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Developing a BIM Single Source of Truth Prototype Using Blockchain Technology

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Abstract: Blockchain technology has been proposed as a potential solution for coordinating information and trust to aid the development of a single source of the truth data model, going beyond peer-to-peer cash transactions. It is, therefore, argued that the construction supply chain (CSC) will resolve issues related to the lack of reliable platforms for construction and asset management operations once blockchain technology and Building Information Modelling (BIM) are integrated. Though there is no longer any debate about the importance of integrating blockchain technology with BIM, there is still a lack of academic literature on its proof of concept. This study aims to create a thorough proof of concept for integrating blockchain technology and BIM for supply chain data delivery. It demonstrated a step-by-step methodology starting from understanding the current business scenario and proposing logical system architecture, followed by selecting a blockchain platform, designing system architecture related to technologies, prototyping, and evaluating through a virtual business scenario. The software prototype presented in this paper helps establish the technological viability of a single source of the truth data model for integrating blockchain technology and BIM. The supply chain data delivery for handover was considered in this software prototype. However, the process used to create this software prototype can be replicated in future work on blockchain technology-based built environment applications or digital transformation in the built environment research.

Keywords: BIM; blockchain; construction supply chain; single source of truth; software prototype

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1. Introduction

Construction is a project-based industry [1] where stakeholders temporarily come together to complete one-off projects [2–6]. Construction projects encounter performance-related challenges throughout asset management operations, final product quality, and stakeholder conflicts [7]. For instance, a subcontractor typically has no direct obligations to anyone other than the main contractor [2]. Therefore, the construction industry has become less trustworthy with more adversarial relationships, which is considered an obstacle to industry performance and innovation [1,8]. Adopting digitalized and smart solution tools will assist in resolving performance issues and contribute to the success of construction projects by increasing industry productivity [9]. However, Mason and Escott [10] stated that transitioning to the smart construction industry still has a path full of challenges due to the traditional procurement mindsets and lack of mature/trusted methodology to enable this. Perera, Ingirige [11] stated that the efficiency of the data workflow and the ability of stakeholders to have a transparent data exchange are critical factors in enabling information and communications technology (ICT) in the construction supply chain (CSC).

Building Information Modeling (BIM) is widely acknowledged as the primary driver of the industry's digital transformation [12,13]. There have been previous studies that used BIM in the CSC to accomplish integrated information delivery all the way through the project's life cycle [3,9,14,15]. Globally, BIM plays a crucial role in facilitating the digitalization of design and related workflow in the construction industry [14–17]. Through BIM coordination tools and collaboration processes, CSC stakeholders are better informed of one another's activities [18]. There are still several obstacles to the widespread use of BIM in supply chain operations, including the construction industry's inherent complexities, a lack of openness, adversarial relationships, fragmented data, and disputes among players [2–5,8,13,14,19,20]. Because "*Construction Operation Building Information Exchange*" (COBie) data is maintained centrally by a single actor, disagreements arise across CSC parties and prevent BIM from being a legally recognized delivery model [4,8,15,19]. Furthermore, BIM tools cannot generate digital proofs for various transactions [21]. In addition, traceability issues and the inability of BIM to contain all project compliance and product data are also among the limitations of BIM [14]. Deng, Ren [22] emphasized that any future framework for the CSC's BIM integration must include trust as a prerequisite for effective communication between project stakeholders. Consequently, any future CSC research should take reliable data exchange into account.

Blockchain technology has been heralded as revolutionary [4,23–25] and is set to upend many facets of enterprises that rely on coordinating information and trust to allow a trustworthy database architecture with multiple control entities [26,27]. Blockchain is a type of distributed ledger technology, which securely records information in cryptographically sealed blocks replicated across a peer-to-peer network [14,27,28]. Due to its tamper-resistant properties and suitability for data auditability and transparency, blockchain is being recognized by a growing number of sectors as a key innovation with a trusted data exchange platform [14,27,29]. However, according to "*Australia's Department of Industry, Science, Energy, and Resources National Blockchain Roadmap*", the construction industry is lagging behind other industries in terms of the proportion of business activities involving blockchain technology [30]. For the design and development phases of a BIM model, existing academic studies have validated the authoring copyright, but not the ownership of CSC product data or the supply and manufacturer data node (*which includes production data, compliance data, reliability data, maintenance, and warranty*) [21,31,32]. Due to poor CSC data quality and reliability, the advancement of BIM implementation for operations may not produce the desired results for its higher levels of digitalization [8,12,19,33], as it is not possible to act on a digital asset that cannot be trusted [33].

This study aims to create a prototype proof of concept for integrating blockchain and BIM for construction supply chain data delivery. The software prototype presented in this paper helps establish the technological feasibility of a single source of truth model for integrating blockchain technology and BIM. The concept of a single source of truth model was borrowed from the ICT sector [34]. The "*single source of truth*" is defined as an "*authoritative source of its data that offers data services to other entities while ensuring that business entity decisions are based on the same datasets*" [34–36]. This paper demonstrates a step-by-step methodology starting from understanding the current business scenario and proposing logical system architecture, followed by selecting a blockchain technology platform, designing system architecture related to technologies, prototyping, and evaluating it through a virtual business scenario. The process stated by Qing and Yu-Liu [37] detailing the development of software prototypes was used in this research for developing a software prototype. The scope of this paper is limited to the delivery of CSC data in preparation for handover and operation. Because it does not influence the supplier and manufacturer data node for the handover stage, Building Information Modeling (BIM) for the design stage, which is where the process is centered on BIM 3D model authoring, is excluded.

The paper is structured as follows. First, the authors conduct an in-depth analysis of the current situation of BIM and blockchain integration to investigate how blockchain technology might be used to solve the issues faced by the CSC (Section 2). Then, the authors introduce the research method, design, and tools for the BIM single source of truth prototype model development using blockchain technology (Section 3). Next, the paper presents step-by-step software prototype development and how it was comprehensively evaluated to ensure the accurate execution of the smart contract using a virtual business scenario that included external validation (Section 4). Following that, the discussion is presented, including practical implications, managerial insights, limitations of this study, and future research directions (Section 5). Finally, the authors present the conclusions and contributions of this study (Section 6).

2. Literature Review

Though there is no longer any debate about the importance of integrating blockchain technology with BIM, there is still a lack of academic literature on its proof of concept [38–41]. By demonstrating the reliability of the construction supply chain data across all supply chain actors, the integration of blockchain technology and BIM has the potential to alter the definition of BIM supply chain data delivery for facility management from information-centered 3D modeling based on coordination tools to a trusted data exchange model based on a reliable workflow [3,36,42]. However, most academic literature has used hypothetical cases to support this integration, with a significant gap in software prototype approaches [43]. Future works are recommended to demonstrate a step-by-step methodology of integrating BIM and blockchain technology to help various practical scenarios, given that BIM is the best route to implement any emerging technology in the construction industry [28,44,45]. Perera, Hijazi [28] presented a step-by-step methodology for implementing a blockchain in a built environment, which helps to provide the foundation for developing technological feasibility of proofs of concept relevant to land registry transactions; however, the proposed model does not deal with supply chain data. The proposed model [28] could result in introducing blockchain to solve transparency challenges in some built environment applications. Still, data source affects adoption, and this is where BIM needs to be in action with blockchain to create reliable supply chain data [27,35]. Regarding this, Li and Kassem [46] stated that the construction industry is not yet sufficiently digitized to fully benefit from blockchain technology. Due to this, there is still a lack of maturity in the use of blockchain technology with BIM for supply chain data delivery [14,47–49].

