Comparison of BIM Collaboration Paradigms for Digital Twin Readiness: Centralized Files, Decentralized Clouds, and Distributed Blockchains

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Abstract

Building information modeling (BIM) has been widely used as the information hub for collaborations and has increasingly been mandated in the construction industry over the past decade. From the information perspective, there have been three BIM-based exchange paradigms: (i) file-based, (ii) cloud-based, and (iii) blockchain-based. Digital twin (DT) emerges as an integration of both the physical and virtual worlds so that a product synchronizes with its real-time digital representation. However, the readiness of multi-stakeholder BIM collaborations for DT is not a solved problem. This paper compares the DT readiness over the three paradigms' network models of information exchange links. It provides a thorough overview of BIM collaborations using centralized files, cloud-based methods, and distributed blockchains. The benefits and drawbacks are also discussed. The comparative results of the three BIM collaboration paradigms may accelerate mobilizing BIM toward DT.

Keywords: BIM collaboration, information interoperability, blockchain BIM, cloud BIM, network model

1 Introduction

Many building projects in the Architecture, Engineering, Construction, and Operations (AECO) industry involve complex, multidisciplinary, and multi-stakeholder collaborations and information exchanges (Xue et al., 2021). Building Information Modeling (BIM) can be used as a framework for all asset databases to build digital models of buildings or civil infrastructure, allowing for seamless digital data exchange (Eastman et al., 2011). BIM has been widely used as the information hub and increasingly mandated in the AECO industry over the past decade (Succar, 2009). And BIM is increasingly recognized as an IT-based approach to building integrity, virtual prototyping, modeling, distributed access, storage, and building data maintenance (Singh et al., 2011). The wealth of data in BIM provides a brand-new way for people to design, maintain and operate a building.

The core of BIM is the collaborative process in construction projects. The correct and efficient BIM implementation will help project participants and stakeholders, including owners, architects, engineers, contractors, and suppliers, get the best out of the collaborative agreement while increasing productivity and effectiveness (Lu et al., 2013). The essence of collaboration is digital information exchange. Digital Twin (DT) emerges as an integration of both the physical and virtual worlds so that each industrial product gets a real-time digital representation. The physical world is transmitted to virtual models via sensors to complete simulation, validation, and dynamic adjustment. The simulation results can feed, automatically or manually, back to the physics world to respond to changes and improve their operation (Qi & Tao, 2018).

Combining BIM and DT technology can significantly reduce energy demand in residential buildings in construction and operational phases and reduce processing and approval cycles while increasing transparency and collaboration (Alonso et al., 2019). Given the critical role of BIM collaboration in building projects, it is crucial that we need understand the collaborative process in BIM-enabled projects that increase productivity and efficiency (Lu et al., 2013). From the perspective of information exchange, DT has three paradigms for data readability in BIM collaboration: (i) file-based, (ii) cloud-based, and (iii) blockchain-based (Lou et al., 2020). The paradigms' information exchange networks impact the DT readiness and efficiencies.

Studies show that interoperability is vital to cooperation using BIM (Oraee et al., 2019). Recent research direction was the shared data exchange networks to facilitate interoperability among BIM users (Comiskey et al., 2017). Likewise, increasing attention is paid to the definition of effective models and arrangements of cooperation (Zhang & Ashuri, 2018). Nevertheless, the readiness of multi-stakeholder BIM collaboration for DT is an unsolved problem, which arises from synchronizing real-time information (Xue et al., 2020).

This paper aims to compare the DT readiness of the three paradigms based on the network models of information exchange links. DTs in construction are reviewed in Section 2. Section 3 reflects on the centralized BIM files, decentralized clouds, and distributed Blockchains. A thought experiment is presented in Section 4 for testing the paradigms. Section 5 discusses the findings and possible future directions.

2 Digital twins in the construction industry

A DT is a virtual representation that serves as a physical object or process (NIC, 2017). The DT concept and practices have proved successful for monitoring, data analytics, and decision-making in various industries, such as smart city and manufacturing. In addition, DT has been integrated with BIM and technologies such as the Internet of things (IoT), light detection and ranging (LiDAR), and data mining to facilitate construction in the construction industry.

