A Transformative Solution for Construction Safety: Blockchain-based System for Accident Information Management

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Abstract

Effective management of accident information is a crucial component of safety management within the construction industry, as it reflects the safety performance of the company and allows them to identify the root causes of accidents and prevent similar accidents in the future. However, existing safety information systems provide self-owned, isolated, and centralized environments and fail to present a secure, transparent, and trustworthy platform for monitoring and management of accident information. To address these issues, this paper presents a novel decentralized blockchain-based system for accident/incident information management of construction projects. The proposed system leverages the benefits and advantages of blockchain, smart contracts, and decentralized IPFS storage to address the security transparency, tampering, and trustworthiness issues of the conventional approaches. The proposed system is simulated by using real-world construction accident data to demonstrate how blockchain technology can provide a novel solution to assure security, transparency, authenticity, availability, and immutability of the accident/incident data for improving safety management.

Keywords: Blockchain, Smart Contract, Decentralized Storage, Construction Accidents, Safety Information Management

1. Introduction

Occupational health and safety (H&S) refers to the physical, mental, and social well-being of workers (Archer et al., 2018). To ensure and enforce safe workplace conditions and standards, many countries have set stringent H&S regulations. Though, even with stronger regulations regarding H&S, workers are not experiencing a substantial reduction in injuries or diseases (Aguilar & Hewage, 2013). This can be partly attributed to the fact that it is still

common for construction contractors to perceive safety management practices as a burden, incurring extra costs over the project budget which in turn results in the widespread occurrence of occupational accidents across the industry.

A fragmented construction culture, in which multiple stakeholders with competing interests participate in a project, presents coordination challenges such as trust, information exchange, and supply chain issues (Hunhevicz & Hall, 2020; Peck, 2017; Sonmez et al., 2021). The construction industry is often criticized for its limited use of communication and information technologies to enhance the work processes. In most instances, valuable information pertaining to an accident on a construction site is seldom shared with all the internal and external stakeholders. A centralized safety system is often reluctantly adopted by the stakeholders and construction companies rarely grant company-wide access to the accidents and safety data (Aguilar & Hewage, 2013; Yang et al., 2022). By preferring document-based systems, H&S management becomes fragmented and disconnected (Yang et al., 2022). More specifically, all the information needs to be manually checked by the inspector to ensure documents are duly prepared, stored, and shared since document-based information management systems are susceptible to manipulation (Zhang et al., 2017; Zhong et al., 2020).

With the advent of Information Technology (IT), centralized systems like the PMIS (Project Management Information System) have also been used for the documentation of safety inspections. Though, such centralized information systems are criticized for their lack of transparency and reliability (H. Wu et al., 2021) since they fail to maintain a secure and traceable platform, particularly for projects that involve numerous parties (H. Wu et al., 2022). The contractor organization who owns the centralized information system may alter the accident/incident reports in order to absolve themselves from any wrongdoings Thus, a traditional centralized system will typically fall short of providing assurance of authenticity, immutability and integrity of the safety-related data (Pan et al., 2022). Therefore, development

of a secure and trustworthy safety management information platform is very crucial to assure security, transparency, authenticity, and immutability of the safety-related data and to provide timely access to the accident/incident reports. A decentralized safety information management system, that can be trusted by project participants would contribute to improving truthfulness and accountability of safety related information and this would also promote a culture of continuous improvement in construction safety management (Love & Tenekedjiev, 2022; Zhou & Ding, 2017).

Blockchain, the technology that has emerged over recent years, is a promising solution for addressing the foregoing issues by allowing decentralized data storage, ensuring the authenticity of data, and preventing opportunistic actions such as data tampering (Rahman et al., 2022). Blockchain as a distributed and decentralized ledger is capable of recording transactions in a chronological and secure manner (Pan et al., 2022). As a disruptive technology for the fourth industrial revolution (Industry 4.0) (H. Wu et al., 2022), blockchain has proven to be a reliable and viable alternative method for developing secure, traceable, and transparent systems (Aste et al., 2017; J. Li et al., 2019). Blockchain in essence is a decentralized, encrypted, and distributed data repository; seen from this perspective, it carries a great potential for providing an easily verifiable, immutable, and incorruptible record of transactions (Andoni et al., 2019; Hader et al., 2022; Hughes et al., 2019; Karamchandani et al., 2020). Furthermore, Blockchain can effectively address the issues of data integrity and security in centralized cloud-based information management, providing a secure platform for sensitive data communication (Gorkhali & Chowdhury, 2022; Rahman et al., 2022). In addition, with smart contracts, blockchain can automate contract execution and provide data-driven decision-making (Mathews & Bowe, 2017). As a result of using smart contracts, businesses can be executed more efficiently and reliably (Hunhevicz & Hall, 2020). Because of the distributed ledger, cryptography, and decentralized consensus mechanism, blockchain has been widely studied

