Front. Eng. Manag. 2025, 12(3): 467–486
https://doi.org/10.1007/s42524-024-4034-6

RESEARCH ARTICLE

Liupengfei WU, Weisheng LU, Louis CHU, Chen CHEN

Visualizing blockchain in construction projects: Status quo, challenges, and a guideline for implementation

Abstract The use of blockchain technology in construction engineering and management (CEM) is increasing, yet current presentations of blockchain-based data management processes (DMP) are considered too primitive to encourage the technology's broader diffusion in CEM. This research aims to provide a set of guidelines for visualizing blockchain-based DMP in CEM. First, a conceptual model is proposed to guide the research design. Next, 49 cases published in scholarly papers are reviewed, revealing an increasing use of dashboards to visualize blockchain-based DMP. Then, four challenges for visualizing blockchain are identified, namely, data diversity, visualization tools, visualization mediums, and visualization domain. Finally, we present guidelines for visualizing blockchain in construction projects, which involve: (1) targeting the visualization domain, (2) planning the blockchain visualization, (3) choosing a visualization tool, (4) selecting a visualization medium, and (5) fine-tuning the visualization solution. This research encourages researchers to further develop visualization solutions to harness blockchain benefits in CEM.

Keywords data visualization, blockchain systems, construction projects, systematic review, guidelines

Received Feb. 22, 2024; revised Apr. 20, 2024; accepted Apr. 30, 2024

Liupengfei WU, Weisheng LU (✉)
Department of Real Estate and Construction, The University of Hong Kong, Hong Kong 999077, China
E-mail: wilsonlu@hku.hk

Louis CHU
Estate Office, The University of Hong Kong, Hong Kong 999077, China

Chen CHEN
Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong 999077, China

The research was financially supported by the Hong Kong Innovation and Technology Commission (ITC) with the Innovation and Technology Fund (ITF) (Grant No. ITP/029/20LP) and Public Sector Trial Scheme (PSTS) Fund (Grant No. ITT/004/24LP). This funding source had no role in the design and conduction of this study.

1 Introduction

Blockchain, emerging from the technology sphere, could instigate a paradigm shift in construction engineering and management (CEM) (Li et al., 2019). A blockchain is a cryptographically secure shared database with a decentralized consensus mechanism, which can effectively record and endorse transaction data among users in a shared, secure, and traceable manner (Risius and Spohrer, 2017). Numerous benefits of blockchain have been reported in the literature, such as reinforced data transparency, traceability, immutability, and privacy (Elghaish et al., 2020), promotion of democratic decision-making through decentralization (Hamledari and Fischer, 2021a), and reduced costs through the removal of intermediaries (Wu et al., 2022a). It has been explored in CEM for internal administration (Pradeep et al., 2021), immutable records of transactions (Lu et al., 2022a), secure payment (Wu et al., 2022b), accurate information sharing (Wu et al., 2022a), and combined applications with the Internet of Things (IoT), building information modeling (BIM) (Li et al., 2022), and cloud computing (Li and Kassem, 2021). To successfully implement these blockchain applications, construction stakeholders need to visualize blockchain to gain trust in the system.

Developing from a general computer science background, blockchain technology uses a set of unique terminologies and system architectures, which CEM practitioners find less accessible (Xue and Lu, 2020). In the big data era, the amount of data submitted to blockchain is growing exponentially (Tao et al., 2021). A key issue when uploading construction data, in particular, to blockchain systems is how to visualize data management processes (DMP) to give users a sense of user-friendliness and trustworthiness. This paper takes typical DMP, such as data submission, endorsement, storage, and invocation, as the research scope. Data visualization, which is the graphical representation of data using common graphics, such as charts, plots, infographics, and animation (Börner et al., 2019), offers several benefits, such as improved comprehension, increased engagement, effective communication (Sackett et al., 2006), reinforced transparency, enhanced decision-making (Park et al., 2022), and storytelling (Wang et al., 2019). In blockchain, data visualization can quickly help users understand the DMP (Spiller et al., 2021).

It is essential for practitioners in construction projects to trust in the systems and subscribe to the technology and, without clear visualization, construction practitioners may struggle to do so. This lack of trust can result in hesitancy or reluctance to adopt blockchain technology, hindering the potential benefits it offers in terms of transparency, security, and efficiency in DMP. A lack of data visualization can also lead to confusion, misinterpretation, and potential errors in decision-making, undermining the overall effectiveness of DMP and potentially impacting project outcomes. However, the visualization of blockchain-based DMP has received little scholarly attention in the CEM context.

The primary aim of this research, therefore, is to provide a set of guidelines for users to visualize DMP on blockchain systems with a focus on the CEM context. Our research objectives are to:

(1) identify the current patterns and challenges of DMP visualization on blockchain systems in construction projects;

(2) develop guidelines for visualizing blockchain-based DMP according to construction project needs; and

(3) evaluate the effectiveness of the developed guidelines through demonstration and assessment in a case project.

The rest of this paper is organized as follows. Section 2 introduces the research methods. Section 3 shows the analytical results by illustrating the status quo and challenges of visualization methods of blockchain-based DMP in construction projects. Based on the analyzed patterns and challenges, guidelines are developed, demonstrated, and assessed in Section 4. The conclusion is presented in Section 5.

2 Research methods

The primary research method used in this study is an archival study following a four-step methodology involving: (1) development of a guiding conceptual model, (2) data collection through literature search, (3) data extraction and analyses, and (4) results validation.

2.1 A guiding conceptual model

To articulate the research aims and guide the research design, a conceptual model comprising three interlinked CEM components, namely, data inputs, blockchain systems, and DMP visualization, is proposed (Fig. 1). Data inputs are records related to CEM activities that are submitted to blockchain systems, including design, quality, progress, and safety records. Blockchain systems, built on various platforms, can record and share data (i.e., offering data transparency and traceability) to support different applications in construction. These blockchain systems can be permissionless or used in a permissioned manner (Lu et al., 2022a). The DMP visualization component refers to the visualization tools and mediums in blockchain systems, such as charts, dashboards, and blocks.

The types of data input, blockchain system, and DMP visualization components are listed in Table 1.

2.2 Literature search

The literature search conducted in this study was guided by a conceptual model and followed the PRISMA standard (Rethlefsen et al., 2021), which is a widely recognized approach for systematic literature reviews. The search

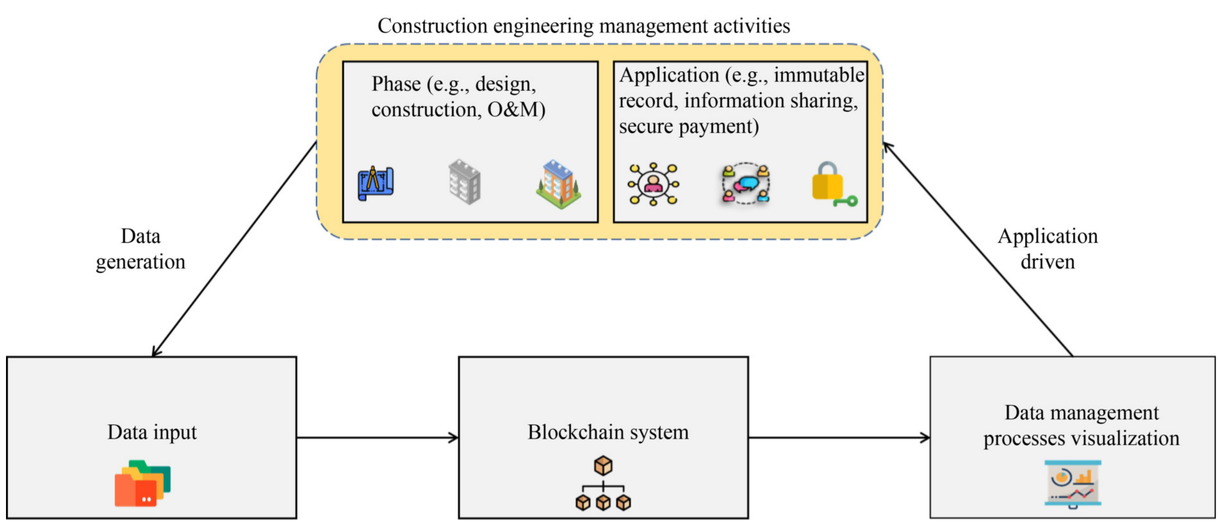

Fig. 1 A conceptual model of data visualization in blockchain systems.

Table 1 Three main components of data visualization on blockchain platforms in construction projects

Component	Possible options	Code	Explanations
Data input	Type	DEI	Design file
		QUA	Quality record
		PRO	Progress approval
		LOG	Logistic status
		SAF	Safety record
		OAM	Operation and maintenance record
		PAY	Payment record
		ENV	Environment record
		OTH	Multiple records
Blockchain system	Platform	HF	Hyperledger Fabric
		ETH	Ethereum
		CP	Customized platform
	Type	PES	Permissionless
		PED	Permissioned
DMP visualization	Tools	CHA	Charts
		TA	Tables
		EXP	Explorer
		DAS	Dashboard
		MAP	Process map
	Mediums	BLC	Blockchain components (e.g., blocks, transaction)
		NET	Network activities
		SMC	Smart contracts
		NO	None

process began on 20 October 2023, using the full-text search engine of Google Scholar with a specific query combination that included technical blockchain terms and construction-related terms. This approach ensured that the target publications explicitly mentioned both terms, thus increasing the relevance of the search results. The search terms used were "("blockchain*" OR "block chain*" OR "smart contract*") and (construction* OR infrastructure* OR building*)." To ensure that all relevant publications were included in the review, the "snowballing" technique was used in Scopus and the university library search engine. This technique involves examining the reference lists of identified publications to identify additional relevant articles. This approach ensured the completeness of the data collected, and all relevant publications were included in the study. The review surveyed literature published between 2008 and 2023 since blockchain technology was not invented until 2008 (Suyambu et al., 2020). The search was further restricted to the literature published in journals, excluding law cases and patents. This approach ensured that the included articles underwent rigorous review processes, providing accurate and trustworthy content. The initial search produced 4930 hits, including journal and conference papers, books, dissertations, and reports. The large number of search results highlighted the need for a rigorous screening process to identify relevant publications for the study.

After the initial literature search, a rapid screening process was conducted to identify relevant articles based on their titles and abstracts. This screening process took place during the literature collection, identification, and scoping stage. Articles that were deemed irrelevant to CEM, such as those focusing on healthcare, were excluded from further consideration. Additionally, articles that did not specifically concentrate on blockchain technology were also excluded, as the study specifically aimed to explore the application of blockchain in CEM. Non-journal articles were also excluded from the study. This decision was made based on the understanding that journal articles undergo rigorous review processes, ensuring the accuracy and reliability of the content they contain, as supported by Li et al. (2019). Following the preliminary screening, the full texts of 323 papers that passed the screening were downloaded and further examined. Two criteria were applied to determine which papers would be included in the analysis. First, papers had to demonstrate the actual application of blockchain in CEM, as empirical research provides verifiable proof, as noted by Oraee et al. (2017). Non-empirical studies, such as review articles and position papers, were excluded from the analysis. Secondly, papers had to offer an original contribution with sufficient technical details of blockchain elaborated in actual applications. Based on these criteria, a total of 49 journal articles were gathered for further analysis and exploration in the study.

