Exploring the Feasibility of Utilizing Blockchain in Cloud Computing and AI-Enabled Building Information Modeling for Enhancing Data Exchange in Construction Supply Chain Management

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***Abstract*—**Construction Supply Chain Management (CSCM) involves the collaboration of many disciplines and actors, which generates vast amounts of data. However, inefficient, fragmented, and non-standardized data storage often hinders this data exchange. The industry has adopted Building Information Modeling (BIM) - a digital representation of a facility's physical and functional characteristics to improve collaboration, enhance transmission security, and provide a common data exchange platform. Still, the volume and complexity of data require tailored information categorization, aligning with stakeholders' preferences and demands. To address this, Artificial Intelligence (AI) can be integrated to handle this data's magnitude and complexities. This research aims to develop an integrated and efficient approach for data exchange in CSCM by utilizing AI. The paper covers five main objectives: (1) Investigate existing framework and BIM adoption; (2) Identify challenges in data exchange; (3) Propose an integrated framework; (4) Enhance data transmission security; and (5) Develop data exchange in CSCM. The proposed framework demonstrates how integrating BIM and other technologies, such as cloud computing, blockchain, and AI applications, can significantly improve the efficiency and accuracy of data exchange in CSCM.

***Keywords*—**Construction supply chain management, Building Information Modeling, BIM, data exchange, artificial intelligence, AI.

I. Introduction

INDUSTRY 4.0 represents the fourth industrial revolution, following mechanization, electrification, and computerization of production environments [1]. It focuses on digitization and automation in the manufacturing industry, especially utilizing digital value chains among products, machines, and operators [2]. Industry 4.0 is poised to revolutionize manufacturing, with far-reaching impacts on the construction industry and its associated supply chains [2], leading to the development of CSCM. As is well acknowledged, the use of BIM in construction has grown, and it has become a key tool for digitizing and automating various construction processes [3]. One of the areas where BIM has gained traction is CSCM, which has been used to improve workflows and coordination among various stakeholders in the construction industry [4].

The construction industry requires assistance in managing fragmented and siloed information, ensuring quality control, and facilitating data exchange, especially with the limited adoption of cloud-based BIM governance solutions [5]. However, BIM alone is not a complete solution since the centralized BIM platform and the collaboration among multiple parties within this single platform can introduce data security vulnerabilities [6]. In addition, issues like insufficient trust among interdisciplinary teams, limited protection of intellectual property and data privacy, and vulnerability to cyber-attacks [7] pose significant security risks for the construction industry. The reasons for having these significant data security risks relate to inadequate cyber risk management, lack of well-established cybersecurity provisions and mitigation frameworks, and vulnerabilities in data storage [8].

To address the growing complexity of projects, new methods and technologies, including AI, blockchain, and cloud computing, were developed and applied to increase the efficiency and quality of data exchange in CSCM. While new challenges arise with implementing these innovative technologies, better integration outcomes are to be pursued. In this research, we focus on addressing some of the most pertinent challenges in CSCM data exchange identified in the literature. The results of this study include an enhanced BIM-based approach for data exchange in CSCM by integrating AI, cloud computing, and blockchain. Additionally, a process flowchart utilization of machine learning algorithms is also proposed, explaining the information classification procedure based on different clearances among stakeholders within CSCM data exchange.

II. Literature Review

Fig. 1 introduces a research schema that presents innovative solutions to improve CSCM. The proposed solutions include using BIM to standardize data, combining BIM and cloud computing to enhance communication and collaboration, and employing blockchain technology to centralize cloud computing platforms and improve information security by minimizing data fragmentation. These solutions will improve information flow in the supply chain, leading to better decision-making and enhanced security in the construction industry.