and practiced for data security and privacy protection (di Giuda et al., 2020; Li et al., 2021; Xue & Lu, 2020). Several studies have investigated the use of blockchain technology in the construction industry by narrowing their focus on a particular area, namely, the management of H&S for scaffolding works (Yang et al., 2022), security management of equipment-related accidents (Pan et al., 2022), safety inspection of tower cranes (H. Wu et al., 2022), supply chain management (Tezel et al., 2020), payment management (Ahmadisheykhsarmast & Sonmez, 2020; Hamledari & Fischer, 2021b; Sonmez et al., 2022), quality management (H. Wu et al., 2021; Zhong et al., 2020), and tender management (Ahmadisheykhsarmast et al., 2023). However, the use of blockchain technology in the accident/incident information management of construction projects has been largely ignored. This can mainly be attributed to the fact that blockchain is not designed for recording and sharing large-size data (Lu et al., 2019; Perera et al., 2020). This is while accident records often contain large documents including photographs that serve as valuable evidence holding invaluable information. The main focus of this study is, therefore, to extend blockchain technology with the capability to record and share the ever-growing large-size safety-related data on a decentralized platform.

As discussed herein, on the one hand, falsification of safety data will have serious consequences as it will limit learning lessons from the accidents and will preclude obtaining an objective evaluation of the safety performance of a contractor. On the other hand, with the advancements in technology, the size of safety-related data is increasing tremendously in size making cloud-based data storage services expensive options. On the contrary, blockchain's promising characteristics provide a practical option for record-keeping purposes. The main objective of this study is, therefore, to design and develop a new blockchain-based system for decentralized monitoring and management of accident/incident information in the construction industry. The proposed system is designed to leverage the decentralized Inter Planetary File

System (IPFS) as a large-size off-chain data storage platform and exploits blockchain technology to record all the transactions on the chain.

The remainder of the paper is organized as follows. Section 2 reviews the limitations of the conventional methods for safety information management as well as a review of the relevant blockchain and smart contract studies. The research methodology is described in Section 3 and the proposed blockchain-based system for secure and transparent management of accident/incident information is presented in Section 4. The proposed system is applied to a real construction project in Section 5 and the results of the structured interviews performed with the participants of the case project are presented in Section 6. The contributions and limitations of the proposed system are discussed in Section 7, while concluding remarks are made in Section 8.

2. Literature Review

2.1. The importance of occupational health and safety in construction industry

The construction industry is the backbone of infrastructural development which plays an essential role in securing a prosperous economy and powering Gross Domestic Product (GDP) growth (Chi et al., 2005; Haadir & Panuwatwanich, 2011; Ramli et al., 2013; Suárez Sánchez et al., 2017). Hence, one of the major contributions of this industry is providing employment opportunities to millions of individuals globally (Khalid et al., 2021; Rostami et al., 2015). It is estimated that annually $10 trillion is spent on construction-related projects globally accounting for 13% of the world's GDP (Barbosa et al., 2020). This is while in the United States alone, the construction industry contributed approximately $1,090 billion to the GDP in 2022 (BEA, 2022). Such contributions substantially rely on the production of the industry's workforce (Kamas et al., 2019) as the global construction industry employs around 7% of the

total workforce. According to the Bureau of Labor Statistics (BLS), the US construction industry provides jobs to over 7.7 million people (BLS, 2022b), with a steadily increased employment rate which is anticipated to grow by 4% by attracting more than 200,000 new construction workers over the next decade (BLS, 2022b, 2022a). Every year, 374 million non-fatal workplace-related incidents and 2.78 million occupational fatalities are recorded globally (ILO, 2021).