2.3 Data extraction and analyses

Data were manually mined from the selected publications, with basic information extracted using the code defined in Table 1. Table 2 summarizes the information, including the reference, details of the data input, blockchain system adopted, visualization tools and mediums, project phase, and actual application. For example, the first item, Ahmadisheykhsarmast and Sonmez (2020), first entered progress and payment data into the Ethereum blockchain, which is a permissionless blockchain. Input data was visualized through a dashboard with details of blockchain components. The visualization was adopted in the construction phase and applied to the secure payment application. Overall, the information in Table 2 provides an understanding of the current status and related challenges of blockchain-based DMP visualization methods. Based on this, guidelines for visualizing blockchain-based DMP in construction projects can be proposed (Section 4).

Table 2 List of 49 actual cases of using blockchain in construction

Reference	Data	Blockchain		DMP visualization		CEM activities	
	Type	Platform	Type	Tool	Medium	Phase[a]	Application[b]
Ahmadisheykhsarmast and Sonmez (2020)	PRO + PAY	ETH	PES	DAS	BLC	CON	SEP
Das et al. (2020)	PRO + PAY	ETH	PES	TA	NET	CON	SEP
Elghaish et al. (2020)	PAY	HF	PED	EXP	BLC + SMC + NET	PRC	SEP
Shemov et al. (2020)	OTH	HF	PED	TA	NO	PRD + TRA + CON	IR + IA
Sheng et al. (2020)	QUA	HF	PED	EXP + DAS	BLC	CON	IR
Wang et al. (2020)	QUA	HF	PED	EXP	BLC	PRD + TRA + CON	IR + IS
Yang et al. (2020)	OTH	HF + ETH	PED + PES	DAS + MAP	BLC + SMC	PRC + DES	IA
Zhong et al. (2020)	QUA	HF	PED	EXP	BLC	CON	IR
Cho et al. (2021)	ENV	HF	PED	EXP + DAS	BLC	CON	IS + COA
Ciotta et al. (2021)	OTH	ETH	PED	DAS	BLC	CON	IA
Hamledari and Fischer (2021a)	PRO + PAY	ETH	PED	CHA + TA	NO	CON	SEP + COA
Hamledari and Fischer (2021b)	PRO + PAY	ETH	PED	CHA	BLC	CON	SEP + COA
Jiang et al. (2021)	OTH	ETH	PED	EXP + DAS	BLC	PRD + TRA + CON	IR + IS + IA
Li et al. (2021a)	QUA	HF	PED	EXP + DAS	BLC	PRD	PP
Li et al. (2021b)	QUA + LOG + PRO	CP	PED	DAS	NO	PRD + TRA + CON	IR + COA
Lu et al. (2021a)	QUA + OTH	HF	PED	EXP + DAS	BLC	CON	IR
Lu et al. (2021b)	QUA + LOG	HF	PED	CHA	SMC	TRA + CON	IR + IS
Lee et al. (2021)	OAM	ETH	PED	CHA + DAS	BLC	CON	IS + COA
Pradeep et al. (2021)	DEI	ETH	PES	DAS	BLC	DES	IR + IS
Sigalov et al. (2021)	PRO + PAY	ETH	PED	DAS	BLC + SMC	CON	SEP
Tezel et al. (2021)	PAY	ETH	PED	EXP + MAP	SMC	PRC + CON	SEP + IA
Tao et al. (2021)	DEI	HF	PED	MAP + DAS	BLC + SMC	DES	IR + COA
Wu et al. (2021)	QUA	HF	PED	EXP + DAS	BLC + SMC	CON	IR
Zhang et al. (2021b)	OTH	HF	PED	CHA + TA	BLC	CON	IR
Zhang et al. (2021a)	PAY	HF	PED	CHA + TA	NO	PRC	SEP
Das et al. (2022)	OTH	HF	PED	DAS	BLC + SMC + NET	CON	IR + IA
Elghaish et al. (2022)	PRO + PAY	HF	PED	EXP	BLC + SMC + NET	PRC + CON	SEP
Lu et al. (2022a)	QUA	HF	PED	EXP + DAS	BLC	PRD	IR
Li et al. (2022)	LOG + QUA	HF	PED	EXP + DAS	BLC + SMC	PRD	IR + COA
Pan et al. (2022)	OTH	HF	PED	CHA + DAS	NO	CON	IR + COA
Saygili et al. (2022)	PAY	ETH	PES	CHA + TA	BLC	CON	IA
Sonmez et al. (2022)	PRO + PAY	ETH	PED	DAS	SMC	CON	SEP + COA
Shu et al. (2022)	ENV	ETH	PED	CHA	BLC	PRD	IA + COA
Tao et al. (2022)	DEI	HF	PED	EXP + MAP	BLC + SMC	DES	PP + COA
Wu et al. (2022a)	LOG + QUA	HF	PED	EXP + DAS	BLC + SMC	TRA + CON	IS
Wu et al. (2022b)	PRO + PAY	HF	PED	DAS	BLC + SMC	PRD	SEP
Wu et al. (2022c)	QUA	HF	PED	EXP + DAS	BLC + SMC	PRD	IR + COA
Wu et al. (2022)	OAM + SAF	HF	PED	EXP + CHA	BLC	CON	IA + COA
Xu et al. (2022)	SAF	HF	PED	EXP	BLC	CON	PP
Yang et al. (2022)	OAM	HF	PED	EXP + DAS	BLC + SMC	CON	IA
Zhong et al. (2022)	ENV	HF	PED	DAS	NO	CON	IR
Ahmadisheykhsarmast et al. (2023)	OTH	ETH	PED	DAS	SMC	PRC	IS
Cheng et al. (2023)	PAY	HF	PED	EXP + MAP	BLC	CON	PP + SEP

(*Continued*)

Reference	Data	Blockchain		DMP visualization		CEM activities	
	Type	Platform	Type	Tool	Medium	Phase[a]	Application[b]
Elghaish et al. (2023)	ENV	HF	PED	CHA	SMC	DES	IR + COA
Kim et al. (2023)	OTH	HF	PED	EXP	BLC	TRA	IS
Lu et al. (20223)	QUA	HF	PED	EXP + DAS	BLC	PRD	IR
Tao et al. (2023)	DEI	HF	PED	EXP + TA + MAP	BLC	DES	IR + COA
Wu et al. (2023)	ENV	HF	PED	EXP + CHA	BLC	CON	IS
Zhao et al. (2023)	OTH	HF	PED	EXP + CHA	BLC	CON	IA

Note. [a] PRD = housing production, CON = construction, TRA = transportation, DES = design, PRC = pre-construction; [b] IR = immutable records, IS = information sharing and transparency, PP = privacy protection, IA = internal administration, COA = combined applications with the IoT, BIM, and other digital technologies, SEP = secure payment.

2.4 Case study

The focal project of this study is a high-rise residential building project in Hong Kong, which fully adopts modular integrated construction (MiC), shown in Fig. 2(a). The project comprises four towers on a single-story common podium, with rooms formed from about 2000 integrated modules manufactured in an offsite factory in mainland China and transported to Hong Kong for onsite assembly, as illustrated in Fig. 2(b). The case project customizes a blockchain-based e-Inspection system developed by Lu et al. (2022a) for the same project client and for a project with the same requirements, mainly to monitor the quality of modules produced by an offsite MiC manufacturer. Thus, frontline workers from the MiC factory are required to upload photos related to module production at each hold point. The project client, main contractor, registered structural engineer (RSE), authorized person (AP), and building service inspector (BSI) should then endorse the uploaded photos through the decentralized consensus mechanism of the distributed network of the blockchain system. Therefore, they asked the research team to help them visualize DMP on the blockchain system to enhance user-friendliness so that they could further increase their trust in the system.

Using the proposed guidelines for visualizing blockchain-based DMP in construction projects, we worked closely with the project team to visualize the DMP on the blockchain system to enhance user-friendliness and trust in the system. To uncover the views of participants concerning the visualization processes, we conducted structured interviews comprising a set of pre-prepared questions and multiple answer options. Structured or standardized interviews are commonly used in social sciences (Lewis-Beck et al., 2004). These interviews involve pre-developed questions and answer categories, which are organized in an interview schedule before the actual interview. This approach aims to ensure consistency and standardization in the interview process. The study implemented the structured interview protocol described by Lewis-Beck et al. (2004). This protocol involved several vital elements. First, the questions were asked as they were worded and in the predetermined order specified in the interview schedule. This ensured that all participants were asked the same questions in the same way, minimizing variations in the data collected. Secondly, if an interviewee did not provide a complete answer to a question, follow-up questions were asked to prompt for further details or clarification. This allowed for a more comprehensive understanding of the interviewee's responses. Thirdly, the interviewer recorded the answers provided by the interviewee without exercising personal discretion or bias. This approach aimed to capture the interviewee's responses as they were given accurately. Lastly, the interviewer minimized personal judgment and feedback during the interview process. This was done to create an environment that facilitated honest and unbiased responses from the interviewees. By adhering to the structured interview protocol, the study aimed to collect reliable and consistent data from the participants, enhancing the validity of the findings.

Four participants from the client organization, two from the main contractor, and one from the manufacturer (Table 3), were asked four pre-worded questions in the same order, as shown in Table 4. All interviewees fulfilled three participant selection criteria. The first criterion was that participants needed to be actively engaged in utilizing the blockchain system within the project, demonstrating their fundamental understanding of blockchain technology. This ensured that the participants had practical experience in using blockchain technology, which would provide valuable insights into its application in the construction industry. The second criterion was that participants needed to be closely collaborating with the research team, employing the suggested guidelines to visualize the blockchain-based DMP. This ensured that the participants had a good understanding of the study's objectives and were committed to use the proposed guidelines in practice. The third criterion was that participants needed to demonstrate a willingness to provide feedback on the suggested guidelines. This ensured that the participants were willing to engage in a constructive