Current academic literature focuses primarily on how this integration may occur, presenting blockchain as a new technological tool only for aiding transparent transactions for BIM 3D modeling files in the form of "*project-centric*" 3D modeling files [32,46,50]. Celik, Petri [51] proposed a blockchain technology-based BIM model; it integrates by saving the IFC (Industry Foundation Classes) file hash code (a BIM file) and its action using smart contracts. However, this integration approach drastically restricts the utilization of blockchain technology's potential for value transfer in the form of a digital ecosystem of connected databases with multiple control entities; it also isolates BIM delivery in siloed electronic files, such as Revit files [8]. Revit is one of part of the BIM software that includes 3D modeling graphical and non-graphical information to enable the project delivery through coordination by avoiding gaps and overlap in team members' work utilizing an electronic file-based model [52]. The integration needs to ensure an ecosystem of linked databases within the blockchain technology (a decentralized database) to be connected, not isolated, to BIM (a centralized database) [36,50]. This results in the advancement of BIM delivery toward machine-readable datasets "*enabling an ecosystem of connected databases based on consistently organised dataset*s", as viable solutions for the automation of operations and facilities management [12,53]. A recent study by Hijazi, Perera [36] provided the data model for integrating BIM with blockchain technology to help construct organized and trustworthy datasets for BIM supply chain data delivery; nevertheless, the study does not illustrate in-depth validation of the suggested model and its technological feasibility. In the industrial scenario, "*BIMCHAIN*" was developed by a French startup that presents a solution for integrating blockchain technology capabilities with BIM [21,35]. It intends to generate digital evidence of different BIM transactions. However, the blockchain technology in this scenario only keeps a hash of the digital Revit file's alteration record, not the actual data update, which means a single party (the model authoring stakeholder) is responsible for reconciling diverse BIM transactions. Thus, this solution might validate the 3D BIM model authoring file copyright for the design delivery [21], or ensure a confidentiality-minded framework between the project members in case of a sensitive BIM design collaboration model [54], but not the ownership for the supply chain product data where there are multiple control entities in the 3D BIM model during the handover phase [8]. Copyright is only one type of intellectual property (IP) protection; the contract could ensure it as it comes under the responsibility definition, such as the case of the Construction Industry Council (CIC) BIM protocol, which detailed how the BIM model and objects should be created, and where BIM delivery is still struggling to be reliable by ensuring the ownership of the supply chain product data [36,55].

A blockchain platform is one of the most secure database platforms because it is a decentralized and distributed database, and its data is immutable [3,46,56]. Therefore, the blocks (i.e., transactions) within a blockchain platform are copied across numerous computers, ensuring that the data contents of each block cannot be modified. Moreover, the algorithm can verify and validate the block's proof-of-work by itself [23]. In contrast, Coyne and Onabolu [57] stated that the blockchain struggles to overcome the privacy issue. There are different blockchain platforms available. "*Ethereum*" is the first public blockchain platform to allow smart contracts for general consumption, and it is now utilized mostly by the financial industry [29,50,54,58–60]; however, it is not appropriate for many types of businesses, such as the construction industry, where data privacy is crucial [28,50]. Thus, the blockchain should guarantee the veracity and accessibility of information while protecting its confidentiality [3,45,61]. Privacy and identity management methods have and will continue to have a substantial influence on business blockchain development [62]. Thus, the "*FIBREE*" blockchain industry report [63] strongly recommended "Hyperledger Fabric" as a blockchain platform with private permissions to meet the privacy requirements for a broad range of industry use cases, including data transactions in the construction industry [60,64]. Multiple software development kits based on modular and pluggable components [50,64] are provided by Hyperledger Fabric to accommodate varied applications and ease participant buy-in [60]. Section 3 explains why Hyperledger Fabric blockchain technology was selected as the best platform for constructing a system prototype that integrates BIM and blockchain technology.

A smart contract can be programmed to process a self-executing contract by translating the rules from the terms of the agreement into lines of code using a "*Generalized Adaptive Framework*" (GAF) [65] for a neutral data standard, such as the "*International Foundation Class*" (IFC). This allows for the automation of code verification procedures for routing data that must be stored in the blockchain network. The suggested GAF concept for automated processes entails the construction of a computable representation of predefined laws, as well as means for transferring data between the framework's various components (blockchain network) and BIM data [66]. A further approach might be a smart contract that secures the enforceability of transparency by executing the CSC data, thus making the CSC data immutable and accurate. The prototype proposed in this article implemented the second alternative by directly linking CSC data from external entities to a blockchain network and implementing transactions on top of a blockchain ledger using a smart contract solution. The section that follows describes, in detail, the methodologies used to illustrate the technical viability of a single source of truth approach for integrating BIM with blockchain technology.

3. Research Method, Design, and Tools

The development process of the software prototype follows the procedure stated by Qing and Yu-Liu [37] for the development of software prototypes. Several other researchers, such as Perera, Hijazi [28], Xue and Lu [67], and Ahmadisheykhsarmast and Sonmez [68], working on blockchain at the application layer, have also used similar developmental steps. Thus, we designed the development process of the BIM single source of truth prototype using blockchain by performing the following steps: understand the current business scenario and propose logical system architecture, select the blockchain platform, design the physical system architecture related to technologies, and develop the prototype and evaluate it, as illustrated in Figure 1 and described below.

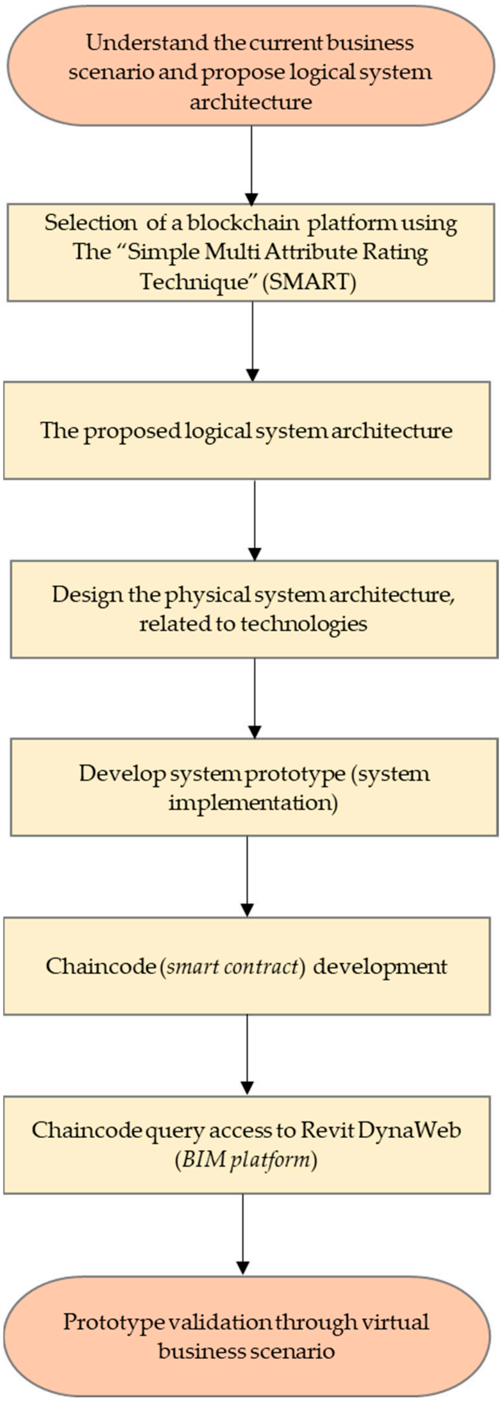

Figure 1. The development process of the BIM single source of truth prototype using blockchain technology.

To understand the current business scenario, the data flow diagram (DFD) was used to structurally identify the existing process of the BIM construction supply chain data delivery by describing data flows of a system at various detail levels and propositioning logic models that express data transformation in a system [36,37,69,70]. The information delivery for the current business scenario is set up to work in line with the "*Common Data Environment* (CDE)" workflow, which was outlined in "*ISO-19650 Part 1, Section 12*", and

"*BIM maturity Level 2*" deliverables adhere to the guidelines of the "*PAS 1192-2-2013*". The current business scenario is described in Section 4.1 and the proposed system overview for the logical system architecture, independent of technology is elaborated in Section 4.2.