However, despite its crucial role in generating revenue, it is also widely acknowledged that the construction industry is fraught with hazards, characterized by its labor-intensive, fragmented, and dynamic nature (Wang et al., 2019). The occupational accidents, injuries, and fatalities rate within the construction industry is worrisomely high, surpassing that of the other industries (Awwad et al., 2016; Sawacha et al., 1999; Sunindijo & Zou, 2012) , thus solidifying its position as one of the most hazardous industries (Pinto et al., 2011). In fact, it is estimated that construction workers have a three to four times greater chance of being killed on the job than workers across other industries (Gurcanli & Mungen, 2013; Hinze & Appelgate, 1991; ILO, 2021; Jin et al., 2019). Due to the dynamic and unique nature of construction activities, accidents causing non-fatal injuries with lasting disabilities or fatal injuries are common (Chan et al., 2008), making this industry one of the most dangerous and highly hazardous industries (Pinto et al., 2011). Construction workers are frequently subjected to dangerous working conditions, such as working at heights and are at risk of being caught by equipment and machinery on site, resulting in accidents (Mohammadi et al., 2018).

The perilous nature of the construction industry in terms of accidents or incidents, therefore, has an adverse effect on the cost, quality, and time of the project (Hare et al., 2006). In order to investigate the contributing factors to accidents, each year the regulating bodies in many countries analyze and publish accident statistics with details about the location, industry, cause,

source, etc. of the accidents (Graves et al., 2015; McKenzie et al., 2010; Taylor et al., 2014). However, such safety-related data are often released later next year which renders it difficult to make informed decisions about the safety of active projects. On the other hand, construction sites being exposed to hazardous conditions makes investigating the root causes and particularly those at the helm of the accidents an imperative yet challenging task (J. Li et al., 2021).

2.2. Existing safety information management systems within the construction industry

In order to mitigate accidents on construction sites, a systematic approach to measuring and assessing safety performance is vital. This approach necessitates thorough records of safety-related events throughout the project lifecycle (Cheung et al., 2004). The importance of proper record-keeping in the construction industry, specifically with regard to accidents and incidents, to effectively address the issue of accidents on construction sites has been emphasized by numerous researchers (Garza et al., 1998; Hinze & Russell, 1995; Jaselskis et al., 1996; Kamardeen, 2009). This is due to the unique and dynamic nature of the industry, which requires a comprehensive understanding of potential risks and hazards. The assessment of safety performance generally involves utilizing recorded accident information (Choudhry, 2014). Based on this data, actions are taken to address any negative trends in identified accidents or injury events (Hallowell et al., 2013). Therefore, the proper record keeping of accidents/incidents enables the identification of their patterns and trends, which can then be used to implement preventative measures and enhance safety performance in construction projects.

In recent years, various studies have explored ways to improve the efficiency of health and safety information management in the construction industry. Cheung et al. (2004) proposed a web-based system that utilizes a centralized database for monitoring and assessing information on construction safety performance. The system enables remote access, facilitates

data collection, and streamlines the recording of information related to safety tasks. Kamardeen (2009) developed a framework that enhances construction safety performance through a web-based system that allows for the submission of safety data via smart devices and recording in a centralized network. Zou et al. (2017) introduced a cloud-based system for safety information management, communication, and recording. The system employs cloud computing, GIS, and mobile technology to provide real-time data processing and visualization and includes spatial information in the record-keeping process. Wu et al., (2018) proposed a cloud-based safety monitoring application that utilizes wearable sensors and IoT devices to monitor and record environmental conditions and the health status of workers in real-time. These studies highlight the potential of web-based, cloud-based and centralized technologies in improving the efficiency of health and safety information management in the construction industry.

Despite the fact that the proposed systems offer major advantages for efficient management of safety information, security concerns related to the safety information rise as these data are stored in the centralized database. These systems often rely on intermediaries to maintain and manage the recorded information, making it difficult to ensure data integrity, security, transparency, and traceability (H. Wu et al., 2022). Centralized information management systems are frequently characterized by their self-owned and isolated environments (Chan et al., 2008; Davis & Tomasin, 1990) which at the same time are potentially vulnerable to hacker attacks data tampering, loss, and fraud (Ho et al., 2021; X. Liu et al., 2021). These limitations of centralized information management systems leads to poor authenticity of records, privacy issues, and insufficient information sharing, which hinders the transparency and reliability of the system (D. Li et al., 2018). The poor safety performance of some managers, for example, may be disguised by underreporting the near-miss accidents (Love & Tenekedjiev, 2022). Such forged or incomplete information would make safety accountability more difficult, rendering a fair and impartial verdict on an accident/incident impossible (Tam & Fung, 2011). If data is

lost or tampering occurs, the entire centralized system may become distrusted (Ma et al., 2020). Hence, it is crucial to maintain accurate safety data without alteration as it can result in severe consequences such as a lack of understanding of hazards and distorted reports of a contractor's safety performance. Additionally, the lack of authenticated safety information and the possibility of data removal or loss can lead to disputes about the accuracy of the information in the event of a safety accident, resulting in prolonged court proceedings (H. Wu et al., 2022). Therefore, in order to address the aforementioned issues, it is imperative that the current centralized systems for the management of safety information be improved.