DT frameworks can be developed for information updating to update BIM with IoT sensors and perform compliance checks between as-built and as-planned models (Lee et al., 2021). Furthermore, the applications of DT to anomaly detection or fragility assessment have also been demonstrated in cases such as bridge collapse (Lin et al., 2021) and built asset monitoring (Lu et al., 2020). Besides, DT can better understand the construction progress and the corresponding collaborative networks, making the bottleneck predictions and decision-making more successful (Lin & Wu, 2021; Pan & Zhang, 2021).

However, the existing pilot DTs in construction were mainly under constrained laboratory settings. The data sharing for DTs, referred to as BIM collaboration with DTs, is crucial to transplanting the pilot DT systems into the real-world construction industry. DTs' real-time, detailed, and large-scale natures make it significantly challenging to coordinate DTs into BIM collaboration and guarantee the efficiency, fidelity, and security of information sharing, updating, and tracking.

Emerging technologies, such as cloud computing and blockchain, have been introduced into the BIM collaboration for DT readiness. Cloud computing, for example, is an innovation delivery enabler for BIM, IoT, and virtual reality in construction. Bello et al. (2020), which can be derived, could be essential for DT in the construction industry. Blockchain, integrating the chain structure with the encryption and distribution features, is another promising technology for transactions in dynamic DTs (Das et al., 2021; Xue & Lu, 2020). To further analyze and compare the traditional file-based and the emerging cloud-and blockchain-based BIM collaboration, the following of this paper will introduce the definitions, typical application scenes and practice, advantages, and disadvantages of these three paradigms.

3 BIM collaboration paradigms

3.1 Centralized files

The centralized file model represents the conventional collaboration over a file, where the hub of interoperability is the BIM file. At the top-most level, the BIM tools allow users to work together to improve the building artifact's view. Collaborative efforts are greatly enhanced if the partners can share their models to view, analyze, edit, and develop (Eastman et al., 2011).

Since the 1970s, when computer-aided design (CAD) was introduced, there have been interoperability issues between engineering software systems (Pratt, 1993). As a result, file-based data exchange methods such as DXF, IGES, and SAT were developed to exchange geometric entities between CAD structures (Light & Gossard, 1982). In the late 1980s, the manufacturing industry faced more complex interoperability problems, developing product information exchange technologies in ISO-STEP (Standard for the Exchange of Product) model code, also known as the ISO 10303 Standard (Fowler, 1996). For data modeling, standard reusable structure libraries, and methods to develop various exchange functions based on specific data schemes, the STEP has provided EXPRESS language (ISO 1994) (Schenck & Wilson, 1994). With this technology, object-based data schemes have been created in over 20 production and electronics areas (Eastman, 1999).

In the past, the U.S. AECO industry had spent more than $15 billion to address BIM collaborative operations due to insufficient interoperability (Eastman et al., 2011). To address the above issues, BuildingSMART was promoted as an Industry Foundation Class (IFC), the ISO-STEP technology-based building product model exchange program that people had already worked to develop in the mid-1990s (Young, 2005). The IFC model offers several options for defining building objects, procedures, and other data in a publicly accessible data schema. It was designed as a framework model that addresses the broader range of construction, engineering, building, and operation (Björk, 1995). It offers numerous methods of form definition and means of representing relationships between objects. IFC aims to display all information related to a building, from the building's feasibility and the design to the construction, operation, and exchanges (Shayeganfar et al., 2008).

As shown in Figure 1, a 'sender' can use the IFC files in the local BIM model and pass the files to recipients. The 'receiver' imports the model from the received IFC files. Appropriate importing modules convert the IFC files with local data bindings. IFC extensions and standards can thus solve the interoperability problem between various BIM users. A well-analyzed IFC file helps extend the coverage and interoperability of BIM users (Ren et al., 2018).