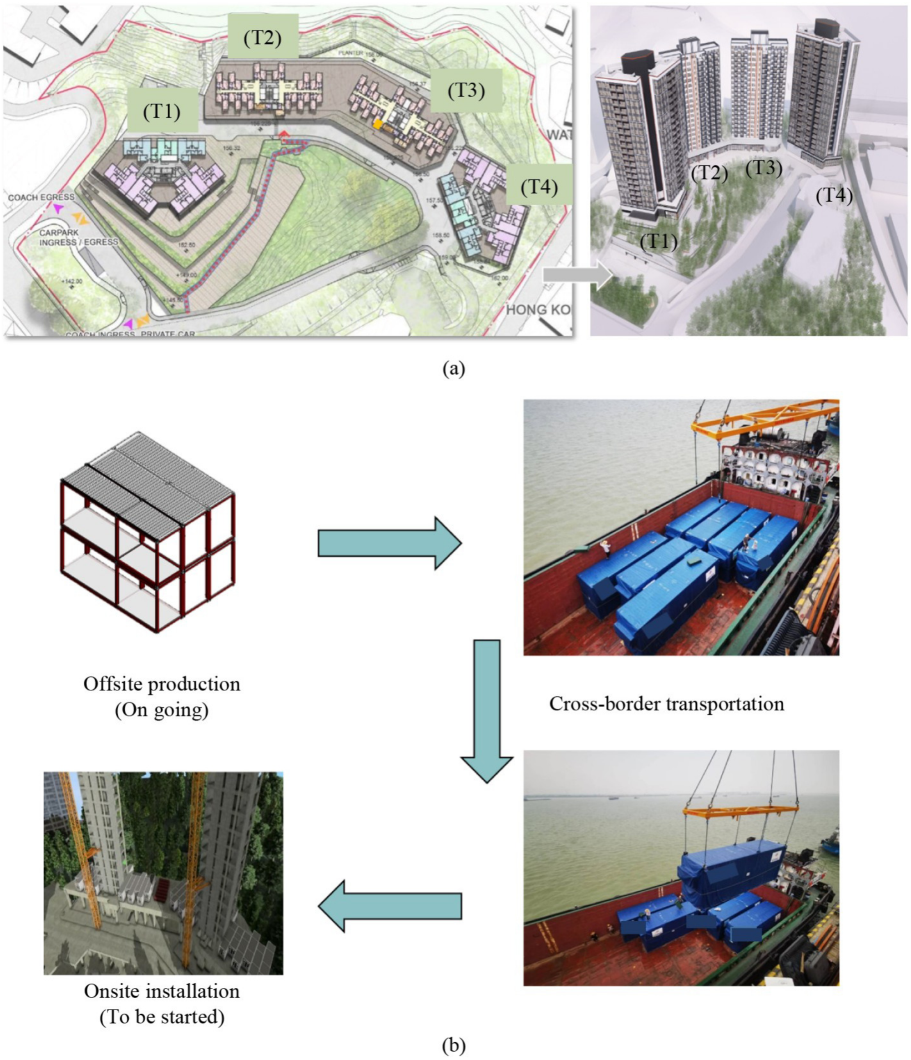

Fig. 2 Case project: (a) Project overview and (b) Modular housing offsite production, cross-border transportation, and onsite installation.

Table 3 Interviewee information

ID	Organization	Position	Working experience (years)
OW1	Client	Senior technical manager	14
OW2	Client	Senior technical manager	15.5
OW3	Client	Senior technical manager	16
OW4	Client	Senior technical manager	16
MC1	Main contractor	Project engineer	8
MC2	Main contractor	Project technical consultant	7
MA1	Manufacturer	Site engineer	4

Table 4 Interview questions

Interview questions
Question 1: After using the suggested guidelines, does the visualization enhance your trust in the blockchain system?
Question 2: What are the benefits of using the proposed guidelines for visualizing blockchain-based DMP in construction projects?
Question 3: What are the drawbacks of using the proposed guidelines for visualizing blockchain-based DMP in construction projects?
Question 4: Do you have any suggestions to improve the guidelines?

dialog with the research team and provide valuable feedback on the suggested guidelines. The responses provided by the interviewees were documented and transcribed to enable further examination.

3 Analytical results

3.1 Status quo of data visualization methods on blockchain systems

The Sankey chart presented in Fig. 3 offers a graphical overview of the Table 2 data extracted from studies visualizing blockchain-based DMP for different CEM activities. In the chart, the size of a rectangle indicates the number of actual descriptors mentioning data inputs, blockchain systems, and data visualization tools and mediums for various CEM phases and applications. Among on studied 49 cases, multiple descriptors can be found in one case.

3.1.2 Blockchain platforms and types

In most reviewed cases, the uploaded data was recorded in Hyperledger Fabric (34 cases), an open-source platform for all industries, including construction (Sheng et al., 2020). Data was recorded in 15 cases on the blockchain platform Ethereum, which has a native cryptocurrency (Ether). This indicates that the construction industry can take advantage of what cryptocurrency can offer, such as automatic progress payments (Ahmadisheykhsarmast and Sonmez, 2020). Only one case built a custom blockchain to record data, likely because to do so requires in-depth understanding of blockchain technology and CEM processes (Lu et al., 2021a). A notable trend is that the number of cases using a Hyperledger Fabric platform has increased over time while the number of cases adopting the Ethereum platform have shown a decreasing trend (Fig. 4(a)).

We observed that permissioned blockchain was mainly selected for recording data. In a permissioned blockchain, users are preauthorized to participate, thereby ensuring the data privacy of construction projects (e.g., Tao et al., 2022). Permissionless blockchains were adopted in only five cases, mainly because data transparency was a priority. Figure 4(b) shows an increase in adoption of permissioned blockchains over the last two years due to increasing data privacy concerns.

3.1.2 Data inputs

The pattern of data inputs is summarized as follows, based on Table 2 and Fig. 5.

(1) Quality and payment records were the most popular data inputs, appearing in over 41% (26 over 64) of descriptors. Construction quality data are still recorded mainly on paper, risking document loss and data manipulation, jeopardizing quality accountability (Wu et al., 2021; Lu et al., 2022a). The immutability of blockchain allows it to securely record quality-related data, effectively addressing the issue of information fraud (Zhong et al., 2020; Lu et al., 2021a). Payment records were primarily

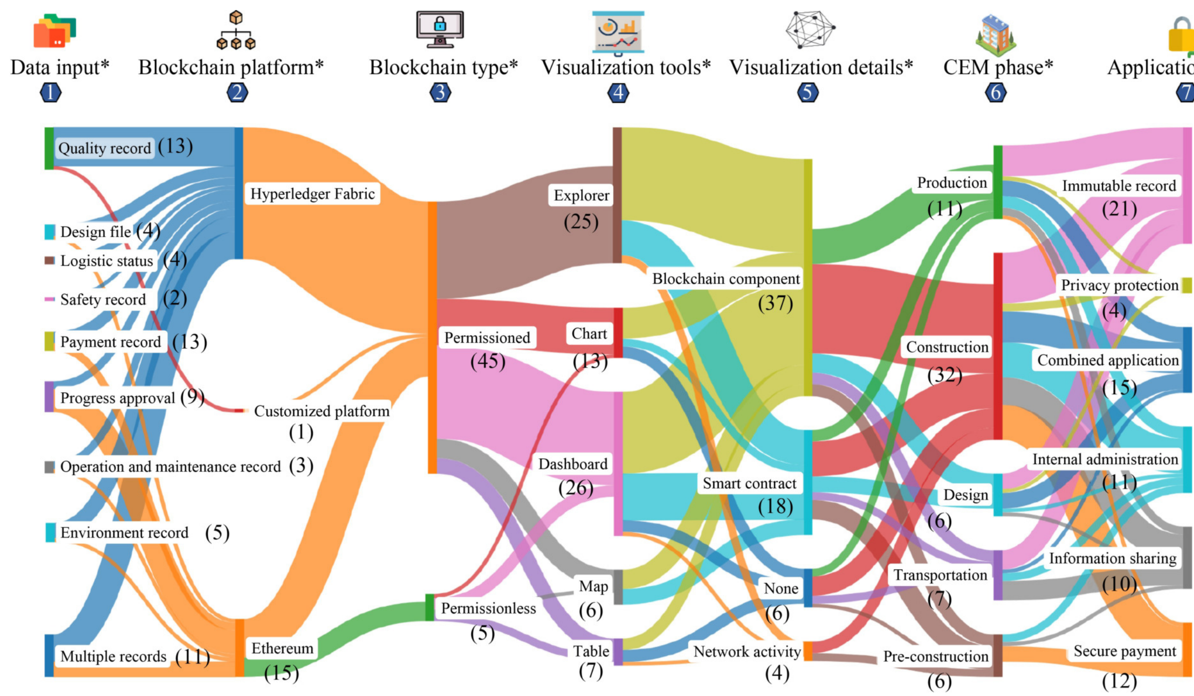

Fig. 3 Overview of the reported cases.

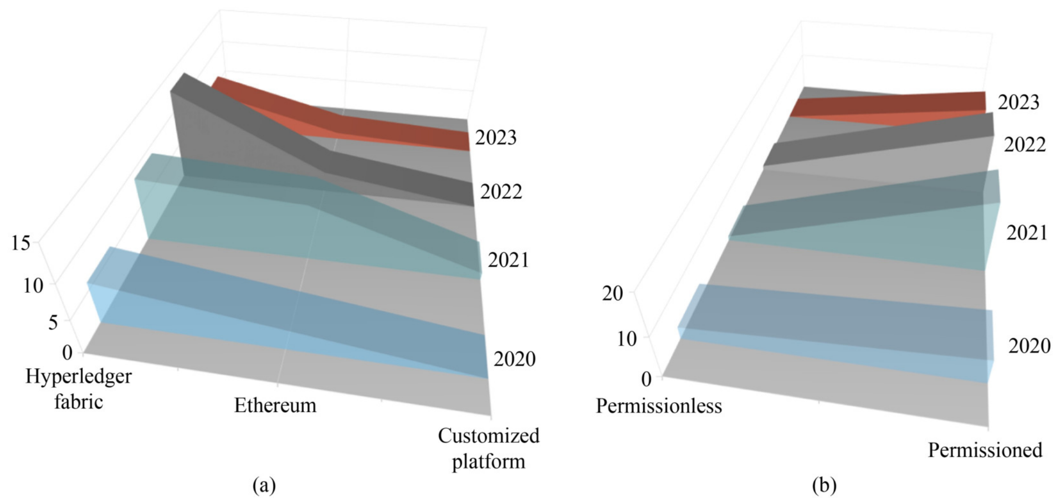

Fig. 4 Blockchain for data submission trends: (a) platforms; (b) types.

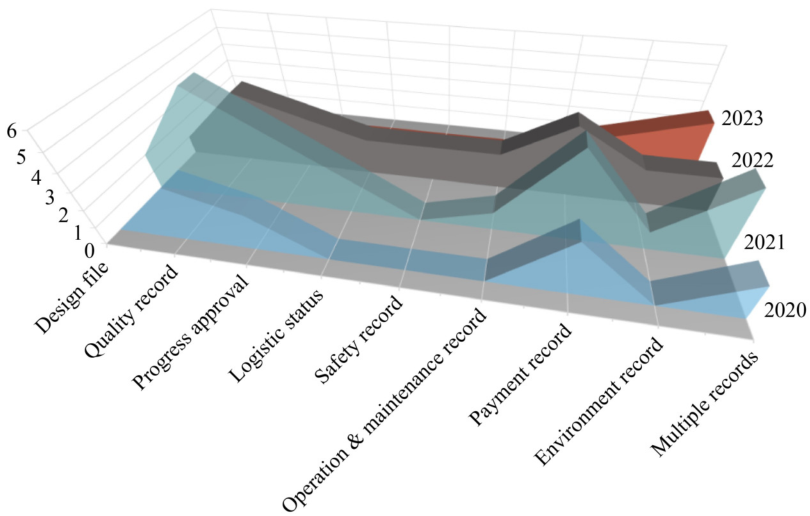

Fig. 5 Trend of data inputs.

for reducing late interim payments in construction projects. Blockchain-enabled smart contracts have attracted increasing attention from the construction industry because they decentralize the execution of contract terms to ensure payment certainty (Hamledari and Fischer, 2021a).