A. Using BIM to Standardize Data

Operating within a Common Data Environment (CDE), BIM

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always serves as a centralized platform for data management. This environment enforces standardized data structures, formats, and naming conventions, ensuring that all stakeholders, either construction projects or facility management, share and access data in a standard manner [9], [10]. BIM software includes libraries of standardized building objects, such as walls, doors, and windows, with predefined properties and attributes. These objects follow consistent data standards, making exchanging and integrating data easier across different software platforms [11]-[13]. Besides, generating reports and documentation complying with predefined data standards, including libraries, is easier within the BIM platform [14].

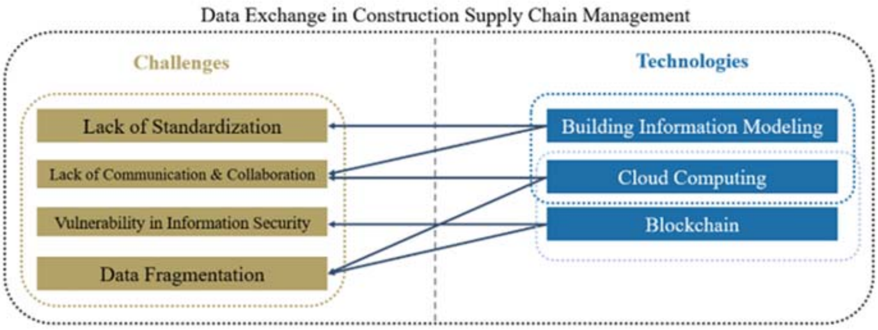

Fig. 1 The proposed research schema for data exchange and workflows in CSCM

Due to a lack of standardization and interoperability among different software tools and platforms, data distribution and integration are not an easy task [15]. In addition, communication breakdowns and documentation processes are often inefficient and unproductive [16]. To address these challenges, BIM is proposed to improve coordination and communication among stakeholders in the CSCM [17]. It has been identified as a potential catalyst for building alliances and promoting construction supply chain (CSC) partnerships [18]. Leveraging digital technologies such as BIM can facilitate collaboration and coordination within the SC by establishing a unified platform for information exchange and knowledge sharing [15], [18], [19].

BIM in CSCM involves sharing sensitive data between various stakeholders, including designers, contractors, and suppliers. This data exchange poses a risk of data breaches and privacy violations [20]. With substantial BIM data available during a project, identifying and effectively isolating valuable CSCM data that must be exchanged for the next steps remain challenging [21]. One of the significant limitations of BIM is its lack of data exchange needed to integrate it with other technologies [5], [21].

Despite the substantial amount of engineering information generated throughout construction project lifecycles, adopting new information management technologies within the industry remains comparatively limited [22]. Using traditional communication and collaboration methods causes a lot of errors and creates a lot of waste in the AECO construction industry. Innovative solutions such as AI are applied to make effective BIM models as collaboration tools in the CSCM to address this challenge. Integrating AI and BIM can be utilized to classify objects and data and facilitate information management [23].

B. Using Cloud Computing and BIM to Enhance Communication and Collaboration

Cloud computing, which first emerged in 2006, represents a significant shift in the way technology is used. It combines ideas from parallel computing, distributed computing, utility computing, and grid computing and has been refined through advancements in network storage, virtualization, and load balancing [24]. Essentially, cloud computing involves creating a virtualized environment for computing resources by centralizing separate resources connected by a network and then offering services such as infrastructure, platform, and software. This virtualized environment is referred to as the "cloud" [25].

Given their low-profit margins, cost poses a significant barrier to construction companies' adoption of IT solutions. Consequently, construction companies are actively exploring innovative approaches to reduce infrastructure and operational costs [26]. Since CSCM operates on a project-based model with a limited timeframe, the on-demand scalability of the cloud proves invaluable for construction companies. This flexibility enables them to efficiently manage costs by utilizing the cloud resources based on the specific needs of their ongoing projects. Che et al. [25] stated that the cloud, functioning as a secured environment, also allows companies to efficiently handle extensive data typically generated from the initial stages of projects and organize it for future utilization.

