders throughout the lifecycle of sourcing the material by introducing five functions, namely, Issue Purchase Order, material production, transport material, deliver material, and material approval/invoice preparation.

4.2.1.1. Issuing the purchase order. The supply chain manager invokes the transaction using his client peer. The endorsing peers for this transaction would be 1) the project client, 2) the material supplier, and 3) the recommended logistics provider. The following parameters should be determined before invoking the transaction: 1) Purchase Order Number, 2) Material type, 3) Delivery date, 4) Purchase order value, 5) Payment terms, 6) Purchase order status, and 7) Material quantity. Fig. 5 shows the developed smart contract's functions to issue the purchase order and manage the function on the blockchain network. As it can be seen from Fig. 6 that The endorsing peers will check the proposed transaction, and if satisfied, they will transmit their responses with signatures. After verifying the endorsing peers' signatures, the ordering service node collects the responses, orders them chronologically, and creates the block for

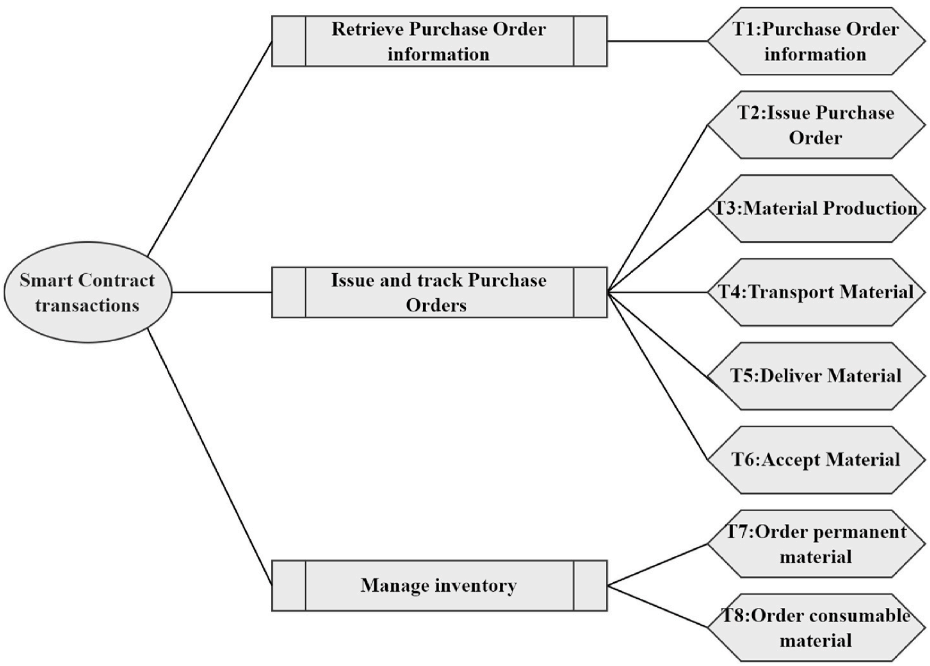

Fig. 3. The proposed chaincode transactions for the developed solution.

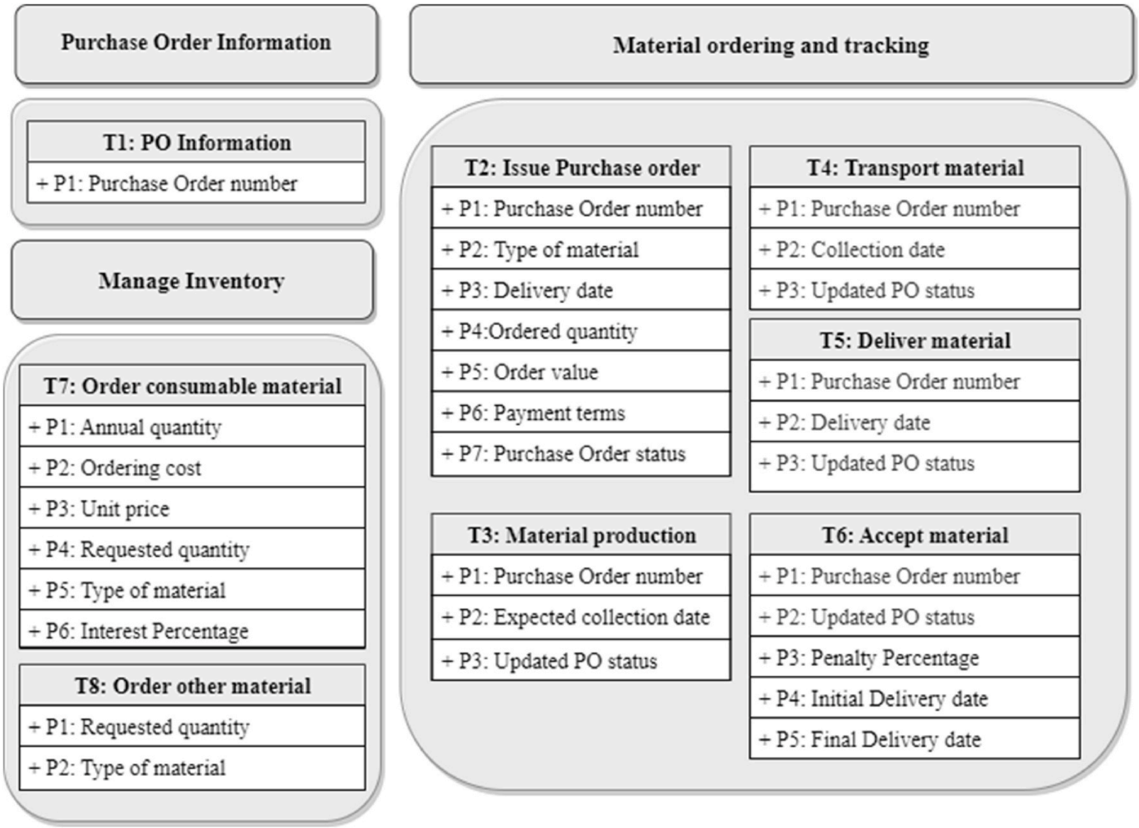

Fig. 4. Transactions parameters in the proposed framework.

the transaction. Next, the transaction block will be sent to all endorsing peers to validate the transaction. Once validated, the ledger will be updated with the new block. It is vital to mention that the network's consensus for this transaction will not be reached unless all the endorsing peers agree to accept the transaction. The flow of transactions is shown in Fig. 5.

4.2.1.2. Material production, collecting and delivery. This function serves as a response to the preceding function, updating the material acquisition status. With specified parameters, it enables the material supplier to include "expected collection data" by the logistics provider, as depicted in Fig. 6. The supplier's client peer initiates the transaction, subject to automatic validation through a pre-determined consensus mechanism. The transport function takes material status tracking a step further; the materials supplier triggers the transaction to confirm the readiness of the ordered material for collection. This enables the logistics provider to validate their resources (trailers, lorries) for collection and delivery, determining the required number of vehicles and enhancing decision-making. Illustrated in Fig. 7, the transaction undergoes processing only upon consensus among endorsing peers, meticulously evaluating

```
@Transaction()
public async IssuePurchaseOrder(ctx: Context, purchaseOrderId: string,  value: number, DeliveryDate: string,
    MaterialType: string, OrderedQuantity: string, PaymentTerms: string, PurchaseOrderStatus: string): Promise<void> {
    const exists: boolean = await this.purchaseOrdersExists(ctx, purchaseOrderId);
    if (exists) {
        throw new Error(`The purchase orders ${purchaseOrderId} already exists`);
    }
    const purchaseOrders: PurchaseOrders = new PurchaseOrders();
    purchaseOrders.value = value;
    purchaseOrders.DeliveryDate= DeliveryDate
    purchaseOrders.PaymentTerms= PaymentTerms
    purchaseOrders.PurchaseOrderStatus= PurchaseOrderStatus
    purchaseOrders.MaterialType= MaterialType
    purchaseOrders.OrderedQuantity= OrderedQuantity
    const buffer: Buffer = Buffer.from(JSON.stringify(purchaseOrders));
    await ctx.stub.putState(purchaseOrderId, buffer);
```

Transaction to Issue Purchase Order

Fig. 5. Smart's contract chaincode for "Issue purchase order" transaction.

