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BIM-blockchain integrated automatic asset tracking and delay propagation analysis for prefabricated construction projects

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ABSTRACT

Asset tracking is crucial for managing prefabricated construction projects, as delayed deliveries might disrupt interdependent offsite and onsite activities, causing economic losses and disputes. To clarify liabilities, tamperproof asset tracking and delay propagation analysis are necessary. To achieve this, a BIM-blockchain integrated framework via smart contracts is proposed given rich information in BIM and blockchain's immutable records. First, asset information and interdependent activity schedule are automatically transmitted from BIM to blockchain. Then, QR codes are generated and attached to physical assets for tracking. If any delays, compiled smart contracts will automatically derive propagated impacts on offsite and onsite activities considering their interdependencies and proactively notify relevant parties. Affected activities with assets, certification time, and responsible parties are automatically visualized in 4D BIM for timely collaboration. The developed IFC-Ethereum prototype demonstrates the framework's feasibility and effectiveness, reducing coordination overhead costs and time. Traceable records help further calculate parties' penalties and compensation.

1. Introduction

For buildings, compared with traditional cast-in-situ construction, prefabricated construction has several advantages, such as a shorter construction period, better quality control, low pollution, low energy consumption, and safety improvement [1–4]. Hence, as a viable alternative, it promotes construction industrialization [5,6], and is increasingly adopted and expected to have a significant increase in the market [7]. Meanwhile, compared with traditional projects, prefabricated construction projects involve many assets manufactured from prefabricated factories at diverse locations and subsequently transported to the construction site for assembly [8], thus consisting of a series of offsite and onsite activities. Those activities have their own durations and interdependent relationships [9]. Such relationships present the required logic and sequences for work completion, like precast components' delivery arrivals, crane arrivals, and their lifting and installations. Prefabricated construction projects thus have a high requirement for offsite and onsite coordination. According to the definition provided by the International Organization for Standardization (2014:55000) [10], assets refer to items, things, or entities that hold potential or actual values for organizations. In the construction context, assets encompass various tangible and intangible resources used or managed throughout the construction process, such as labor, equipment, temporary facilities, and building components. The suppliers of prefabricated components need to deliver them in batches on time and meanwhile timely coordinate with onsite activities, ensuring seamless project execution as planned. In the real world, several uncertainties occurred, such as weather and natural disasters, logistical issues, worker strikes, and poor inventory, which might cause offsite and onsite activities' delays and schedule changes. Different types and degrees of delays will have different impacts on overall project progress [11]. Assessing the total impact on overall project duration is not simply a case of summing up the delay dates of individual activities. As stated by Chen et al. (2021), delays in activities that belong to the critical path pose a greater risk to the overall project duration [12]. Since offsite asset delivery status directly impacts their lifting and installation on the construction site, their delays will generally exert ripple effects on other offsite and onsite activities due to their interdependency nature [13,14]. Correspondingly, the overall construction progress might be impacted, such as postponement and even disruption [15]. This could result in change orders,

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determination of liability, financial losses, and claims. Therefore, to avoid these potential issues, proper progress management and coordination of offsite and onsite are crucial to ensure on-time and consistent asset supply and on-site construction, which significantly contribute to the project's success [16,17].

One key task for progress management is asset tracking, which is monitoring assets' location, movement, condition, and status to ensure their deliveries on time or make dynamic adjustments promptly. Previously, asset tracking was typically conducted through inefficient manual processes, which might cause information missing and delayed. To address these limitations, many studies have investigated automatic asset tracking. Nowadays, diverse sensor-based techniques, such as QR code scanning [18], Radio-Frequency Identification (RFID) [19–21], Global Positioning System (GPS) [22,23], and Internet of Things (IoT) [24,25], have demonstrated great potential in automatically gathering and processing asset data to streamline manpower tasks. However, the general contractor still needs to act as an information transit center to receive asset tracking information from suppliers and notify potential propagated changes to affected parties. This coordination process needs information from multiple sources, e.g., interdependent construction activities and subcontractors. If multiple delays occur within a short period, it is difficult for the general contractor to promptly communicate the latest schedule to affected parties. Relying on the general contractor for this coordination not only incurs overhead costs but also increases the risk of errors and potential rework costs when managing complex and large amounts of information. Previous studies [26,27] based on industry surveys have highlighted that updating schedules and identifying potential delays are among the most frequent and time-consuming coordination activities. Consequently, the process of asset tracking and delay propagation has not been automated and integrated.

Furthermore, responsibility [27] is crucial in managing construction project activities. Considering the interdependencies of offsite and onsite activities, one or more parties' performance may have propagated impacts on other activities, thus posing risks to change orders for other affected parties. When significant impacts occur, there is a need to identify the initially responsible parties, file necessary claims, and compensate affected parties for changes beyond their controls. However, in the event of disputes or claims, the project typically lacks enough valid data as proof to trace and elucidate liability. Although some companies maintain work records necessary to support claims, managing these data is time-consuming [27] and these data cannot guarantee trustworthiness. Thus, resolving confusions and conflicts among relevant parties and managing contractual issues also consumes significant time, which ranked fifth and twenty-second among all 68 construction coordination tasks [27]. Therefore, this process also has not been trusted and tamper-proof, not enabling effectively tracing and clarifying accountability relationships.

Since blockchain's decentralized distributed ledger technology enables quick detection and correction of any tampering [28,29], it holds promise to promote trust among various project stakeholders. In the blockchain ledger, each asset is tagged with comprehensive information, including time, location, user, and previous records, providing information traceability on the chain [30,31]. Moreover, the integration of blockchain with BIM allows providing the tagged asset data transparently and precisely [32,33]. This is because the 4D BIM environment encompasses not only static semantic, topological, and geometric asset details but also dynamic construction activity information, such as dependencies, status, and associated resources [34,35]. Based on BIM and blockchain, smart contracts, as self-executed digital agreements, hold the potential for automatically processing physical assets' tracking data and deriving their propagated impacts. Users can write agreement terms into code and save them in smart contracts [36]. Once these predetermined terms are fulfilled, the smart contract can be activated and self-executed on the blockchain. Given the above merits, recent research has incorporated blockchain, BIM, and smart contracts in various scenarios, e.g., design collaboration, circular economy, and progress payment [37–40]. Existing studies focus on tracking assets' offsite activities, neglecting to explore how their delivery status may impact other activities [41]. Given offsite and onsite activities' interdependencies, prompt notification and validation of updated activity status are important in prefabricated construction projects. Subsequently, to enhance comprehensibility and foster collaboration among different parties, it is also necessary to investigate how these certified changes in work progress can be visualized in the 4D BIM environment clearly and promptly. Taken together, the integration of BIM and blockchain enabling automatic and tamperproof asset tracking and delay propagation analysis in the 4D BIM environment through domain-specific smart contracts remains underexplored in prefabricated construction projects.

To address these gaps, we propose the integration of BIM with blockchain, aiming to automatically track assets, derive their potential interdependency-based impacts via the compiled smart contract, and visualize these certified impacts with parties in the 4D BIM. The remainder of this research is organized as follows: Section 2 reviews state-of-the-art related studies to identify knowledge gaps. Section 3 outlines the research process and Section 4 describes a BIM-blockchain integrated framework across five modules. Subsequent Section 5 entails the implementation of the developed prototype system within a prefabricated construction project. Section 6 evaluates the system's cost and time performance and compares it with current industry practices. Section 7 discusses its theoretical, technical, and practical contributions through comparisons with other similar studies, along with limitations and suggestions for future endeavors. Section 8 concludes this study.

2. Literature review

2.1. BIM-based offsite and onsite coordination management in prefabricated construction projects

In prefabricated construction projects, the entire building structure is divided into several prefabricated sections. Prefabrications with varying degrees involve different combinations of 1D single elements (e.g., beams, columns, and stairs), 2D panelized systems (e.g., walls and slabs), and 3D prefinished volumetric modules [42,43]. The increased adoption of prefabricated components in construction projects necessitates a robust supply network connecting off-site factories to the construction site. Given that asset tracking is one key step in supply chain and traditional manual method is inefficient, current literature focuses on automatic asset tracking through BIM and geospatial tracking technologies [44–48]. BIM provides static asset information, e.g., semantic details (material, dimension, element type, structural design), and geometric and topological information. Geospatial tracking technologies, e.g., RFID, a tag or sensor [49–53], support real-time location that can be integrated into BIM models for asset status tracking. In practice, uncertainties often arise in asset delivery from factors like weather conditions, labor strikes, or transportation regulation changes [54]. Since asset delivery changes might impact interdependent onsite activities, only automatically tracking assets is insufficient, and promptly capturing their propagated impacts is also required. Some researchers recognized this problem and explored how to achieve automatic offsite and onsite coordination management. For example, Zeng et al. (2022) utilized BIM as a data source and employed customer order decoupling point classification to present element data during offsite production and transportation [14]. Through the extraction of construction activities from 4D BIM, linking based on elements was built between offsite and onsite processes, enabling early detection of schedule changes due to offsite disruptions. They also indicate that future research needs further linking real-time logistics data to track supply chain activities. Zhang et al. (2024) retrieved data from BIM, Google Maps, and Microsoft Project and optimized re-planning strategies to minimize costs and carbon emissions under uncertainties, effectively managing offsite element prefabrication and delivery with onsite construction [55]. However, this system still requires users for importing delayed activities and corresponding periods [56]. It is also challenging to synchronize the latest schedule with all project participants timely to help better address potential uncertainties arising from changes [56]. According to Wang et al. (2022)'s review [57], BIM can help address most of the disputes throughout the project lifecycle given that it improves visualization, information management, and collaboration. However, as highlighted from industry views in this paper [58], the pure BIM implementation might bring about misunderstandings and disputes [59] due to the lack of clarify in accountability and risk allocation among relevant parties, which is regarded as "BIM-related disputes" [60,61].

These studies highlight the significance of offsite and onsite coordination [9,62]. However, these BIM-based systems cannot guarantee data immutability and traceability. They also cannot achieve proactive coordination management. Considering interdependencies among construction activities, poor performance by one or more parties may pose risks to change orders for other stakeholders. With the project going on, tracing and clarifying responsible parties become increasingly challenging. Since each party focuses solely on its own goals and interests, it is prone to disputes over contracts and trust crises [41]. When significant changes occur, it is necessary to trace back to initially responsible parties, file necessary claims, and compensate impacted stakeholders for changes, delays, and cost increases that are beyond their control. These specific liability determination and compensation require valid evidence's support. Additionally, current systems still need general contractors or owners as coordination centers to communicate asset delays with potentially impacted parties, significantly increasing their coordination burdens and being error-prone. Therefore, there is a compelling need to establish a transparent, trustworthy, and tamperproof data system among stakeholders as effective proof to trace supply chain status and analyze their propagated impacts, thus clarifying accountability relationships.

2.2. The integration of blockchain and BIM

Blockchain, as an emerging information technology, offers a prospective solution, since its Decentralized Distributed Ledger Technology (DLT) converts contract trust into code trust [63]. This transformation brings various benefits, including trust, security, transparency, traceability, consensus, tamper-proofing, and efficiency in data records. Consequently, blockchain's adoption is increasingly important in the architecture, engineering, and construction (AEC) industry [64,65], especially for claim and dispute resolutions [66,67]. Ye et al. (2024) integrated blockchain with emerging information and communication technologies to enable data traceability and transparency in the complex and lengthy construction claim procedure [66]. Sun et al. (2023) reviewed recent literature and identified the above characteristics as critical success factors for implementing blockchain in construction [68]. Some studies improved information-sharing accuracy through blockchain [69,70]. However, it is time-consuming to manually input data into the blockchain system. In light of this limitation, much scholarly attention has been converged on automatically obtaining data by integrating BIM as an extra dataset with blockchain to enhance construction project management since BIM contains required building asset details [38,71–75]. Baldawa and co-workers (2023) reviewed the advantages of integrating BIM with blockchain for construction management [76]. Specifically, Rifat Sonmez et al. (2022) used Revit as an as-constructed object data source and integrated blockchain via the smart contract for progress payment calculation and administration among parties [38]. Furthermore, to promote timely BIM information updates and support accountable information sharing, some scholars also used IOT sensors to automatically monitor the physical status of digital twins into blockchain [77,78]. Tao's BIM component-based workflows (2021,2022) demonstrated the viability and strong performance in blockchain-enabled design collaboration [40,79]. Recent studies utilized the blockchain network as a bank of re-use BIM families for asset-based circular economy design [37] and construction lifecycle [80–82] across the supply chain [83,84]. Several studies have found that the integration of BIM and blockchain also benefits government authorities for facility management [85], like building operations and maintenance [86,87]. It also had potential in asset procurement [88], quality assessment [89–91], risk management [92], and financial credit management [93,94]. Collectively, these studies underscore that the integration of blockchain with BIM is critical across diverse phases of construction project management.