Using cloud computing in digital supply chain systems has been highlighted as a powerful tool by researchers Bhattacharya et al. [27]. According to their findings, it facilitates early integration and collaboration with key suppliers to enhance design quality and cooperation. However, cybersecurity is crucial in protecting shared data in digital supply chain systems. Ko et al. [28] also noted that cloud platforms offer a cost-effective solution to improve information flow and collaboration in the construction supply chain. Sharing information with suppliers can reduce inventory levels and improve material management. Additionally, Abedi et al. [29] and Oke et al. [30] emphasized that cloud computing offers reduced infrastructure costs, flexibility, and enhanced

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performance.

The benefits of multi-cloud storage, including eliminating vendor lock-in, were discussed by Seth et al. [31]. Security concerns, such as confidentiality, integrity, and authorization, were emphasized, and data fragmentation was highlighted to enhance cloud storage security. Security has been identified as the main factor hindering customer migration to the cloud. The data fragmentation process was described by Hon et al. [32], which involves software automatically splitting data into smaller fragments distributed across different equipment, possibly in other locations, based on the provider's policies. Data fragmentation enhances availability as retrieving smaller fragments is faster, which improves response times. A team of researchers led by Hudic [33] proposed a way to store data securely in the cloud by fragmenting it and distributing it among multiple Cloud Service Providers (CSPs) with appropriate confidentiality levels. This method aims to reduce computational overhead by minimizing encryption. The fragments are kept isolated in separate locations to enhance security and confidentiality.

The fundamental issue of trust, the major concern in hybrid cloud computing platforms, encourages users and entities to divide their data into segments and store them in different locations, representing a data fragmentation method. Data transparency, diminished control over data resources, and ambiguous security guarantees are other factors that make fragmentations a preferred method [34]. However, storing multiple data sources in diverse locations may pose challenges regarding data transfer and access, particularly for large and frequently updated datasets [35]. Plus, providing security by third parties can introduce vulnerabilities and escalate the risk of data loss [36].

C. Using Cloud Computing and Blockchain to Enhance Information Security and Centralize Data

Blockchain is a revolutionary technology that has gained popularity due to its ability to enhance data security in various industries. It offers a secure and transparent way to store and share data, making it tamper-proof and immutable [37]. One of the key strengths of blockchain is its decentralized structure [38], which differs from traditional centralized systems. In blockchain, data are stored in a distributed ledger [39] that is updated block-by-block using a collaboratively selected validator. This structure provides powerful safeguards against data manipulation, unauthorized access, and breaches [7], [40].

By using complex algorithms to encrypt data [21], [37], blockchain makes it difficult for unauthorized parties to tamper with or access sensitive information. This is because any attempt to modify the data will require the attacker to have access to the private key used to encrypt the data, which is virtually impossible to obtain without authorization. Additionally, blockchain's use of digital signatures [37] ensures that any changes made to the data are recorded and can be traced back to the original source, providing an additional layer of security.

Moreover, blockchain technology can enhance information security in addition to its security functions by fostering stakeholder trust [41]. It builds trust between parties by maintaining an unchangeable and transparent record of all transactions, which reduces the likelihood of fraud and other malicious activity [38], [40]. Furthermore, blockchain technology can enhance information security by automating processes through smart contracts. These self-executing agreements between buyers and sellers are directly written into lines of code, providing an additional layer of information security [39], [41].

Big data processing stages have several risks, such as data integrity loss, access control problems, delayed detection, and compromised data provenance. Alhazmi et al. [42] explored the potential of blockchain technology to address these weaknesses. They proposed a framework that uses blockchain and data fragmentation to secure data transactions and processing in big data sources while granting access to qualified users and detecting the data sensitivity level. The use of hash values allows for easy tracking of every transaction, thereby enhancing the level of data security. A recent study shows that a consortium blockchain system can efficiently handle access management tasks, significantly reducing the computational and storage workload [43]. This system enhances data security in untrusted cloud environments and ensures straightforward integration of a fast-access revocation system that relies on fragment re-encryption. Furthermore, using blockchain in local computers and cloud interaction has been investigated [44]. Their results show that blockchain is an effective tool that can lower data transmission expenses, enhance cache hit rates, and optimize overall social welfare while ensuring security. However, widespread data usage and methods to assist the system with easy access procedures are still needed.