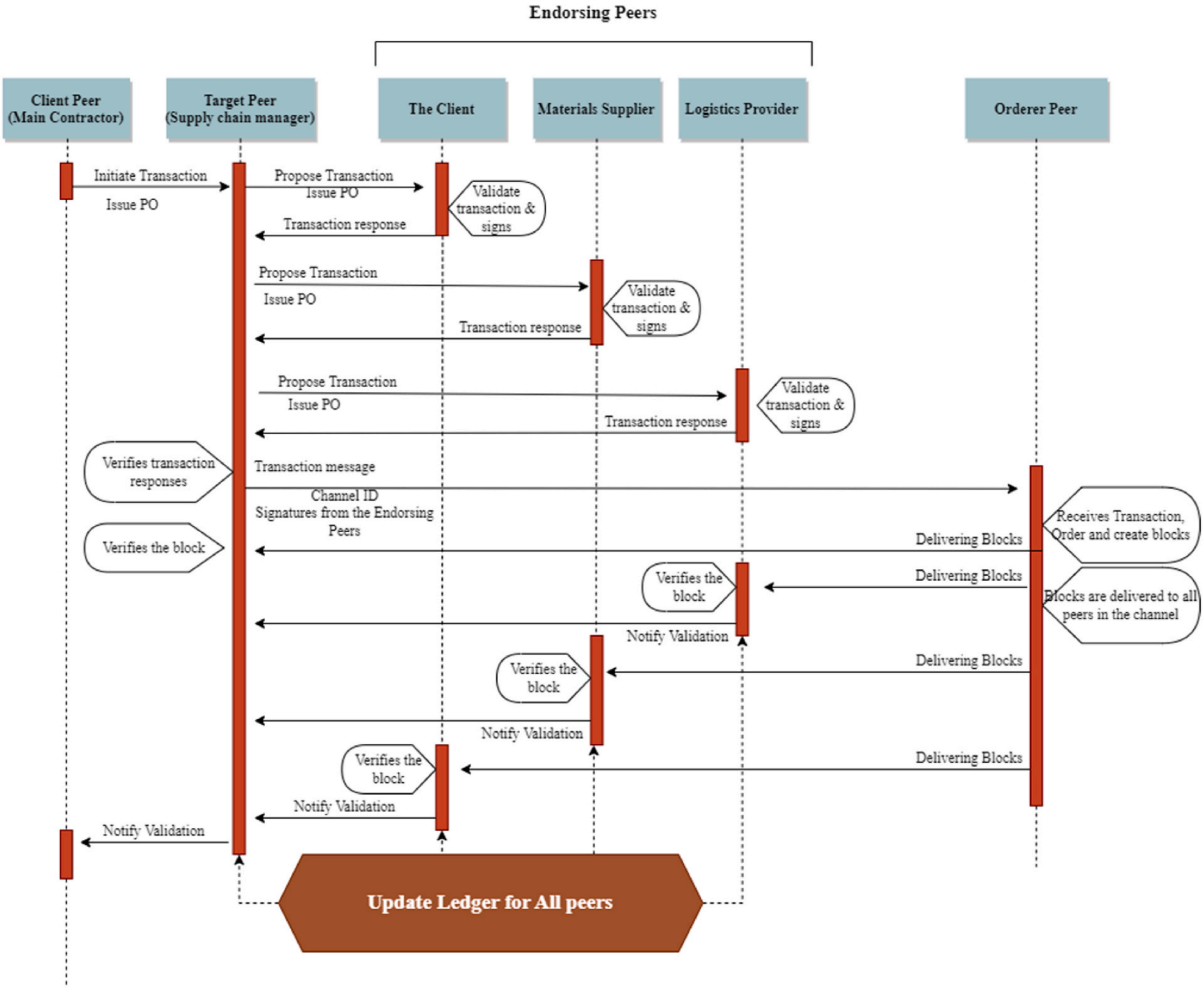

Fig. 6. Transactions sequence in the proposed solution.

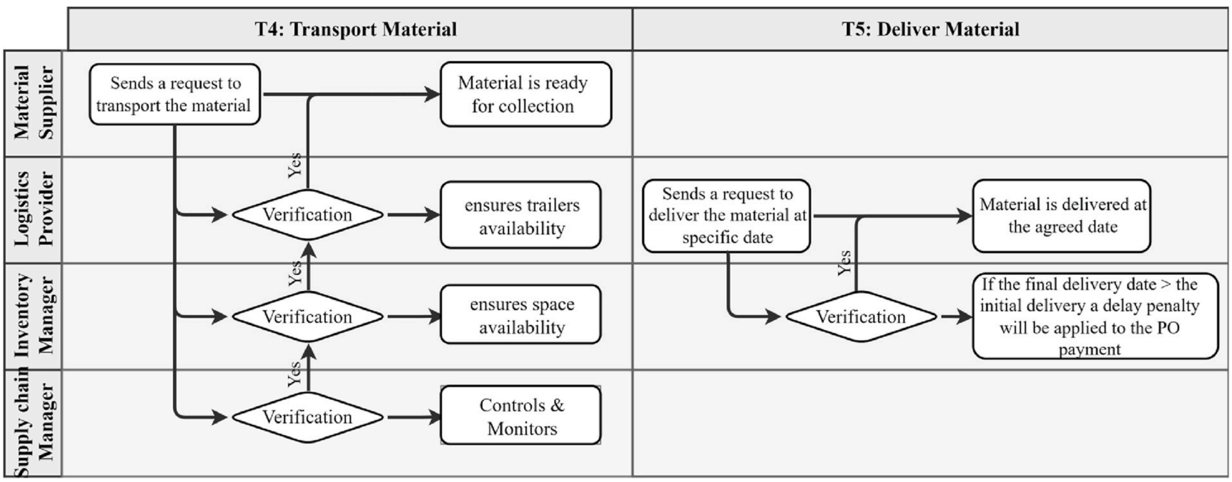

Fig. 7. Flow of information for Transport and delivery of material functions.

provided parameters.

Upon material collection, the delivery function is triggered to validate the delivery date of the material to the agreed-upon location of the main contractor. This function holds significance in aiding the decision-maker within the contractor project team to assess space availability for the expected material. Similar to all blockchain transactions within the network, the function's information remains dormant until the pre-assigned project endorsing parties verify the transmitted parameters of the transaction, as illustrated in Fig. 7.

An essential parameter incorporated into this transaction is the final delivery date of the material. The code has been devised to compare this parameter with the initial delivery date and securely record any changes in the blockchain as encrypted data. Fig. 8 illustrates the smart contract functions for material production, 'ready for collection,' and delivery. These functions are interconnected, ensuring that parameters seamlessly cascade from one function to another, thereby preventing fragmentation in the process.

4.2.1.3. Material approval, invoice preparation and data retrieval functions. The final step is to confirm that the received material matches the pre-agreed-upon material specifications. To carry out this confirmation, a function is employed to verify the material received and ensure that it complies with the pre-agreed specifications. This function's smart contract chaincode is encoded with logical statements that compare the final delivery date with the recorded delivery date. If there is a discrepancy between these dates, a pre-determined delay penalty percentage is automatically applied to the amount of the purchase order invoice.

It is important to note that this solution does not use cryptocurrency, but the penalty incurred due to the delay will be recorded in the blockchain. The Supply Chain Manager can refer to this information when preparing payments for the supplier. The payments for the supply chain will be transacted using fiat currencies. Additionally, the recorded information about the penalty imposed will be available for the supplier to view.

Overall, this solution provides an automated and transparent approach to monitoring and enforcing adherence to agreed-upon specifications and delivery timelines while also facilitating communication and collaboration between suppliers and supply chain

Fig. 8. Part of the smart contract's chain code for tracking material functions.

managers. Fig. 9 presents a part of the smart contract's chaincode.

The main contractor's inventory manager invokes the function, and the consensus will be reached by the function's endorsement of the contractor's project team based on the determined parameters. This function will assist in sharing the material status with the different supply chain stakeholders and, most importantly, the quantity surveyor to consider the acceptance date while preparing the payment, considering the payment latency per the payment terms.