An example is the BIM Collaboration Format (BCF) in IFC with data requirements. A traditional BCF workflow defines a file-based transfer, sometimes via e-mails or other communications, of issues. Therefore, it is difficult to analyze and quickly overview the whole series of problems (van Berlo & Krijnen, 2014). Besides, certain information can be missed or untraceable in exporting and importing an IFC model from one software. Manual redefining data takes time and is susceptible to human error (Wan et al., 2004). Even with direct IFC file support, missing information in the import/export of IFC files, particularly undetected ones, can be a significant issue (Kiviniemi, 2006). To fix the case of information loss, developers can manually or semi-automatically search for possible information loss before file exchange to avoid/reduce anonymous information missing during the file exchange (Ren et al., 2018).

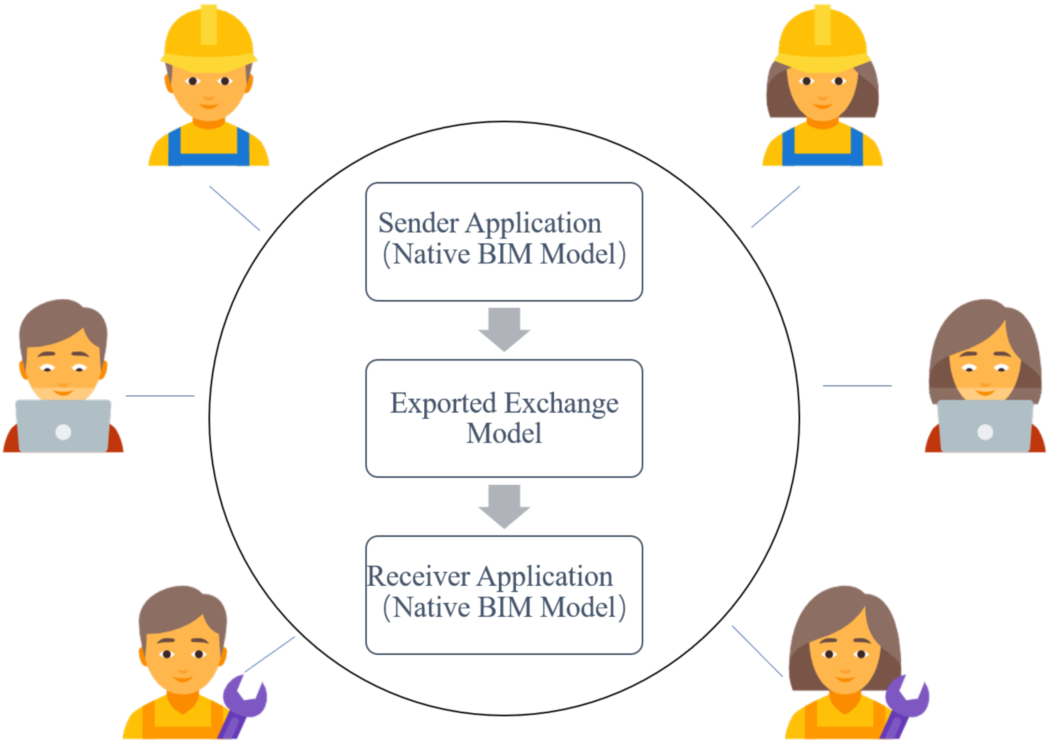

Figure 1. Centralized BIM collaboration process

3.2 Decentralized clouds

Since the mid-2010s, cloud BIM has become a new field in the AECO industry as a rapidly evolving technology (Wong et al., 2014). Cloud computing is a paradigm that enables users to access a shared pool of configurable computing resources on-demand, e.g., networks, servers, storage, applications, or software (Pearson & Benameur, 2010). Cloud BIM is believed to allow project partners and design disciplines to share and exchange design data requirements and solutions (Redmond et al., 2012).

Cloud storage includes both the programs provided as services over the Internet and the hardware and systems in data centers (Juan & Zheng, 2014). There are three primary categories of cloud products (Pearson & Benameur, 2010): Software-as-a-Service (SaaS) for total enterprise applications, Platform-as-a-Service (PaaS) for remote platform development and customization, and Technology-as-a-Service (TaaS) for processing and storage infrastructure leasing. Besides, hybrid clouds incorporate the public and private cloud models (Sengupta et al., 2011). The public clouds offer services to the general public, while private clouds are designed and operated by individual entities—similar to conventional database management.