2.3. Blockchain-based construction safety information management systems

To ensure the integrity and security of accident/incident information, it is crucial to employ a distributed and decentralized platform for the data reporting and recording process to significantly minimize concerns regarding the immutability, security, privacy, and transparency of this information. The recent advancements in blockchain technologies have led to a change in the way traditional business processes are managed, which typically rely on centralized systems and require trusted third parties (Casino et al., 2019), providing a secure, traceable, decentralized, and transparent information management environment. Numerous studies have explored the potential use of blockchain technologies in the construction industry to promote digital transformation, improve collaboration, and increase trust (Ahmadisheykhsarmast, 2020; Das et al., 2022; Hamledari & Fischer, 2021a; Hunhevicz et al., 2022; H. Liu et al., 2023; Tao et al., 2021; Tezel et al., 2022; Uysal et al., 2022).

Few studies have mentioned the capabilities of blockchain technologies for establishing a secure platform for safety information management. Wei & Cui (2020) proposed a blockchain-based model for the safety information management of construction workers by which the security, transparency, and distribution of safety data are assured. Morteza et al. (2022) presented a decentralized framework for construction safety information management where

the blockchain maintains the decentralized control of the safety data. The framework offers a new architecture of trust for reliably sharing and recording safety data in an accessible, traceable, and immutable manner. Musa & Fathib (2019) discussed the potential benefits of blockchain technologies for assuring the reliability, security, and accuracy of data in occupational safety and health management systems. H. Wu et al. (2022) developed a smart contract system to demonstrate the potential of blockchain technology in streamlining tower crane safety management through the self-execution of safety inspections and the creation of secure inspection records, thereby fostering trust among all parties involved. Pan et al. (2022) developed a system that employs blockchain and deep learning technologies to enhance the efficiency of equipment security information management. The proposed system performed management of equipment security information on a consortium blockchain using Hyperledger Fabric, hence the system is partially decentralized. Xu et al. (2022) pointed out that the use of blockchain technology in the construction industry has the potential to enhance privacy protection for workers' personal information which is a core value in safety management systems. The study suggests that blockchain is well-suited as a platform for securely encrypting and storing workers' identification and biometric information during safety management procedures.

Previous studies have identified significant limitations in existing safety information management practices in terms of data transparency, immutability, traceability, security, and distribution within the construction industry. Musa & Fathib, (2019) and Xu et al., (2022) discussed the potential of blockchain for safety management, Wei & Cui, (2020) proposed a general framework for safety information management. However, these studies are mainly conceptual studies and do not include a blockchain-based system that can be implemented for safety information management. Pan et al., (2022) developed a partially decentralized blockchain for equipment security information management. However, the proposed system is

designed for consortium-based equipment security information management and cannot be used to assure security, transparency, authenticity, and immutability of the accident/incident data. A consortium blockchain would not only require presence of a consortium for the lifetime of the information management system but would also enable altering of the information and smart contract conditions according to defined consensus. The existing research also do not provide a solution for how the large amount of accident/incident data will be stored and managed on a decentralized blockchain-based system which a major limitation for achieving a secure, transparent and trustworthy platform for safety information management. Hence, the primary aim of this study is to narrow the gap in the literature by designing and developing a decentralized blockchain-based system for accident/incident information management of construction projects, to assure security, transparency, authenticity, and immutability of the data throughout the process for improving safety management.

3. Research Methodology

This study aims to design and develop a blockchain-based system to provide a decentralized, secure, traceable, and transparent method for accident/incident information management of construction projects. To achieve that goal, the design science research approach of Peffers et al. (2007) is adopted to guide the research progress. This research method is a problem-solving paradigm that focuses on comprehending problems and seeks to enhance technology and science knowledge bases to propose alternative solutions for improving the existing methods (vom Brocke et al., 2020). This approach mainly contains five sequential steps which are: i) identification of the problem and motivation, ii) definition of objectives for the solution, iii) design and development, iv) demonstration and v) evaluation (Geerts, 2011; Hevner & Chatterjee, 2010; Kuechler & Vaishnavi, 2008).