The inquiry function in Fig. 10 is developed to enable parties to enquire about the real-time status of any purchase order. It can be used throughout all the stages of the material supply. The only parameter needed for this transaction is the purchase order ID. The chain code of the smart contract governing the purchase order information retrieval is shown in Fig. 10.

4.2.2. Managing inventory

In the proposed solution, the material inventory can be managed using two functions, namely "Order Consumable Material" and "Order Permanent Material". These functions will be deployed separately from other network participants, consisting only of the Supply chain Manager and Inventory Manager. Fig. 11 summarises the inventory management functions architecture. As shown in Fig. 11, the inventory manager will determine and enter the transaction parameters before invoking the transaction. Once the transaction is invoked, the information will be verified discreetly by the Supply chain manager and recorded in the blockchain.

4.2.2.1. Blockchain information channel among supply chain parties. There are two main functions to manage the inventory according to the type of materials. The first function is to manage consumable materials, which should be invoked to order consumables for construction projects, such as nails, hammers, and PPEs. The Economic Order Quantity equation is coded into the function's smart contract to determine the optimum quantities ordered, as shown in Fig. 12. The following parameters determine the transaction endorsement by the supply chain manager: 1) Historical Annual Quantity, 2) ordering cost, 3) unit price,4) requested quantity, and 5) type of material. The transaction will be automatically terminated if the requested quantity value exceeds the Economic Order Quantity shown in the chaincode.

The permanent material, such as Steel reinforcement, anchor bolts, and insulation material, can be invoked using the second transaction, as shown in Fig. 12. The parameters of this function are 1) the requested quantity and 2) the type of material.

As can be seen from Fig. 13, construction Projects' 3D BIM Models can be transferred to 4D BIM models by adding the start dates and the finish date to all the model elements. Consequently, Material take-off schedules can be extracted for all the model elements linked to their respective installation dates. These schedules will cover primarily permanent material. Exporting these schedules to XLS format and considering each material lead time a material Planning schedules can be developed based on the following:

$$\text{Order date} = \text{Installation date} - \text{Material lead time (days)} \tag{1}$$

In the previous equation, the term "Material lead time" encompasses activities related to transporting, delivering, accepting, and handling the material until it reaches the installation location.

Within the proposed solution, the supply chain manager will employ the material planning schedules to manually initiate and track orders, utilising the "Issue PO" function integrated into the smart contract. Since this process takes place during the construction phase, it is advisable, as suggested by Latiffi et al. [74], that the Level of Detail and Level of Information in the BIM models fall within the range of 350–400. This range ensures the presence of precise and reliable information suitable for the procurement of construction materials.

4.3. Endorsement policy

Typically, Every Chaincode (Smart Contract) has one endorsement policy that specifies the endorsing peers on the channel. However, in the developed solution, "Channel-2″ has several functions, raising the need to change the endorsing peers for each function. For instance, for "IssuePO" function, the endorsing peers are 1) the client, 2) the steel supplier, and 3) the logistics provider.

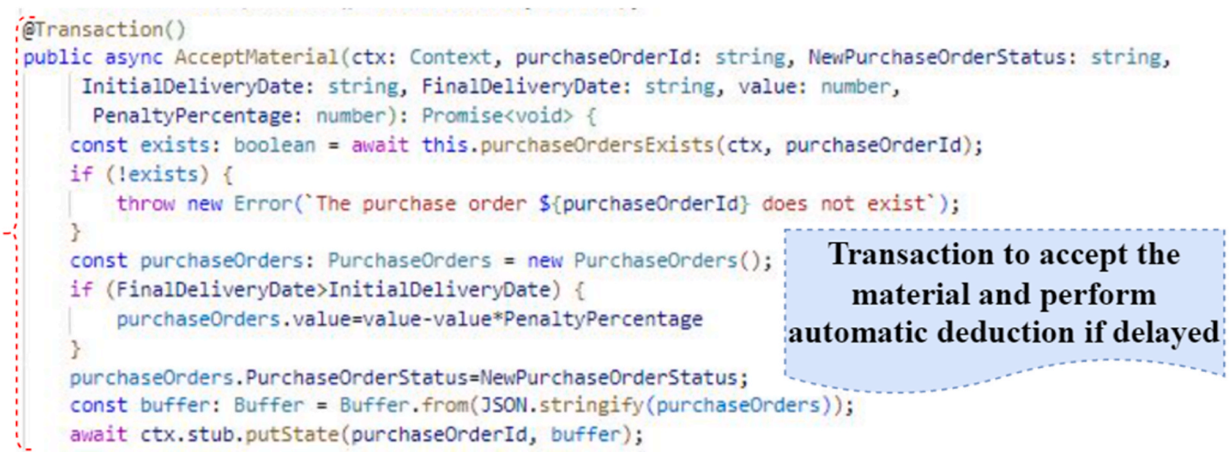

Fig. 9. Part of the function smart contract chaincode for material approval function.

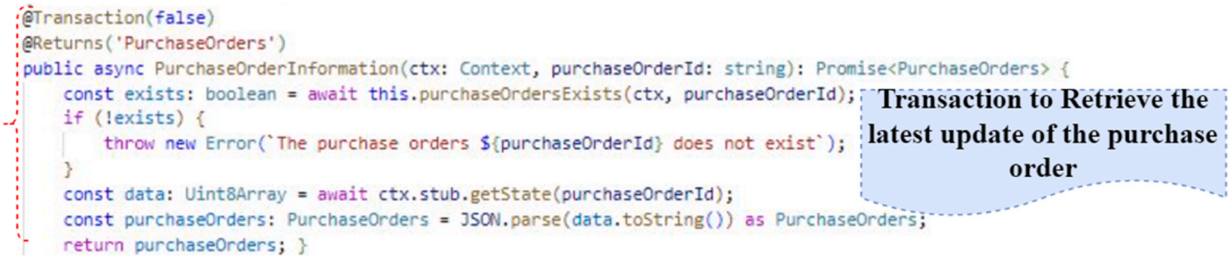

Fig. 10. Part of the function smart contract chaincode for the material approval function.