(2) Construction progress records were the second most popular data inputs, appearing in over 14% (9 over 64) descriptors. Recording construction progress on a blockchain can bring increased transparency and accountability. Thus, all parties involved in the construction project can access consistent progress data and can make informed decisions (Ahmadisheykhsarmast and Sonmez, 2020). Additionally, blockchain can help reduce disputes and delays by providing immutable and tamper-proof records of all construction activities (Wu et al., 2022b).

(3) Design files, logistics status, environmental data, operation and maintenance and safety records were not frequently uploaded to blockchain systems in the reviewed cases. This may be attributed to the specialized nature of blockchain technology, such that individuals without expertise in this area, including construction practitioners, may find it challenging to engage with and utilize blockchain effectively (Xue and Lu, 2020). Therefore, the visualization of DMP on blockchain is necessary.

(4) In the remaining cases, multiple types of records were uploaded to the blockchain. In these studies, blockchain was mainly used for data immutability and transparent sharing (e.g., Kim et al., 2023; Zhao et al., 2023).

The trend of data inputs for the reviewed cases is summarized in Fig. 5. Before 2021, the types of data input for recording on the blockchain system were less diverse than after 2021. Among the pre-2021 cases, quality (e.g., Sheng et al., 2020; Wang et al., 2020) and payment (e.g., Elghaish et al., 2020) records were of most concern. In 2021, increased attention was paid to inputting logistic status (Li et al., 2021b; Lu et al., 2021b) and design files (Tao et al., 2021) to the blockchain system. In 2022, the number of cases inputting records of operation and maintenance (Yang et al., 2022), environment (Zhong et al., 2022), and safety (Xu et al., 2022) increased, while in 2023, environmental records began to be actively submitted to blockchain (Wu et al., 2023).

3.1.3 Visualization tools and mediums for data submitted on blockchain

Concerning the selection pattern of the data visualization tools, most studies (26 out of 77 descriptors) used dashboards to present blockchain-based DMP. Dashboards allow construction project teams to visually present complex data collected from CEM activities in one place (e.g., Wu et al., 2022b). It organizes, groups, and presents essential project information with a few clicks (Pradeep et al., 2021). The second most used visualization tool was explorers (25 descriptors), such as Hyperledger Explorer. These platform-provided explorers are Web application tools to view, invoke, deploy, or query transaction data (Elghaish et al., 2020). Comparatively, charts, process maps, and tables were used less frequently. One reason may be that describing the data submitted to blockchain platforms in many solutions does not make it intuitive and easy for users to understand. For example, users may not know whether the recorded data was successfully packed into blocks and stored in ledgers immutably.

The trend of visualization tools for blockchain-based DMP can be observed in Fig. 6(a). The number of descriptors using charts, explorers, and dashboards were used less frequently. For example, Hamledari and Fischer

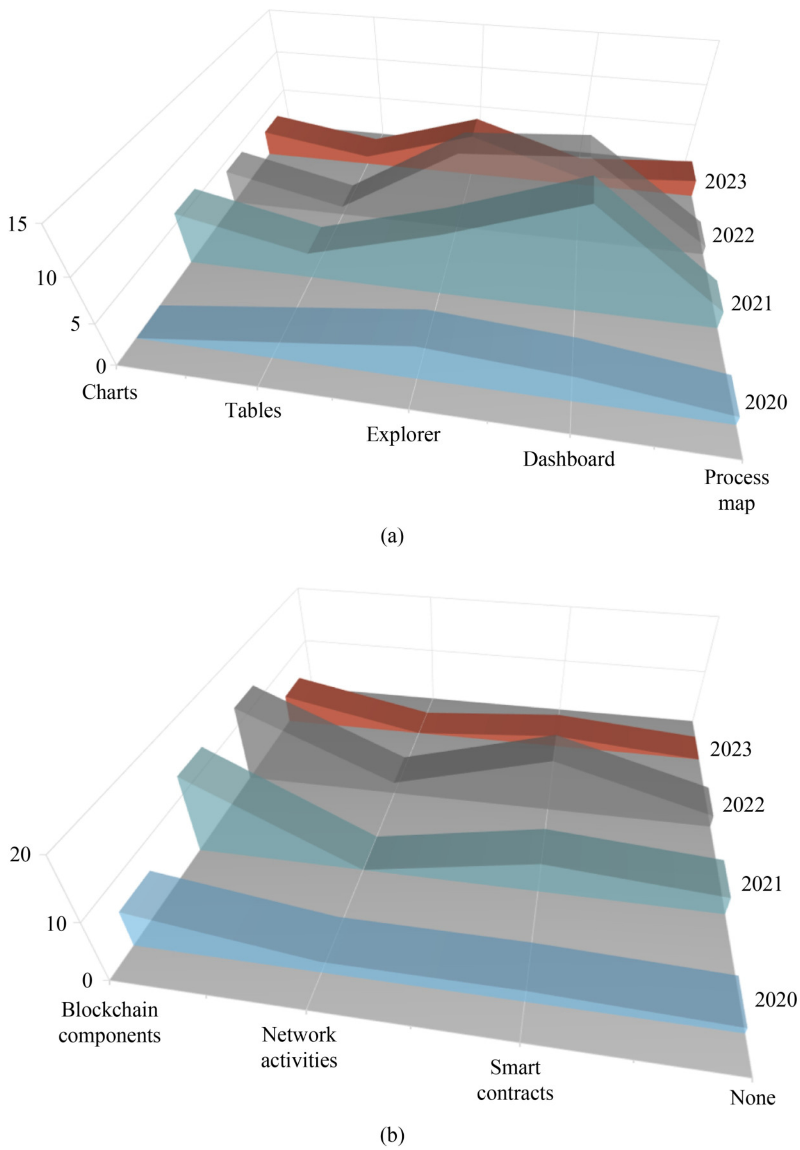

Fig. 6 Trend of visualization: (a) tools; (b) mediums.

(2021a) employed charts to help demonstrate an automated construction payment process based on blockchain-enabled smart contracts. In addition, many descriptors (e.g., Jiang et al., 2021) employed the explorers provided by the platforms to view the number of transactions and blocks generated by the case studies. Self-designed dashboards were commonly used to upload and query transaction data due to their customizability and visibility (e.g., Sigalov et al., 2021).

Most studies (37 descriptors) visualized the DMP by allowing users to invoke stored transactions from blocks. Eighteen descriptors visualized smart contracts, allowing users to understand the automated process of contract execution, and four descriptors visualized network information to make the blockchain network (e.g., project participants) transparent. However, there were six descriptors where blockchain details were not visualized, which could limit user satisfaction. Figure 6(b) reveals that more descriptors showing blockchain components and smart contracts have appeared in the last two years. For example, Tao et al. (2022) illustrated how design files are converted into transactions and packaged into blocks and execution processes of smart contracts.

3.1.4 Visualized data in CEM phases and applications

More than half of the descriptors (32) covered the construction stage, and about 18% (11 out of 62) of descriptors covered offsite or offshore prefabrication housing production. In contrast, only a few descriptors (7 out of 62) concerned transportation. Only 6 descriptors focused on pre-construction and design phases, respectively. Regarding applications, most descriptors (19 out of 73) applied blockchain to record data because of its immutability. Also, many descriptors (15 out of 73) focused on combined applications. For example, Wu et al. (2022c) adopted blockchain to avoid the single point of failure (SPOF) of IoT and BIM. Almost the same number of descriptors focused on secure payment (12 descriptors) and internal administration (11 descriptors), respectively. Blockchain was less explored in information sharing (10 descriptors), and encryption was even less used in privacy protection (4 descriptors).

In 2020, blockchain-based DMP was concentrated in the construction phase (Fig. 7). Among post-2020 descriptors, increased attention was paid to recording data in offsite housing production, transportation, and design phases. Among those post-2020 descriptors is Lu et al. (2022a)'s blockchain e-Inspection 2.0 system developed to supervise modular housing production. This system is adopted in our case study, as mentioned above. Li et al. (2021b) adopted blockchain to monitor the supply chain in prefabrication construction. Pradeep et al. (2021) adopted blockchain for liability control in the design phase. Another notable trend is that the number of descriptors applying blockchain for information sharing, privacy protection, and combined application has increased over time. Among those descriptors, Lee et al. (2021) proposed a blockchain framework to support accountable information sharing in construction projects. Recently, Tao et al. (2022) proposed a blockchain-enabled framework to protect sensitive design data. Wu et al. (2022c) aimed to link the permissioned blockchain to the IoT-BIM platform for offsite production management in modular construction. These trends expand the visibility of blockchain-based DMP in various CEM applications.

3.2 Challenges

The challenges of visualizing blockchain-based DMP submitted to blockchain systems are summarized below.

• Data diversity: construction projects involve a wide range of data, such as design files, quality records, progress approvals, and logistic status. Each data type may have its unique format, structure, and requirements.

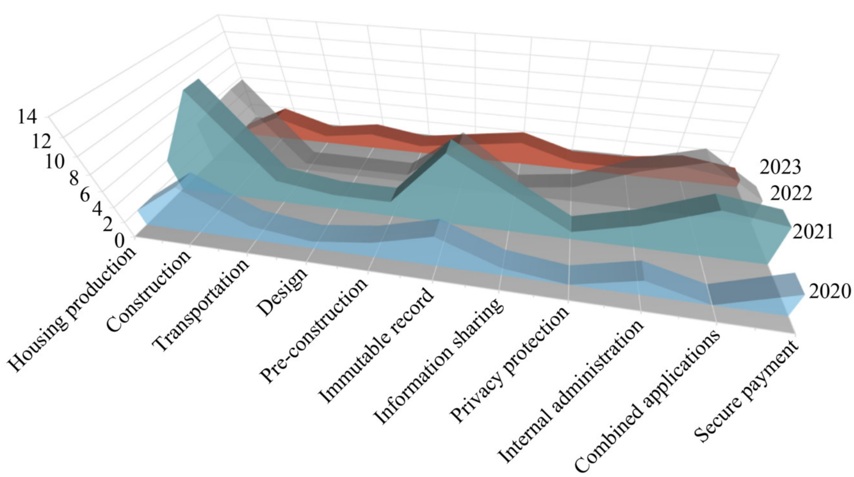

Fig. 7 Trend of visualized data in CEM phases and applications.

Visualizing these diverse data types can be complex and time-consuming. Additionally, ensuring the accurate visualization of different data sources can pose challenges.

• Visualization tools: there is a lack of guidelines for users and system developers to guide their selection of appropriate blockchain visualization tools. Thus, visualized data on blockchain systems may not be understood by construction practitioners, thereby reducing users' trust in such systems.

• Visualization mediums: without criteria for selecting visualization mediums, there are no clear user requirements as to what details should be visualized to reflect that the DMP can be visualized by certain blockchain components to increase user trust in blockchain systems.

• Visualization domain: there are no clear reminders for system developers and users about what types of CEM applications and phases data visualization will involve, leading to miscommunication on blockchain visualization.

Section 4 will present proposed guidelines for visualizing blockchain-based DMP in construction projects, based on a review of 49 real-world cases.

4 Guidelines for visualizing blockchain-based DMP in construction projects

4.1 Five-step guidelines

The proposed guidelines for visualizing blockchain-based DMP in construction projects are demonstrated in Fig. 8 and are introduced below.