III. Research Methodology

The research methodology employed in this study aimed to propose a conceptual framework for integrating BIM, AI, cloud computing, and blockchain in CSCM to enhance data exchange efficiency, accuracy, and security. The methodology involved a comprehensive review of scholarly publications from various sources, including Google Scholar, Scopus, and Web of Science. We analyzed the concepts, experiences, and insights presented in the literature to identify research gaps and emerging trends in relevant topics.

The initial phase of the research involved the identification of relevant literature using keywords such as "Construction Supply Chain Management," "BIM," and "Data Exchange." The selected academic papers were critically analyzed to identify research gaps and emerging trends in CSCM and integrated technologies. The analysis of the selected academic papers focused on understanding the challenges of data exchange in CSCM and the potential of integrated technologies, such as BIM, AI, cloud computing, and blockchain, to address these challenges.

The insights and concepts derived from the literature review were systematically reviewed to provide a comprehensive understanding of the current state of data exchange in CSCM and the applicability of integrated technologies. The outcome of this methodology is the proposal of a framework that integrates BIM, AI, cloud computing, and blockchain to enhance data exchange in CSCM.

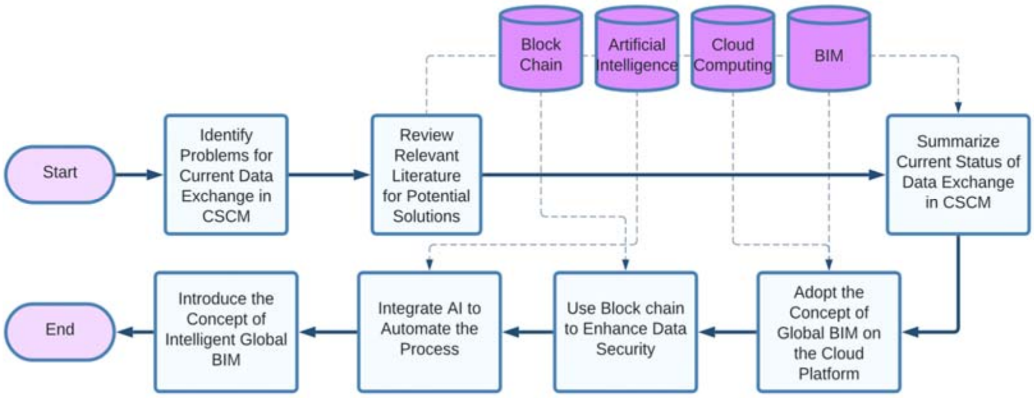

Fig. 2 Research Methodology Diagram

IV. Results and Discussion

A. Improvements for Data Exchange in CSCM

Xue and colleagues [45] presented a comprehensive model for CSCM. Their proposed model delineates the various stakeholders participating in the CSCM process and highlights the diverse types of data exchanges, including the flow of information, materials, and financial resources. Notably, [45] integrated three distinct categories of suppliers into their model, which is unique compared to the conventional CSCM process. Distinguished by their direct engagement, these supplier categories encompass owner–contracted suppliers designated as (I–III), general-contracted suppliers designated as (1–3), and subcontractor-engaged suppliers designated as (A–C). Additionally, [45] incorporated two tiers of designers within the stakeholder framework, comprising first- and second-level designers specializing in structural, architectural, electrical, and other design facets, respectively.