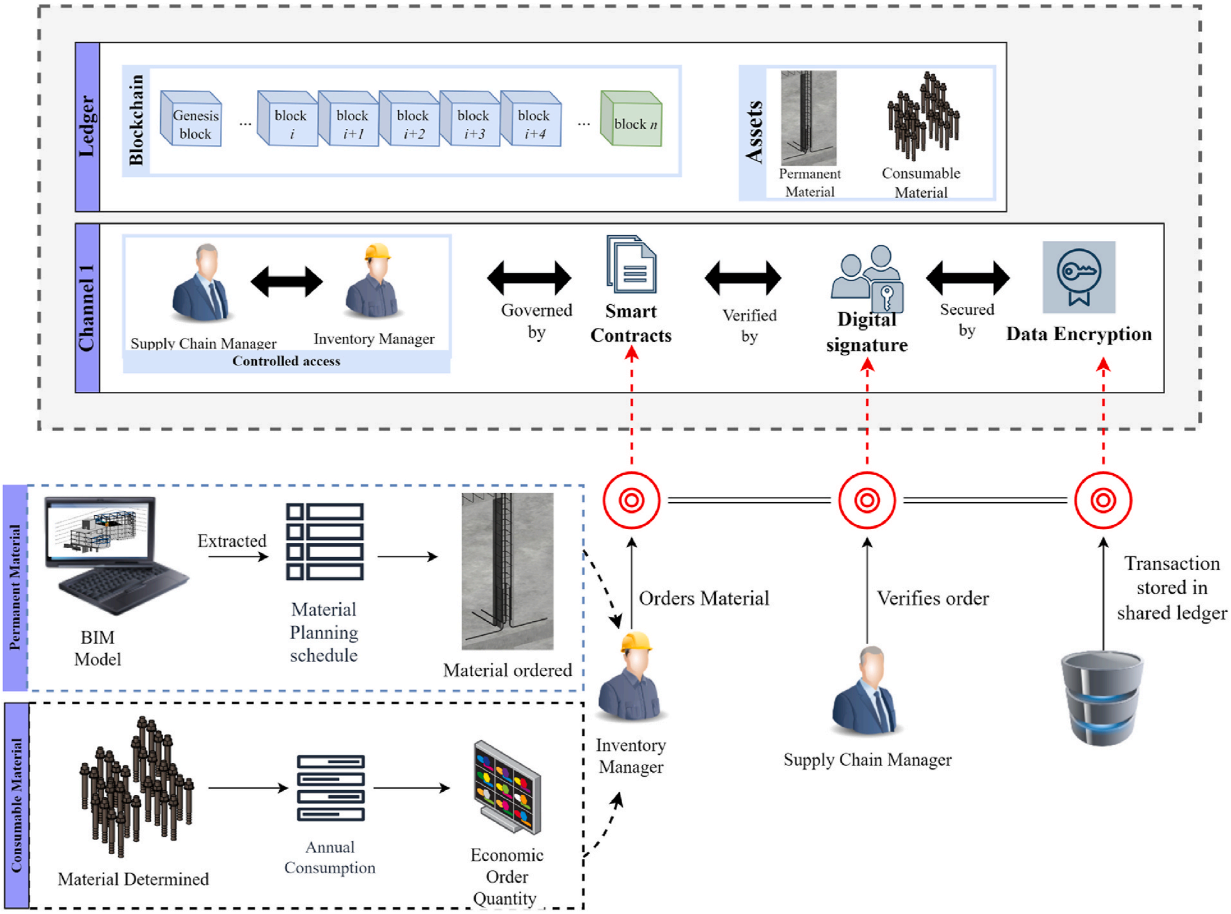

Fig. 11. Inventory Management function architecture.

On the other hand, the endorsing peers for "Material production" are 1) the Supply chain Manager and 2) the logistics provider. A state-based endorsement policy can be used for each function to overcome this issue. In this case, the state-based endorsement permits overriding the chain code-level endorsement policy and defining an endorsement policy for each function. This modification is considered part of the read-write transaction.

Fig. 14 shows the adjusted endorsement policy in the blockchain network to enable the supply chain manager and the logistics company as the endorsing peers for the "Material Production" function to maximise transparency and security.

4.4. *Alignment of the proposed solution with the different material management stages*

As it can be seen from Fig. 15, the proposed solution took into consideration the different stages of the material management process, starting from the strategic planning for purchasing, acquiring the material, and controlling the material flow. The network is developed at the end of the planning stage by adding the supplier into the network and creating separate channels with each supplier. At the acquiring stage, the solution provides detailed real-time material tracking. Furthermore, the material is controlled by a semi-

Fig. 12. Part of the Inventory management function smart contract's chaincode.

automatic process based on integrating the 4D BIM model and incorporating the Economic order quantity equation for ordering material.

4.5. Case project

To effectively convey the solution to potential users in a straightforward manner, an illustrative project case was employed to showcase the proposed resolution. In this scenario, a major infrastructure contractor secured a contract for the initial phase of a multi-billion-dollar gas power plant project. The scope encompasses various tasks, including project site preparation and the delivery of five Gas Turbine Generators' Reinforced Concrete Foundations. This involves a substantial amount of materials, totaling 10,000m3 of concrete, 1000 tons of T25 steel reinforcement, and the installation of 1400 M36 Anchor Bolts.

The client oversees the engineering aspects of the project, having developed a 3D Building Information Modeling (BIM) model, shared with the primary contractor. However, crucial project milestones were missed due to material shortages and miscommunication in the material supply chain. Consequently, the main contractor opted to leverage Blockchain technology to improve collaboration and information sharing within the supporting material supply chain. Additionally, the main contractor faces challenges in maintaining the client's trust, stemming from failure to adhere to monthly plans and provide accurate information about material status. Another issue arises from delayed payments to suppliers, a result of flawed communication between the inventory manager and the quantity surveyor, leading to intentional material delays from the steel reinforcement supplier.

In the proposed solution, the Supply Chain Manager extracts steel reinforcement quantities from 4D BIM models. Based on developed schedules, materials will be ordered. The envisioned Blockchain network will include key stakeholders such as the client representative, supply chain manager, inventory manager, steel reinforcement supplier, logistics provider, quality control inspector, and quantity surveyor.

4.5.1. The blockchain network

As mentioned in the previous section, the proposed blockchain network will be composed of seven members, as shown in Fig. 16.

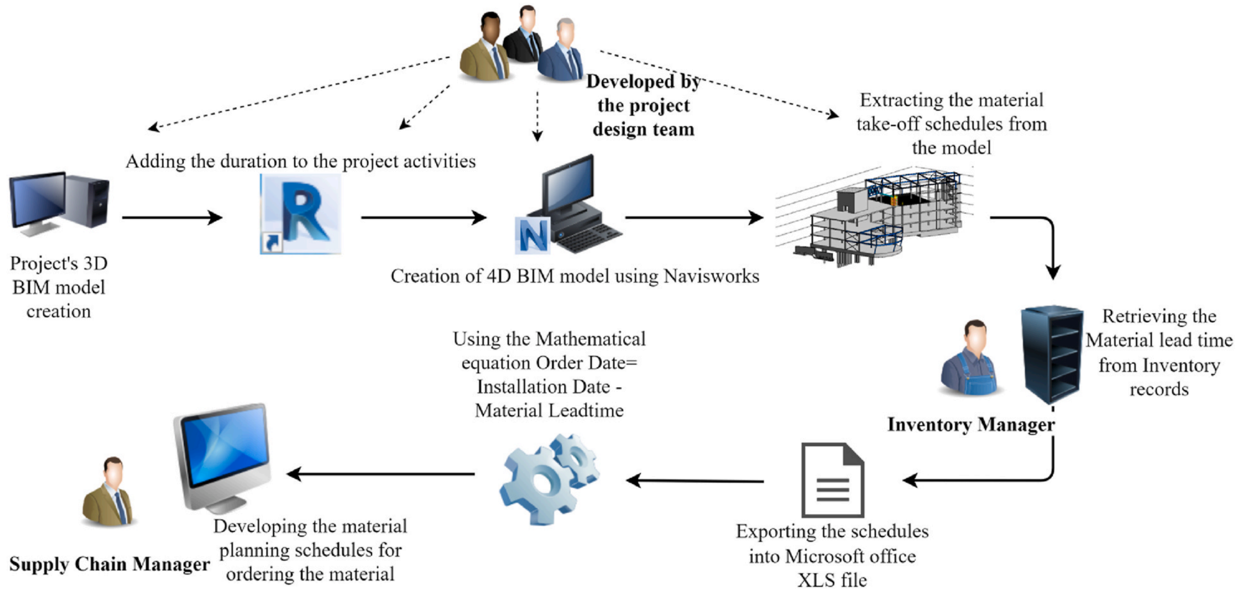

Fig. 13. Integrating 4D BIM model into the proposed solution to prepare Material Planning Schedules.

```
const ep = new KeyEndorsementPolicy()
ep.addOrgs('MainContractorMSP.peer,LogisticsCompanyMSP.peer');
await ctx.stub.setStateValidationParameter(thePurchaseOrderId, ep.getPolicy()
```

Fig. 14. Adjusted endorsement policy for 'Material Production' function.

The snapshot from the IBM blockchain platform shows the prominent members collaborating in this network. Moreover, it shows each organisation's Certificate Authority (CA), which is used to add new members to the network. Fig. 16 presents the four organisation profiles added to the network. Since four of the peers are part of the main contractor's team, only the main contractor's organisation is shown in the figure. The nature of private data sharing between the same organisation members was considered while developing the solution. Therefore, two channels were created. Channel-1 consists of the main contractor's supply chain manager and the inventory Manager to share the Inventory information without intervention from other peers. Similarly, Channel-2 was created to share information about the purchase orders' status between the concerned stakeholders.

Moving forward, Fig. 17 represents the channel peers of the created communication channel-1 and the channel member of the communication channel-2, respectively.

4.5.2. 4.8 scenarios evaluation

4.5.2.1. Purchase ordering tracking. In order to test the developed solution in a real-life scenario, the below assumptions were made.

1) The main contractor wants to supply the steel reinforcement for one Gas Turbine Generator Steel.
2) The quantity of the rebar would be 250 Ton of T25 rebar size.
3) The steel supplier is pre-qualified and considered one of the main contractor's approved vendors.
4) The purchase order value would be £125,000, assuming that one Ton of T25 sold for £500.
5) The agreed-upon delivery date between the steel supplier and the supply chain manager is 15/08/2022
6) The purchase order payment would be 30 days after the material's delivery and acceptance.