As shown in Figure 2, users access cloud BIM data and information via cloud-based software and hardware. Ideally, a cloud BIM system eliminates complex infrastructure spend on hardware, software, and storage management, which means significant savings in IT resource consumption for AECO. Any user can use any web browser on any device to upload their BIM models to the cloud, edit and re-save them there, or download them to their devices, such as iPads, laptops, or desktop computers. From there, they can start projects, create central files and invite collaborators.

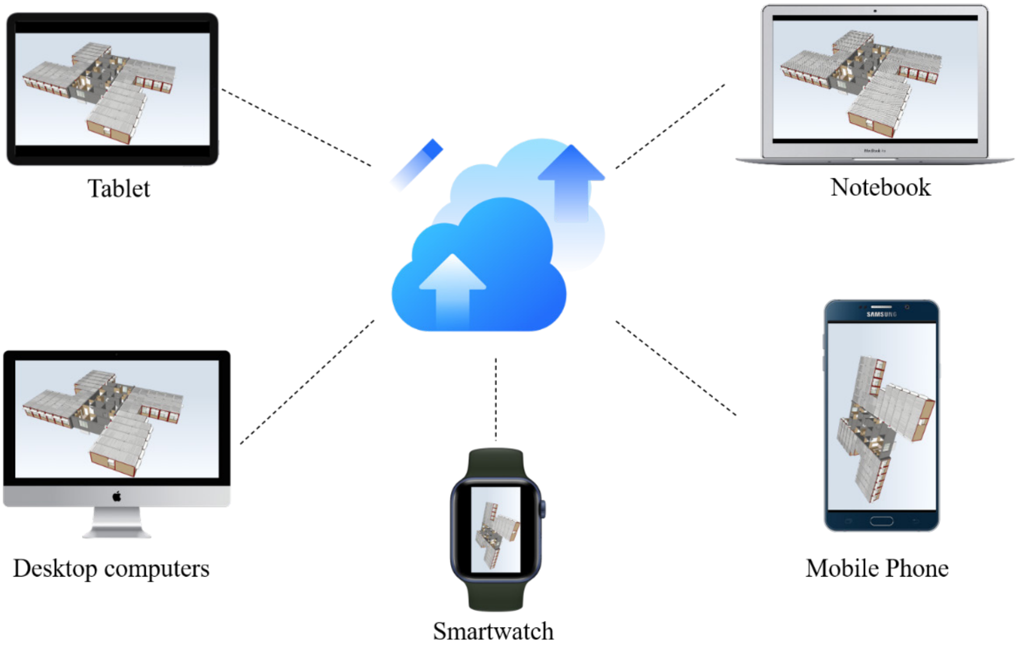

Figure 2. Devices for cloud BIM collaboration

Cloud BIM technology is recognized as a cost-effective alternative to conventional data sharing and storage methods (Mahamadu et al., 2013). Outsourced data processing can offer significant upfront and maintenance costs and scalability (Fathi et al., 2012). Furthermore, a cloud BIM creates a decentralized environment that integrates multiple stakeholders (Juan & Zheng, 2014).

However, impediments, such as security threats and business secrets, exist against the adoption of cloud BIMs (Sengupta et al., 2011). There are concerns about the impact of pervasiveness, transparency, and multi-party participation on data integrity and privacy, too (Takabi et al., 2010). Plus, there is a lack of cloud-specific BIM standards. As more cloud BIM services are developed, standardization among them becomes essential. Open standards, such as IFC or BCF, should be expanded to meet cloud BIM applications' requirements (Afsari et al., 2016).

3.3 Distributed blockchains

Blockchain is a distributed file system (DFS) consisting of a sequence of Cryptography-generated data blocks (Crosby et al., 2016). Blockchain is an impactful digital transformation technology in many industries (Di Giuda et al., 2020). The main idea behind blockchain is creating a digital trust when data is equally distributed across many nodes and no actor has complete control over the network. As a result, blockchain can radically alter an enterprise's practices. The success of blockchain applications shows a slew of advantages, including mutual learning, instant data sharing, automatic contract execution, cybersecurity, and enhanced teamwork (Nawari & Ravindran, 2019).