2.2.1. BIM-blockchain integrated asset tracking

To ensure reliable and certified information trace, some published studies introduced blockchain in prefabricated supply chain management [95–98], as the authentication approach of peer-to-peer public networks enables data trustworthiness and traceability of elements in the supply chain. Specifically, Kim (2023) enhanced supply chain coordination through the utilization of blockchain during offsite construction [99]. It can also benefit information-sharing accuracy for precast material on-site assembly in modular construction [69]. Regarding asset tracking, several researchers utilized smart contracts within blockchain technology to facilitate automatic information sharing, traceability, and transparency during offsite asset tracking in the supply chain [32,33]. Through smart contracts, Wouter van Groesen implemented a semi-automated comparison between the planning and physical status of assets supported by a mobile QR application [41]. Brandín and Abrishami (2024) improved data traceability across the offsite manufacturing supply chain through a BIM, IoT, and blockchain-based real-time framework [100]. However, the utilization of BIM (Revit) in this study remains solely as a 3D component library. Overall, these BIM-blockchain integrated studies enable the reliability and traceability of asset data for offsite activities. However, their focus is only on tracking assets, neglecting how asset delivery delays will have propagated impacts on other offsite and onsite activities considering interdependency. Furthermore, current studies only use 3D BIM as a data source to extract and process asset data which is then input to blockchain for parties' collaboration. Nevertheless, they overlook the potential of integrating blockchain with 4D BIM that contains dynamic construction activities. It can also be a blockchain receiver to present immutable outputs from the blockchain as feedback to facilitate coordination and collaboration.

2.2.2. Potentials of smart contracts in the construction industry

To enable automatic asset status communication, timely delay propagation analysis, and liability tracing among multiple parties, smart contracts can play a role. Smart contracts are programmable functions capable of predominantly running on blockchain, improving blockchain networks' functionality and making it more flexible to handle diverse agreements with specified terms. The blockchain, in turn, provides decentralized networks for deploying and self-executing smart contracts, protecting them from tampering. Consequently, transparency, security, and trust can be ensured in transactions. Attention has focused on the utilization of smart contracts for construction management [36,101,102]. Specifically, Ye et al. (2022) reviewed smart contracts within the construction sector, identifying three main applications (contract and payment, supply chain and logistics, and information management) [36]. This study also highlights that there is abundant room for further exploring the smart contract's unique connotation and value in other specific domains. Sethi and co-workers (2024) reviewed automatic contract analysis and management, noting smart contracts' potential in secure information processing [102]. However, there is a lack of smart contracts designed and applied for offsite and onsite activities' coordination management, considering interdependencies.

2.2.3. Knowledge gaps

Overall, in prefabricated construction projects, existing studies only use BIM and blockchain to automatically and reliably track assets across offsite activities but ignore how the status of asset delivery will affect other offsite asset delivery and onsite construction activities for accountable records, based on their interdependencies. Then, promptly communicating schedule changes among stakeholders is still challenging. Therefore, this study proposes to integrate BIM, blockchain, and smart contracts for automatic and reliable asset tracking and delay propagation analysis. To facilitate communication among stakeholders, we also propose to bring verified changes and responsible parties back into 4D BIM for visualization.

3. Research methodology

The methodology outlines the research process, as shown in Fig. 1. It encompasses the design, validation, and evaluation of a framework for automatic and reliable asset tracking and delay propagation analysis. It aims to address offsite and onsite coordination management challenges in prefabricated construction projects. Initially, we review literature to understand current practices and identify research gaps. We found that the automatic and reliable coordination management between offsite and onsite activities remains underexplored. To address it, a BIM-blockchain integrated framework is proposed, consisting of five modules. For validation, an IFC-Ethereum prototype system is developed and tested using a prefabricated construction project. To evaluate the performance of our developed system, the total gas price [103] is utilized to assess the cost while computing time [104] and latency [105] are used to represent time efficacy, under 3 scenarios related to different building components. Additionally, we compare this research with current industry practices via semi-structured interviews. Finally, our study's contributions are analyzed from theoretical, technical, and practical perspectives. The limitations are also discussed for offering future directions.

4. BIM-blockchain automatic asset tracking and delay propagation visualization framework

This research proposes a BIM-blockchain integrated framework to support automatic asset tracking, delay propagation analysis among diverse stakeholders, and schedule change visualization. Fig. 2 describes the framework's overview, encompassing five modules. For this system's technical development, the programming languages, environments, or platforms utilized for each module are listed in Table 1.

4.1. Asset information and construction schedule transmission between BIM and blockchain platform

To avoid manually inputting extensive semantic data on building assets, we employ BIM as the data source to automatically import asset data in batches into the blockchain platform. This research uses Gotrace, a blockchain-based asset tracking system compatible with Ethereum, to support the prototype system's development. This is because Gotrace enables building a network with multi-asset delivery information while engaging a project team into the space. This module outlines the approaches devised for this transmission, consisting of two parts. Firstly, to improve the framework's generality, we use Industrial Foundation Class (IFC)-based BIM models. We automatically retrieve and extract asset semantic data, including id, type, name, material, size, etc., from BIM. Additionally, we automatically capture asset image information in batches for tracking by using the virtual camera in BIM. To ensure images encompass comprehensive and unique asset features, we

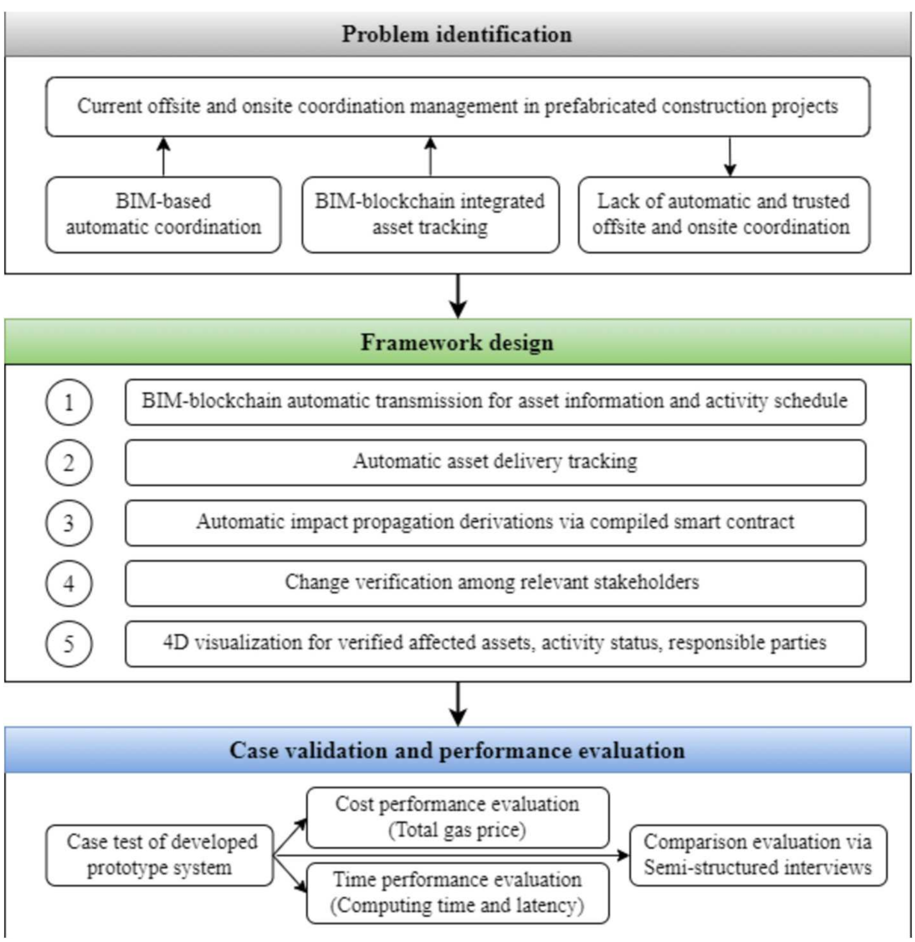


Fig. 1. Research methodology.

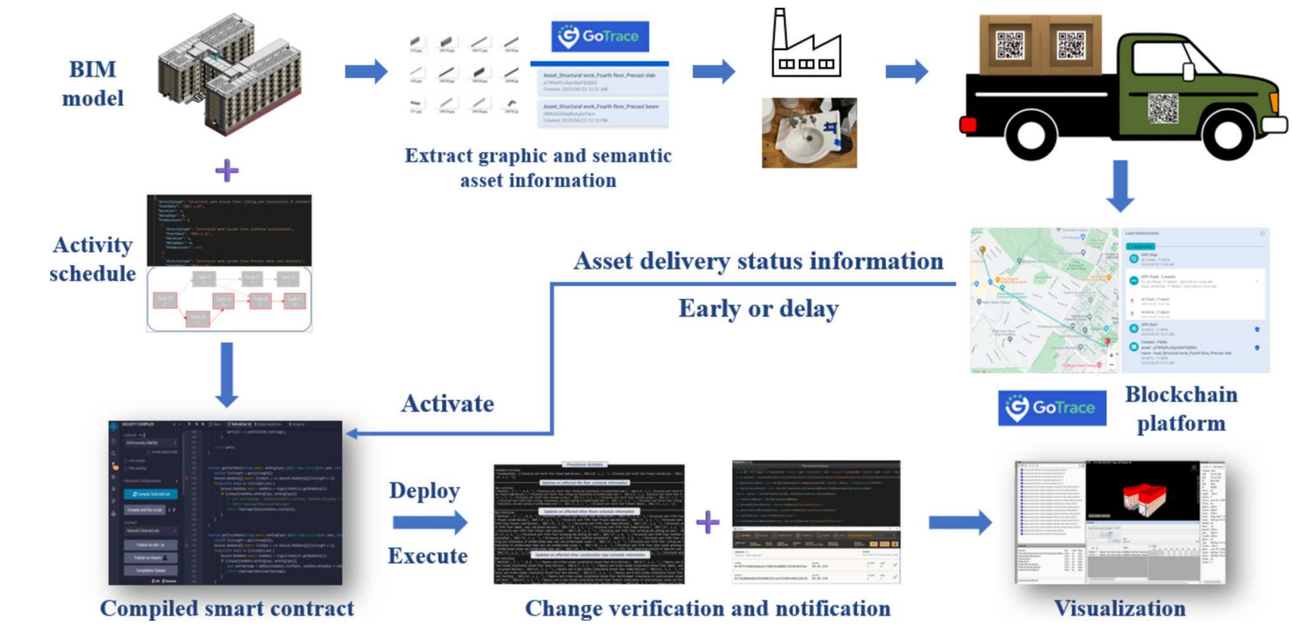


Fig. 2. BIM and blockchain integrated framework.

Table 1
Coding languages and development environments.