In our research, we have undertaken a process of integration and simplification of Xue et al.'s [45] CSC model, culminating in the formulation of our own model, as depicted in Fig. 3. Our specific focus within this refined model centers on a singular dimension of stakeholder interaction: the information flow. As elucidated in the preceding sections, the flow of information within the CSC framework assumes a position of paramount importance. It is pivotal in facilitating effective project management, risk mitigation, cost control, quality assurance, and, ultimately, the successful execution of construction projects. The efficient exchange of information among stakeholders enables them to collaborate harmoniously and make well-informed decisions, thus leading to improved project outcomes and the contentment of project owners. For simplicity and alignment with the prevailing characteristics of the standard CSC process, our model incorporates a single category of suppliers designated as "supplier_x." This consolidated category is equivalent to the amalgamation of suppliers (A–C) found in the original model of Xue et al. [45]. This simplification is underpinned by the inherent structure of the general CSC process, in which suppliers are directly contracted by subcontractors, obviating the differentiation between the other two supplier categories. Moreover, in line with our pursuit of simplicity and feasibility, we have condensed the two-tiered designer classification expounded by [45] into a singular tier of designers encompassing architects and engineers. This streamlined representation retains the critical role of design professionals within the construction process while streamlining the complexity associated with a multi-tiered designer framework.

Given our specific focus on the flow of information within the CSC process, it is also imperative to elucidate the various types of BIMs employed in our model. These diverse BIMs are comprehensively detailed in Table I.

TABLE I
Differences in Level of Detail (LOD) for BIM Types in the Construction Supply Chain

BIM Types	ARCH	MECH	ELEC	PLUM
Primary BIM	High	Low	Low	Low
Local BIM_1	Low	High	Low	Low
Local BIM_2	Low	Low	High	Low
Local BIM_3	Low	Low	Low	High
Global BIM	High	High	High	High

In our model, we primarily recognize three distinct BIM types. The first type is the primary BIM, which originates from the collaboration of architects and engineers. This BIM serves as a repository of detailed information, with a high Level of Detail (LOD) about architectural design and a lower LOD regarding the conceptual design produced by engineers for other systems within the project. As for the second BIM type, we introduce the concept of Local BIM_Xs, generated by subcontractor_Xsm, which means various subcontractors in our CSC model for simplification. Subcontractor_Xs encompassing entities such as mechanical subcontractor (subcontractor_1), electrical subcontractor (subcontractor_2), plumbing subcontractor (subcontractor_3), and so forth. Each subcontractor generates a Local BIM_X specific to their discipline, characterized by a high LOD for their specialized field and a lower LOD for all other disciplines. For instance, as

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delineated in Table I, the mechanical subcontractor (subcontractor_1) produces a Local BIM_1 with a high LOD for mechanical systems and a lower LOD for all other disciplines. Finally, our model incorporates another BIM type named Global BIM, originating from the efforts of the general contractor while combining all the information gathered from the subcontractors. The Global BIM features a high LOD across all project disciplines. This design choice is informed by the pivotal role of the general contractor, necessitating comprehensive coordination across all project disciplines.

As for the model, we propose, as depicted in Fig. 4, resting on a foundational premise that all participants within the CSC should have access to what we term the "Global BIM" in Fig. 3.