The "*Simple Multi-Attribute Rating Technique*" (SMART), which is a common tool for assisting in correct decision-making to solve a problem and find the best solution [71], was used to rank and identify the most suited blockchain platform among the identified platforms. Permissioned networks were chosen as the best sort of blockchain for CSC data transactions because stakeholders should be identified and held responsible for their conduct. For CSC activities, the blockchain database for a project contains sensitive information that organizations intend to keep private, such as commercial information [72]. As a result, the list of candidates with blockchain platforms included *Corda R3* [73], *Elements* [74], *Hyperledger Fabric* [75], *IBM Blockchain* [76], and *NEM* [77]. The Hyperledger Fabric blockchain platform was chosen as the best fit for the defined needs since it obtained the greatest value. In its design and implementation, the Hyperledger Fabric architecture provides great levels of flexibility and secrecy, making it applicable in a wide range of environment applications [25,50,78,79]. It aids in attaining privacy since it needs permission to read and write through the permission model, which is characterized by the capacity to modify the state of the ledger community [79].

By separating transaction processing into three steps, the Hyperledger Fabric design provides auditability. Phase one: utilizing distributed logic processing via Chaincode services to create a smart contract, which is the business logic code of a transaction on the Hyperledger Fabric platform; phase two: utilizing transaction ordering via consensus services to create blocks of transactions and facilitate network trust; and phase three: transaction validation via membership services [50,80,81]. The outputs of the selection of a blockchain platform, *the Hyperledger Fabric*, directly contributed to the system architecture (Section 4.3). This step includes designing the physical system architecture, identifying the technology that will be used, and determining where the described system processes used Hyperledger Fabric terminology. According to the process flow stated by Qing and Yu-Liu [37], the next step in developing system architecture is validation by developing a system prototype including the "*process sequence*", which is a process planning of a successful transaction within the system prototype for integrating BIM, blockchain, and Chaincode (smart contract) development, as explained in Section 4.4.

Finally, the software prototype was comprehensively evaluated to ensure the accurate execution of the smart contract using a virtual business scenario that included external validation. The attributes of the virtual business scenario were set to conduct the test run. Cladding attributes, as a sample of the CSC data delivery, were considered the CSC element to execute the smart contract. The cladding has become an incandescent topic of attention in several countries as an example of a CSC object that is not considered a "structural" part of the building [82], but it could cause a threat to the safety of the residences during the operation phase [83], such as what happened at the Grenfell Tower (London), which led to an unprecedented loss of life [84,85], and the fire incidents at the Lacrosse Apartment Building (Melbourne) and the Torch Tower (Dubai), which led to unavoidable multi-million-dollar bills for property owners [83]. Even when several ad-hoc actions have been implemented to combat non-compliant cladding products, the Australasian Procurement and Construction Council mentioned that more than 50% of cladding products might still be non-compliant, with the majority of stakeholders completely unaware of the financial burden it could present [83,86]. Keeping the preceding discussion in mind, cladding was deemed an excellent example for the virtual business scenario to help introduce a BIM single source of truth prototype using blockchain. The external entity's (supplier) role was performed by the researchers, whereas the main contractor's role was performed by a participant organisation. The protocol for the virtual business scenario, selection criteria, data collection, data analysis, and the test case and its results are explained in detail in Section 4.5.

4. Develop, Validate, and Test the Proof of Concept

4.1. The Current Business Scenario

In the main process of the current BIM supply chain data flow, the BIM model is developed during a project's construction phase in response to requirements set out in the "Employer's Information Requirements" (EIR) to work in line with the Common Data Environment workflow, which is outlined in "ISO-19650 Part 1, Section 12", and "BIM maturity Level 2" deliverables adhere to the guidelines of the "PAS 1192-2-2013 specification for information management for the capital/delivery phase of construction projects using building information modelling". In this process, suppliers are required to prepare an IFC file for the product data (CSC element) to be sent to a subcontractor or consultant (the author of the IFC BIM model). The "BIM execution plan" (BEP) then details how the 3D BIM model is to be delivered to the client through the main contractor in order to fulfill the client's asset information demands (AIR). In the construction phase, the "responsible" party is the main contractor, who is in charge of coordinating the transfer of the federated 3D BIM model used to create the "asset information model" (AIM). This process is decomposed into three main subprocesses. The first subprocess (Process 1.0) is to acquire CSC data. Each task team is required to send the IFC model data to the main contractor through the CDE. This subprocess will create considerable ambiguity about the ownership and authoring liability of the IFC data between the suppliers, subcontractors, and the main contractor for the CSC elements and/or model. The second subprocess (Process 2.0) is to review the CSC data provided by the main contractor and share it with other appropriate task teams or delivery teams or with the appointing party. In this subprocess, the main contractor is responsible for managing the construction phase's workflow and for transferring the federated BIM model to generate the AIM. As they are not responsible for the model components, there is a benefit in preserving an immutable record of where the CSC model elements were obtained. The federated BIM model must reflect the facility as built and be enhanced with CSC data (as defined in the EIR) before being "published" as the third subprocess (Process 3.0). In this subprocess, the AIM is derived through a combination of federated BIM model deliverables and COBie datasheets, all of which are underpinned by Uniclass 2015. As mentioned in Section 2, BIM is yet to be considered a reliable delivery model, as the COBie data are "centrally stored" by a single actor [3,4,10,15]. In this scenario, the main contractor has three subprocesses for acquiring the CSCs that were developed by their originator or task team (consultants, subcontractors, or suppliers). Process 1.1 will be decomposed into three child diagrams (subprocesses), Process 1.2 will be decomposed into six child diagrams, and Process 1.3 will be decomposed into six child diagrams, as illustrated in Figure 2. The decomposition involves the top-down development of a DFD to reduce the complexity of the system [37]. This will help to provide a clear picture of the existing information delivery system (existing work packages) and create a functional process network for developing the proposed model. It will also demonstrate the relationship between the CSC stakeholders and how the function of reconciling different data is still usually undertaken by one or a limited number of parties. This is a key point in understanding how the proposed solution needs to be adapted to the existing work packages. However, analyzing information delivery for more than one CSC element to aid in the understanding of the existing information delivery system would be redundant, as all elements have the same work package. A single CSC element can be used to mimic the current data flow.