Step 1: Targeting the visualization domain. Through project meetings, the project team must first discuss which phase of CEM needs to involve blockchain-based DMP. After that, they need to determine the application domain, i.e., the purpose of using the blockchain. A series of questions, such as "should the blockchain ensure data immutability"?, "Should the blockchain be used to improve information sharing"?, must be raised during project meetings.

Step 2: Planning blockchain visualization. Since CEM activities can generate various types of data, including quality and safety data, the project management team must determine the type of data input to be recorded on

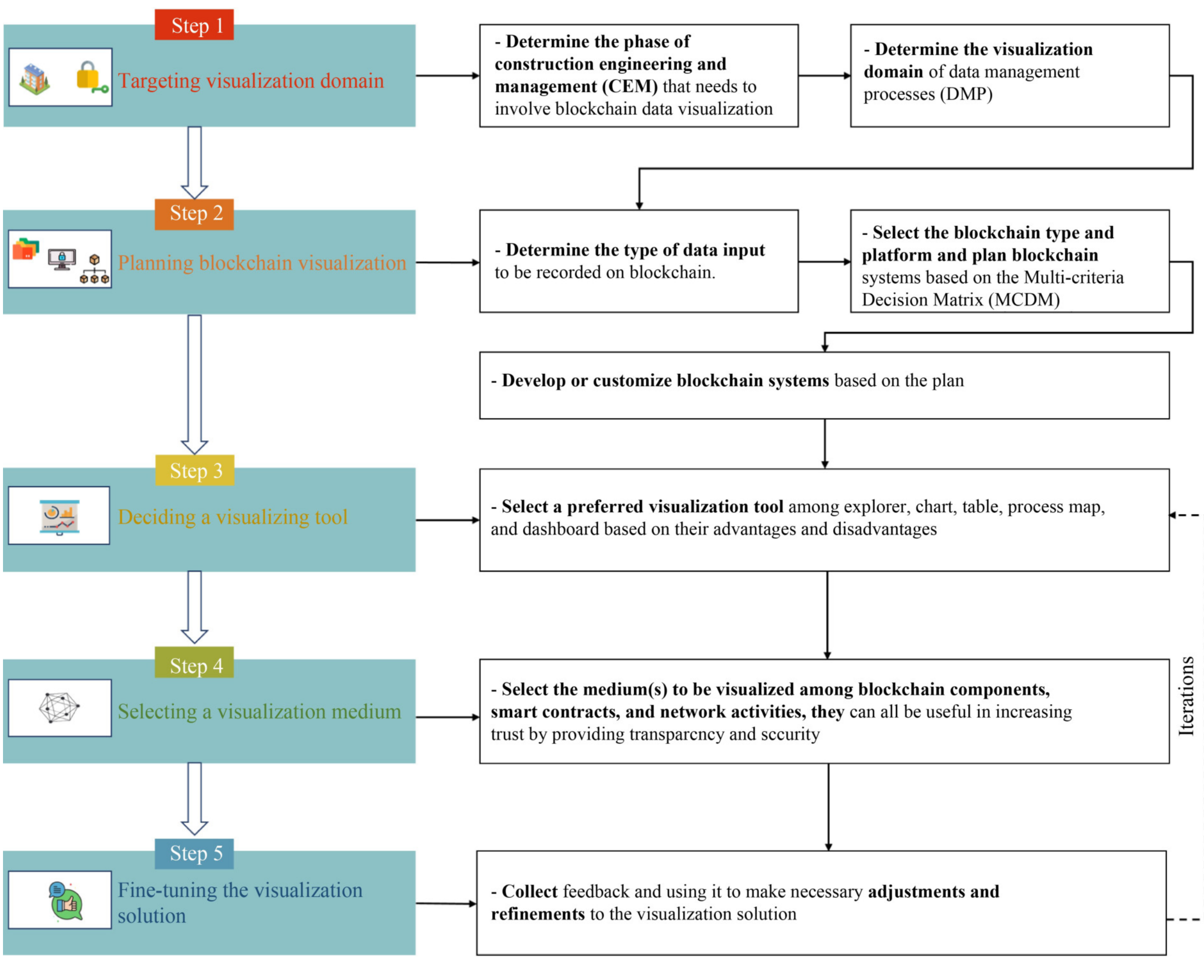

Fig. 8 Five-step guidelines for visualizing blockchain-based DMP in construction projects.

blockchain systems. Depending on the degree of network centralization, blockchain systems can be permissioned or permissionless (Wu et al., 2022c). A permissionless blockchain is accessible to everyone (Yang et al., 2020), while control of the permissioned blockchain is allocated to pre-authorized organizations participating in the operation of the system. The teams must also choose a blockchain platform such as Bitcoin, Ethereum, or Hyperledger Fabric, all of which have different focus domains, or they may build a customized blockchain. Lu et al. (2022b) developed a multicriteria decision matrix (MCDM) for project management practitioners, which will support blockchain type selection and evaluate blockchain platforms. Users of our guidelines are suggested to use this MCDM, after which system developers should work with project teams to develop or customize blockchain systems.

Step 3: Choosing a visualizing tool. According to the specific project situation, project teams should work with system developers to select their preferred visualization tool based on their advantages and disadvantages (Table 5) through a point-based scoring method. For each advantage of each tool in Table 5, one point can be awarded if they meet the project requirements; otherwise, no point is given. Similarly, for each disadvantage of each tool, one point is deducted if it does not meet the project requirements; otherwise, no point is deducted.

Step 4: Selecting a visualization medium. When deciding on visualization mediums for a blockchain system, it is important to consider the level of trust that users have in the system. Blockchain components, smart contracts, and network activities can all be useful in increasing trust by providing transparency and security. Blockchain components can create an immutable ledger that records every transaction, ensuring that no data are lost or altered. Smart contracts can automate processes and ensure that all parties involved in a transaction are held accountable. Network activities can provide real-time monitoring and alert users to any suspicious activity. By implementing these visualization mediums, users can have greater confidence in blockchain. The finalization of data visualization processes entails presenting a solution that successfully conveys the processing of data on blockchain systems. By presenting a solution that effectively communicates the data, stakeholders can obtain valuable insights from the visualization and develop trust in blockchain systems.

Step 5: Fine-tuning the visualization solution. This is a critical step in ensuring its effectiveness and usability. By soliciting feedback from users, it becomes possible to understand any potential issues they may have encountered. This feedback can then be used to make necessary adjustments and refinements to the visualization solution. This iterative process helps to improve the clarity, comprehensibility, and overall user experience of the visualization.

4.2 Demonstration in a case project

The applicability of the guidelines developed here is demonstrated in a real-life case, where a blockchain system was customized to record MiC offsite production quality data. The project team wanted to visualize blockchain-based DMP to enhance trust in the blockchain system. Thus, the project and research teams were invited to use the proposed guidelines to visualize the MiC quality blockchain-based DMP.

The guidelines shown in Fig. 8 were followed to determine the target CEM phase and application domain of the blockchain system. In Step 1, since the project client has

Table 5 Comparison of advantages and disadvantages of data visualization tools of blockchain

Tools	Advantages	Disadvantages
Explorer	1. Enhanced transparency and real-time access to blockchain-based DMP 2. Simplified data analysis and interpretation 3. Debugging and troubleshooting capabilities	1. Limited customization options and flexibility 2. May require technical knowledge to fully utilize its features 3. Potential security risks if not implemented properly
Chart	1. Presents data in a visually appealing and easy-to-understand format 2. Enables identification of patterns and trends 3. Allows for comparison and analysis of different data sets	1. Limited capacity to handle large volumes of data 2. May oversimplify complex data relationships 3. Requires careful selection of appropriate chart types for accurate representation
Table	1. Organizes and presents data in a structured manner 2. Allows for efficient data sorting, filtering, and analysis 3. Enables easy comparison of data values	1. Limited visual representation 2. Potential difficulty in understanding complex data relationships 3. May not be suitable for displaying large data sets
Process Map	1. Provides a visual representation of the sequential flow of blockchain processes 2. Helps identify bottlenecks, inefficiencies, and potential improvements 3. Facilitates understanding of complex workflows	1. May oversimplify complex processes 2. Limited capacity to represent nonlinear or parallel processes 3.No real-time access to blockchain-based DMP
Dashboard	1. Consolidates multiple customizable and interactive visualizations and data sources into a single interface 2. Enables easy monitoring and analysis of key performance indicators 3. Provides real-time updates and alerts	1. Requires careful design and planning to ensure effective representation of relevant data 2. May require technical expertise for setup and maintenance 3. Can become overwhelming if too many visualizations or data sources are included

high requirements for the quality of modules produced by the offsite MiC manufacturer, offsite production is selected as the target CEM phase for the blockchain application (Fig. 9(a) and 9(b)). In addition, the project team selected immutable records as the application domain (Fig. 9(c) and 9(d)).

In Step 2, photos showing the production quality of the MiC module at each checkpoint were selected as data input to be uploaded to the blockchain system (Fig. 9(e)), allowing project stakeholders from Hong Kong (e.g., authorized persons, registered structural engineers) to inspect and endorse the quality remotely through the decentralized consensus mechanism of the blockchain system (Fig. 9(f)).

In addition, the project team used the organization criteria of the MCDM developed by Lu et al. (2022b) to choose the blockchain type (in the previous case project) (Fig. 10(a)). The project team believed permissioned blockchain could meet their requirements based on criteria such as range of use, transparency, centralization, auditability, cost, privacy, security, and scalability (Fig. 10(b)). Also, the project team selected Hyperledger Fabric as the platform by using the performance criteria of the MCDM (in the previous case project) (Fig. 10(c)). The project team believed that transaction throughput, block time, consensus network, smart contract language, cryptocurrency availability, and transaction fees of Hyperledger Fabric could meet their requirements in projects (Fig. 10(d)).

Subsequently, the blockchain system developed in the previous project (Lu et al., 2022a) was customized for the case project of this study. The customization was mainly achieved by adjusting the project participants and their permission level (Fig. 10(e)).