As summarized in Fig.1, in the first step, the initial motivation is identified as the lack of a secure, traceable, and transparent accident/incident information management system stemming from a detailed literature review. In the second step, it emerges that the blockchain and decentralized storage technologies are the proper technologies by which security, distributivity, traceability, and transparency of accident/incident information management systems can be achieved. The third step consisted of the design of the architecture of the proposed system, depicting the modules required and their relationships, and the choice of development platforms for the modules. In this step a solution is presented for the research question "How can the recent developments in blockchain technologies be adopted to achieve a decentralized accident/incident information management system?". In the fourth step, a blockchain-based accident/incident information management system is developed which includes the smart contract, blockchain-integrated decentralized storage, and decentralized application modules. In the final step, accident/incident information of a real construction project is used to simulate the application of the developed system for corroborating its practicability and feasibility in providing a novel secure, and transparent decentralized method for accident/incident information management of projects. In this stage, the proposed system was also evaluated by the parties involved in the case project through structured interviews.

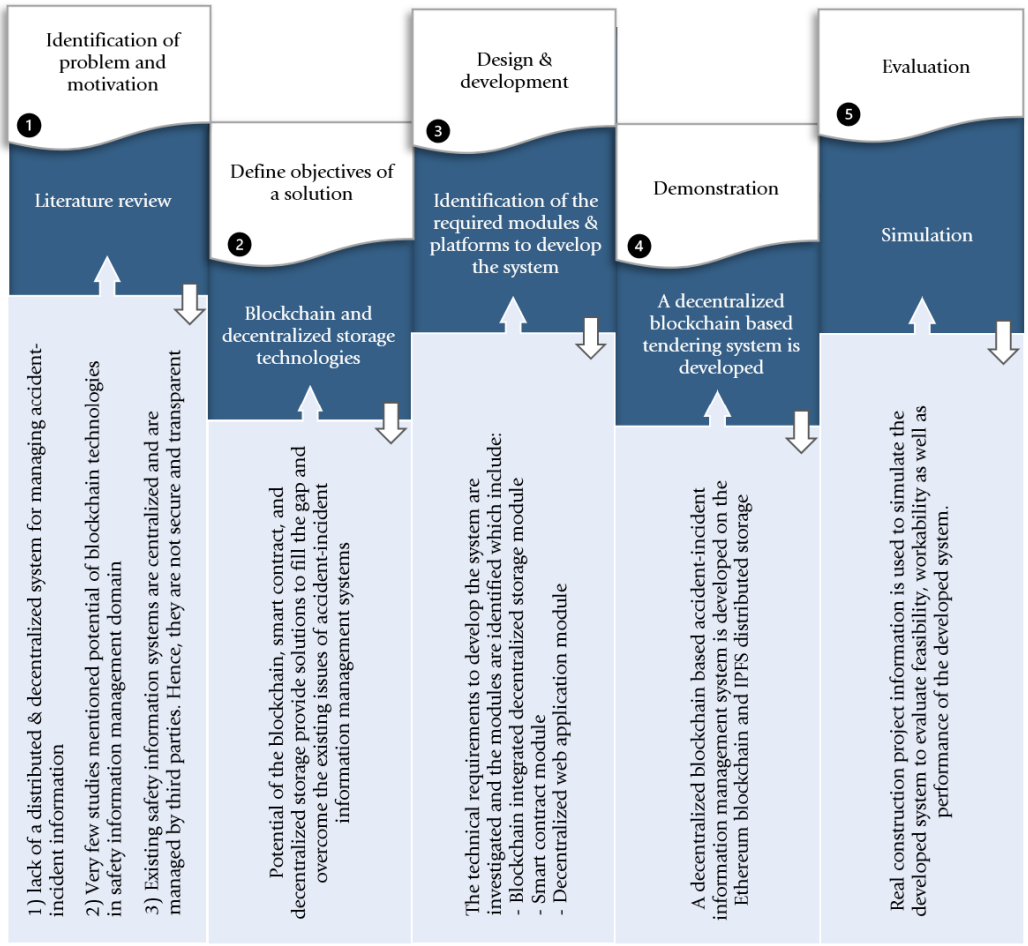


Fig.1 Research methodology

The details of the research methods including an explanation of a procedure for the blockchain-based accident/incident information management system, design of architecture and modules, selection of the software development and blockchain platforms, case project implementation, and performance analysis results are provided in the following sections.