Upon receiving the purchase order, the steel supplier will start the production of the material and initiate the "Material production" function assuming the following.

1) The rebar production will start upon the receipt of the Purchase order.
2) The expected collection data of the material is 13/08/2022, as shown in Fig. 18.

Whenever the material is ready for collection, the steel supplier uses the "Transport Material" function to ask the logistics provider to confirm collecting the material at a specific date. In this demonstration, the following assumption is considered.

1) The collection date has been changed to 15/08/2022.

Upon material delivery, the quality control inspector will conduct a thorough examination, and the inventory manager will utilise

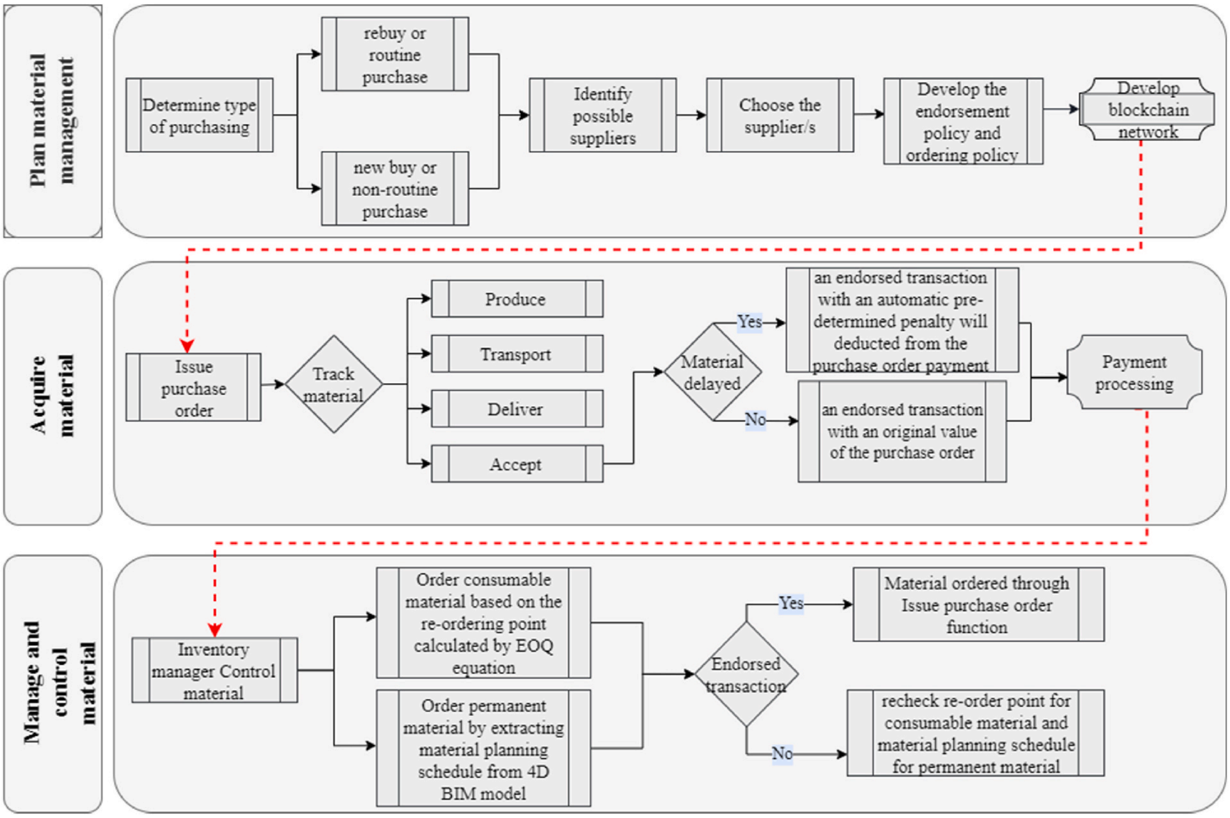

Fig. 15. Alignment of the proposed solution with different material management stages.

the "Accept material" function to officially acknowledge the quality control inspector's approval.

It's crucial to note that the material's final delivery date is set for 17/08/2022, whereas the initially agreed-upon date was 15/08/2022. Consequently, assuming a 5 % material delay penalty stipulated in the steel supplier agreement, an automatic deduction has been applied to the final value of the Purchase Order. With this adjusted final value, the quantity surveyor will initiate the payment process 30 days following the actual material delivery date.

4.5.3. *Inventory management functions*

To test the inventory management functions, the below assumptions will be made to test the consumable material ordering function.

1) The Historical annual consumption of Safety Protective helmets for a similar construction project was 4000 units.
2) The Ordering cost for each Purchase Order is £700
3) The unit price for the protective helmet is £15.
4) The holding cost for each unit equals = the unit price x Carrying cost (interest rate). The interest rate is assumed to be 15 %
5) The economic order quantity for the abovementioned parameters would be 1,577 units, which can be translated to making two to three purchase orders annually.
6) The required quantity is 1600 units to check if the transaction will be successfully made or rejected for exceeding the economic order quantity. Refer to Fig. 19.

However, the transaction was successful when the requested quantity was changed to 1500 units, as shown in Fig. 19.

5. Usability test

A usability test seeks to assess how effectively a specific group of users can navigate a system to achieve defined objectives within a given context, simultaneously gauging their satisfaction levels, as outlined in BS EN ISO 9241–11:2018. To gauge the usability of the proposed system, eight construction supply chain experts were invited to participate in the study. These evaluators were tasked with providing feedback through a pre-distributed questionnaire, meticulously designed to capture their insights on the system's usability. The questionnaire's queries were structured to align with the usability evaluation standards set forth in BS EN ISO 9241–11:2018.

The selection of interviewees was grounded in their expertise in construction projects, proficiency in materials supply chain dynamics, and familiarity with employing digital technologies in construction endeavors. The characteristics of the interviewees are

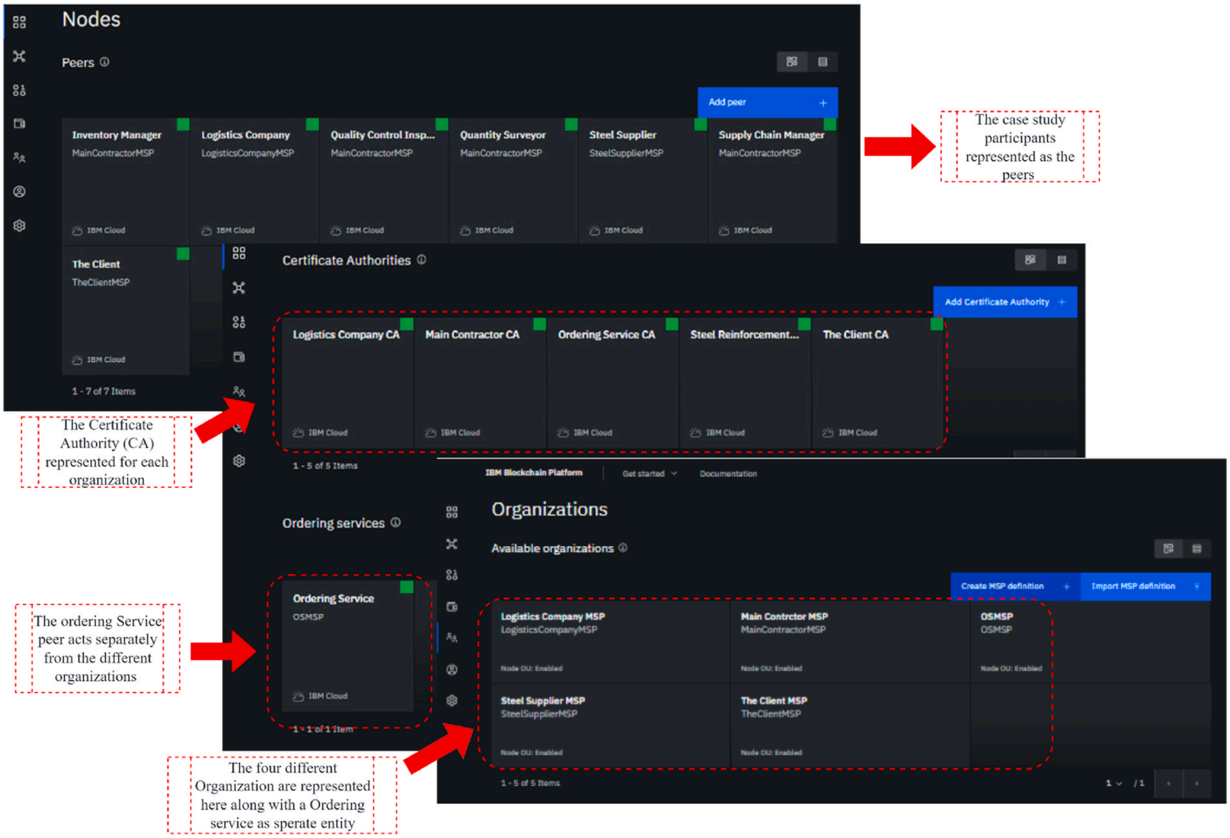

Fig. 16. Peers, Certificate Authorities (CA), and the organisations in the proposed network.

detailed in Table 2.