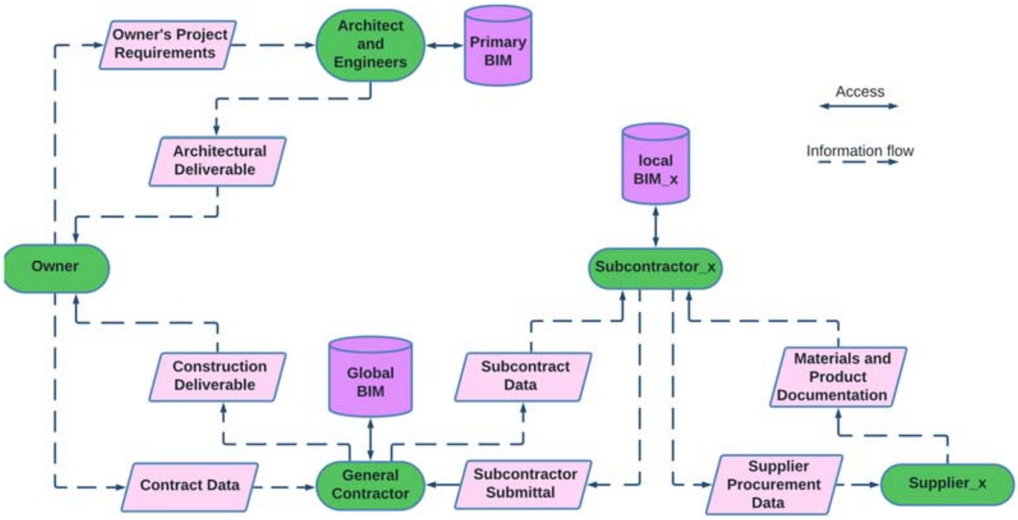

Fig. 3 The simplified data exchange enabled by BIM in construction supply chain

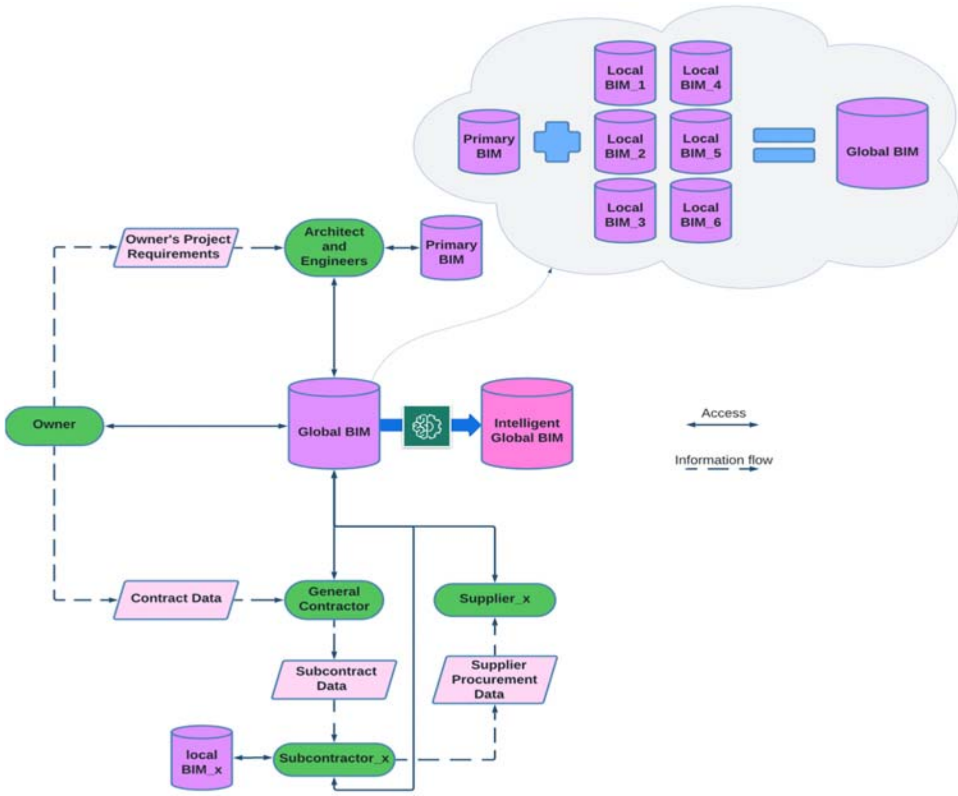

Fig. 4 The intelligent data exchange enabled by BIM in CSCM

The necessity for such access to the Global BIM underscores the incorporation of AI capabilities, transforming the Global BIM into an "Intelligent Global BIM." AI is harnessed to categorize the clearance and sensitivity of information