4. A novel blockchain-based system for accident/incident information management

This research offers an in-depth exploration of blockchain, smart contracts, and decentralized storage technologies to design and implement a novel fully decentralized solution for construction accident/incident information management. Therefore, a blockchain-based system named DECAIMNG (DECentralized Accident Information MaNaGement) is designed

and developed for construction projects to ensure security, transparency, and efficiency in accident/incident information management. The main novelty of the proposed system is that it is designed to present a fully decentralized accident/information management system including a decentralized storage. DECAIMNG includes three modules as shown in Fig 2. The first module is blockchain-integrated decentralized storage that provides a distributed and secure layer for the decentralization of storing and exchanging large-size supportive documents. The second module is a smart contract that performs the execution of the functions related to the process and also provides a data storage layer for managing the transactions data throughout the process. The third module includes user interfaces and a web application that enables the end-users to interact with the system to input the information and invoke the smart contract functions as well.

The first module of the proposed system enables decentralized storage of the accident/incident data. The second module manages the accident/incident information that is stored in the decentralized storage, through a decentralized smart contract based on a set of predefined conditions. The third module includes the user interfaces which allow the users to execute the smart contracts for managing the accident/incident information, and at the same time facilitate regulating the access to the system and data based on the authority of the user. Hence, a user of the system would first use the third module to invoke a smart contract, which would enable the user to access the data in the decentralized storage. The decentralized smart contract layer ensures the security, authenticity, and immutability of the accident/incident data as the safety data cannot be accessed without the smart contract, and a smart contract which is deployed on a public blockchain is immutable. The details of the modules and their relations are described in detail in the following sections.