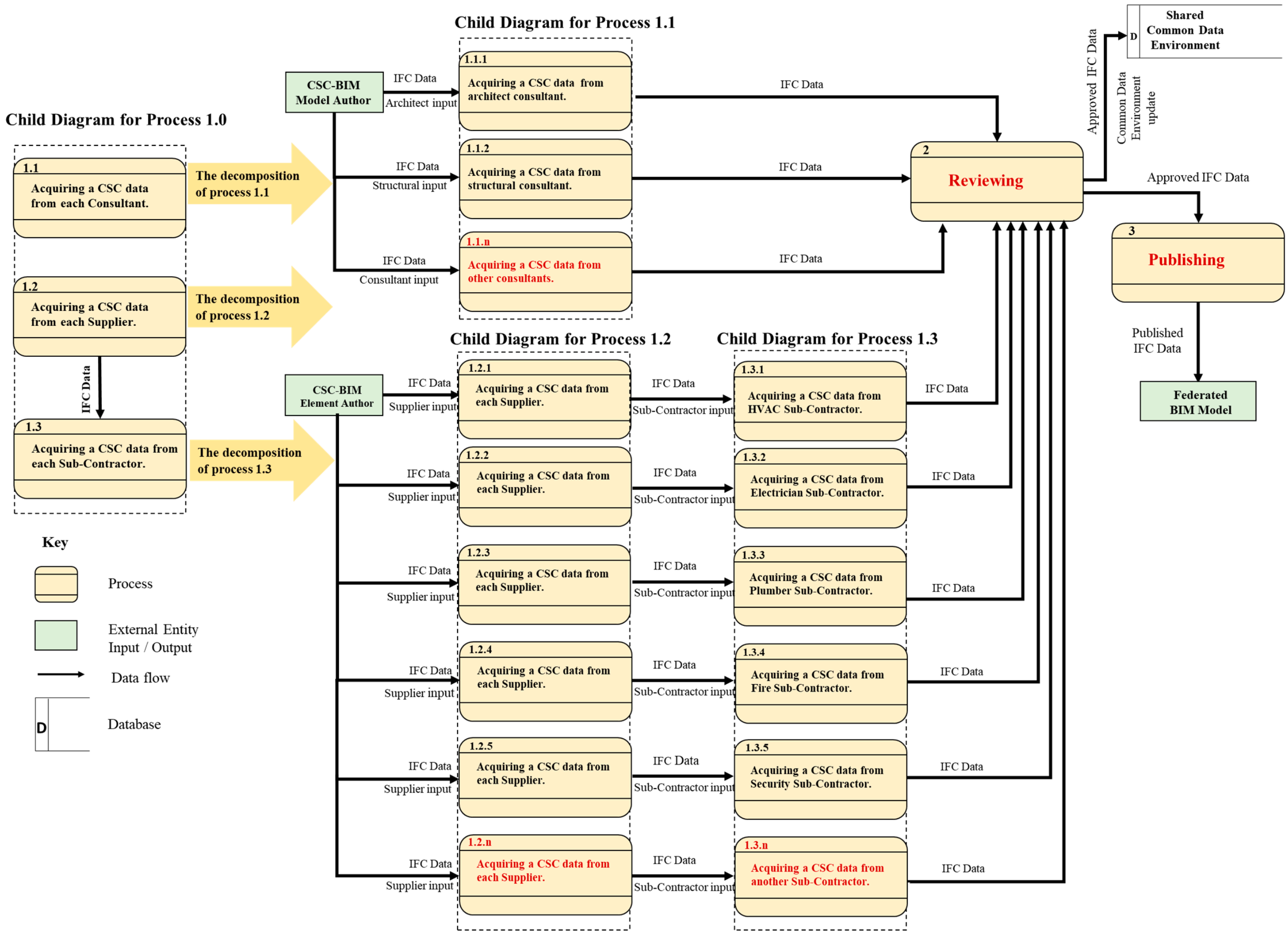

Figure 2. The data flow diagram (DFD) for BIM construction supply chain data delivery.

4.2. The Proposed Logical System Architecture

In the proposed logical system architecture, independent of technology, as illustrated in Figure 3, the CSC external entities, including consultants, sub-contractors, and suppliers, deploy CSC data directly to a blockchain using a smart contract. As discussed in Section 2, the proposed prototype in this study would directly connect supply chain data from "*external entities*" to a blockchain by deploying transactions on top of the ledger utilizing a smart contract method.

In order to centrally link the supply chain data delivery that is operating in blockchain in a BIM platform, blockchain and BIM are connected through a "*REST Application Programming Interface*" (API) that allows access to the CSC data transaction. This allows for the blockchain to centrally link the supply chain data delivery that is operating in blockchain. This subprocess makes it possible to quickly retrieve the history of the data delivery throughout a supply chain for a project. Subsequently, the findings of the selection of a blockchain platform were utilized to translate the independent system architecture (logical system architecture) into the software components of Hyperledger Fabric (*physical system architecture related to technologies*), which will be explained in the following sub-section.

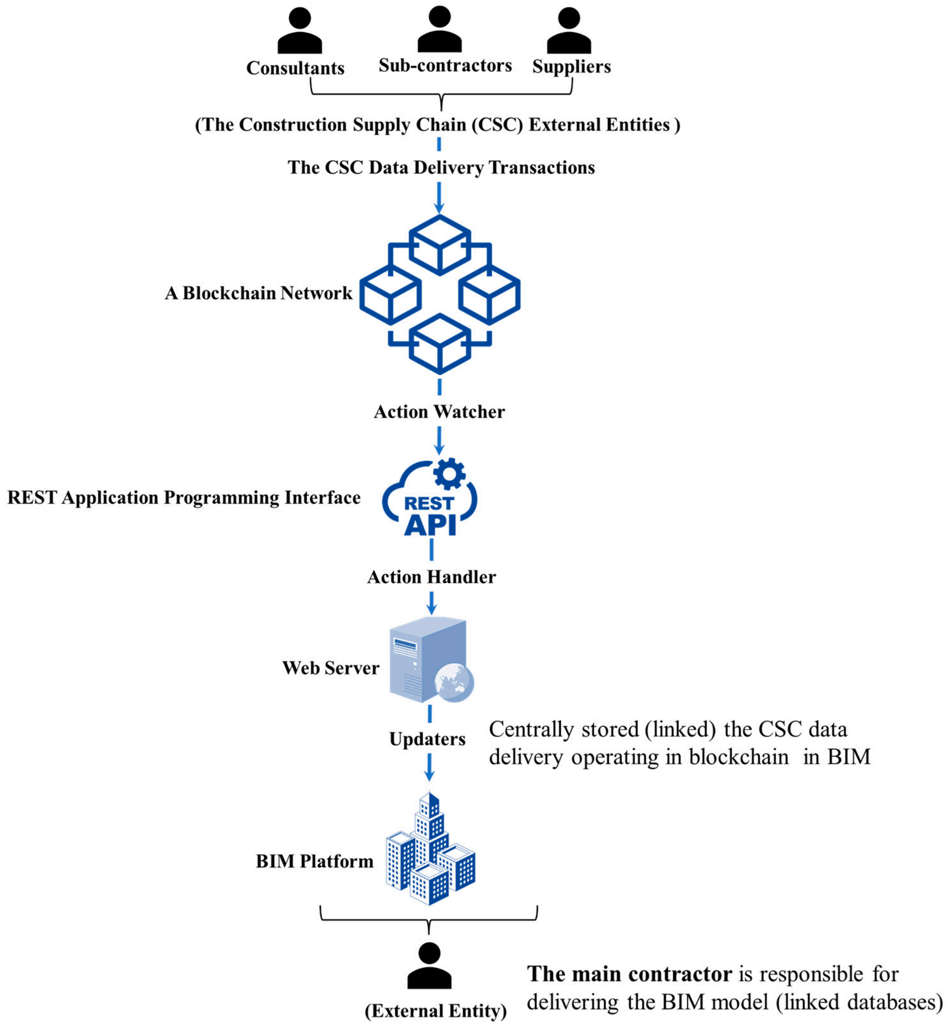

Figure 3. The proposed logical system architecture is independent of technology for the BIM single source of truth prototype using blockchain technology.

4.3. The Proposed Physical System Architecture

The physical system architecture related to technologies has the same components as the logical system architecture: the blockchain network, the REST Application Programming Interface (API), the web server, and the BIM platform. However, the components are demonstrated with a particular technology with sufficient detail for system implementation in the physical system architecture.

In the "*physical system architecture*", the client or system user "*external entity*" refers to an application that is separate from the blockchain and that connects to the ledger in order to perform supply chain data transactions [75]. All authorized prototype users will have immediate access to the blockchain through the "*Node.js console application*" or via graphical user interfaces in the client application, the "*Node.js web application*". For this technologically-related physical system design, the Node.js console application is made available for authorized users so that they may interact directly with the blockchain via the usage of the console [87]. The ordering service and the peers who each have a copy of the ledger and Chaincode are connected to one another over the blockchain network. The BIM platform "*Revit DynaWeb*" accesses the blockchain system using the REST API, supported by a web server on the local machine, providing easy access to the project's CSC data history recorded in the blockchain. It is crucial in today's web-enabled world to provide machine-readable forms of text content, commonly in "Extensible Markup Language" (XML) [88]. The physical system architecture is illustrated in Figure 4. In a blockchain system, the user (client application) initiates communication with the blockchain. The Chaincode (smart contract) is executed, which comprises the application logic for the CSC attributes' smart contract, in order to obtain or update ledger data (depending on the data model requirements).

(Step 1) The command to invoke the chaincode is known as a transaction proposal (the CSC attributes), which is sent by the client application (system user- external entity) to the endorsing peers on the blockchain network via Node.js console application.

(Step 2) The endorsing peers verify the transaction proposal and execute it by invoking the chaincode.

(Step 3) The endorsing peers create a proposal response including the transaction results and peer's signature and send it to the client application.

(Step 4) If the transaction proposal was only a query, the process ends by displaying the result to the user.

(Step 5) If a ledger update is required, the client application packages the transaction proposal and endorsed responses into a transaction and broadcasts it to the ordering service.

(Step 6) The ordering service receives transactions from the entire network, orders the transactions, and creates a block of transactions.

(Step 7) The ordering service transmits the block to the leading peer,

(Step 8) which then distributes the block to all the other peers.

(Step 9) The peers validate the transactions within the block and tag the transactions as valid or invalid. If the transaction is valid, then the world state is updated, whereas all valid and invalid transactions are added to the blockchain, which ensures auditability.