Module	Coding language	Development environment
Asset information and construction schedule transmission in BIM	C#	Visual Studio
Digital twin of asset delivery in Gotrace	C#	Visual Studio
Automatic impact propagation via smart contract	Solidity	Remix Online IDE
Change verification (Interaction via Web3)	C#	Visual Studio
4D visualization	C#	Visual Studio

implement different rotation angles to distinct element categories in the BIM model for fitting well. Revit is used for image capture. In Revit, we iterate through all selectable elements, determine one by one if the element is a host and line element (e.g., wall, beam) or a point element attached to the host element (e.g., window, door), and rotate them into horizontal or vertical orientation based on their class. After taking images and fitting the screen, complete image features of different types of elements are automatically captured. Additionally, prefabricated construction projects involve various offsite and onsite activities that exhibit interdependency relationships. To articulate them with clarity and precision, a JSON format file is created to store all relationships and corresponding activity details. For each activity, this JSON file includes its activity type, start date, duration, delay days, precedence activities, associated assets, and the responsible party. To match the asset's IFC-based semantic and image information with its delivery activity, we develop the approach with the following steps: 1) read the “ActivityInfo.json” file; 2) use the xBIM third-party library to read the IFC file exported from BIM; 3) obtain all “IfcBuildingStorey” floors, and traverse these floors to find the associated “IfcRelContainedInSpatialStructure”; 4) based on these “IfcBuildingStorey” floors, find the corresponding delivery activity in JSON file; 5) obtain all the associated IFC elements from “IfcRelContainedInSpatialStructure”; 6) traverse these IFC elements based on their types, read the information for the “BIMInfo”, and write it into the corresponding delivery activity. This approach can thus automatically group and package assets in batches based on their same attributes (floor and type) to match their delivery activities. Secondly, we utilize web development to automatically transmit these data into the Gotrace, including submitting the request to URL, obtaining the response from the web, and automatically writing the packaged BIM asset data into the web (Gotrace -> “Asset Details” -> “Name” and “Description”) based on the Gotrace API documentation. After these elements' semantic and graphic information has been batch uploaded into the Gotrace platform, their QR codes can be generated and later attached to corresponding physical assets. Therefore, consistency of asset data is guaranteed between BIM and Gotrace.

4.2. *Asset delivery tracking*

This module aims to link the digital and physical worlds by synchronizing real-world asset tracking data into Gotrace. Specifically, as each asset is assigned a unique ID, corresponding QR code, and supplier information within the blockchain in Module 1, the relevant physical asset is tracked by scanning its QR code. Its delivery information is also promptly and automatically updated in the blockchain, encompassing location, time, events, and status. Given the diverse types of assets delivered by various suppliers via different routes in the project, the Gotrace platform provides collection and management of integrated data through real-time updates on their delivery statuses. As for several assets provided by the same supplier in the same batch, their delivery path from the GPS start to the GPS stop can be clearly shown on the platform, which is named as a “load” and thus simplifies the management process. Additionally, the corresponding supplier ID and asset semantic information can be matched to this load. As the real-world asset delivery status is updated and recorded on the blockchain, we devise approaches to automatically replace assets' planned arrival date in the project schedule file with their actual arrival status. Considering that one activity may involve multiple associated assets, through the combination of the data within Gotrace, we can automatically calculate the latest arrival time of the required asset for an activity based on the developed functions. Consequently, through blockchain, complex information within the physical supply chain network can be stored clearly and logically. This module allows us to simultaneously and

Table 2
Pseudocode of compiled smart contracts.

Input: mainChain_activities, precedence_activities	
Output: delayed_mainChain_activities, delayed_precedence_activities	
1:	main_chain ← insertNodesToMainChain(mainChain_activities)
2:	precedence_chain ← insertNodesToPrecedenceChain(precedence_activities)
3:	If main_chain != Empty And precedence_activities != Empty:
4:	bindPrecedenceActivitiesToMainChain(main_chain, precedence_activities) // bind precedence activity to main activity
5:	End If
6:	If precedence_chain != Empty And precedence_activities != Empty:
7:	setPrecedenceChainNodesDelay(precedence_chain, precedence_activities) // set precedence activity delay days first because main chain delay depends on precedence
8:	End If
9:	If main_chain != Empty And mainChain_activities != Empty:
10:	setMainChainNodesDelay(main_chain, mainChain_activities) // set main activity delay days
11:	End If
12:	delayed_precedence_activities ← calculateDelayedPrecedenceChainNodes(precedence_chain) // calculate total delay days of every precedence activity
13:	delayed_mainChain_activities ← calculateDelayedMainChainNodes(main_chain) // calculate total delay days of every main activity

timely update multiple assets' physical delivery status into a planned activity schedule.

4.3. Automatic impact propagation via smart contract

As multiple assets update their physical delivery statuses, in this module, we consider interdependency and thus compile smart contracts to automatically derive all the affected activities' updated status (their type, planned start date, duration, delay days, actual start date, planned finish date, and actual finish date) with relevant assets. As a specific category of smart contracts, application logic contracts (ALC) present a viable solution for deriving propagated effects on other offsite asset delivery and onsite construction activities. This is because they contain executable function codes and remain synchronized with blockchain platforms [106]. Remix, an open-source web-based integrated development environment for solidity smart contract development, is utilized for basic compilation, local or test network deployment, and contract execution [107]. Ethereum is utilized as a platform to develop decentralized applications (Dapps), where Ether is the cryptocurrency. Solidity, as Ethereum's officially designed and supported programming language, is employed exclusively for smart contracts' compilation. We devised a set of functions within the smart contract for automatic impact propagation analysis, thus being well-suited for interdependent offsite and onsite activities in prefabricated construction projects. We particularly consider incorporating the critical path while designing these functions. Specifically, as shown in Table 2, we create a chain-table structure to store a series of offsite and onsite activities. According to the actual project schedule in the last modules, asset delivery and construction activities with their name, date, and duration are inserted as nodes on the chain. For every activity node, its predecessor is created and corresponding precedence activities are then inserted on the chain. Next, if any activity encounters a delay, we set the delay days in both the activity node and the predecessors containing this activity. Finally, we calculate the actual start date and finish date for each affected activity based on the interdependency and actual data prepared in the former modules. As two external manifestations of smart contract source code, our compiled smart contract's Bytecode and ABI are deployed in the next module for machine execution as deployment and for Dapp developers to use the contract interface specification described in natural language as invocation respectively.

Table 3
Blockchain architecture in this study.

Blockchain architecture in this study	
Application layer	Dapps
Execution layer	Smart contracts
Data model layer	Chain structure
Concensus layer	Proof-of-Stake (PoS)
Network layer	Peer-to-Peer (P2P) protocol

4.4. Change verification

This module is to authenticate changes by various stakeholders via the blockchain system, where Web3-based approaches are developed for interaction and automation. Table 3 describes this study's blockchain architecture- Ethereum 2.0 [108]. Proof of Stake (PoS) is adopted in the consensus layer since it is more secure and energy-efficient than Proof of Work (PoW) regarding the network's scalability, accessibility, and transaction throughput [109]. Smart contracts are used to deploy and execute transactions. The procedures are outlined in the following 5 steps: 1) register members of different stakeholders as accounts within one project (owner, general contractor, different suppliers, supervisor, etc.,); 2) deploy the smart contract as functions according to its ABI and bytecode; 3) read updated JSON file (Module 2) as the input; 4) execute the smart contract among all pertinent parties as interactions; 5) successfully confirm and update blocks and transactions as records of the output. This module uses C# to connect with Solidity to realize functions in the developed system given its common use and convenience. For technical development, first, we import Web3 and JSON third-party support libraries. Then, we create the Web 3 instance and get the wallet address. After inputting our compiled smart contract's ABI and bytecode, the contract instance can be created and then deployed into the provided wallet address. Next, as the Module 2 output, the JSON file of the activity schedule with interdependency relationship and updated asset delivery information as local data is read. Subsequently, we iterate through all offsite asset delivery and onsite construction activities and insert each activity with its content as a node on the chain. Whether there are any precedence activities in this activity needs to be determined, and if yes, its predecessors will be generated on the chain. Correspondingly, the delay days of both the precedence activities and the corresponding activity are set on the chain through calculations. As all relevant parties successfully execute smart contracts to certify these changes, the blocks and transactions are confirmed and updated in the blockchain system. We use Ganache, an Ethereum blockchain platform, to simulate block and transaction generation for predefined accounts in the framework testing and validation since it can run tests, execute commands, inspect states, and control the chain operation.

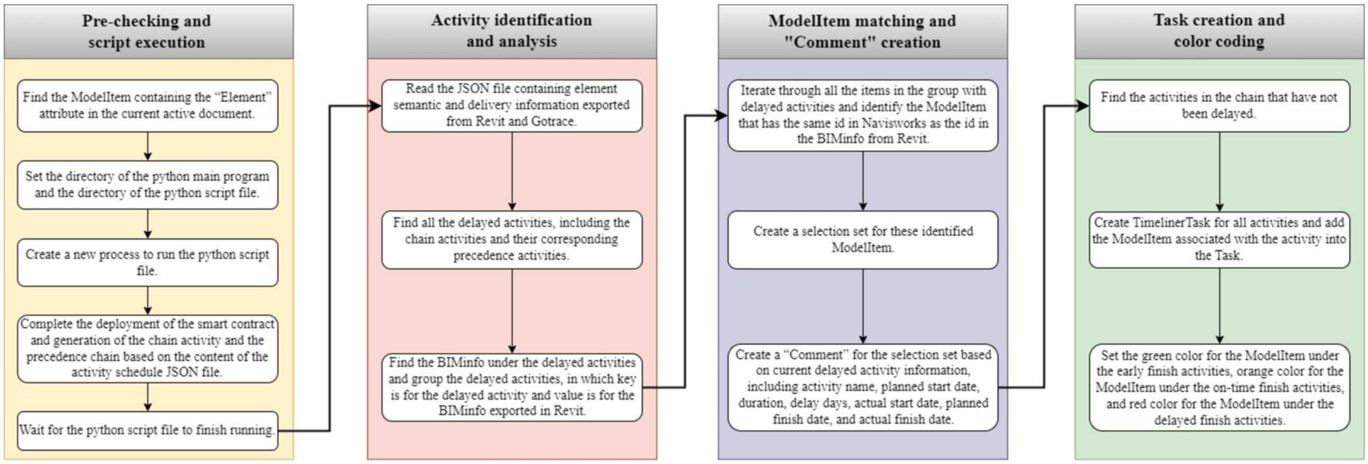


Fig. 3. Specific steps for 4D visualization.

4.5. 4D visualization

After stakeholders certified these changes, to enhance the comprehensibility and readability, a plugin is developed in Navisworks to synchronously and automatically update and visualize propagated impacts in the 4D BIM environment, including affected assets with their semantic details, activities' schedule change, responsible parties, and certification timestamps. It facilitates collaboration among diverse stakeholders while reducing the likelihood of manual tampering with the updated information within the BIM. Fig. 3 describes specific steps. Under the latest activity schedule, the animation is employed to simulate the updated entire 4D construction process. We also automatically label impacted assets' statuses in 4D animation with different colors: red for delayed assets, green for early arrival assets, and orange for normal unaffected assets. Additionally, all construction activity information is listed in "TimeLiner" following their interdependency and sequences, including task name, status (delay, advance, on-time) with the comparison of planned dates (start and end) against actual dates (start and end), and associated assets. We also added "Comments" to elaborate on the specific task information, the certification time of dynamic changes, the responsible parties incurring these changes, and the status. It can thus present the traceability of activity changes based on dependences, including the author, timestamp, status, and change details. For static resources, assets as required resources of affected construction activities will also be impacted regarding delivery time, which are listed as sets customized in the selection tree. The specific asset's properties shown in Navisworks, like name, type, family, ID, dimension, location, structural details, etc., are consistent with the original Revit BIM model since these data are automatically transmitted from the Revit model through our developed approaches. Therefore, this BIM-blockchain integrated framework achieves automatic data transfer, processing, propagated impact analysis, certification, and visualization.