Figure 3 shows a blockchain system comprising of four building blocks generally:

(1) Shared ledger,
(2) Encrypted data,
(3) Consensus, and
(4) Smart contracts.

A shared ledger is a distributed record of network transactions. It stores essential information about business objects, such as the current values of object attributes and the transaction history that created those current values.

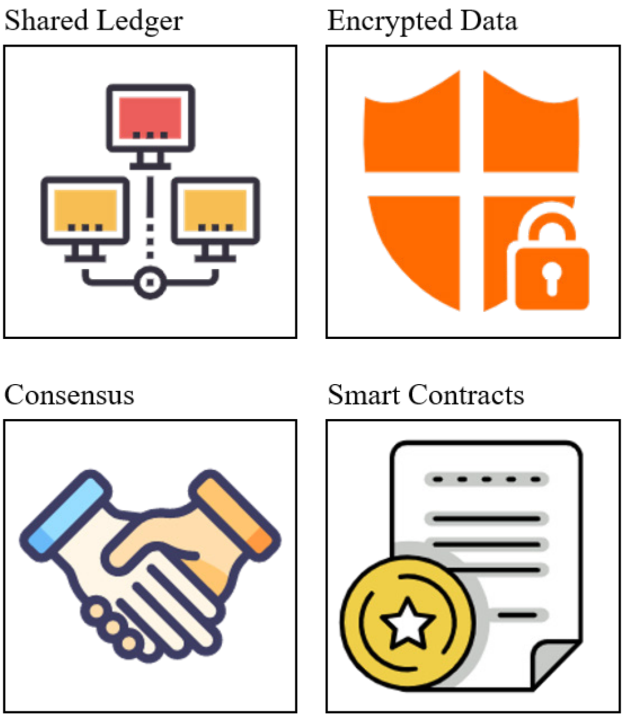
Shared Ledger
Encrypted Data
Consensus
Smart Contracts

Figure 3. Components of Blockchain

Encrypted data ensures transactions' validity and authentication. Thus, encryption is a critical component of blockchains' enhanced security, rendering distributed networks more difficult to compromise on the web. Besides, consensus refers to the use of the network's capacity to validate data transactions.

The consensus model is at the heart of blockchain and makes principles such as trust, trade, and ownership possible. When new participants enter a blockchain network or apply the blockchain to a new use case, the consensus system updates automatically.

Lastly, smart contracts are commercial or noncommercial arrangements embedded in a transaction database and executed automatically in conjunction with the transactions. Contracts in the blockchain world are called smart contracts. When it applies computerized protocols to enforce contract terms, various contract terms can be converted into machine language to ensure that the contract terms are adhered to, and the agreement is completed. Smart contracts are designed to ensure that one party keeps its commitment to the other. One aim of smart contracts is to lower authentication and enforcement costs. (Nawari & Ravindran, 2019).