(Step 10) The peers emit an event to notify the client that the transaction is valid or invalid, and that it has been added to the blockchain, and the result is displayed to the user .

(Step 11) API Server Node runs the API Server code. The web server allows access to the data stored in the blockchain. This ensures that the proposed system architecture solution is vendor-agnostic.

Finally, ***(Step 12)*** the server code accesses Revit DynaWeb to enable the BIM user (external entity- sink) to access the data (CSC attributes). DynaWeb is a *dynamo* package providing support for interaction with the innerweb in general and with REST APIs in particular.

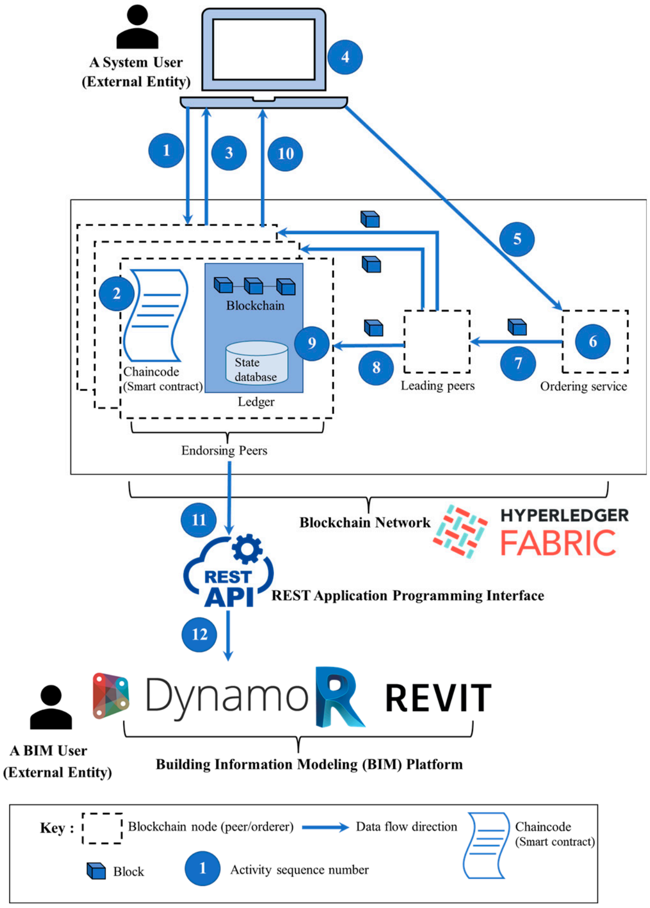

Figure 4. Physical system architecture for integrating BIM with the Hyperledger Fabric platform (*a blockchain technology platform*).

According to the process flow stated by Qing and Yu-Liu [37], the subsequent step to the development of system architecture is validation by developing a system prototype (system implementation) which will be explained in the following section.

4.4. System Prototype (System Implementation)

The system prototype is used to translate the validated data model into a technological solution utilizing the physical system architecture developed in the previous section. Figure 5 shows the steps involved in a transaction within the proposed system prototype, from the time a data owner (suppliers, sub-contractors, or consultants) invokes (writes) the on-chain attributes on the blockchain network to the time the on-chain attributes are centrally stored (linked) to the BIM platform by the main contractor. For simplicity, the interactions between the REST API and the web server were excluded from the diagram; these operations would occur between the API server node and the BIM platform. The prototype also handles unsuccessful searches and changes, albeit these procedures are not displayed in the figure for readability.

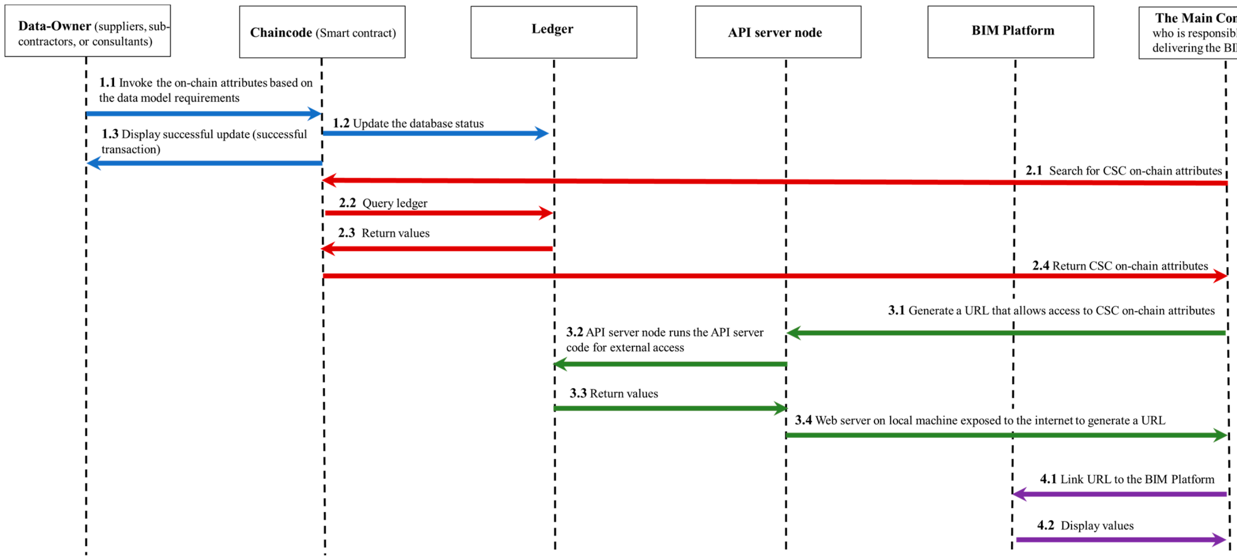

Figure 5. The process sequence for a successful transaction in the BIM–blockchain system prototype.Implementing the system prototype included installing "*Hyperledger Fabric v2.3.3* [89]", generating the network to implement and write a Chaincode (smart contract) using the "*JavaScript* [90]" programming language, and establishing an API server node to access "*Revit* [52] *DynaWeb* [91]". This section demonstrates and discusses the smart contract (Hyperledger Fabric Chaincode) development to hand over on-chain data delivery and is linked to the BIM platform, in this case "*Revit DynaWeb*", to provide ready access to the record of on-chain supply chain data delivery transactions.

4.4.1. Chaincode (Smart Contract) Development

In the Hyperledger Fabric network, the Chaincode can be written in one of the following programming languages: *Go*, *Java*, *TypeScript*, or *JavaScript* [92]. For this prototype, the *JavaScript* programming language was used to write the Chaincode (smart contract) to support the development of the system prototype for API applications. The Chaincode requires supply chain stakeholders to submit transactions using the invoke application to provide on-chain data. The query application assures the supply chain element's transaction history (amendment and revision) by using the Chaincode or smart contract. As illustrated in Figure 5, for the process sequence of a successful transaction, the query application return values provide ready access to the record of on-chain data delivery transactions. Given this, the primary methods used in the proposed Chaincode were defined below.

initLedgedr(ctx): The constraint *ctx* is a set of *ChaincodeStub* structures in JSON format. This function initializes on-chain data delivery based on the provided data model attributes (or the proposed business logic) in JSON format, and stringifies and stores all those data into *ctx* using <async> *putState* (key, value) [87]. Thus, to submit the on-chain CSC data transaction, ***invokeProcess (ctx, myArgs[0] . . . . myArgs[20])*** includes all the arguments (the data attributes of the business logic for the smart contract) that need to be entered by the CSC stakeholder passing through the Node.js console application. Suppose an argument (attribute) has been missed, or its value has been wrongly entered. In this case, the Node.js console application will display this message as a *console error* (*failed to submit transaction*). However, if it is run successfully, the Node.js console application will display this message as a *console log* (*transaction has been submitted*), as illustrated in Figure 6.