5. Case validation

5.1. Data preparation

To validate the proposed framework's applicability, we develop a prototype system and simulate its implementation using a prefabricated construction project. It is a campus dormitory with a construction area of 15,707.68 m^2 and a total height of 22.8 m, having 6 levels with a ground floor. Precast components are utilized on standardized floors from the second floor to the fifth floor, including stairs, beams, slabs, columns, and shear walls. Additionally, cast-in-situ as the traditional construction type is used for the foundation, ground floor, first floor, sixth floor, and topping floor. In addition to the host structure, the

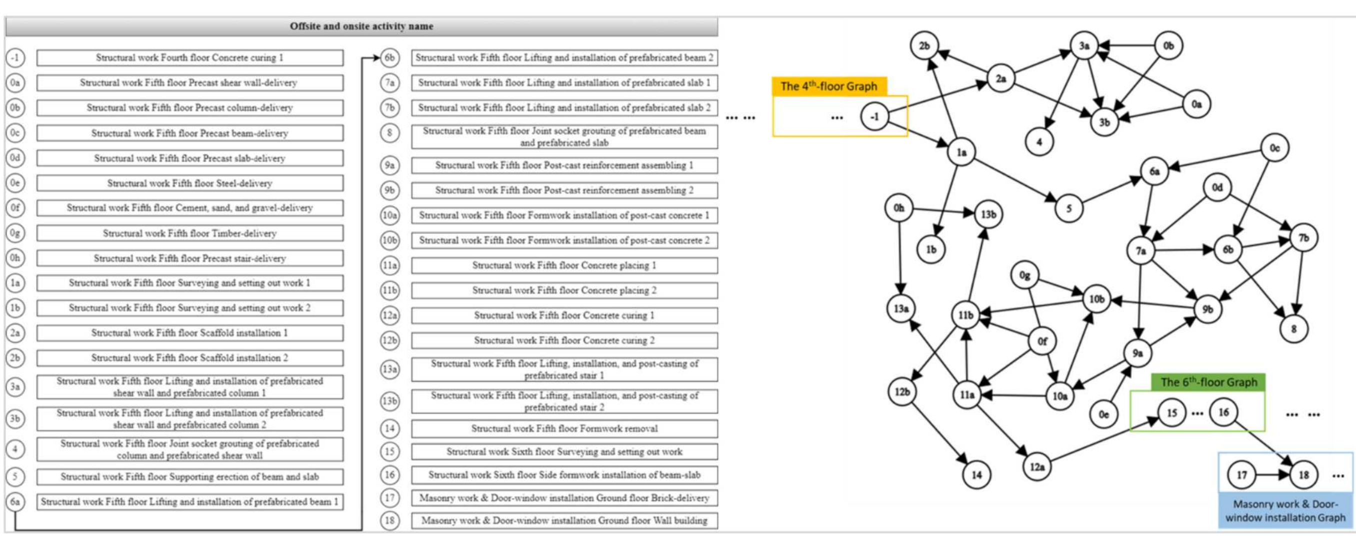


Fig. 4. Graph representation of activity interdependencies using some typical offsite asset delivery and onsite construction activities in the prefabricated construction project.

masonry work, door and window work, and sporadic work (step outside, etc.,) are also added. The BIM model used in the experiment is built based on building design documents, containing rich static semantic information. Short Interval Production Scheduling is used as the construction planning method and each standardized precast floor is divided into 2 zones to improve work efficiency and reduce cost. Fig. 4 lists some typical offsite asset delivery and onsite construction activities in the prefabricated construction project with their interdependencies. To be compatible with our system, JSON format is used to express each activity information in the planned construction schedule, such as ActivityType, StartDate, Duration, DelayDays, and its Predecessors. To distinguish same activities on different floors and same activities on the same floor but in different construction zones, we use "Construction type name + Floor number + Material Delivery/task name + Zone number" to name the activity to ensure that it is unique and not duplicated with other activities, thus avoiding confusion and errors.

Regarding asset delivery, we consider representative materials associated with construction planning. Specifically, precast beams, precast slabs, precast columns, precast shear walls, and precast stairs are 5 types of precast components for standardized floors. Cement, sand, and gravel, steel, timber, brick, and door and window represent 5 types of cast-in-situ construction of concrete, structural components, formwork, masonry work, and decoration work respectively for all floors. In the construction project, even the same type of materials may be delivered multiple times based on the planned schedule and limited construction site. We assume that the same type of materials with the same supplier are delivered multiple times based on the number of floors. Therefore, we set 10 material delivery routes for simulation, involving 11 parties (1 project manager and 10 material suppliers). Correspondingly, 11 accounts are created on the Gotrace and Ganache platforms.

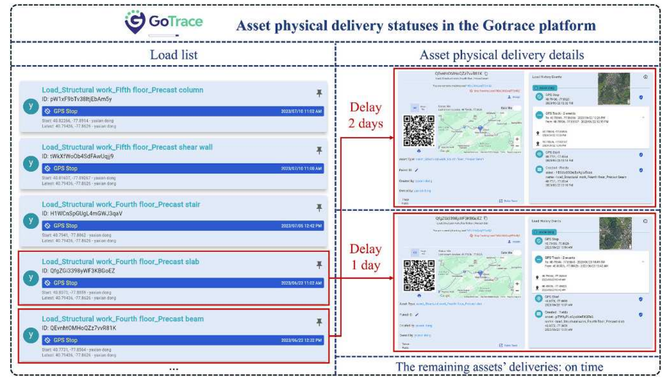


Fig. 6. Load list and asset physical delivery statuses in the Gotrace platform.

5.2. Experimental testing

5.2.1. Asset information and construction schedule transmission between BIM and blockchain platform & Asset delivery tracking

Through Section 4.1 approaches, all asset semantic and graphic information in the BIM model has been transmitted into the Gotrace platform. We group assets with the same type of materials on the same floor as a package. Fig. 5 presents the asset list and asset details transmitted from BIM in the Gotrace platform.

As these assets' QR codes are generated in the blockchain and assigned to the relevant physical element to link the digital and physical worlds, by scanning the QR code, real-world asset tracking data are automatically updated on the blockchain. In the Gotrace platform, the physical delivery information for the same floor and type of materials is

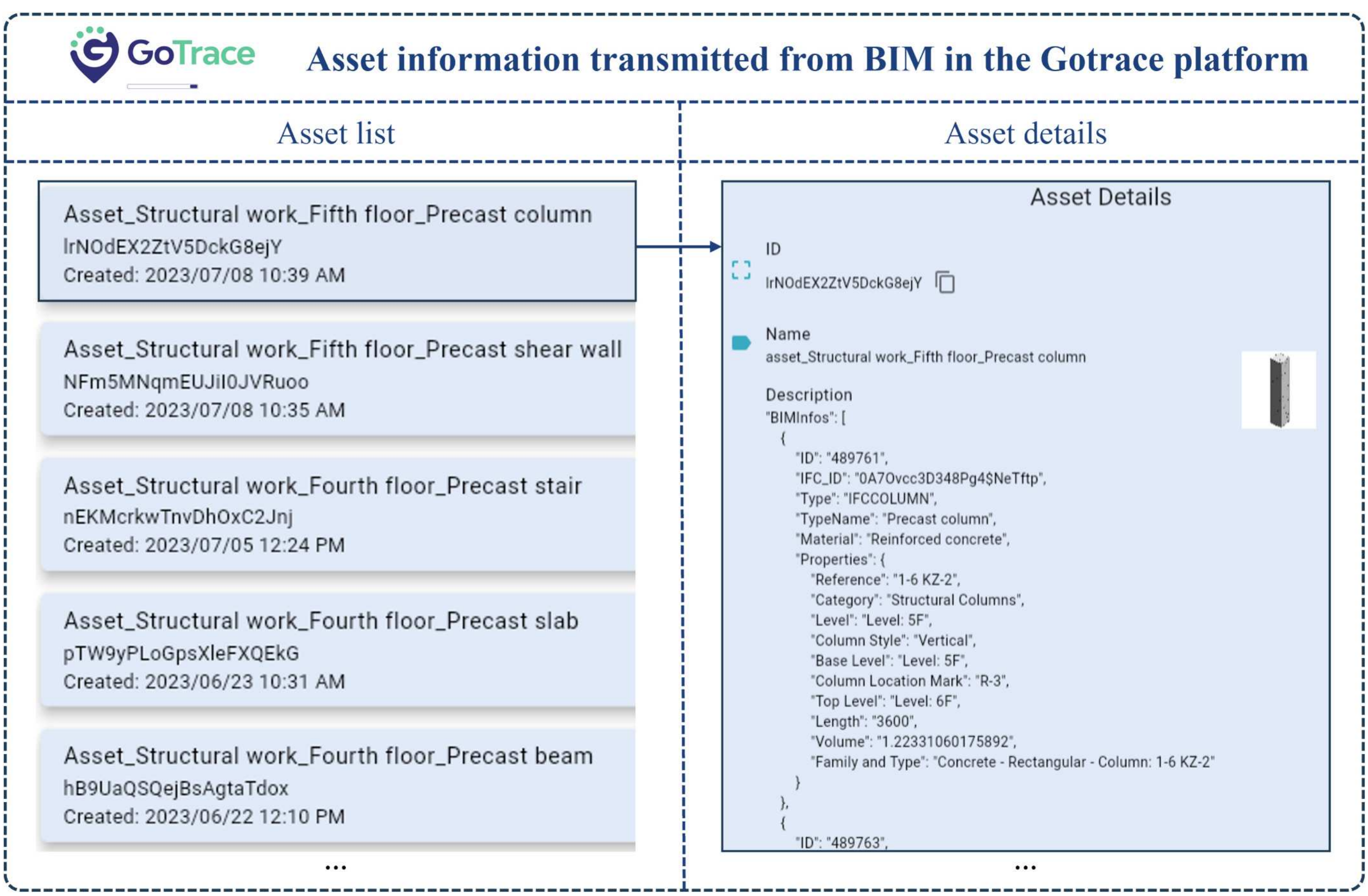
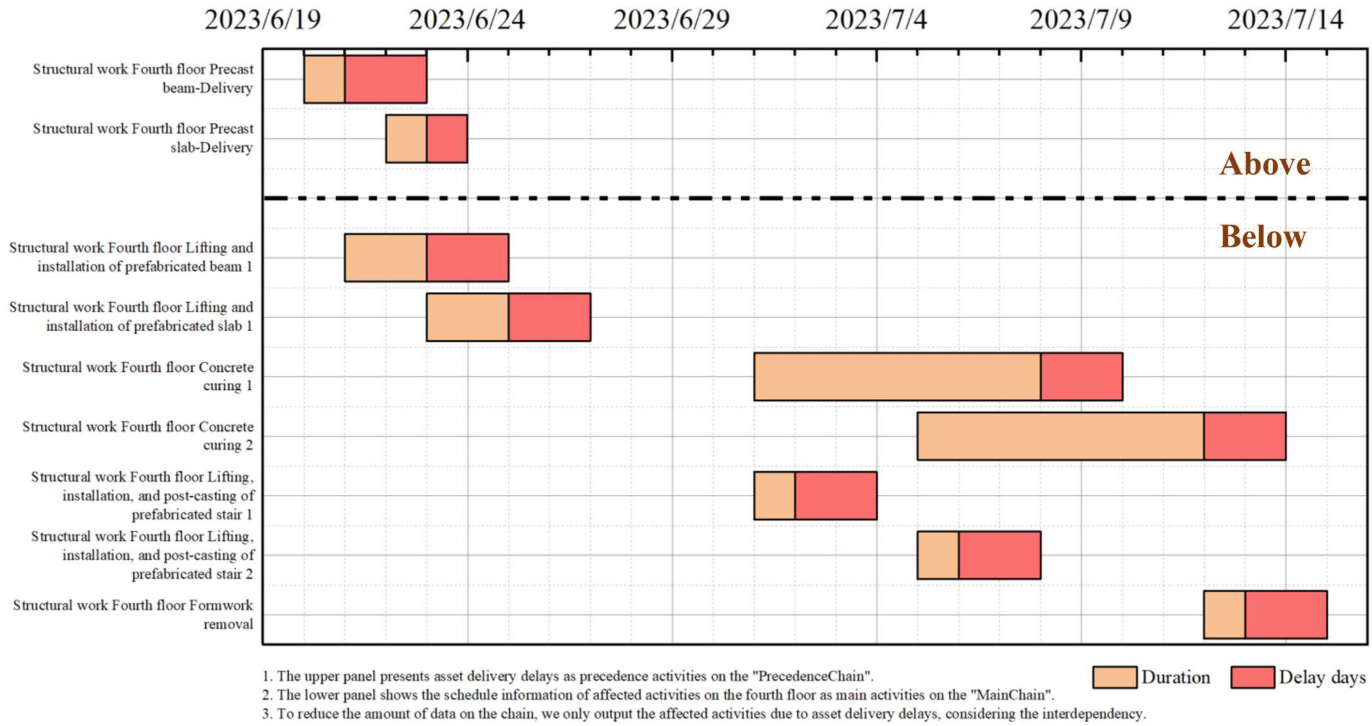


Fig. 5. Asset list and details transmitted from BIM in the Gotrace platform.