The interviews started with an introduction to the developed solution and an elaboration of a project case that would be used to demonstrate the developed solution. After that, A real-life construction material supply case was presented to the interviewees. During the interviews, the participants were encouraged to ask questions to ensure precise information communication. A short questionnaire was sent to the interviewees to evaluate the solution's applicability and usability in construction projects.

The analysis of the interviewees' feedback revealed a positive experience with the solution, demonstrating effectiveness, efficiency, and high user satisfaction. Furthermore, unanimous consent from all eight interviewees affirmed the solution's applicability and validity within the construction industry. The average rating for applicability and usability, as provided by the eight interviewees, stands at an impressive 4/5.

Summarizing the interviewees' responses, key points emerge: (1) The solution contributes to heightened material visibility and trackability, (2) Facilitates enhanced collaboration within the construction supply chain, leading to improved decision-making, and (3) Delivers heightened transparency and traceability of information.

For instance, U5 commented on the benefits gained from using the solution:

"Seamless transfer of information, transparency and improved material control and trackability."

The sixth user, U6, highlighted the benefits of using the system in a construction environment: "The provided concept aims to create a transparent collaboration environment between all the concerned parties. This is highly required in any business, increasing stakeholders' commitment, liability and efficiency."

Given the fact that the employees came from different geographical backgrounds and with different experiences in the construction industry. The interviewees could share their recommendations for improving the solution in future iterations. For example, the third user U3 recommended integrating the solution with ERP and accounting system, saying:

"Integrating the platform with ERP and accounting system."

Another area of improvement was suggested by the first user U1, regarding the solution's interface, commenting:

"Increased visualisations of the program in terms of user friendly".

6. Discussion, originality, and practical implication

The proposed chained material management system provides an innovative way to deal with different construction material challenges. The suggested solutions came to answer the following challenges.

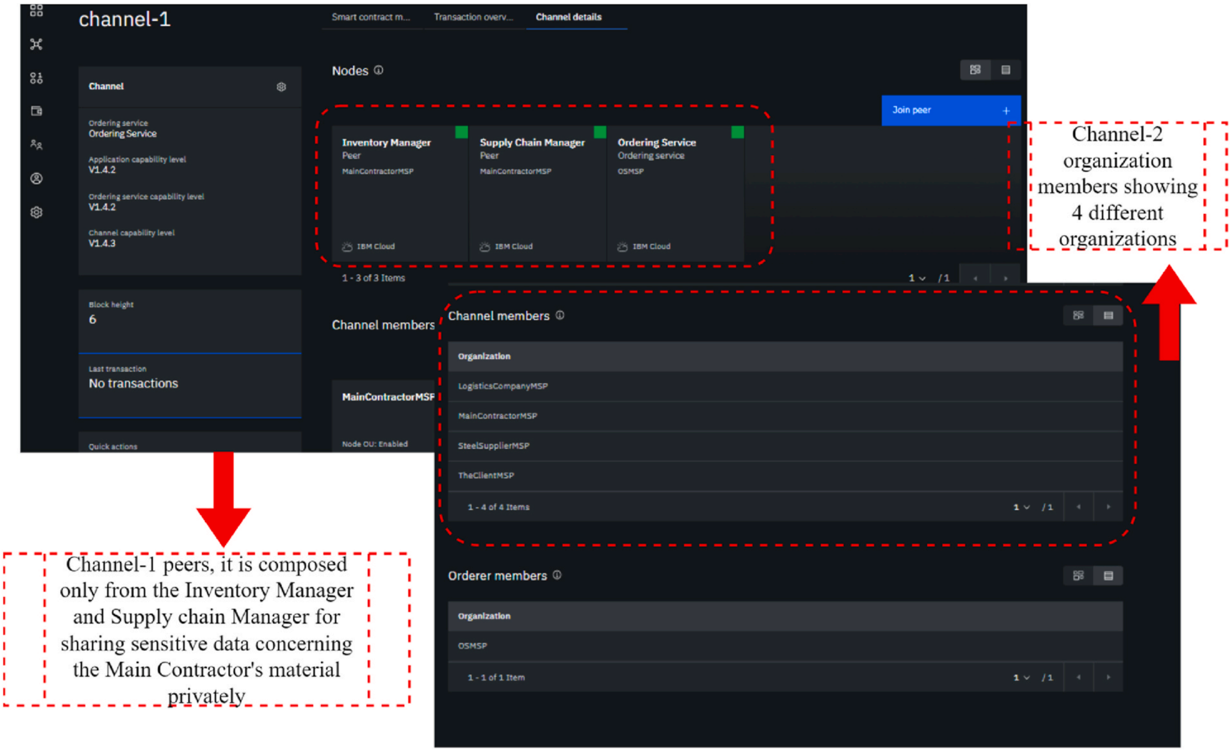

Fig. 17. Channel-1 nodes and Channel-2 organization members.

- **Construction material delays:** In reviewing the literature, it was unveiled that the primary reasons for material delays are the logistics of transporting/delivering the material and poor material planning/scheduling. The proposed solution was designed to minimise the material delays from logistics issues. This is represented in the proposed transactions, which are directly determined to include the logistics provider as an integral part of the created network. Moreover, the proposed transactions counted on the logistics provider's affirmation of the Issue Purchase order, produce material, transport material, and delivery material transactions. Therefore, including the logistics provider as the network's leading actor will minimise unexpected material delays and enhance the decision-making process, reflected in improved site activities planning and scheduling.

Furthermore, the solution tackled the area of poor material planning and scheduling as one of the main reasons for material delays. This is demonstrated by integrating the 4D BIM schedules in a semi-automated material ordering process. This process introduced the material ordering dates based on the available material installation dates extracted from the 4D BIM model and previous project data on the lead time of the material.

- **Legal disputes in construction supply chains:** It was revealed during the literature review that legal dispute is one of the main reasons that hinder collaboration in construction supply chains. However, the very nature of the blockchain-based solution promotes open information sharing between project parties since all the purchasing process status changes are visible and stored in a shared ledger between all the network participants. Having said that, this feature would reduce the material-related conflicts between project parties generated from the rooted blame culture.
- **High total material costs:** Bildsten and Manley [32] suggested an eight-stepped process to source construction materials starting from identifying the need to supply material and ending the process by following up with the supplier to ensure delivery. Van Weele [31] matched the formers with a five-stepped process to source the material. All these process steps will contribute to forming the total material costs. The more complicated the process, the higher the total cost of the material. Although these relatively similar processes seem to serve the need, the solution proposed a different approach by developing a smart contract function to manage the Economic Order Quantity (EOQ), which resulted in decreasing the number of repetitive purchase orders.
- Consequently, this will eliminate the non-value, time-consuming activities performed on repetitive orders. Moreover, in its designed nature, the proposed solution promotes establishing long-term relationships with the suppliers, which will be reflected in fewer suppliers. This will reduce overhead costs associated with qualifying, registering, and boarding a supplier.

Moreover, this solution incorporated a delay penalty equation for the delayed deliveries to deduct a pre-agreed percentage from the purchase order payment automatically. The delay penalty is usually found in end-users and suppliers' purchase order agreements. That being said, the automatic delay penalties will decrease the total material cost by reimbursing the main contractor some of the incurred costs of missed project deadlines due to the absence of material.