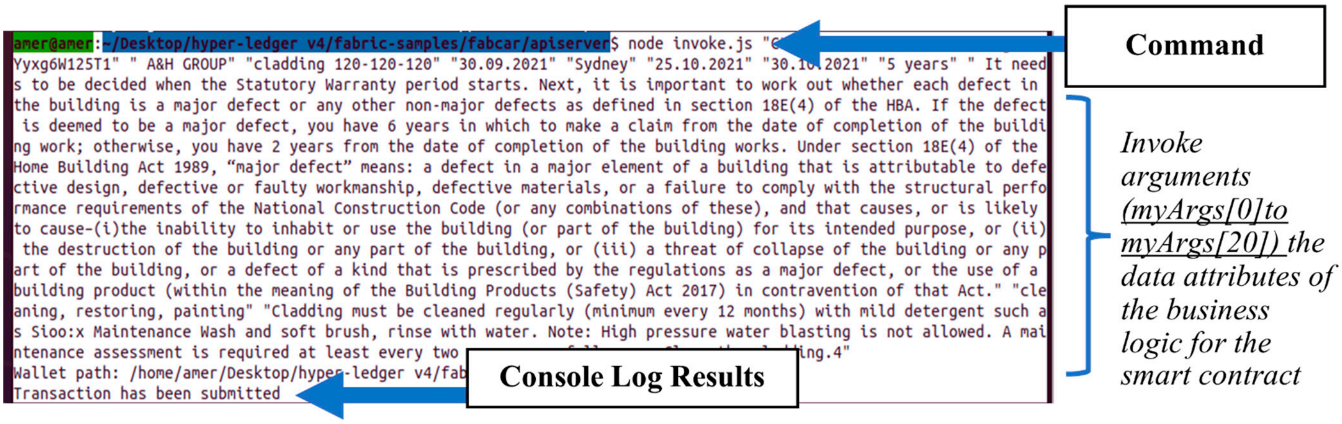

Figure 6. We invoked the application's arguments, as shown in the Git console.

queryID (ctx, myArgs): This method calls the return values for on-chain CSC data delivery attributes linked to a specific ***invokeProcess*** (submitted transaction) with the value of *myArgs* (a specific attribute) [75,87]. All values with that *queryValue* will be returned in stringified JSON format by calling <*async*> *putState*(key, value). To run this method, the *queryID* application needs to be passed through the Node.js console application. The return values are displayed on the Git console, as illustrated in Figure 7.

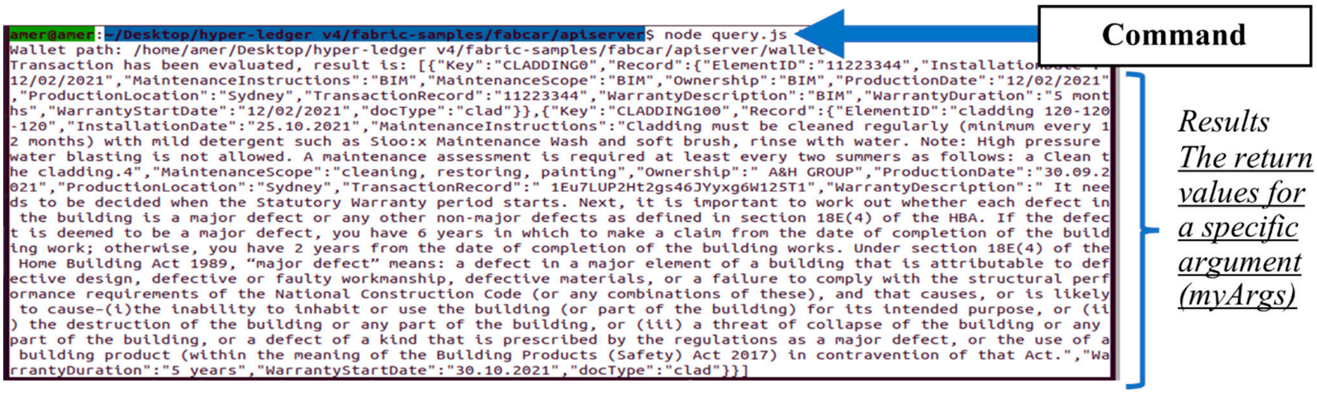

Figure 7. We successfully ran the queryID application and the return values for a specific argument, as shown in the Git console.

queryAll (ctx): In this method, all values (all on-chain CSC data delivery for a project) inside this blockchain will be returned after calling this method. To run this method, the ***queryAll*** application needs to pass through the Node.js console application. Once a block is created after running the ***invokeProcess*** application, it cannot be modified. However, a block can have more than one transaction, and tracking its history of transactions can be detailed after running the ***queryAll*** application.

The prototype API supports two methods. The first method, GET, returns values for CSC data delivery (return values of query application). The second method, POST, provides access to add a new record to the ledger. The supply chain element's transaction history may be shown using the GET method again (amendment and revision). To connect the API server node to Revit Dynamo (the next step, Section 4.4.2.), a web server solution was implemented. To enable access from the Internet to the machine, a reverse proxy, Ngrok, was used.

Then, the URL link generated by the reverse proxy was used to access the server. The operation ran successfully and the result was the HTTP request–response from other machines. At this level, the system prototype was dealing only with the blockchain platform and exposing a web server on the local machine to the internet for its return values of query applications. Given the physical system architecture, as explained in Section 4.4.2., the following sub-section demonstrates how the reverse proxy was linked to Revit DynaWeb to access the transaction (return values of query application) by the BIM user (external entity sink).

4.4.2. Chaincode Query Access to Revit DynaWeb (BIM Platform)

This section illustrates the last step required to centrally integrate (store) on-chain data delivery with the BIM platform or tools. "*Revit DynaWeb*" is used as a BIM platform to demonstrate this integration. As explained previously, *DynaWeb* is a "*dynamo package providing support for interaction with the interwebz in general and with REST APIs in particular*" [91]. Thus, it assists in retrieving (GET) information from the web and sending (POST) information to the web. It also contains some handy JSON de/serialization nodes for using web data directly in Dynamo graphs as native types [91]. Using DynaWeb, which is included in the Dynamo package, simplifies routine tasks by providing a centralized interface for linking on-chain data transfer with the BIM model (Revit model). Therefore, this solution guarantees that the distributed database (from the Hyperledger Fabric Network) may be linked to several BIM models (Revit models) to store supply chain data delivery. At the same time, the traditional BIM CDE will go operating as a hub for a network of datasets sources. The *Dynamo* workplace environment was accessed from the *Manage* tab in the *Revit* visual programming panel and by clicking on *Dynamo*. Then, the *DynaWeb* package was successfully implemented in the *Dynamo* workplace environment. The "*DynaWeb*" package includes "*WebRequest: the web request that gets executed*", "WebClient: the context in which a request is executed", "*WebResponse: this contains the response from the server as well as additional metadata about the response and server itself*", "*Execution: this provides nodes that simply execute requests, making it easier and clearer to use standard Hypertext Transfer Protocol (HTTP) verbs such as GET*", and the "*Helpers: a few helper nodes, with a particular focus on deserialisation*". In addition, the above *DynaWeb* package was extended to add new scripts (new nodes) to automate repetitive processes that check if the on-chain dataset has been linked centrally to the *Revit* model or not, as shown in Figure 8. To check if selecting a CSC element on the Revit model has linked the on-chain dataset (return values of query application), the watch function displays the message "*URL found and opened*" and, if it is not found, the watch function displays the message "*Valid URL not found*", as the on-chain dataset is not linked to this item.