In Step 3, the project team was requested to select a preferred data visualization tool. Based on the pros and cons of the available visualization tools in Table 4, the project team held two workshops to conduct a scoring-

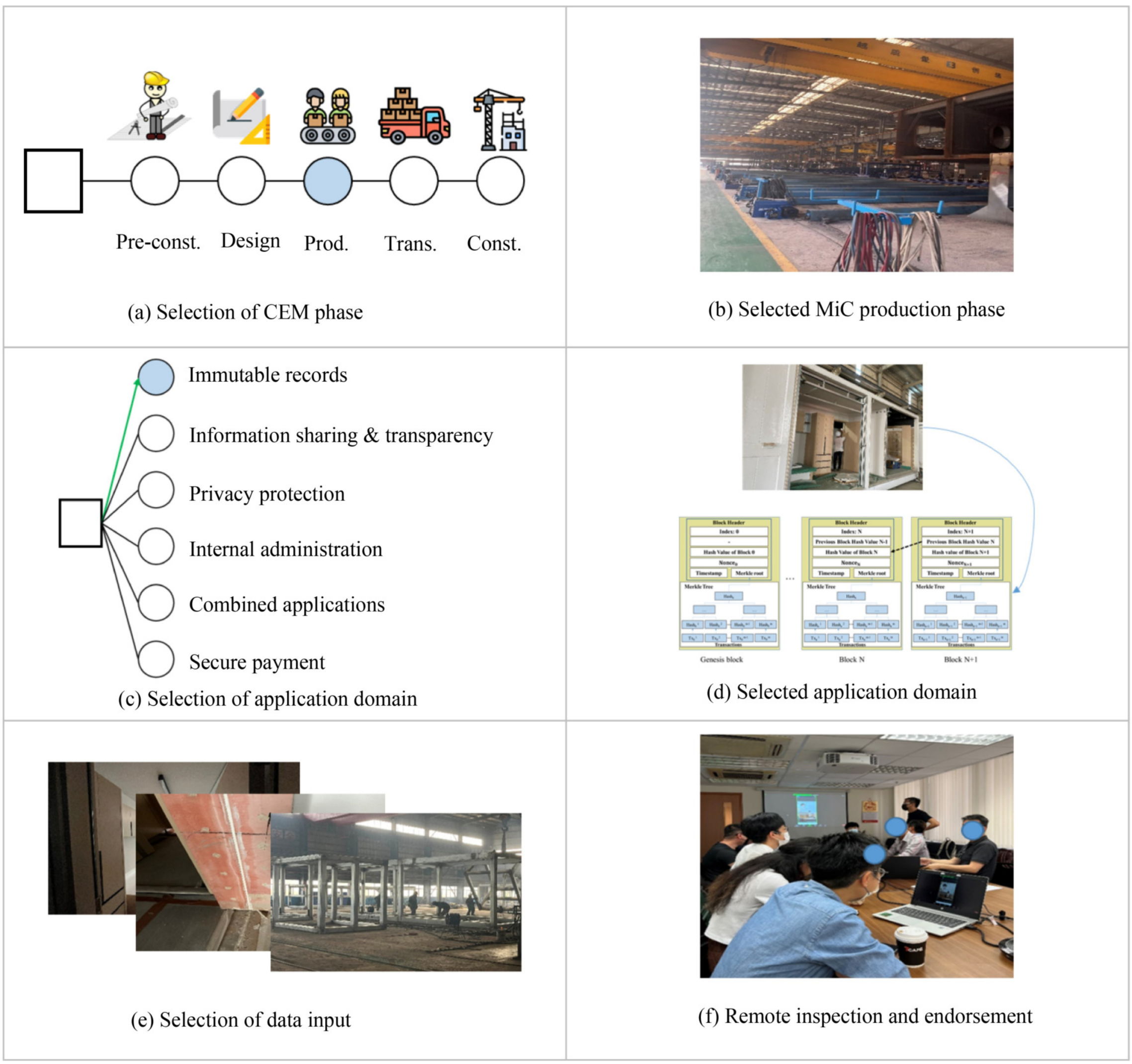

Fig. 9 Selecting CEM phase, application domain, and data inputs of the blockchain system.

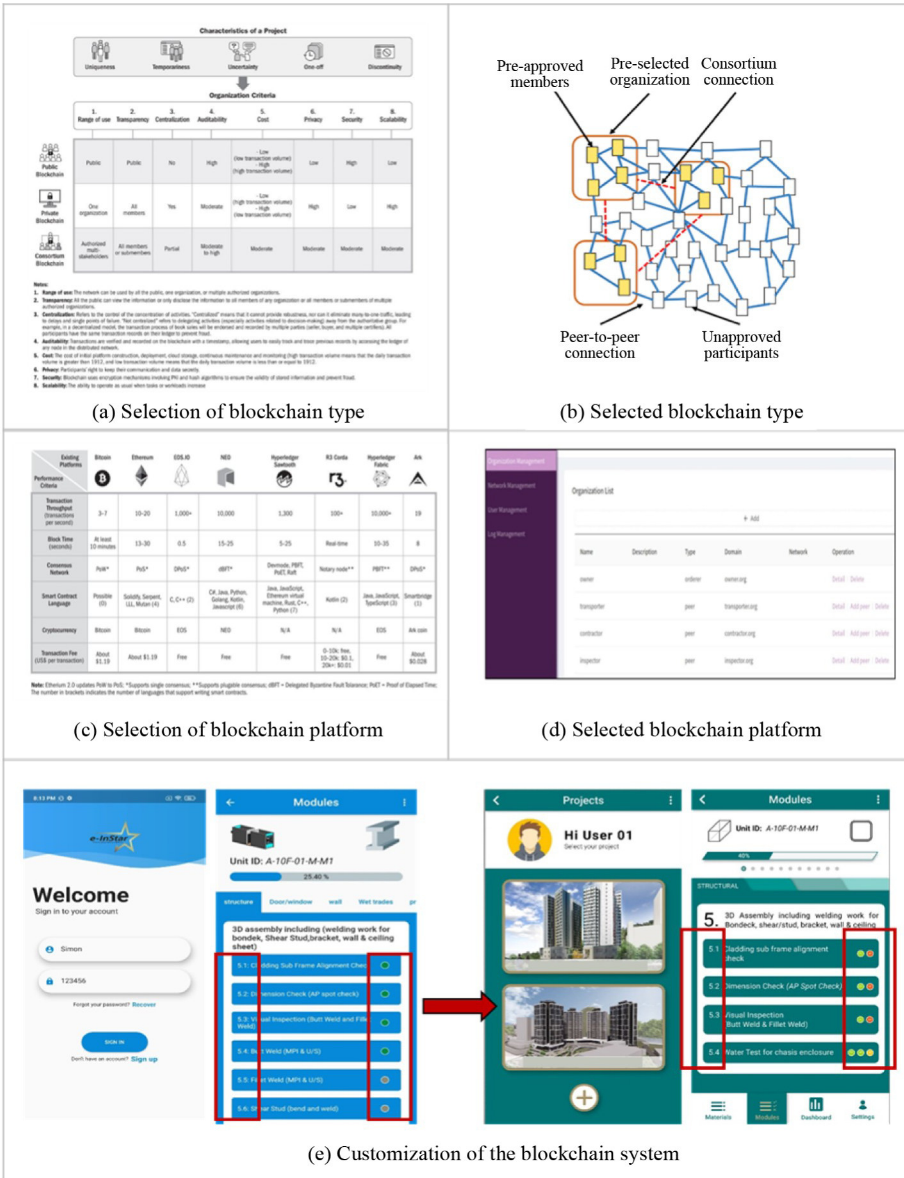

Fig. 10 Selecting blockchain type and platform, and customizing the blockchain system.

based strength and weakness analysis to select the appropriate tool. As a result, the dashboard was selected as the visualization tool.

In Step 4, the project team selected the visualization mediums for the blockchain system. In a joint project meeting with the research team, the project team first selected the blockchain component to ensure that the production and inspection data of the modules during the offsite production phase could be successfully stored in the block and recalled when needed. Next, the project team selected the network as they wanted to ensure that peer nodes were active and not offline to store data in their distributed ledgers.

A dashboard was thereby developed to visualize blockchain-based DMP based on the selections and knowledge gained from Steps 1–3. Manufacturers submitted the data related to module offsite production via the front-end interface, and inspectors then endorsed the data through the decentralized network of the blockchain. Therefore, as shown in Fig. 11(a), the dashboard displays the blockchain network by showing all users and their categories and locations. In this way, users can improve their trust in the blockchain system by understanding the active users in the network who submit and endorse production data and their corresponding locations. After endorsing the production data, the data are packed as transactions and stored in a block. The developed dashboard allows users to recall the corresponding production data in the block by searching the Module ID and Workstage, thus enhancing trust in the system by ensuring that the data are successfully endorsed and stored on the blockchain (Fig. 11(b)).

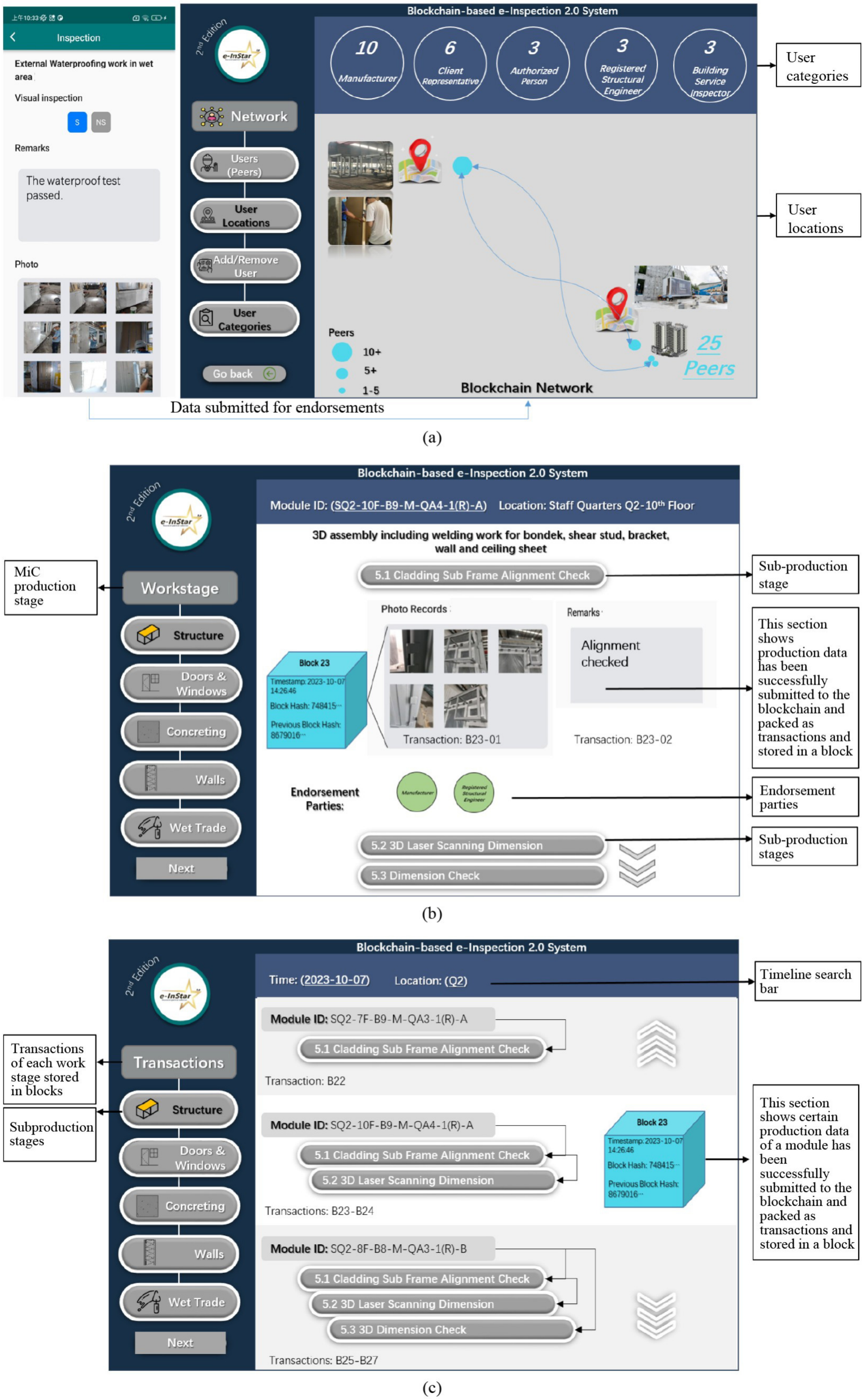

Fig. 11 Blockchain-based DMP visualization through the dashboard: (a) Data submission via a blockchain network; (b) Data endorsement and storage in blocks; (c) Data invoking for a particular date.