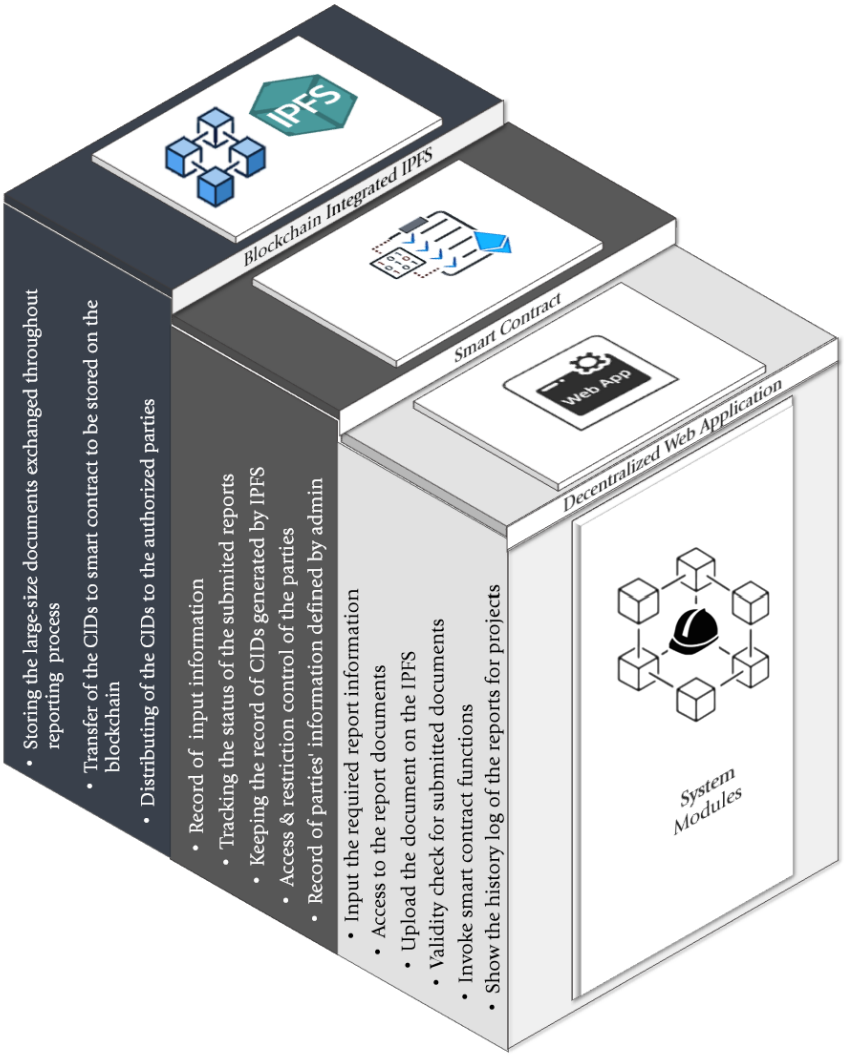


Fig.2 Modules of DECAIMNG system

4.1. The procedure of the proposed DECAIMNG system

The employer and general contractor, as the main parties involved, initially establish and agree upon the specific protocol and requirements for the accident/incident reporting and recording procedures of the project. These terms and conditions are then encoded as a computerized agreement in the smart contract development stage and are executed accordingly. Subsequently, the smart contract is deployed and run on a decentralized public blockchain to manage and ensure the secure execution of the entire procedure without the need for a trusted party.

Smart contract conditions are unique for each project as organizations adhere to predefined specific standards for accident/incident reporting and recording processes. The smart contract conditions for the proposed system involve functions for access control and the recording and management of the information of authorized safety supervisors. These supervisors have the authority to access the data and verify the validity of submitted reports. Additionally, functions to store the information of participants who are eligible to submit safety reports, conditions for recording data on the blockchain network, as well as document exchange procedures among participants are outlined in the smart contract development process.

The contract parties appoint a trusted administrator who has the sole responsibility of registering the information of all users involved throughout the process. In construction projects, when an employee witnesses or is involved in an accident or incident, they are required to report it to safety supervisors. To facilitate this, the admin registers the blockchain addresses of employees at the construction site, such as foremen, inspectors, site engineers, and site supervisors, through the system. This allows them to access the system and report any accident or incident occurrences that take place at the construction site. The safety supervisors of the employer and main contractor are authorized to verify the accuracy of reported events to prevent the recording of any inaccurate information. As a result, the blockchain account addresses of the safety supervisors are also registered through the system to enable them to review and validate the submitted reports. The registered information is recorded in the smart contract and blockchain, which allows the smart contract to distinguish between reporter and validator users and manage their access limits to the system. In addition, users' names, their relevant parties, job title, and project information are also defined during the user registration stage of the procedure and are stored on the blockchain, along with the content identifier (CID) of the documents which is discussed in the next section. DECAIMNG was designed to have the minimum amount of information required for executing the smart contracts to be stored in

the blockchain, as the blockchain is an expensive and inefficient platform for storing information. The accident/incident information and reports are stored in the decentralized storage.

The accident/incident reporting stage begins when all of the pertinent information is gathered immediately after the event has occurred at the construction site. The employee involved or who witnessed the accident/incident uses the system to input detailed information regarding the event and compile a formal accident/incident report. The designed reporting form of the proposed system contains all necessary information required to be captured including event category, incident severity, affected victim, damaged machinery or equipment, environmental hazards, primary cause, date, and location of incidence, and comprehensive description of the event. Furthermore, reporters submit related supportive documents through the system to provide evidence for the occurred incident. Additional information about the accident/incident such as the work type and worker's age or any related information can be included in the event description type if needed. The reporting form and related supportive documents will be stored in the decentralized storage, hence there is no limit on the size of the form or documents. After submission of the report, the system will subsequently forward the published information as well as the submitted files to the employer for approval of correctness. The smart contract procedure also presents the reporter employee's information by tracking the users' blockchain address.

To finalize the reporting procedure, the proposed system requires the mutual approval of safety supervisors of both employer and contractor parties on the authenticity of the accident/incident information. Therefore, once they reach this consensus, the information will be marked as valid and recorded on the decentralized blockchain network in a tamper-resistant manner. The participants can access the stored information and track the reports of the

accident/incident through the developed system. If the consensus on the information validity is not reached, the report will be recorded as the rejected report on the system.