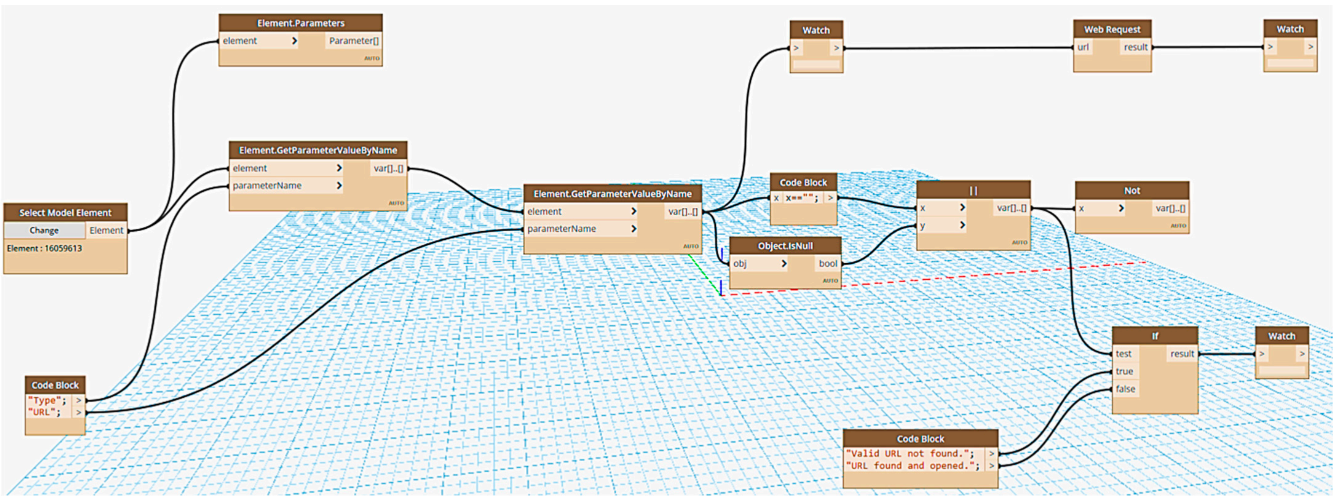

Figure 8. Implementation of the DynaWeb package in the Dynamo workplace environment.

Assimilating the above, the on-chain dataset based on the URL that was created from *Ngrok* (as explained in the previous Section 4.4.1) was copied in the *String* node, and the data resulted in the *Watch* box with JSON format. At the same time, as shown in Figure 9, the BIM user may access the on-chain dataset from inside *Revit* by selecting the element's attributes and then choosing the *URL property*.

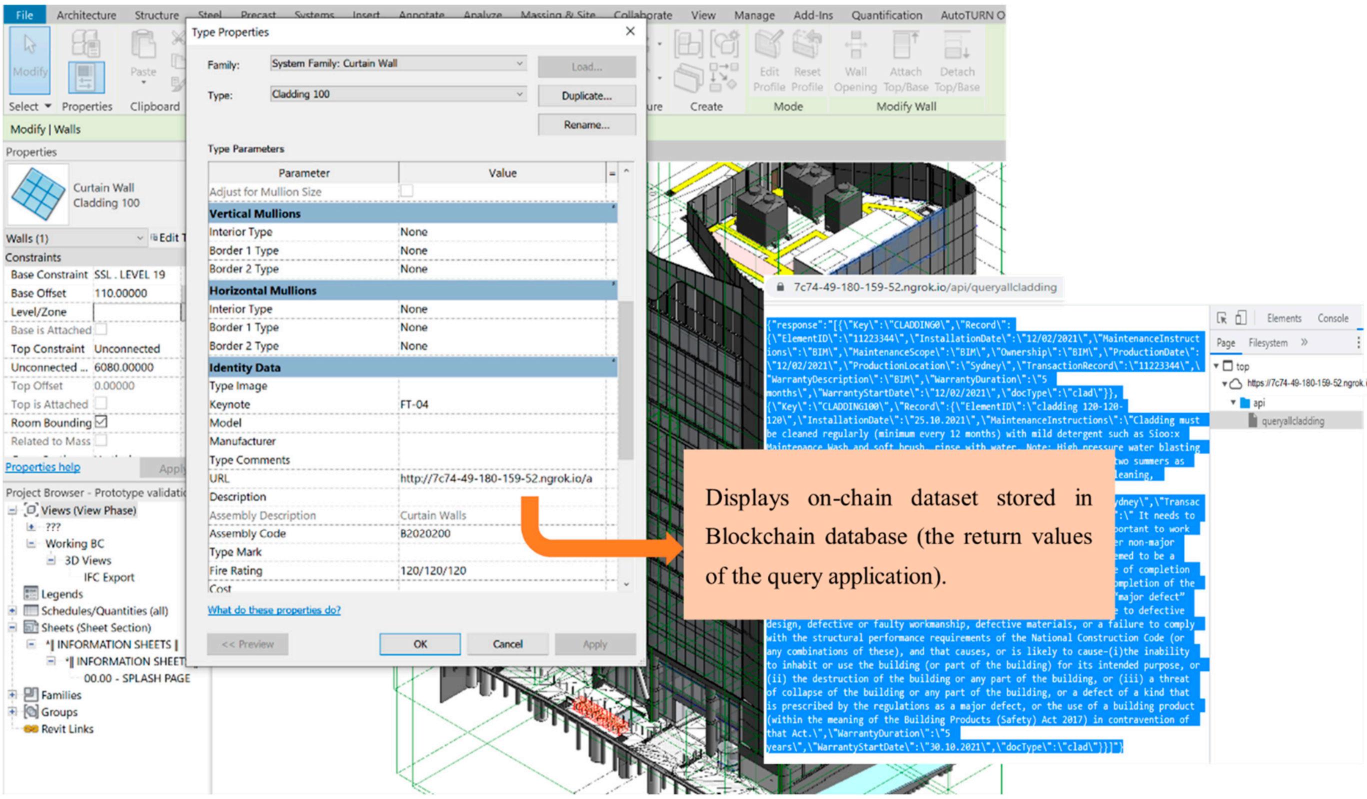

Figure 9. Successful linking of the on-chain dataset (the return values of the query application) to Revit (the BIM platform) and displaying (accessed) its transaction values.

Considering this, the system prototype successfully demonstrated the solution for or integrated blockchain and BIM using *Hyperledger Fabric v2.3* and *Revit DynaWeb v2021*. According to Qing and Yu-Liu [37], evaluating the prototype is the next step for which a virtual business scenario is utilized in this research, as explained in the following section.

4.5. Prototype Validation with a Virtual Business Scenario

The prototype was comprehensively evaluated to ensure accurate execution of the smart contract using a virtual business scenario that involves external validation. The attributes of the virtual business scenario were set to conduct the test run. A building project was considered as a project type, and cladding attributes, as discussed in Section 3, were considered the CSC element to execute the smart contract. The role of the external entity (supplier) was performed by the researcher, while a participant organization performed the role of the main contractor. It was ensured that the information delivery system used by the participant organization is configured to work in accordance with the workflows for the CDE that are outlined in "*ISO-19650 Part 1, Section 12*", and the deliverables for the "BIM maturity Level 2" were based on the "*PAS 1192-2-2013*" standard. Table 1 illustrates the protocol for the virtual business scenario.

Table 1. Protocol for the virtual business scenario.

Attributes	Attribute Description
Project Type	Building
CSC Element Type	Cladding
External Entity (Supplier)	Researchers
Main Contractor	Participant Organisation
Developer	Researchers
BIM Platform	Revit v2021.
BIM API	Revit DynaWeb v2021.
Blockchain Platform	Hyperledger Fabric v2.3.

Data Collection: The prototype developed, as discussed in Section 4.4, was used to validate the integration of BIM and blockchain. Subsequently, the actors invoked and queried to test the system. The virtual business scenario concluded with a structured interview to complete the evaluation of the prototype.

Data Analysis: The test case scenario was used and the results of the test run were tabulated in the form of a checklist. This was performed to confirm that the prototype fulfills all of the system criteria and provides a software prototype for the integration of BIM and blockchain, as illustrated in Table 2.

Table 2. A virtual business scenario test case and its results.