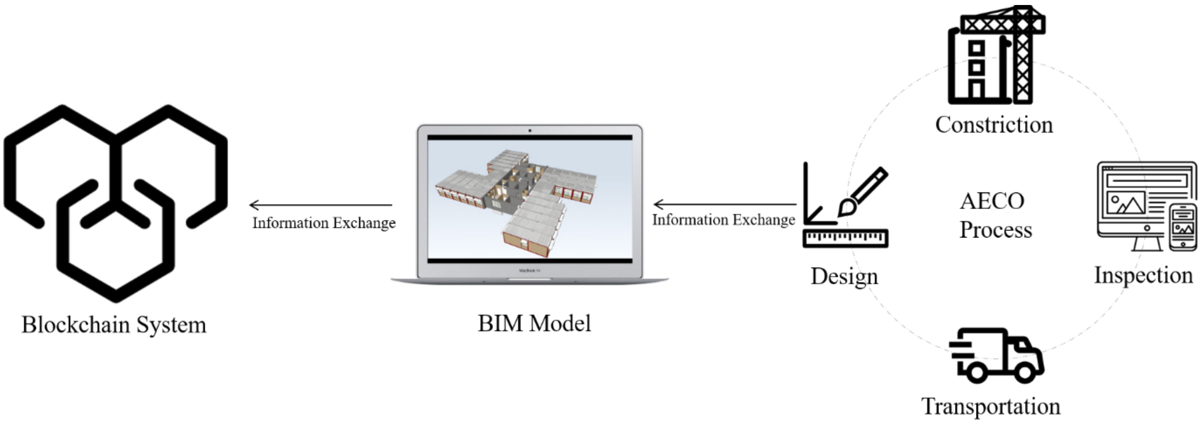

Figure 4. Blockchain-based BIM collaboration

An archive of all modifications to the BIM file can be permanently recorded through the blockchain and help handle changes to the model during construction by negotiating edit permissions and storing the design. One distinctive feature of BIM in construction projects is the large amount of data stored in the model. One solution is to combine BIM and a distributed database to achieve a valuable information source shared by multiple users in a single project (Xue & Lu, 2020). As shown in Figure 4, in the context of this innovation, The BIM model used in the project is composed of reliable and unchanging information sources that can be accessed and queried by all participants projects such as BIM customers, clients, architects, building structure designers, building service designers and other professionals, so that they could make transactions in BIM through the process of blockchain. Since there is often a lack of trust between project participants resulting in wasted time and unnecessary data validation, storing traceable and immutable data in a blockchain database can effectively avoid this lack of confidence. (Di Giuda et al., 2020).

Blockchain technology and smart contracts facilitate project workflow and coordination and increase transparency in the development process. Since all transactions are specific to the user's point in operation time, project participants tend to perform better due to increased accountability. (Alonso et al., 2019). The programmability of blockchain allows smart contracts, which are contracts written in code, effectively. Both parties define their rights and obligations through the smart contract on the chain, and the owner can monitor the execution process. The contract results ensure consistency in contract formation and execution and achieve machine trust, improving transparency and reducing operational costs (Giancaspro, 2017).

Blockchain networks mean that no one node has full access to all information in the network. By accepting more than one key, transactions can benefit from an additional layer of authentication provided by multiple signature authentication. If more than half of the nodes are hacked, hackers will obtain full access to the network (Kshetri, 2017). A stable system that adheres to the necessary licensing standards can provide effective interoperability by serving as a reliable medium for data repositories and data sharing and maintaining participant identifiability and authentication (Hasan & Salah, 2018). Additionally, blockchain will provide a safe and open Proof of Delivery (PoD) mechanism for transporting and delivering physical assets (Li et al., 2021).

While blockchain can bring numerous new opportunities to the AECO industry, there are also challenges and risks. Since the calculation outcomes are immutable, defective code will jeopardize project data integrity or result in financial loss. Before deploying the computerized code, the parties must ensure sound (Narayanan et al., 2016). Other threats arise as a result of blockchains' vulnerability to attacks from their peer-to-peer network. A 51% assault on the network is needed to sabotage the blockchain consensus algorithm. It requires more than half the hash and computational power in the blockchains using the Working Proof (PoW) protocol (Nakamoto & Bitcoin, 2008) by obtaining other mining bathrooms and amassing the computing force equivalent to the current hash rates as a miner.

4 Thought experiment on the digital twin readiness

Figure 5 shows an IDEF0 (Icam DEFinition for Function Modeling) diagram of a thought experiment on DT readiness. The left arrow indicates inputs; the right-hand shows the outputs as experimental metrics. The bottom arrow lists the three BIM collaboration paradigms to test. The top arrow represents the control parameters, such as the number of BIM user nodes and stakeholder groups. As shown in Figure 5, the experiment will use the same BIM collaboration cases to benchmark the centralized model, decentralized cloud model, and distributed blockchain model. The parameter sensitivity can be tested with tunable values to the nodes, trades, and task groups. The final results will quantify the DT readiness of different BIM collaboration paradigms regarding latency, error, and transmission efficiency. A finally weighted sum can tell us the overall rankings.