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contained within the Global BIM and regulate information dissemination by the preferences and directives of information owners. The forthcoming section will offer a detailed flowchart explaining the AI's functions and how the Global BIM is transformed to have intelligence. Additionally, our model posits that suppliers, vital stakeholders in the CSC process, should be provided access to the Intelligent Global BIM. The inclusion of suppliers in the CSC process is important, as it bolsters collaboration between stakeholders, heightens operational efficiency, and ultimately promotes the successful delivery of construction projects. Access to the Intelligent Global BIM could also streamline the alignment of all stakeholders and minimize errors and communication breakdowns, thereby leading to cost savings and improved project outcomes.

B. Discussion of Integrating AI to Improve Data Exchange

In summary, Figs. 3 and 4 represent improved versions of the original model by simplifying the data exchange process and stakeholders' interactions, introducing AI capabilities, and involving all the stakeholders in accessing Global BIM. Since all the data of the entire CSC process are accessible in the Global BIM, data could become unstructured, disorganized, and chaotic for stakeholders. In addition, due to the need for information categorization, dissemination regulation, and alignment with stakeholders' preferences and directives, data need to be cleaned, classified, and masked based on their clearance and sensitivity among stakeholders. Consequently, AI could be integrated for this purpose because AI presents a powerful solution to the challenge of managing vast and chaotic data. It can automatically categorize and organize data to make it searchable and retrievable. What is more, it underscores data quality issues, including removal of duplicates and cleaning of inconsistencies to ensure the reliability of the dataset. Natural Language Processing (NLP) capabilities allow AI to extract valuable insights from unstructured data. Data could be prioritized, and access controls could be enforced to enhance security. In conclusion, AI could transform the data in the Global BIM to become more efficient for better decision-making in CSC projects.

In the context of managing and harnessing the power of AI with Global BIM, we developed a comprehensive AI flowchart illustrating how AI could streamline data management and prioritize data with different clearances. This flowchart offers a visual roadmap of how AI techniques are applied to address the challenges of data organization, quality assurance, and data categorization.

The flowchart encompasses three key phases: data preparation and preprocessing, model development and training, and model development and maintenance. In phase 1, the process collects data from various stakeholders' contributions to the Global BIM. Subsequently, data are cleaned to be aligned with established standards, rendering it machine-readable. Categorization and data type identification ensue, followed by attaching clearance labels to a portion of the data, ultimately converting it into machine-manipulatable numerical features. Concluding phase 1, the labeled data are partitioned into three segments: training data (70%), validation data (15%), and testing data (15%), paving the way for phase 2. Phase 2 begins with selecting an appropriate machine learning model for text information clearance classification. The model undergoes training using the training data and evaluation using the validation data. Evaluation results may necessitate fine-tuning of hyperparameters to meet predefined criteria. Once refined, the model proceeds to testing to ensure stability and accuracy. If the model performs as desired, phase 3 commences, where it predicts clearance classifications for unlabeled data. Data with relatively high clearance undergo blockchain masking for security reasons before being transmitted to cloud computing. Conversely, data with lower clearance are directly forwarded to cloud computing. After this process, continuous monitoring and updates are implemented to maintain high accuracy and data integrity.