Action ID	The Test Case Scenario Taken	Output	Test Result
#1	Developer (*Researcher*) brings the Hyperledger Network up by running/startFabric.sh javascript	The Hyperledger Network generated and started running	**Pass**
#2	Developer (*Researcher*) enrolls the admin and imports it into the wallet and registers the user	Successfully registered and enrolled admin user "appUser" and imported it into the wallet	**Pass**
#3	Developer (*Researcher*) sets up the API Server for the Hyperledger Fabric Network and runs the webserver that links to Revit DynaWeb	Successfully set up a channel from the public internet to a port on the local machine	**Pass**
#4	Supplier (*Researcher*) is required to enter the following attributes of the CLADDING element	Successfully ran the Invoke application and entered its arguments based on the proposed Entity–Relationship Diagram data model attributes	**Pass**

Table 2. *Cont.*

Action ID	The Test Case Scenario Taken	Output	Test Result
#5	Main Contractor (*Participant Organization*) queries to read the CSC element on-chain dataset submitted by the supplier by using any one of the attributes (myArgs[0] . . . . mArgs[20]) from the Hyperledger Fabric	Successfully ran the queryID application and the return values for a specific argument (myArgs)	**Pass**
#6	Main Contractor (*Participant Organization*) uses Dynamo to select the CSC element on the Revit model, the watch function displays "URL found and opened"	Successfully ran the DynaWeb package in the Dynamo and the watch function displayed this message "URL found and opened"	**Pass**
#7	Main Contractor (*Participant Organization*) reads the on-chain dataset from Dynamo by using the watch function	Successfully displayed and read the on-chain dataset (return values of query application)	**Pass**
#8	Main Contractor (*Participant Organization*) clicks on the CSC element on the Revit model, goes to properties, and clicks on the URL in the URL field to read the on-chain dataset	Successfully linked the on-chain dataset (return values of query application) to Revit (BIM platform) and displayed (accessed) its transaction values	**Pass**
#9	Main Contractor (*Participant Organzsation*) uses the Dynamo change button to select a different CSC element on the Revit model, the watch function displays "Valid URL not found"	The watch function successfully displayed the message "Valid URL not found" as the on-chain dataset (the return values of the query application) is not linked to this item	**Pass**

There was consensus from the Participant Organization that the software prototype ensures the reliability of supply chain data delivery by enforcing the supply chain stakeholders to hand over on-chain data delivery. Further, the *Participant Organization* acknowledged that the software prototype for the integration of BIM and blockchain paves the way for the progression of the 3D BIM model toward the *digital engineering framework* [93] by enabling "machine-readable data" in the form of a reliably structured dataset. The *Participant Organization* acknowledged that there is a benefit in centrally integrating the on-chain supply chain data delivery utilizing the URL (XML format) because it assures that the software prototype delivers a vendor-agnostic solution that is compatible with several BIM vendor's software packages. The test run concluded with the recommendations to adopt the software prototype solution; the delivery partner should submit all project deliverables as structured datasets; thus, it should be contractually bound and represented as part of the Professional Services Agreement (PSA). The BIM execution plan needs to include the implementation costs and time. The software prototype is a new technological solution and the hardware requirements of blockchain are very expensive.

5. Discussion

Transparency, traceability, and a lack of supply chain data are some of the deficiencies of BIM use. Blockchain may alleviate the shortcomings of BIM by providing transparency and accountability and by ensuring ownership through smart contracts. However, its adoption is contingent on the data source, where BIM may play a significant role when paired with blockchain to provide verifiable data for supply chain operations [27,67]. By not restricting BIM to isolated electronic files, the prototype proposed in this study exploits blockchain's potential for value transfer toward a reliable ecosystem of interconnected databases. In addition, it facilitates machine-readable data in the form of uniformly formatted databases, opening the way for the progression of BIM toward digital engineering. The results of the test run validated the technical viability of the BIM single source of truth prototype using blockchain to ensure the delivery of trustworthy supply chain data in blockchain that is centrally tied to BIM. As it links and stores on-chain supply chain data delivery through a URL, the system prototype offers a vendor-agnostic solution that is suitable for a variety of BIM software applications. The URL-XML format ensures semantic consistency across all disciplines of a project. The participating organization noted that the system prototype ensures a constant and predictable dataset of on-chain supply chain data delivery by using a logical and familiar navigation and use interface. The deployment of the system prototype for the virtual company scenario proved that businesses are keen to commercialize this solution not only to ensure consistent digital output but also to maintain a competitive advantage. The scalability of the suggested method was not, however, explored in this study. The development of the BIM single source of truth prototype utilizing blockchain technology will pave the way for the BIM handover model to enable the definition of the digital twin, as it has received significant attention as an emerging technology and is now regarded as a crucial component of Industry 4.0 [94]. The trust, which is the main quality of this prototype, will improve the BIM data quality and ensure its reliability for operation and facilities management, which was also introduced by the Centre for Digital Built Britain as one of the Gemini principles pillars placed on the digital twins for being a single source of information for operation and facilities management [33]. However, as the digital twin model supports the future vision of smart cities, the remaining question is, what about the sustainability position of this prototype? This paper does not study the sustainability impact of blockchain; however, this prototype is considered an industrial application (Blockchain 3.0) that operates without miners through the help of nodes, unlike the cryptocurrencies, such as Bitcoin (Blockchain 1.0) and smart contracts and financial applications, such as Ethereum (Blockchain 2.0) [95].

Despite the significance of this paper's results, it is important to acknowledge a few limitations. The system prototype does not account for variations that may result from different procurement procedures, in which the role of each stakeholder in the logical system may be modified. In order for the integration of BIM and blockchain to be really effective, however, individuals and organizations must rethink their traditional procurement practices and boost their investment in innovation. Future research could examine the relationship between the various procurement systems (Public-Private Partnership, Alliancing/Integrated Project Delivery, Design Bid Build, Partnering, Traditional, Management or Early Contractor Engagement, etc.), and the proposed method for the integration of BIM and blockchain. Therefore, the system prototype should emphasize the use of the "Generalized Adaptive Framework" (GAF) to automate the code verification processes for routing the data that must be deposited in the blockchain system. This may need the development of a computable representation of the rules and techniques for the interchange of data between the different framework components and the BIM data.

6. Conclusions

This article advanced the state of knowledge primarily by the contribution of a proof of concept prototype for integrating blockchain and BIM for supply chain data delivery. In doing so, this paper demonstrated a step-by-step methodology starting from understanding the current business scenario and proposing logical system architecture, selecting a blockchain platform, designing system architecture related to technologies, and prototyping development and evaluation. The deployment of the system prototype for the virtual business scenario revealed that organizations are keen on transforming this solution to the commercialization stage not only to guarantee a trustworthy digital delivery but also to preserve a competitive advantage. There is a value in centrally linking the on-chain supply chain data delivery using the URL (XML format) as it ensures that the software prototype offers a vendor-agnostic solution that is interoperable with various BIM vendor's software packages. The system prototype proved Hyperledger Fabric's suitability for integration and provided a solution compatible with many BIM software vendors. The Hyperledger Fabric architecture enables high levels of flexibility and privacy in its design and implementation, making it suited for a variety of built environment applications. It helps achieve privacy by requiring permission to read and write using a permission paradigm that is characterized by the capacity to modify the state of the ledger community.

This study's recommended strategy for the integration of BIM and blockchain took into account construction supply chain data delivery for handover and operation throughout the building phase. Future research might leverage these results to build methodologies for other project phases, such as design (pre-construction) or facilities management (post-construction). Future development of the system prototype might concentrate on using the GAF to automate code verification techniques for routing data that must be saved in the blockchain system. This might need the creation of a computable representation of stated rules and data exchange protocols between the various framework components and BIM data. Legality is one of the most daunting blockchain-related concerns, according to industry insiders. Future construction research should concentrate on collaborating closely with legal specialists to investigate the legal implications of blockchain technology, the use of smart contracts in addition to conventional contracts, and the necessary revisions to contract language.

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Abbreviations

AIM	Asset Information Model
API	Application Programming Interface
BEP	BIM Execution Plan
BIM	Building Information Modelling
BIMXP	BIM Execution Plan
CDE	Common Data Environment
CIC	Construction Industry Council
COBie	Construction Operation Building Information Exchange
CSC	Construction Supply Chain
DFD	Data Flow Diagram
EIR	Employer's Information Requirements
ERD	Entity–Relationship Diagram
GAF	Generalized Adaptive Framework
HTTP	Hypertext Transfer Protocol
ICT	Information and Communications Technology
IFC	Industry Foundation Class
IP	Intellectual Property
KECS	Knowledge Elicitation Case Study
PAS	Publicly Available Specifications
PDBB	Project Data Building Blocks

SCM	Supply Chain Management
SMART	Simple Multi Attribute Rating Technique
SSoT	Single Source of Truth
URL	Uniform Resource Locator
WMS	Web Map Service

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