In Step 5, a survey was conducted to collect user feedback in order to improve the developed blockchain dashboard. For example, a technical manager from the client pointed out that the dashboard should allow users to use the timeline search bar to find the corresponding production data submitted on a particular date on the blockchain system. Thus, the research team further developed an interface based on this feedback, as shown in Fig. 11(c).

4.3 Assessment

After utilizing the guidelines in the visualization processes, individuals responded to four interview queries. The responses are summarized in the supplementary information in Appendix A. In response to Question 1, the interviewee from MiC manufacturer confirmed that the guidelines helped them understand the data submission process of MiC modules on the blockchain system because it helped frontline staff perceive and confirm that relevant photos were successfully submitted through the user dashboard developed by the research team. Therefore, the visualization processes enhanced their trust in the blockchain system. Main contractor interviewees also noted that they can now feel the presence of the blockchain system as they can now call up production data in blockchain ledgers. However, in addition to visualizing data submission, endorsement, storage, and invocation, they stressed that guidelines should also include guidance on how to visualize opportunistic events, such as alerting users where data has been manipulated. Likewise, project clients stated that the guidelines can guide users like them in perceiving DMP on blockchain systems, rather than incomprehensible coding.

When answering Question 2, interviewees from the project client organization and the MiC manufacturer pointed out that the guidelines have clear and straightforward steps to visualize blockchain-based DMP without wasting time. Interviewees from the project client organization further stated that another two benefits of the guidelines are the presentation of the pros and cons of various visualization tools and the usefulness of enabling practitioners to visualize and perceive data submission, endorsement, secure storage, and invocation processes on blockchain systems systematically. Interviewees from the project client organization, main contractor, and MiC manufacturer reflected that the guidelines could help bridge the knowledge gap between practitioners and blockchain system developers for visualizing blockchain-based DMP by allowing them to understand what system developers can do for them to visualize blockchain and propose corresponding user requirements.

Nevertheless, when answering Question 3, interviewees reflected on two disadvantages of the guidelines: (1) selecting the blockchain type and platform using the developed MCDM and choosing the visualization tool using the scoring method consume additional time, and (2) more explanation is needed in the guidelines to help users choose different visualization mediums. These crucial concerns should be addressed in the future. For Question 4, interviewees recommended providing an example of how to use the scoring method to select visualization tools, requiring blockchain system developers in the selection of visualization tools, attaching the developed MCDM as a sub-guide with some explanations, offering descriptions for visualization mediums that clarify how the data can be shown through them, and formatting the guide as a booklet for better readability and attraction purposes —all excellent suggestions for further study.

5 Conclusions

The study aimed to provide a set of guidelines for users to visualize data management processes (DMPs) on blockchain systems in the construction and engineering management (CEM) context. First, it identified the status quo of blockchain-based DMP visualization by reviewing 49 actual cases published in scholarly papers. It is discovered that current blockchain-based DMP are predominantly focused on safeguarding quality inspection and payment records in the construction phase of a project. Most of the systems adopted the Hyperledger Fabric platform and favored a permissioned type of blockchain. Dashboards were widely used to visualize blockchain-based DMP by only allowing users to invoke transactions from blocks for query purposes. Therefore, how to visualize blockchain-based DMP, including submission, endorsement, storage and invocation so that users have a sense of user-friendliness and trustworthiness has become the point of departure of this study.

Then, the research identified the challenges as seen in the blockchain-based DMP visualization approaches. First, heterogeneous data and non-standard DMP add to the difficulties. A lack of proper visualization tools and mediums, together with a poor understanding of the visualization domain, all challenge the current practices of blockchain-based DMP visualization. Building on the findings, guidelines were developed for users to visualize the blockchain-based DMP and thereby harness the powers of these systems in CEM. The guidelines comprise five major steps: (1) targeting the visualization domain, (2) planning blockchain visualization, (3) choosing a visualization tool, (4) selecting a visualization medium, and (5) fine-tuning the visualization solution. The usefulness of the guidelines was demonstrated and assessed in a case study of blockchain applications in offsite modular housing production.

This study brings both theoretical contributions and practical implications. Compared with the previous blockchain studies, the theoretical contribution of this study first lies in its systematic articulation of the status quo of blockchain-based DMP visualization in the context of CEM. Second, this study identifies key challenges in visualizing blockchain-based DMPs from the existing blockchain literature related to CEM. Third, this study develops novel guidelines that enable construction practitioners to collaborate with system developers to visualize and comprehend the processes of data submission, endorsement, secure storage, and invocation on blockchain systems.

The proposed guidelines for visualizing blockchain-based DMPs also have practical implications for construction stakeholders. First, the guidelines facilitate collaboration between construction practitioners and system developers by providing a shared understanding of how data submission, endorsement, secure storage, and invocation occur on blockchain systems. This collaboration can lead to more effective decision-making and problem-solving processes. Secondly, the proposed guidelines help to streamline decision-making processes. Clear visualization of the blockchain-based DMP processes enables construction stakeholders to make more informed decisions. By understanding the flow of data and the interactions between different entities on the blockchain, stakeholders can identify potential bottlenecks, inefficiencies, or vulnerabilities, leading to more effective decision-making and process optimization. Thirdly, the proposed guidelines help to enhance trust among stakeholders. Blockchain technology is known for its ability to provide trust and security. By visualizing the processes involved in DMPs on the blockchain using the guidelines, construction stakeholders can gain confidence in the integrity of the data and the overall system. This increased trust can foster better relationships among stakeholders, including contractors, clients, and regulators.

The limitations of this research present significant opportunities for future investigations. First, the proposed guidelines were only demonstrated in one case project. Future studies should test the guidelines in more CEM scenarios. Secondly, the evaluation of the proposed guidelines was conducted only in a qualitative manner. More systematic and quantitative assessment frameworks should be studied and the guidelines should be refined based on further evaluation. Thirdly, the project performance after adopting blockchain-based DMP visualization guidelines remains to be studied. Additional research is necessary to investigate how visualization solutions for blockchain-based DMP affect project performance in CEM.

Competing Interests The authors declare that they have no competing interests.

Appendix A

Table A1 Responses from interviewees

Interviewee	Response	Category
Question 1: After using the suggested guidelines, does the visualization enhances your trust in the blockchain system?		
OW1	Indeed, it is possible that doing so could assist us in confirming that all MiC production-related photos have been effectively uploaded to the blockchain system.	Yes
OW2	Yes, before doing visualization, I believe that most users, including me, could not feel the existence of blockchain. Now I can clearly see that the data is submitted, endorsed, stored, and invoked in each block.	Yes
OW3	Ultimately, when blockchain processes are visualized through the dashboard, users like us will trust the system because we face and use it every day, rather than some incomprehensible coding behind the blockchain. It's also layman-friendly.	Yes
OW4	You can't just tell users that they have used the blockchain, but they can't perceive the verification and security of the blockchain. Visualization is very important because it not only increases our trust in blockchain but also helps us persuade more contractors to use and accept blockchain.	Yes
MC1	Yes, I can retrieve and view the production data stored in the blockchain at any time to ensure the quality of the modules.	Yes
MC2	I can now feel the difference between blockchain and existing systems. But it would be nice if the visualization could also display warning messages if there are any data manipulations.	Partial
MA1	For us, we needed this interface to help frontline workers ensure they had successfully submitted photos to the blockchain system.	Yes
Question 2: What are the benefits of using the proposed guidelines for visualizing blockchain-based data management processes in construction projects?		
OW1	Steps are clear and easy to follow	1
	Providing the advantages and disadvantages of different visualization tools	2

(*Continued*)

Interviewee	Response	Category
OW2	Enabling practitioners to visualize and perceive data endorsement, storage and retrieve processes submitted on the blockchain We can compare different visualization tools and mediums.	3 2
OW3	Bridging the knowledge gap between practitioners and system developers Not time consuming and easy to follow	4 1
OW4	Let practitioners like us be able to express our user requirements for the blockchain system so that we can use it comfortably.	4
MC1	Without showing us complex coding, it provides us with a communication channel that helps system developers better visualize the data we actually want.	4
MC2	It's easy for users to understand what needs to be done to visualize the data management processes on the blockchain.	1
MA1	We can better understand what system developers can do for us to visualize blockchain.	4
Question 3: What are the drawbacks of using the proposed guidelines for visualizing blockchain-based data management processes in construction projects?		
OW1	Scoring visualization tools requires a team effort, which can take some time.	5
OW2	It may need to add some explanation to help users choose different visualization mediums. For example, explain how blocks ensure data remains unchanged,	6
OW3	Using the suggested MCDM may take some time	5
OW4	Selecting a visualization tool based on the scoring method can take some time.	5
MC1	No.	7
MC2	The process of choosing a visualization tool using the scoring method may require a certain amount of time.	5
MA1	It may require some time to use the recommended MCDM.	5
Question 4: Do you have other suggestions to improve the guidelines?		
OW1	It would be great if the guideline could provide an example of how to use the scoring method to select visualization tools.	8
OW2	This guide can engage blockchain system developers in the selection of visualization tools if possible.	9
OW3	The developed MCDM can be attached as a sub-guide with some explanations.	10
OW4	Supplying descriptions for visualization mediums that clarify how the data management processes can be shown through them.	11
MC1	Providing some explanations for each visualization medium about how the data management processes is visualized through them	11
MC2	Adding an example to illustrate the processes of scoring method to select visualization tools.	8
MA1	I have no comment on the content, but you can format the guide as a booklet for better readability and appeal.	12

References

Ahmadisheykhsarmast S, Senji S G, Sonmez R (2023). Decentralized tendering of construction projects using blockchain-based smart contracts and storage systems. Automation in Construction, 151: 104900

Ahmadisheykhsarmast S, Sonmez R (2020). A smart contract system for security of payment of construction contracts. Automation in Construction, 120: 103401

Börner K, Bueckle A, Ginda M (2019). Data visualization literacy: Definitions, conceptual frameworks, exercises, and assessments. Proceedings of the National Academy of Sciences of the United States of America, 116(6): 1857–1864

Cheng J C, Liu H, Gan V J, Das M, Tao X, Zhou S (2023). Construction cost management using blockchain and encryption. Automation in Construction, 152: 104841

Cho S, Khan M, Pyeon J, Park C (2021). Blockchain-based network concept model for reliable and accessible fine dust management system at construction sites. Applied Sciences, 11(18): 8686

Ciotta V, Mariniello G, Asprone D, Botta A, Manfredi G (2021). Integration of blockchains and smart contracts into construction information flows: Proof-of-concept. Automation in Construction, 132: 103925

Das M, Luo H, Cheng J C (2020). Securing interim payments in construction projects through a blockchain-based framework. Automation in Construction, 118: 103284

Das M, Tao X, Liu Y, Cheng J C (2022). A blockchain-based integrated document management framework for construction applications. Automation in Construction, 133: 104001