(a)

Fig. 7. (a) Updates on the affected fourth floor's schedule information; (b) Updates on the affected other floors' schedule information; (c) Updates on the affected other construction type schedule information.

regarded as a load. Fig. 6 shows the load list and the updates of asset physical delivery statuses in the Gotrace platform. Specifically, by scanning QR codes below, the journey presents the dynamic status while information shows the static BIM asset semantic and graphic information. In the test scenario, we set that fourth-floor precast beams were delayed for 2 days while fourth-floor precast slabs were delayed for 1 day, and the remaining assets were delivered to the construction site on time.

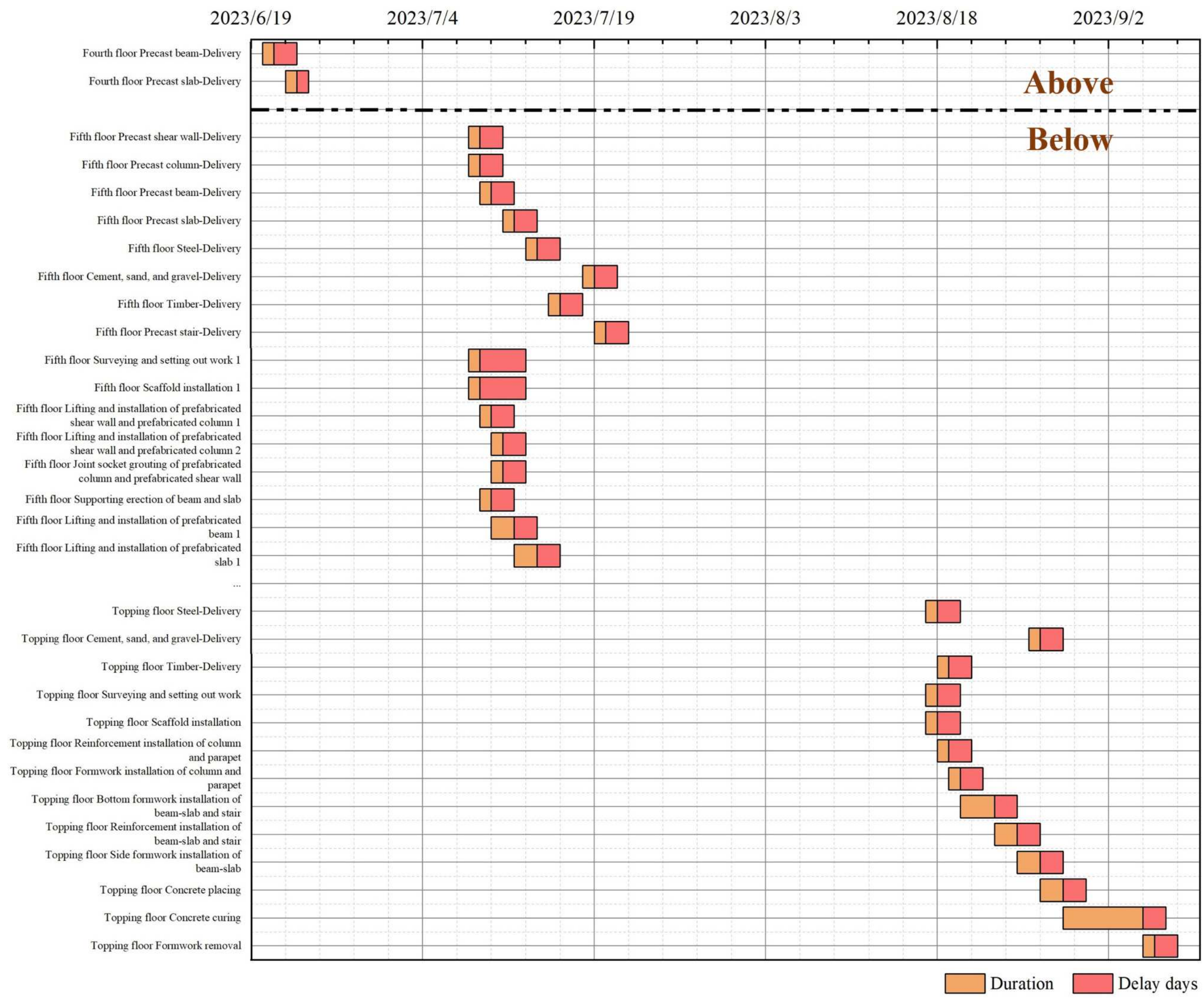
5.2.2. *Automatic impact propagation via smart contract & Change verification*

Considering interdependency, how the delay statuses of these two individual assets dynamically affect other activities is required. Through users executing compiled ALC-based smart contracts, based on the above planned construction schedule and the updated asset delivery status in the physical world, impact propagations for other activities due to asset delivery delays are automatically derived. Not only the updated construction schedule can be obtained, but we can also know which are precedence activities that cause these dynamic changes to provide valid data as evidence to trace and clarify the liability. Fig. 7 presents the updates on the affected fourth floor and other floors' schedule information (e.g., 5th floor, 6th floor, topping floor) as well as affected other construction type schedule information (e.g., Wall and Door work, Masonry work).

After the general contractor uses his/her account in Ganache to obtain the updated schedule, there is a need to let relevant stakeholders know about these changes and trace liabilities. Each stakeholder has his/her own account managed in the same project. Through Web3-based interaction and automation among stakeholders in the blockchain system, changes are authenticated. When all the transactions have been completed, these changes will be certified and uploaded as blocks, thus removing concentrating authority in one stakeholder's hands. Fig. 8(a) respectively shows the block list and block details, including block number, gas used, gas limit, Time mined on, and block hash ID. Correspondingly, Fig. 8(b) respectively presents the transaction list and the transaction details that contain its hash ID, the addresses of both the sender and to contract, and its value in ETH set 1.6 Gwei as gas price/per gas used in this experiment [103]. This blockchain system ensures that certified changes are tamperproof and that every relevant stakeholder keeps informed of the same material delivery status promptly (on the same page).

5.3. *4D visualization*

Having certified and notified updated changes in activities to corresponding stakeholders, these propagated impacts are visualized automatically and promptly in the 4D environment, through the developed plugin in Navisworks. Fig. 9 shows a one-frame progress scenario of the 4D visualization in Navisworks in the test. Specifically, because 4th-floor precast beams were delayed 2 days and 4th-floor precast slabs were delayed 1 day, other offsite asset delivery and onsite construction activities are also affected regarding project planning, as elaborated in “TimeLiner”. In addition to impacted tasks' information, certification completion times for changes and the responsible party accountable for them can be found in “Comments”. In the updated 4D construction simulation animation, elements marked in “Red” signify assets necessitating delayed deliveries, which are systematically categorized within the “Sets” of the “Selection Tree”. Their semantic, topological, and geometric attributes are expounded upon in the “Properties”. Under this scenario, construction activities on the critical path are impacted, as the arrival time change of the 4th-floor precast beam-Delivery makes it become a critical task, as presented in Fig. 10. Consequently, the total duration of the prefabricated construction project has been changed from 212 days to 214 days (2/20/2023–9/21/2023). The above results demonstrate its feasibility in automatic and reliable asset tracking and change visualization. By



1. The upper panel presents asset delivery delays as precedence activities on the "PrecedenceChain".
2. The lower panel shows the schedule information of affected activities on other floors (e.g., 5th floor, 6th floor, topping floor) as main activities on the "MainChain".
3. For the fifth floor, the figure shows all the affected offsite asset delivery activities but only illustrates some of the affected onsite construction activities for conciseness. Other affected onsite construction activities that are not shown in this figure can be derived based on their interdependencies presented in Table 4 and Figure 4.
4. The figure does not display the affected offsite and onsite activities on the sixth floor for conciseness, since the sixth floor has similar interdependent activities as the topping floor.
5. To reduce the amount of data on the chain, we only output the affected activities due to asset delivery delays, considering the interdependency.

(b)

Fig. 7. (*continued*).

integrating BIM with blockchain, this research provides a trusted, unchangeable, and traceable way for timely notification and collaboration among diverse stakeholders.

6. Performance evaluation

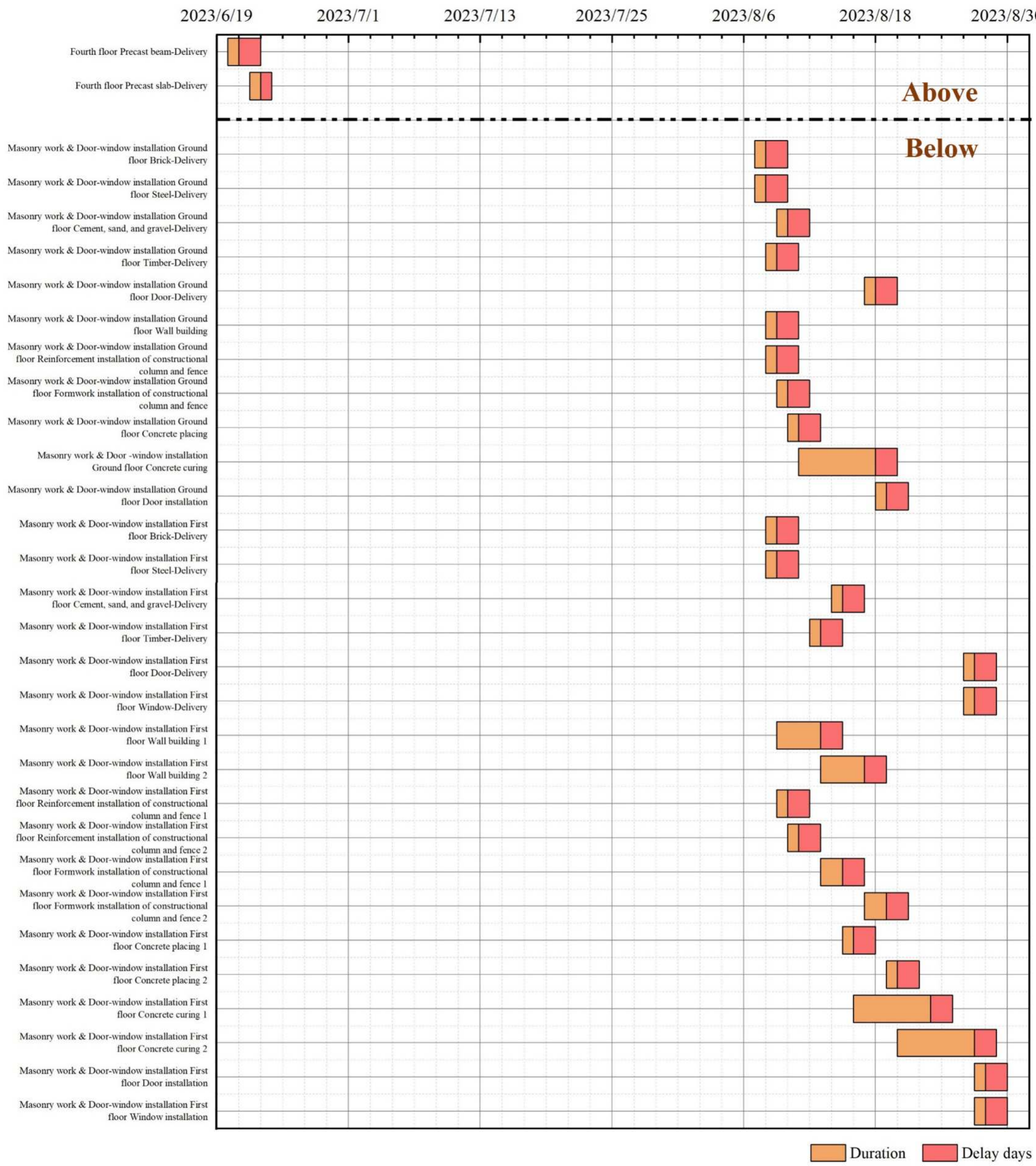
6.1. Cost performance evaluation

The proposed framework's cost mainly depends on the cost of completing an Ethereum blockchain transaction. To evaluate its cost performance, we use the total gas price associated with interaction as the metric. The total gas price is calculated by multiplying the unit gas price (the cost per unit of gas) by the total amount of gas used, as presented in the following equation.