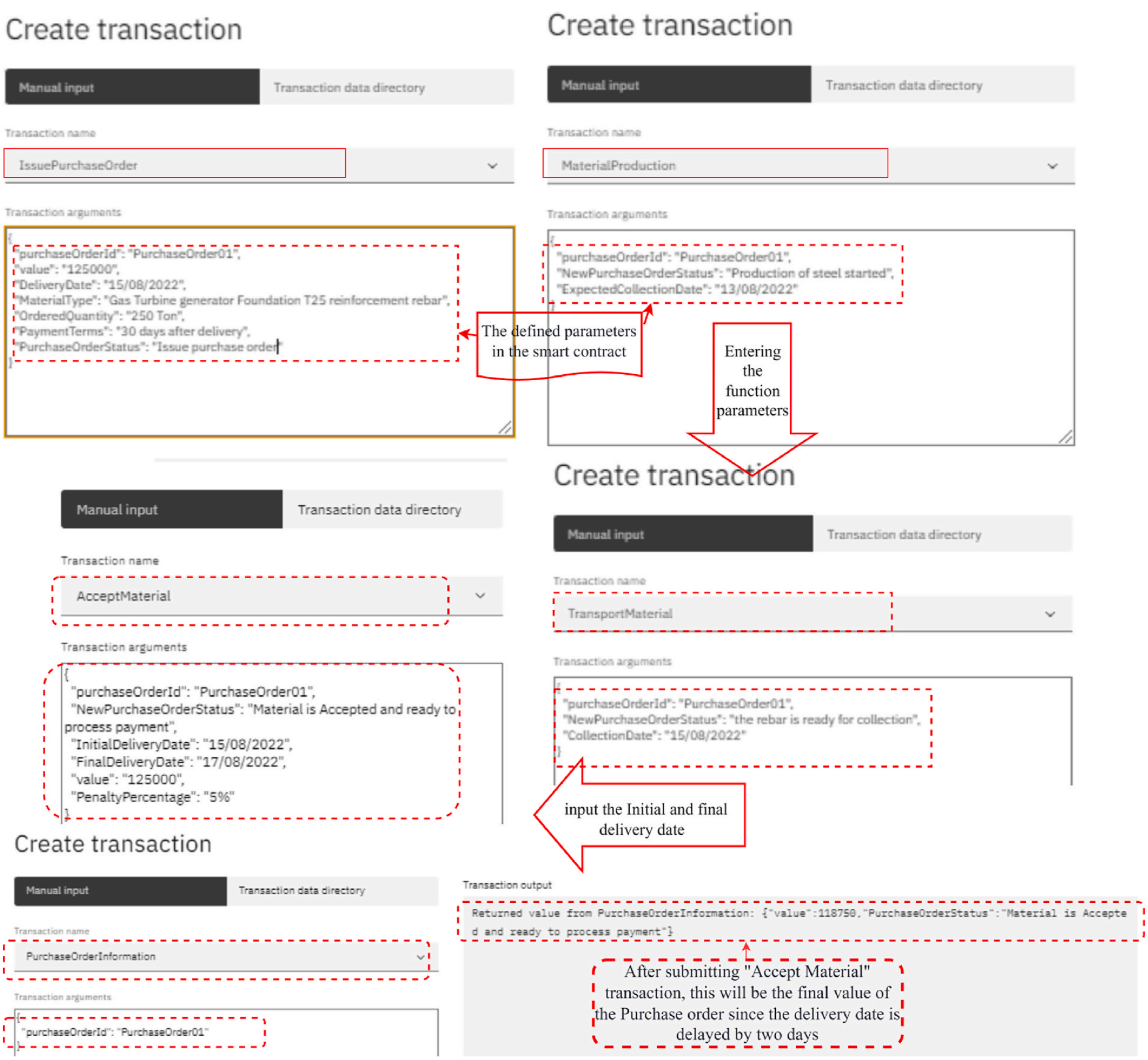

Fig. 18. Performing Issue purchase orders, Material production and Transport Material transactions.

- **Inventory space management:** The proposed solution managed inventory by proposing two functions: one for ordering consumable material and the other for ordering permanent material. While the consumable material is easily forecasted in construction projects based on the annual consumed quantities, the coded EOQ equation into the smart contract permits keeping the stock level of the ordered material at the highest. Inventory management functions in the created chained smart contract addressed ordering permanent material using the prepared Material planning schedules. This process adopts the principles of lean construction and JIT delivery by determining the optimal order date. Employing this process will decrease the holding costs of the material significantly by eliminating the risks of material expiration, storage overhead costs, and material double-handling costs.
- **Fragmentation, Poor information sharing in construction supply chains:** Existing literature review shows that fragmentation [29], lack of trust [7], and information silos are the greatest challenges in the construction supply chain, which hinder the flow of information and proper communication channels between the project participants. In the proposed solution, the inherent nature of the blockchain-based network enhances transparency, open information-sharing, and establishing trust between the project members. This will ultimately enhance collaboration since all the material-related information is shared between the project members.

This research proposes a first-attempt, novel material and inventory information management blockchain-based solution. The proposed solution utilises blockchain technology and smart contract solutions to address the lingering construction material supply chain challenges. Some researchers have attempted to solve construction supply chain challenges using blockchain. For instance, Wang et al. [14] developed a blockchain solution for improving information management in the precast branch of construction. However,

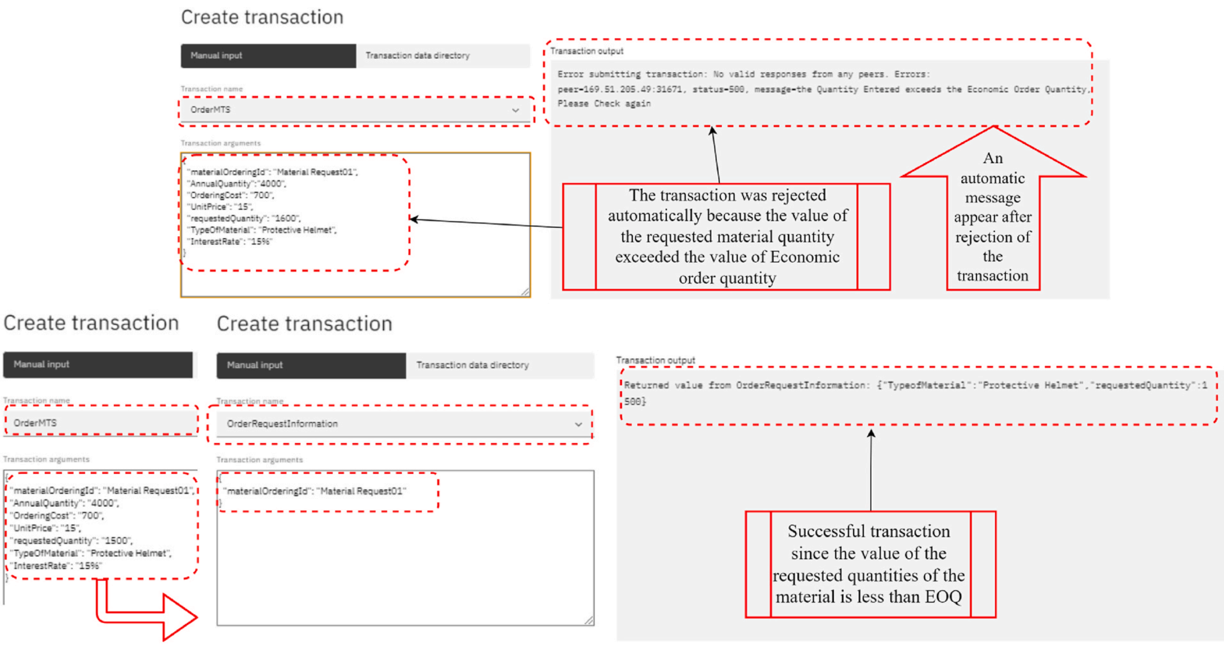

Fig. 19. "Order Consumable material" transaction.

Table 2
The characteristics of interviewees.