Elghaish F, Abrishami S, Hosseini M R (2020). Integrated project delivery with blockchain: An automated financial system. Automation in Construction, 114: 103182

Elghaish F, Hosseini M R, Kocaturk T, Arashpour M, Ledari M B (2023). Digitalised circular construction supply chain: An integrated BIM-blockchain solution. Automation in Construction, 148: 104746

Elghaish F, Pour Rahimian F P, Hosseini M R, Edwards D, Shelbourn M (2022). Financial management of construction projects: Hyperledger Fabric and chaincode solutions. Automation in Construction, 137: 104185

Hamledari H, Fischer M (2021a). Construction payment automation using blockchain-enabled smart contracts and robotic reality capture technologies. Automation in Construction, 132: 103926

Hamledari H, Fischer M (2021b). The application of blockchain-based crypto assets for integrating the physical and financial supply chains in the construction and engineering industry. Automation in Construction, 127: 103711

Jiang Y, Liu X, Kang K, Wang Z, Zhong R Y, Huang G Q (2021). Blockchain-enabled cyber-physical smart modular integrated construction. Computers in Industry, 133: 103553

Kim M, Zhao X, Kim Y W, Rhee B D (2023). Blockchain-enabled supply chain coordination for off-site construction using Bayesian theory for plan reliability. Automation in Construction, 155: 105061

Lee D, Lee S H, Masoud N, Krishnan M S, Li V C (2021). Integrated digital twin and blockchain framework to support accountable information sharing in construction projects. Automation in Construction, 127: 103688

Lewis-Beck M, Bryman A E, Futing Liao T F (2004). The Sage encyclopedia of social science research methods. Thousand Oaks, CA: SAGE

Li C Z, Chen Z, Xue F, Kong X T, Xiao B, Lai X, Zhao Y (2021b). A blockchain-and IoT-based smart product-service system for the sustainability of prefabricated housing construction. Journal of Cleaner Production, 286: 125391

Li J, Greenwood D, Kassem M (2019). Blockchain in the built environment and construction industry: A systematic review, conceptual models and practical use cases. Automation in Construction, 102: 288–307

Li J, Kassem M (2021). Applications of distributed ledger technology (DLT) and blockchain-enabled smart contracts in construction. Automation in Construction, 132: 103955

Li X, Lu W, Xue F, Wu L, Zhao R, Lou J, Xu J (2022). Blockchain-enabled IoT-BIM platform for supply chain management in modular construction. Journal of Construction Engineering and Management, 148(2): 04021195

Li X, Wu L, Zhao R, Lu W, Xue F (2021a). Two-layer adaptive blockchain-based supervision model for off-site modular housing production. Computers in Industry, 128: 103437

Lu W, Li X, Xue F, Zhao R, Wu L, Yeh A G (2021b). Exploring smart construction objects as blockchain oracles in construction supply chain management. Automation in Construction, 129: 103816

Lu W, Wu L, Xu J, Lou J (2022a). Construction E-Inspection 2.0 in the COVID-19 pandemic era: A blockchain-based technical solution. Journal of Management Engineering, 38(4): 04022032

Lu W, Wu L, Xue F (2022b). Blockchain technology for projects: A multicriteria decision matrix. Project Management Journal, 53(1): 84–99

Lu W, Wu L, Zhao R (2023). Rebuilding trust in the construction industry: A blockchain-based deployment framework. International Journal of Construction Management, 1–12

Lu W, Wu L, Zhao R, Li X, Xue F (2021a). Blockchain technology for governmental supervision of construction work: learning from digital currency electronic payment systems. Journal of Construction Engineering and Management, 147(10): 04021122

Oraee M, Hosseini M R, Papadonikolaki E, Palliyaguru R, Arashpour M (2017). Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review. International Journal of Project Management, 35(7): 1288–1301

Pan X, Zhong B, Sheng D, Yuan X, Wang Y (2022). Blockchain and deep learning technologies for construction equipment security information management. Automation in Construction, 136: 104186

Park S, Bekemeier B, Flaxman A, Schultz M (2022). Impact of data visualization on decision-making and its implications for public health practice: A systematic literature review. Informatics for Health & Social Care, 47(2): 175–193

Pradeep A S E, Yiu T W, Zou Y, Amor R (2021). Blockchain-aided information exchange records for design liability control and improved security. Automation in Construction, 126: 103667

Rethlefsen M L, Kirtley S, Waffenschmidt S, Ayala A P, Moher D, Page M J, Koffel J B, Blunt H, Brigham T, Chang S, Clark J, Conway A, Couban R, de Kock S, Farrah K, Fehrmann P, Foster M, Fowler S A, Glanville J, Harris E, Hoffecker L, Isojarvi J, Kaunelis D, Ket H, Levay P, Lyon J, McGowan J, Murad M H, Nicholson J, Pannabecker V, Paynter R, Pinotti R, Ross-White A, Sampson M, Shields T, Stevens A, Sutton A, Weinfurter E, Wright K, Young S (2021). PRISMA-S: An extension to the PRISMA statement for reporting literature searches in systematic reviews. Systematic Reviews, 10(1): 1–19

Risius M, Spohrer K (2017). A blockchain research framework. Business & Information Systems Engineering, 59(6): 385–409

Sackett P J, Al-Gaylani M F, Tiwari A, Williams D (2006). A review of data visualization: Opportunities in manufacturing sequence management. International Journal of Computer Integrated Manufacturing, 19(7): 689–704

Saygili M, Mert I E, Tokdemir O B (2022). A decentralized structure to reduce and resolve construction disputes in a hybrid blockchain network. Automation in Construction, 134: 104056

Shemov G, Garcia de Soto B, Alkhzaimi H (2020). Blockchain applied to the construction supply chain: A case study with threat model. Frontiers of Engineering Management, 7(4): 564–577

Sheng D, Ding L, Zhong B, Love P E, Luo H, Chen J (2020). Construction quality information management with blockchains. Automation in Construction, 120: 103373

Shu Z, Liu W, Fu B, Li Z, He M (2022). Blockchain-enhanced trading systems for construction industry to control carbon emissions. Clean Technologies and Environmental Policy, 24(6): 1851–1870

Sigalov K, Ye X, König M, Hagedorn P, Blum F, Severin B, Hettmer M, Hückinghaus P, Wölkerling J, Groß D (2021). Automated payment and contract management in the construction industry by integrating building information modeling and blockchain-based smart contracts. Applied Sciences, 11(16): 7653

Sonmez R, Ahmadisheykhsarmast S, Güngör A A (2022). BIM integrated smart contract for construction project progress payment administration. Automation in Construction, 139: 104294

Spiller M, Liu Y H, Hossain M Z, Gedeon T, Geissler J, Nürnberger A (2021). Predicting visual search task success from eye gaze data as a basis for user-adaptive information visualization systems. ACM Transactions on Interactive Intelligent Systems, 11(2): 1–25

Suyambu G T, Anand M, Janakirani M (2020). Blockchain–A most disruptive technology on the spotlight of world engineering education paradigm. Procedia Computer Science, 172(1): 152–158

Tao X, Das M, Liu Y, Cheng J C (2021). Distributed common data environment using blockchain and interplanetary file system for secure BIM-based collaborative design. Automation in Construction, 130: 103851

Tao X, Das M, Zheng C, Liu Y, Wong P K Y, Xu Y, Liu H, Gong X, Cheng J C P (2023). Enhancing BIM security in emergency construction projects using lightweight blockchain-as-a-service. Automation in Construction, 150: 104846

Tao X, Liu Y, Wong P K Y, Chen K, Das M, Cheng J C (2022). Confidentiality-minded framework for blockchain-based BIM design collaboration. Automation in Construction, 136: 104172

Tezel A, Febrero P, Papadonikolaki E, Yitmen I (2021). Insights into blockchain implementation in construction: Models for supply chain management. Journal of Management Engineering, 37(4): 04021038

Wang Z, Dingwall H, Bach B (2019). Teaching data visualization and storytelling with data comic workshops. In: Extended abstracts of the 2019 CHI conference on human factors in computing systems: 1–9

Wang Z, Wang T, Hu H, Gong J, Ren X, Xiao Q (2020). Blockchain-based framework for improving supply chain traceability and information sharing in precast construction. Automation in Construction, 111: 103063

Wu H, Zhong B, Li H, Chi H L, Wang Y (2022). On-site safety inspection of tower cranes: A blockchain-enabled conceptual framework. Safety Science, 153: 105815

Wu H, Zhong B, Li H, Guo J, Wang Y (2021). On-site construction quality inspection using blockchain and smart contracts. Journal of Management Engineering, 37(6): 04021065

Wu L, Lu W, Peng Z, Webster C (2023). A blockchain non-fungible token-enabled ‘passport’ for construction waste material cross-jurisdictional trading. Automation in Construction, 149: 104783

Wu L, Lu W, Xu J (2022b). Blockchain-based smart contract for smart payment in construction: A focus on the payment freezing and disbursement cycle. Frontiers of Engineering Management, 1–19

Wu L, Lu W, Xue F, Li X, Zhao R, Tang M (2022c). Linking permissioned blockchain to Internet of Things (IoT)-BIM platform for off-site production management in modular construction. Computers in Industry, 135: 103573

Wu L, Lu W, Zhao R, Xu J, Li X, Xue F (2022a). Using blockchain to improve information sharing accuracy in the onsite assembly of modular construction. Journal of Management Engineering, 38(3): 04022014

Xu J, Lu W, Wu L, Lou J, Li X (2022). Balancing privacy and occupational safety and health in construction: A blockchain-enabled P-OSH deployment framework. Safety Science, 154: 105860

Xue F, Lu W (2020). A semantic differential transaction approach to minimizing information redundancy for BIM and blockchain integration. Automation in Construction, 118: 103270

Yang J, Lee D, Baek C, Park C, Lan B Q, Lee D (2022). Leveraging blockchain for scaffolding work management in construction. IEEE Access: Practical Innovations, Open Solutions, 10: 39220–39238

Yang R, Wakefield R, Lyu S, Jayasuriya S, Han F, Yi X, Yang X, Amarasinghe G, Chen S (2020). Public and private blockchain in construction business process and information integration. Automation in Construction, 118: 103276

Zhang Y, Wang T, Yuen K V (2021b). Construction site information decentralized management using blockchain and smart contracts. Computer-Aided Civil and Infrastructure Engineering, 37(11): 1450–1467

Zhang Y, Wang Z, Deng J, Gong Z, Flood I, Wang Y (2021a). Framework for a blockchain-based infrastructure project financing system. IEEE Access: Practical Innovations, Open Solutions, 9: 141555–141570

Zhao R, Chen Z, Xue F (2023). A blockchain 3.0 paradigm for digital twins in construction project management. Automation in Construction, 145: 104645

Zhong B, Guo J, Zhang L, Wu H, Li H, Wang Y (2022). A blockchain-based framework for on-site construction environmental monitoring: Proof of concept. Building and Environment, 217: 109064

Zhong B, Wu H, Ding L, Luo H, Luo Y, Pan X (2020). Hyperledger fabric-based consortium blockchain for construction quality information management. Frontiers of engineering management, 7(4): 512–527