$$\textit{Total GAS price} = \textit{unit GAS price} \times \textit{total GAS used}$$

In this experiment, we set the unit gas price at $1.6*10^9$ Wei (1.6Gwei) [110,111]. It should be noted that the gas price is changeable. Since miners always prioritize packing transactions with a high gas price, if speeding up the transfer is needed, the higher gas price can be set. Based on the gas price, miner fees can be saved, but the speed at which miners pack is also slowed down. As for the gas used, in transactions, executing smart contracts requires a certain amount of gas consumed for executing code and storing data. To prevent potential network congestion caused by accidental infinite loops or insufficient Ethereum balance, it is essential to set a gas limit as the maximum allowable gas for this transaction. In this experiment, the gas limit is set to 6,721,975 [103], signifying the maximum fee (in gas) a user is willing to pay for the transaction. Therefore, the setting of the gas limit ensures the system's cost stability.

Based on exchange records in this experiment, the total number of both blocks and transactions executed in the system is 287, consisting of three parts. There are affected 4th-floor transactions, affected other floor transactions (e.g., 5th floor, 6th floor, topping floor), and affected other

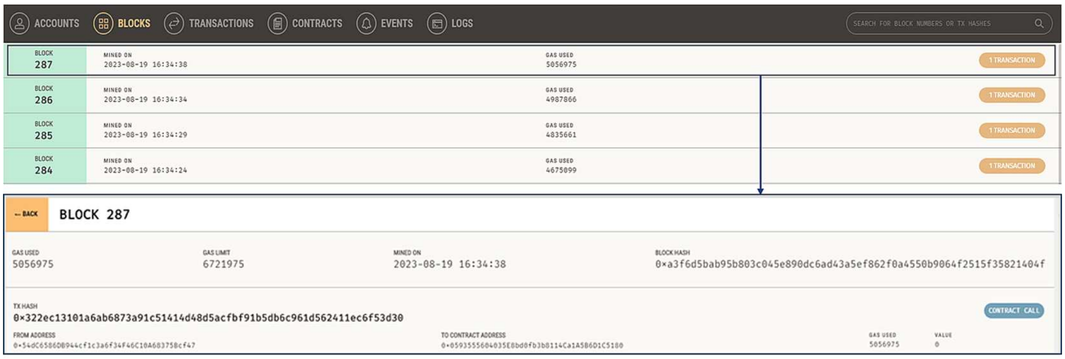


1. The upper panel presents asset delivery delays as precedence activities on the "PrecedenceChain".
2. The lower panel shows the schedule information of affected other construction types of activities (e.g., Wall and Door work, Masonry work) as main activities on the "MainChain".
3. For conciseness, the figure only illustrates the affected other construction types of activities (e.g., Wall and Door work, Masonry work) on the ground floor and the first floor, since other floors have similar interdependent activities as the first floor.
4. To reduce the amount of data on the chain, we only output the affected activities due to asset delivery delays, considering the interdependency.

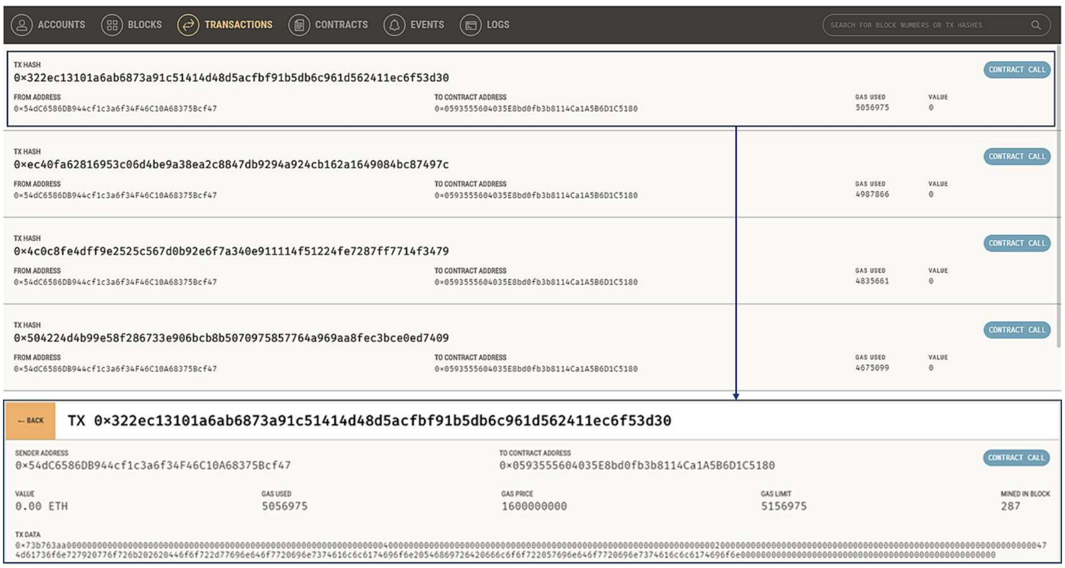
(c)

Fig. 7. (*continued*).

construction type transactions (e.g., Wall and Door work, Masonry work). Fig. 11 shows the amount of gas consumed in each transaction, the cumulative total gas used, and the mean value, regarding each of the three parts of transactions. The initial transaction incurs a significantly high gas consumption (4,554,857 gas used for Transaction 1 in Fig. 11 (a)) due to its responsibility of constructing all the data for the smart contract, commencing with the initialization process. Notably, regarding Fig. 11(b) and (c), the initial batch of approximately sixty transactions involves nodes' insertion and establishment on the chain. This phase demonstrates relatively smooth and low gas consumption due to the similarities in their algorithms that only involve setting without calculations. Subsequent transactions witness gradual growth after a sudden decrease in gas usage. The decrease is attributed to the necessity of processing distinct algorithms, which is the setting of delay days for each node on the chain. Next, given the necessity to find the corresponding node on the chain at first, the process involves initial traversal from the first node to the node itself, thus gathering all its precedence activities. Subsequently, the predecessors are traversed, and the finish date among them is calculated. Should the finish date of the precedence activities exceed the node's start date, the node's date will be changed to the finish date of precedence activities. Consequently, as a node with progressively higher order is traversed, the traversal time increases, resulting in a corresponding rise in gas consumption. Therefore, gas used for subsequent transactions experiences a steady increase. In summary, the total gas used in this experiment is 267,263,769. Based on the 1.6Gwei gas price set, the total gas price is 0.42762203E18 Wei. For better comparison, 0.42762203E18 Wei as the minimum unit of Ethereum can be converted into 0.42762203 ETH ($1*10^{18}$Wei = $1*10^9$



(a) Examples of block lists and details in Ganache.



(b) Examples of transaction lists and details in Ganache.

Fig. 8. Examples of block and transaction lists and details in Ganache.

Gwei = 1 ETH). Under the general contractor's account in Ganache, with the default original 100 ETH and consumed 0.4276 ETH as overhead, the total balance is 99.57 ETH. Correspondingly, according to the current exchange rate (1 Ethereum = 1659.52 US dollars, 18.08.2023), the total cost with US dollars as a unit is 709.65 US dollars. To better evaluate the proposed framework's cost performance, we conduct tests under scenarios related to different building components. Apart from the above scenario (Scenario 1), we illustrate two other scenarios, including a two-day delay for the 5th-floor precast stair (Scenario 2) and two one-day delays for the 1st-floor door and window respectively (Scenario 3). As presented in Table 4, consumed costs for Scenario 2 and Scenario 3 are 0.27 ETH with 164 blocks and 0.12 ETH with 66 blocks respectively. These results present that the more activities that are affected, the more blocks are generated, and the greater the total cost consumption. However, as more blocks are generated, the average gas used and cost per block tend to decrease. According to the recorded tamperproof data in the blockchain, relevant stakeholders' liabilities can be traced and clarified.

6.2. Time performance evaluation

Additionally, our proposed framework's time efficacy is evaluated regarding computing time and latency. The computing time indicates the overall processing time, while latency represents the time taken for a transaction to be confirmed and added to the blockchain. Low latency shows good responsiveness and scalability. A Windows 11 23H2 system with sixteen AMD Core Ryzen Threadripper PRO 5955WX @4.0 GHz processors, 128 GB memory, and a 2 TB disk is used for tests. We test 10 rounds for the 3 scenarios respectively. Under Scenario 1, the total computing time is 21.6 s with 3.45 s for affected 4th-floor transactions, 7.78 s for affected other floor transactions, and 10.37 s for affected other construction type transactions. Its latency is 75.26 ms. For comparisons, Scenarios 2 and 3 have the total computing time of 17.5 s and 5.6 s respectively, as shown in Fig. 12(a). Fig. 12(b) shows their latency at 106.71 ms and 84.85 ms. These results indicate that activity delays occurring in the earlier stages have propagated impacts on more subsequent activities, resulting in more blocks and transactions with a longer processing time. However, regarding the latency, as more blocks are generated, on average each transaction takes less time. Since the acceptable latency is generally about 100 ms or less [112,113], our time performance is within this range. Latency around 150 ms and above may increase the rejection risk due to insufficient computing power. Therefore, maintaining low latency is important.

Theoretically, based on the framework's 5 modules, the total processing time depends on three parts, including the computer's local running speed, internet speed, and the smart contract execution speed in Ethereum. Firstly, for this operation of reading and processing the local JSON file to prepare the data to be uploaded to Ethereum, the time taken depends on the computer's local running speed. Next, uploading the above data to the Ethernet platform is determined by the network speed. Thirdly, interactions and transactions in Ethereum provoked by asset delivery delay data depend on the smart contract execution speed, thus automatically deriving propagated impacts of other activities and tracing liabilities. Compared to the first two parts, the time consumed in