Code	Position	Years of Experience	Type of Organisation
U1	Sr. Projects Engineer	+15	Main Contractor
U2	Sr. Projects Engineer	6–9	Main Contractor
U3	Project manager	10–15	Main Contractor
U4	Construction Sales Director	10–15	Construction Supplier
U5	Projects Control Lead	6–9	Main Contractor
U6	Project Manager	10–15	Consultant
U7	Project Manager	10–15	Consultant
U8	Project Controls Manager	10–15	Main Contractor

this attempt is strictly tailored to the precast industry and does not take a holistic view to include the overall construction material supply chain.

The proposed solution was designed to fit practically in the construction project environments where consumable and permanent construction material was included. Moreover, the proposed solution was a first in automating the process of ordering consumable material based on the coded economic order quantity equation. The proposed solution provides a workable proof of concept for construction industry practitioners to manage material information efficiently in the volatile construction environment. That is achieved by proposing a process to record and share all the information related to the material purchase orders between the network participants solving the rooted problem of lack of trust between project members [7]. That will transform the construction project setting from a competitive blame culture to a collaborative unit working together to achieve mutual benefits for all parties. Moreover, adopting this solution will raise the possibility of gaining the benefits mentioned in the previous section 6.2 from enhanced deadline achievements, reducing the legal disputes between project parties, and reducing the total cost of the material.

Additionally, the proposed blockchain-based solution provided a proactive resolution for the security and reliability of the material shared information [75], as any status change on the material shall be approved by the designated parties and reflected in the shared ledger. Therefore, this will reduce tampering with the posted data and fraud attempts in construction projects.

This solution covered the aspects of material management of planning, sourcing, and managing the material through the alignment of Inventory management activities with the purchasing, tracking, and real-time status update of the material. The inventory management limb of the solution was designed to balance the inevitable human judgment and the scientific approach combined with automation for ordering the material. That was achieved by utilising BIM 4D models to create accurate, up-to-date material planning schedules for ordering permanent material and coding the most Economical order quantity equations into the smart contract to ensure lower purchasing costs for purchasing consumable material.

Similarly, the material tracking limb was designed to leverage blockchain characteristics through complete transparency between the network participants while giving the option to create separate channels to tailor the shared information with the participants. Moreover, the limb was designed to track all the real-time status updates of the material throughout the sourcing stage while giving the option to verify the status changes by the authorised network member.

This study takes a forward step, built on the previous research attempts to promote the utilization of blockchain technology benefits in inventory and material management in construction projects. It opens the doors of the construction industry to the vast horizon of transforming the numerous conceptual studies of utilising blockchain in material management to an empirical stage with workable proofs-of-concept. That will contribute to optimising the process of supplying the material and pulling alongside the advances occurring in several industries.

7. Conclusion and reccomendation

Upon reviewing the existing literature, a series of challenges within the construction material supply chain have come to light. Foremost among these is the issue of material delays, which has been a recurrent concern in the literature due to its detrimental impact on labour productivity at construction sites. Furthermore, material delays result in disruptions to site activity scheduling and planning, leading to suboptimal decision-making and, in some cases, potential legal disputes among project stakeholders.

The adoption of blockchain technology has been proposed to address these challenges, driven by its inherent capabilities. First, blockchain enhances transparency among project stakeholders, enabling real-time access to material status information for all relevant parties. This eliminates the siloed information that has traditionally plagued supply chain operations. Secondly, blockchain technology facilitates the traceability of information, ensuring that every action impacting the material's status is meticulously recorded within a shared ledger among project participants. These advancements are anticipated to transform the project environment, shifting it from a culture of blame, where individuals seek to evade responsibility for their actions, to a collaborative environment where all work together to achieve the common goals of the supply chain.

The proposed solution offers a range of notable capabilities with the potential to significantly impact the construction industry's material supply chain. Its capacity to improve traceability and transparency of shared material information cultivates a collaborative and open environment among stakeholders, promising enhanced cooperation throughout the supply chain process. Through the informed participation of blockchain network members, the solution effectively mitigates material delays, ensuring smoother project operations, minimizing disruptions, and promoting efficiency. Furthermore, its ability to substantially reduce the incidence of legal disputes is underpinned by the secure and tamper-proof storage of information within shared ledgers, fostering a high level of accountability and trustworthiness. The integration of EOQ approach within blockchain smart contracts streamlines procurement processes, resulting in a noteworthy reduction in purchase orders and associated overhead costs. The potential imposition of automatic penalties on delayed material payments contributes to increased material value and reduced waste. Additionally, the solution's alignment with Just-In-Time (JIT) principles in permanent material ordering leads to improved inventory management and a decrease in holding costs. These multifaceted capabilities hold the promise of driving greater efficiency, transparency, and cost-effectiveness within the construction material supply chain, representing a significant advancement for the industry.

Similarly, the segment dedicated to tracking ordered materials is designed to ensure complete transparency among network participants. It also offers the option to create separate channels for tailoring shared information to specific participants. Furthermore, this component tracks real-time status updates of materials throughout the sourcing stage, allowing for verification or rejection of actions by pre-agreed network members. These features promote a collaborative environment within the project and minimise disputes stemming from material delays, as all actions are stored within a shared ledger, with the source of status changes known to all. Moreover, this segment provides full material information visibility, surpassing existing industry solutions.

In light of the above, this research represents a significant advancement. It introduces an innovative approach to recording and tracking material information within construction supply chains, offering full traceability and transparency. Furthermore, this solution marks the development of a functional blockchain and smart contract-based proof-of-concept in construction material management, moving beyond mere conceptual studies as demonstrated in subsequent steps. Additionally, the proposed solution offers a novel attempt to harness blockchain technology features to address the challenges of material supply and management within construction supply chains. While existing research has explored blockchain applications in various branches of construction supply chains, such as financial transactions, design information management, and quality information management, the literature review has revealed a scarcity of research focusing on material information management.

The practical applicability, validity, and effectiveness of the proposed solution were assessed using a real-life project case. Through the simulation of hypothetical material orders within the developed solution, it became evident that the solution could perform its intended tasks seamlessly. Subsequently, the solution was presented to eight construction supply chain professionals, who expressed high satisfaction with its use. They also confirmed its applicability within construction environments and highlighted several key benefits, including reduced material purchasing costs, fewer legal disputes among project parties, and improved decision-making.

With these findings in mind, future research should consider conducting longitudinal studies to confirm the long-term benefits of blockchain-based material management solutions throughout a project's lifecycle. Furthermore, the integration of emerging digital technologies into material management in construction should be explored. For instance, the incorporation of IoT sensors and RFID, combined with blockchain technology, can enable automated inventory monitoring and the issuance of purchase orders to prospective suppliers. Another potential avenue for future research involves combining blockchain with digital twins to provide a comprehensive and transparent visualization of materials for project stakeholders. These endeavours hold significant potential to further enhance the efficiency and effectiveness of construction material supply chains.

Author statement

Mohammad Bashir: Conceptualization, Methodology, Software, Validation. Faris Elghaish: Supervision, Writing – original draft, Conceptualization, Validation. Farzad Pour Rahimian: Visualization, Writing – review & editing, Methodology. Tara Brooks: Visualization, Writing –original draft. Chansik Park: Visualization, Writing – review & editing.

Declaration of competing interest

The authors confirm that all funding agencies have been properly cited and acknowledged in this paper. It is also confirmed that all authors agreed with the current version and revisions and there is no conflict of interest among all authors or with third parties with respect to this paper.

Data availability

No data was used for the research described in the article.

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LIST OF ABBREVIATIONS

CSC	Construction Supply Chain
BCBS	Blockchain Based Solution
BCN	Blockchain Network
JIT	Just in Time
EOQ	Economic Order Quantity
BIM	Building Information Modelling
CAD	Computer-Aided Drafting
4D	Fourth Dimension
IoT	Internet of Things
ATO	Assemble-to-Order
MTO	Make-to-Order
ETO	Engineer-to-Order
GIS	Geographic Information System
DSR	Design Science Research
H&S	Health and Safety
RFID	Radio Frequency Identification
IT	Information Technology
GPS	Global Positioning System
CDE	Common Data Environment
AI	Artificial Intelligence
API	Application Programming Interface
PO	Purchase Order

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