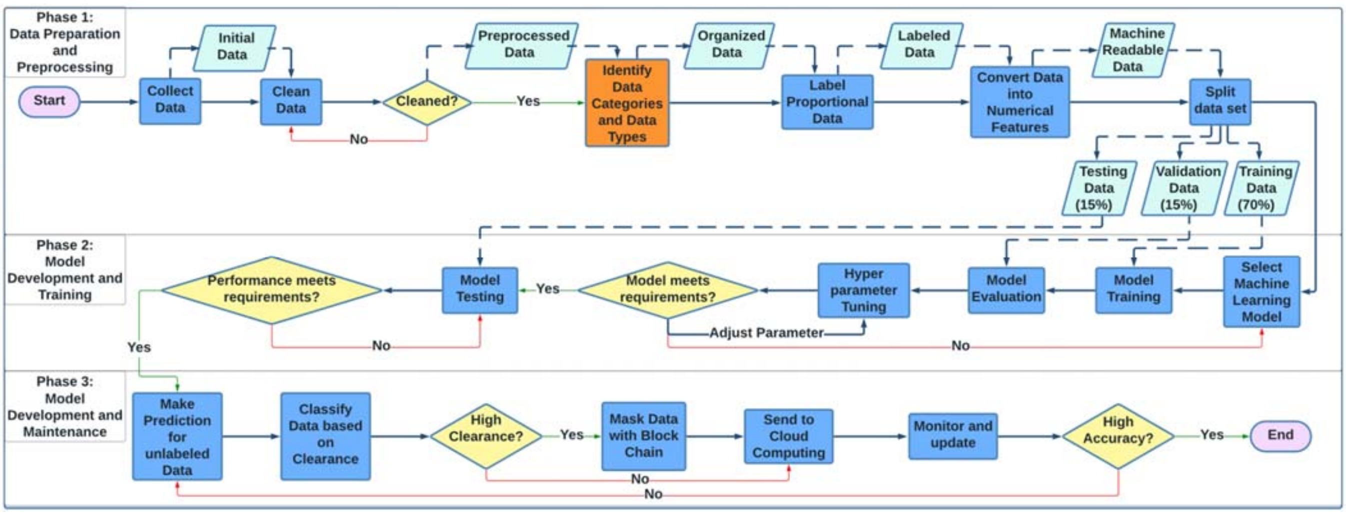

Fig. 5 The process of using AI to improve data exchange

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V. CONCLUSIONS

In this exploration of CSCM, we delved into the challenges inherent in the traditional CSC process. We proposed innovative solutions leveraging BIM, AI, and integrated technologies. The literature review revealed the slow progress of CSCM compared to other sectors, highlighting issues such as fragmented data, lack of standardization, communication breakdowns, and information security vulnerabilities. Also, while conducting the literature review, we have identified that some of these issues are connected. For example, we needed to strengthen information security to minimize fragmented data and enhance communication and collaboration. Based on the literature, blockchain can strengthen information security, promoting the use of cloud computing as a centralized platform to store all the information. Cloud computing as a centralized platform will minimize fragmented data and enhance communication and collaboration.

Our research contributes a refined CSCM model, building upon the work of [45]. Our model emphasizes the streamlined flow of information among stakeholders, recognizing the vital roles of suppliers, architects, and engineers. The introduction of Intelligent Global BIM provides a structured approach to information management within the CSCM process. In our model, all stakeholders will have access to the Intelligent Global BIM, enhancing collaboration and communication through the CSCM process. A significant innovation is the introduction of the Intelligent Global BIM, enriched by AI. This AI-driven system categorizes, regulates, and enhances the security of information exchange based on clearance and sensitivity. Our proposed model envisions an Intelligent Global BIM that not only serves as a comprehensive repository but also adapts to the preferences and directives of information owners. Crucially, our model advocates for inclusive collaboration by providing suppliers access to the Intelligent Global BIM. This approach aims to foster stronger stakeholder alignment, minimize errors, and enhance communication efficiency throughout the construction supply chain. The symbiotic relationship between BIM, AI, and stakeholder collaboration is poised to transform traditional CSCM practices, offering a more intelligent, streamlined, and secure approach to data exchange.

As Industry 4.0 continues to shape the future of construction, our research provides a roadmap for integrating advanced technologies, presenting a holistic vision for an interconnected and efficient CSCM. The proposed model addresses current challenges and lays the foundation for future advancements in the construction industry. In essence, our research underscores the transformative potential of technology-driven solutions in redefining the dynamics of CSCM, ultimately contributing to the construction industry's evolution toward a more efficient, collaborative, and intelligent future.

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