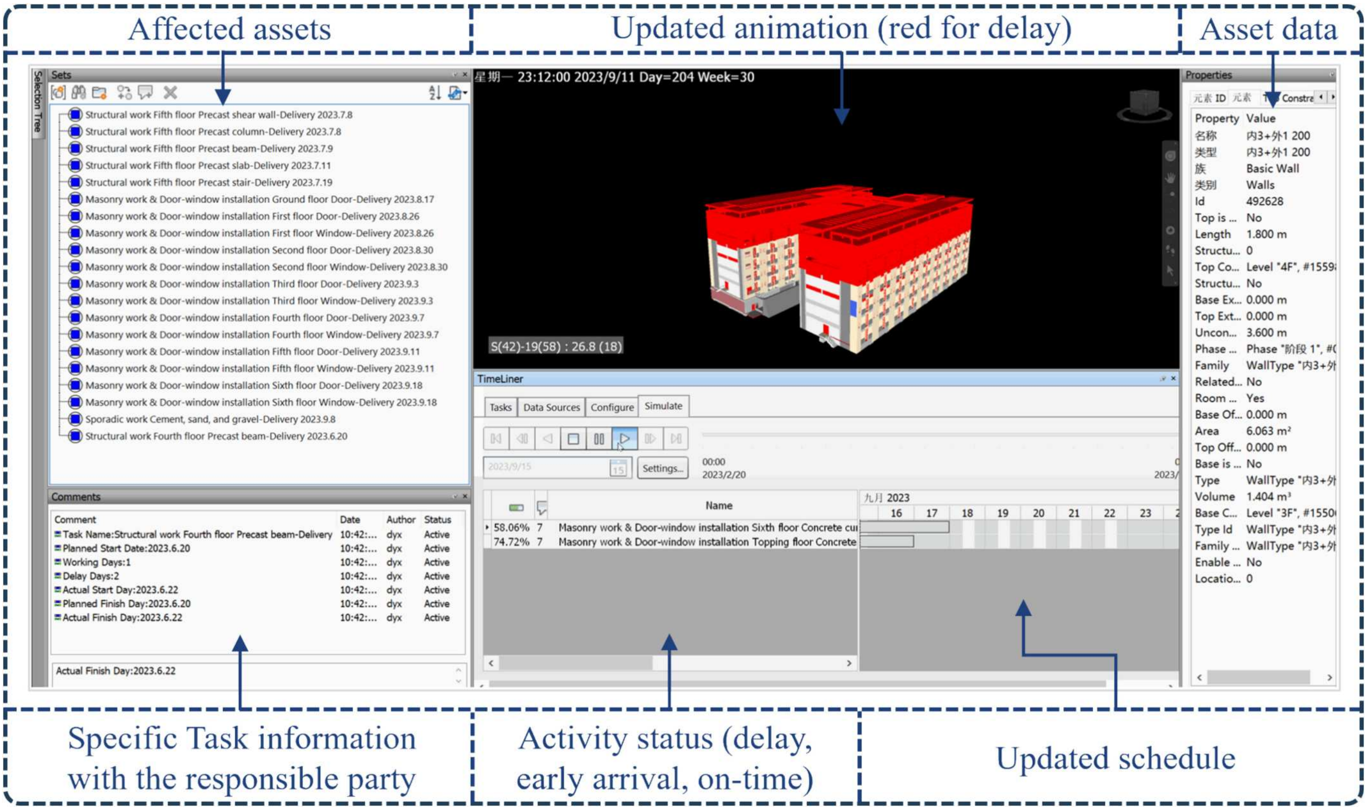


Fig. 9. One-frame progress scenario of 4D visualization in Navisworks.

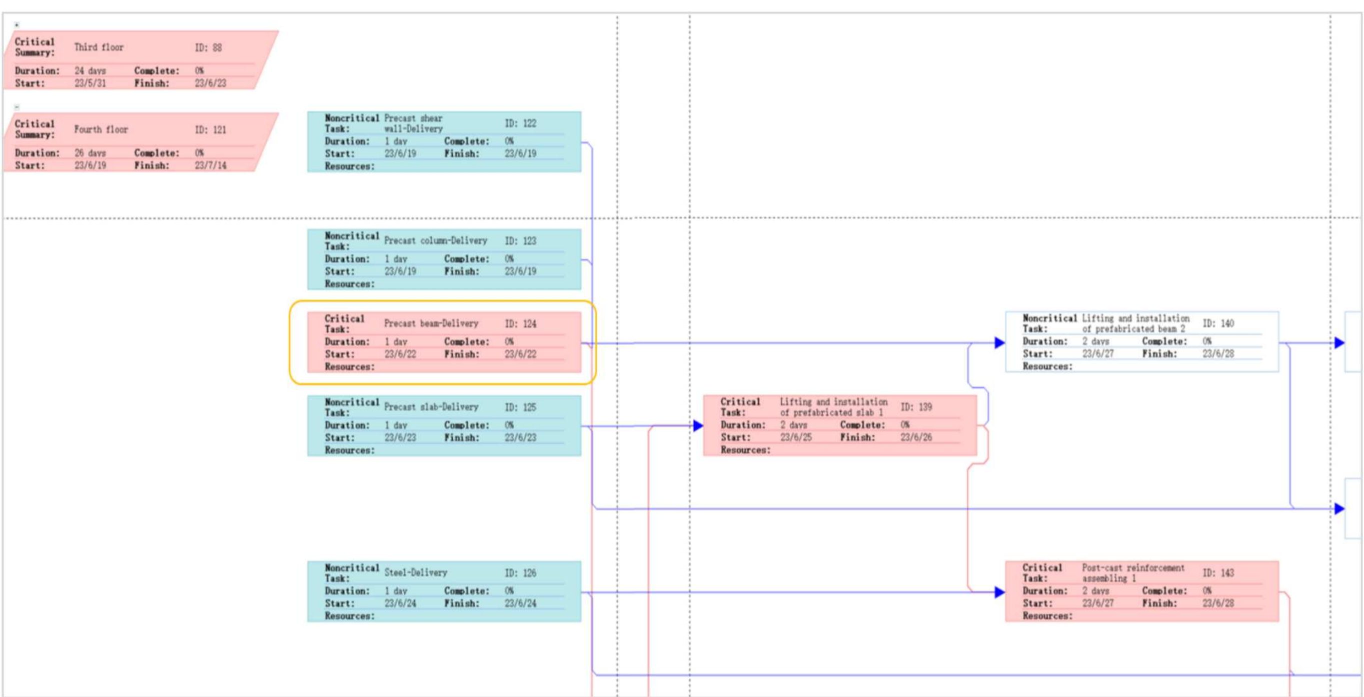


Fig. 10. Impact on critical path activities.

the third part takes up almost all of the time in test running, which is related to algorithms in the compiled smart contract. Algorithms' running time involves the number of steps taken based on input size. Whereas, the time complexity of algorithms is represented by a number T(n), indicating the maximum (worst-case) amount of time taken by algorithms for any input of size n. As the representation of the time complexity, Big O [114] is used to find an asymptotic upper bound of our compiled smart contract. Following these concepts, Table 5 lists the running times of specific algorithms in our compiled smart contract. Regarding the setPrecedenceDelayDays function, this algorithm can be

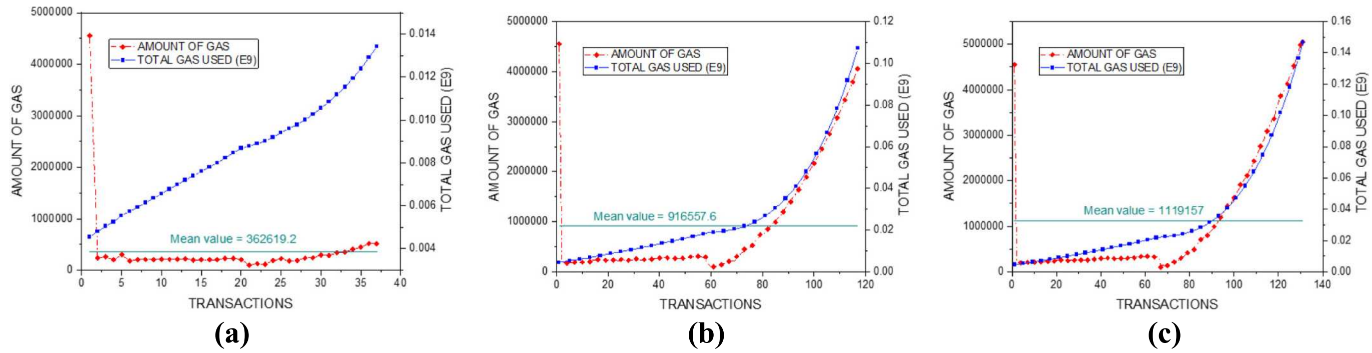


Fig. 11. (a). Cost of completing affected 4th-floor transactions; (b). Cost of completing affected other floor transactions (e.g., 5th floor, 6th floor, topping floor); (c). Cost of completing affected other construction type transactions (e.g., Wall and Door work, Masonry work).

Table 4
Cost performance based on 3 examples of scenarios with different types of delays.

Scenarios	Different types of delays	Balance	Consumed cost	TX count
1	4th-floor precast beam delays 2 days; precast slab delays 1 day.	99.57 ETH	0.43 ETH	287
2	5th-floor precast stair delays 2 days.	99.73 ETH	0.27 ETH	164
3	1st-floor door delays 1 day; window delays 1 day.	99.88 ETH	0.12 ETH	66

perceived as a graph application G = (V, E), where scheduling is interpreted as a Graph, activities as Nodes V, and precedence constraints as Edges E between pairs of nodes. The relative graph size parameters: $n = |V|$, $m = |E|$. Our algorithm first traverses all the nodes on the chain to check if precedence activities exist. If yes, for each node, a Depth First Search (DFS) [115] is then performed to determine if there are precedence activities that we are finding. Here, precedence activities as children are visited before the other chain activity nodes as siblings. Given that our input data structure is an Adjacency List rather than an Adjacency Matrix, the DFS time complexity is $O(V + E)$. Hence, the overall time complexity is $O(V(V + E))$. In the proposed framework, V is the number of affected activity nodes due to asset delivery delays while E represents the number of precedence relationships between these nodes. Under Scenario 1, V is equal to 206 and E is 309.

6.3. Comparison evaluation

To evaluate the proposed prototype, we further examine and compare our prototype and existing practices. Based on Saram's research [27], we select five construction coordination tasks from a total of 68 that align with our framework's 5 modules, as shown in Table 7. To explore current practices in these five aspects, semi-structured interviews are conducted with ten construction professionals in 2024. Table 6 provides their profiles. All participants possess over four years of work experience in their respective roles. To obtain broad perspectives and cross-functional insights, participants are chosen from cost, material market, design, and construction. Their expertise can help us understand current practices in similar scenarios.

For consistency, the five aspects of interview questions are based on the same scenario as the experimental setting (Scenario 1). Participants

Table 5
Running times of specific algorithms in compiled smart contracts.

No.	Functions	Running time (Big O)
1	insert	1
2	setLinkedListPrecedence	O(n)
3	setLinkedListDelayDays	O(n)
4	setPrecedenceDelayDays	$O(n^2 + nm)$
5	setPrecedenceDelayDays2	O(n)
6	getStartDate	O(n)
7	getFinishDate	O(n)
Summary	–	$O(n^2 + nm)$

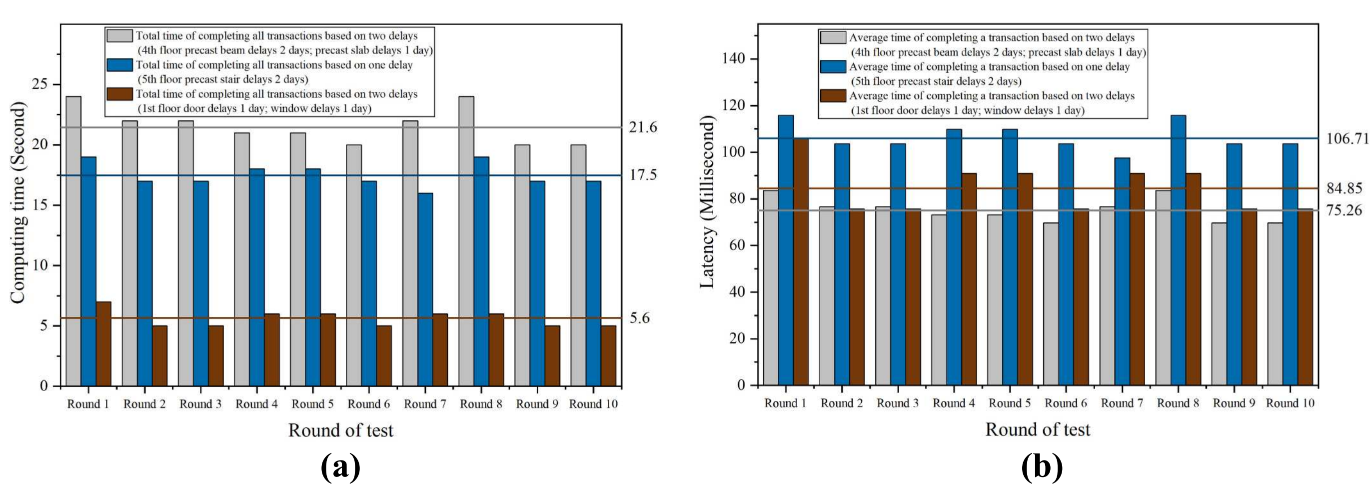


Fig. 12. (a) Computing time under different scenarios; (b) Latency under different scenarios.