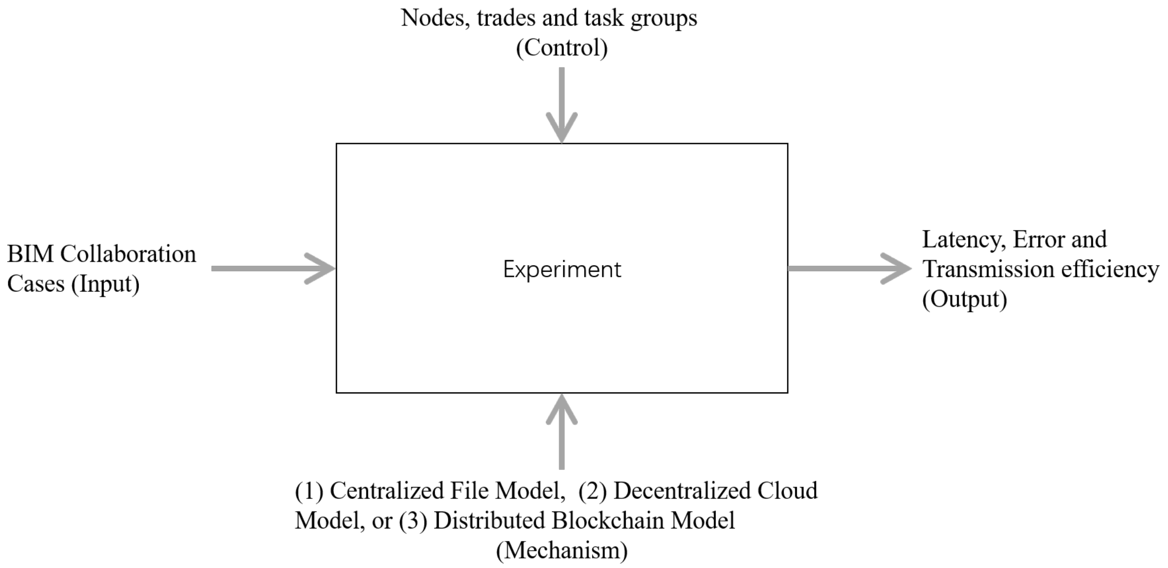

Figure 5 IDEF0 diagram of a thought experiment

5 Discussion

BIM opens new avenues to co-work in the construction industry. With the fulfilled value of BIM collaboration, stakeholders can deliver tasks and share information more effectively. For the exchange of project information and knowledge, the collaborative process using BIM is critical. A deep understanding of the ways of BIM collaborations has potential benefits for BIM users. When AECO industries worldwide are increasingly mandating BIMs, DT-ready BIM collaborations will contribute to project coordination, communication, resource and knowledge sharing, and innovations.

This paper presents a systematic overview of existing BIM collaboration paradigms for DT readiness. The most straightforward solution is file-based centralized BIM collaboration. The one-way file transfer method and inability to function at the object level remain its drawbacks. The performance, low-cost, real-time, and on-demand access to data are praised for cloud-based BIMs. However, cloud BIM also faces several challenges, including a lack of cloud BIM standards and operational and legal problems, e.g., privacy, information security, insufficient technical staff, and clarity of ownership and responsibility. Alternatively, blockchain-based distributed BIM collaboration can track information and ensure BIM data security. However, the new blockchain thinking needs further validation and considerations by the AECO industry, e.g., security, scalability, and usability.

Future research can be directed to the following areas. One potential research area is developing algorithms to collaborate large-scale BIMs in complex network environments with less computation time and resources. Secondly, future research can incorporate artificial intelligence to fill in lost data in BIM collaboration smartly. Thirdly, Researchers can develop methodologies to benefit from linking (blockchain-based) BIM implementation with a DT framework. Fourthly, the potentials of blockchain can be validated and benchmarked for BIM collaborations. Fifthly and finally, a general approach for experimentation and assessment is further suggested.

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