Table 6
Interview participant profiles.

No.	Position	Organization	Work experience (Year)
1	Cost manager	Real estate company	5
2	Market manager	Supply chain company	5
3	Construction manager	General contractor	6
4	Construction manager	General contractor	5
5	Project leader	Design and construction service providers	4
6	Project leader	Design and construction service providers	10
7	Procurement manager	General contractor	6
8	Project manager	General contractor	5.5
9	Project manager	General contractor	4
10	Deputy design manager	General contractor	8

are required to recall the typical time, common methods, effectiveness, and current challenges of completing each coordination task. Table 7 illustrates responses to the 5 aspects' consumed time in current industry practices. Specifically, for identifying ambiguities in asset properties and quantities, most participants report using meetings, which typically last between 0.5 and 1 h. Notably, Participant 5, who prefers drawings over a combination of drawings and 3D BIM tools, averages around 2 h for this task. This extended time is mainly because of detailed review through traditional methods. Regarding detecting asset delivery delays, phone call or email is generally utilized to convey delays from suppliers to general contractors. Participant 2, representing the supplier side, emphasized the need to notify the general contractor about potential delays at least one day in advance. In contrast, Participant 6, as the project leader, highlighted that those delays are only notified from suppliers when having started shipping, being passively reported in practice. Additionally, participants indicate that coordinating and rescheduling activities' sequences is efficient with existing tools like Microsoft Project, whereas communicating schedule changes to all affected parties is very time-consuming. Participant 7 highlights that delivery delays in assets like bricks typically impact few activities, thus only taking about 20 min for communication. However, delays in precast components and steels, which always affect the critical path, require at least 1 h to explain and notify each of the affected parties as soon as possible until everything is made clear, through various methods (phone calls, emails, meetings, etc.,). When conflicts and differences arise among stakeholders, managers always spend considerable time resolving these issues due to the lack of evidential data as support, through meetings and penalty letters' issuance. Managers aiming to maintain collaboration with suppliers typically resolve issues within one day. Otherwise, penalty letters are formally issued to the supplier for enforcement.

While our system's time performance, discussed in Section 6.2, is based on specific scenarios, it can be inferred that even in more complex scenarios, the overall time performance would still be within the range of seconds to minutes. However, as shown in Table 7, the overall process involving these five coordination tasks always takes hours to complete. Notably, current BIM tools, like Revit, are widely adopted in the industry, and scheduling tools based on interdependency relationships, like Microsoft Project, can achieve automatic derivation once delayed activities and corresponding periods are imported by users. However, our research offers significant improvements over current industry practices in the following aspects: 1) proactive coordination management: our framework enables proactive offsite and onsite coordination management by automatically detecting asset delivery delays and notifying affected parties, rather than the general contractor being passively informed by delayed suppliers. While informing asset delivery delays may not take much time, risks arising from passive communication, like unanticipated progress changes, resource allocation, and financial issues, could be mitigated through timely identification. 2) automatic delay propagation and notification: if any delays, our smart contracts are activated and self-executing on the blockchain, enabling automatic delay propagation analysis and change notifications to relevant parties. It overcomes the challenge for the general contractor to act as an information transit center, explaining and notifying each affected party individually. Our system requires only a few seconds, or at most a few minutes, for affected parties to understand the latest schedule, compared to the at least 20 min required from industry participants in Table 7. 3) transparent accountability: in addition to visualizing project progress within the same 4D BIM environment, our system records the parties responsible for delays, ensuring that accountability among involved parties is clear and tamper-proof. The clear visualization of activity and resource changes, along with transparent and immutable liability records, can help clarify the current project status and reduce information differences while alleviating conflicts and maintaining good collaboration relationships with team parties. This research significantly reduces the time spent by general contractors organizing meetings to resolve such issues.

7. Discussion

7.1. Theoretical contributions

This research considers activity interdependency and proposes a new BIM-blockchain integrated framework for enhancing the automation and trustworthiness of the coordination process between offsite and onsite. Compared with recent studies about automatic coordination management [14,55], our research does not need the general contractor as an information transit center to passively receive offsite data from suppliers, update the scheduling frequently, and notify propagated changes to each affected party if any delays. Our framework can flexibly design stakeholders' permissions, enabling them to access interdependent parties' performance and make information transparent. If any

Table 7
Summary of consumed time of five aspects in current industry practices.*

Construction coordination tasks [27]	Time consumed (mins)									
	1	2	3	4	5	6	7	8	9	10
Identifying or gathering information on ambiguities in drawings	60	60	30	N.A.	120	30	30–40	30	30	15
Identifying variances from the schedule	1	1	5	10	5	1	2	5	1	5
Coordinating and rescheduling the sequence of onsite work	2	N.A.	5	5	10	5	5	5	10	5
Communicating project progress, plans, schedules, and changes, to all relevant participants	180	60	60	60	30	20	20 or 60	90	20	150
Resolving conflicts and differences among participants	480	480	60	60	30	25	60	60–120	60	480

* Some questions may not be applicable to certain participants due to their different positions.

physical assets' delivery delays, our smart contract is triggered and self-executed for delay propagation analysis and proactive change notifications to affected activities' parties. Existing BIM implementations [57,58,61] lack clarity in accountability and risk allocation among relevant stakeholders, which might cause misunderstandings and disputes. Our study alleviates these challenges by enabling stakeholders to promptly view verified updates on affected activities with responsible parties in 4D BIM, supported by transparent and immutable data.

7.2. Technical contributions

This research develops an IFC and Ethereum-based prototype system and expands the applications of BIM and blockchain in automatic and reliable offsite and onsite coordination management in prefabricated construction projects. Existing BIM-blockchain integrated studies [32,33,41,69,99,100] only focus on automatic and accountable recording of assets' offsite activities. However, we identify the smart contract's unique value in automatic delay propagation derivation and notification among stakeholders, considering the interdependencies of offsite asset delivery and onsite construction activities. It thus delves deeper into the blockchain's functionality. Additionally, these studies only use 3D BIM for asset data extraction and processing. However, our research incorporates blockchain with 4D BIM to provide straightforward, visualized, and trusted feedback on verified impacts and involved parties. It thus facilitates communication among stakeholders. Meanwhile, to alleviate data volume and redundancy issues, this research only requires tracking asset delivery and storing interdependency relationships among activities on-chain, thus not taking much processing time. The assets off-chain are automatically matched to corresponding activities in 4D BIM visualization. Moreover, applying the IFC schema in this study enhances the system's interoperability and compatibility.

7.3. Practical contributions

This study allows affected parties to clearly recognize responsible parties and their task performance, and propagated impacts caused by them, supported by traceable and immutable data records. If certain assets' delivery delays, other affected assets may need to update their delivery times and be stored longer at suppliers' factories, causing excess inventory. Affected onsite activities may need to rearrange corresponding material, manpower, and equipment. Long waiting times and conflicts in the stockpiling area may cause financial losses. Therefore, regarding such contractual changes, it is necessary to trace back to initially responsible parties, file necessary claims, and compensate impacted stakeholders for changes, delays, and cost increases that are beyond their control. When determining liability and incurred costs, disputes always arise among these parties regarding the reasonableness and the specific value. Hence, additional overhead costs (approximately 5 %–10 % of contract value in the construction industry [116,117]) are incurred, including negotiation, communication, documentation, and oversight. Compared with existing studies on offsite and onsite coordination management [14,55], our research can guarantee data immutability and trustworthiness for responsible and affected parties on asset tracking and delay propagated impacts, by incorporating blockchain technology. It can help trace and clarify the liability among stakeholders, and save overhead costs when facing contractual disputes based on changes.

This study has the time advantage of completing the offsite and onsite coordination in seconds or at most minutes. Current industry practices typically require five steps to complete the whole process, as detailed in Table 7. However, through the integration of these steps, we streamline coordination tasks and meanwhile perform them well. Additionally, our framework allows for the proactive and timely acquisition of asset delivery delay information, addressing the issue identified by general contractors, who currently only receive passive notifications from suppliers after shipping begins if any delays. While many scheduling tools can quickly calculate the impact of delays on other activities, they often fail to involve relevant parties and still require the amount of time to notify them individually. Our research provides timely notifications to all affected parties on the latest activity schedules, improving efficiency. Finally, resolving disputes and information differences can be enhanced. By transparently presenting the responsible party for changes to all affected parties without tampering, we effectively mitigate potential disputes.

7.4. Limitations and future directions

However, this research still has rooms for future improvement. Firstly, blockchain has processing time and data overwhelming issues. Processing extensive data of a prefabricated construction project not only requires increased time but is also challenging to achieve comprehensive on-chain storage at once. Although this research does not require storing all the activities and associated asset data on the chain, optimizing on-chain data is still needed for better computational resource utilization. The BIM work package [80] is recommended to enhance data structure and storage. Secondly, this study uses "Construction type name + Floor number + Material Delivery/task name + Zone number" to name activity for information matching. However, in practice, various activity naming methods exist. For projects with 3D prefinished volumetric modules, using BIM-based room and location tags to distinguish activities is beneficial. Considering these diverse methods, how to accurately match BIM with activity information needs further discussion to improve generalization and adaptability across different scenarios. Thirdly, we utilized Navisworks to visualize verified propagated changes from blockchain in the 4D environment, which is a limitation of the developed system. Future research needs to enhance the compatibility of integrating blockchain with 4D digital construction environments. Fourthly, since BIM models do not contain all asset data required for construction projects, such as some temporary materials or facilities, and equipment, it is important to consider how non-BIM assets automatically get tracked and impact other activities. To enlarge this study's applicability, the developed algorithm can be further improved to be compatible with diverse data sources beyond BIM. Fifthly, as this study offers evidential data for tracing and elucidating liability in disputes or claims, another extension would be how to automatically and quantitatively allocate penalties to stakeholders responsible for delayed compliance, while also determining appropriate compensation mechanisms for other parties adversely affected by the delays.

8. Conclusion

Considering high demands for stakeholder coordination and offsite and onsite activity interdependencies within prefabricated construction projects, the reconfiguration of rights and obligations is always required based on stakeholders' task performance, which thus becomes susceptible to disputes and erodes trust among them. To address the issues, this paper introduces a BIM-blockchain integrated framework through smart contracts for automatic and tamperproof asset tracking and delay propagation and visualization across stakeholders. Notably, as assets' delivery statuses update, if any delays, compiled smart contracts can automatically derive potential propagated impacts on offsite and onsite activities with interdependencies. Status changes to activities and associated liabilities remain tamperproof in the 4D environment, utilizing the developed plugin in Navisworks. Additionally, the proposed framework facilitates communication and collaboration through prompt notification, certification, and visualization of propagated impacts among diverse stakeholders. The automatic and trustworthy framework establishes a traceable path to assign accountability for specific changes. This paper contributes to enhancing proactive collaboration. Meanwhile, future improvement directions are also discussed. For example, on-chain data selection still needs to be optimized for improving blockchain efficiency. It would be very beneficial to provide flexibility to adapt to various construction activity naming methods for matching with BIM models. Moreover, further research should consider non-BIM assets' tracking and impacts from diverse data sources and enhance the compatibility of integrating blockchain with other 4D digital construction environments. This paper also serves as a base for future automatic and quantitative allocations of penalties to parties responsible for delayed compliance and compensation for other parties adversely affected by the delays.

CRediT authorship contribution statement

Yaxian Dong: Writing – original draft, Visualization, Validation, Methodology, Data curation, Conceptualization. **Yuqing Hu:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Shuai Li:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Jiannan Cai:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization. **Zhu Han:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

We declare that we have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.autcon.2024.105854.

Data availability

Data will be made available on request.

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