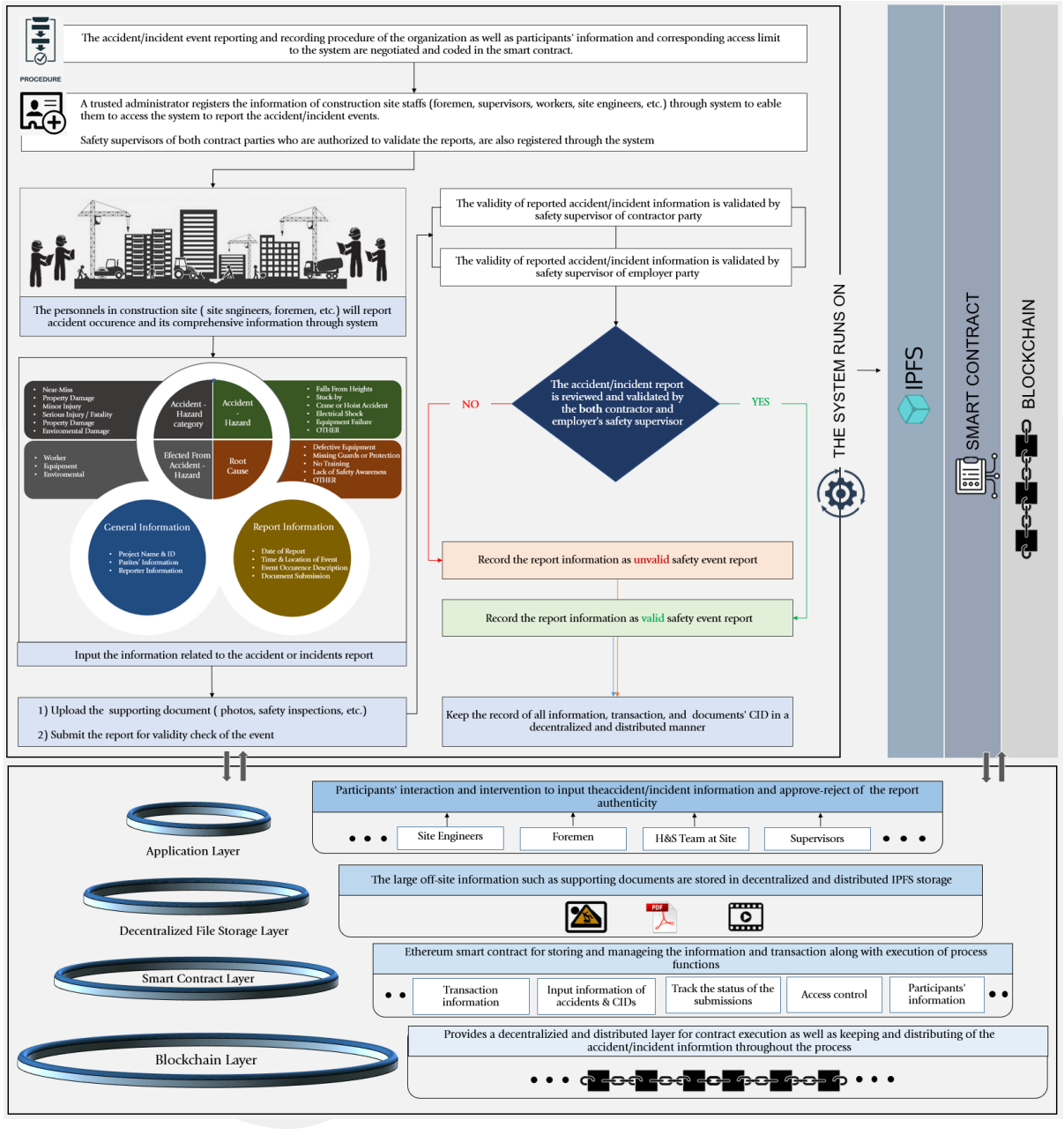


Fig.3 Procedure flow of the proposed system

4.2. Blockchain Integrated IPFS Data Storage

Inherent features of blockchain assure the security of the accident/incident information stored on the network. However, the primary obstacle is that the blockchain is fundamentally

unsuitable for storing large-capacity data (e.g., incident-related photos and other proof) due to the block size limit (Steichen et al., 2018). Storing large data (>1 MB) on the blockchain network would adversely affect the system's scalability and performance as it would cause high latency and network congestion (Tao et al., 2021; Yang et al., 2022). This limitation necessities the integration of blockchain with decentralized storage technologies like Inter Planetary File System (IPFS) (Benet, 2014) to provide a secure platform for storing data and files.

The IPFS is a decentralized and peer-to-peer network for both storing and sharing files and other types of data in a distributed file system (Benet, 2014). It utilizes a content-based addressing system to uniquely identify each file, making it an ideal technology for securely storing and distributing data, specifically large-size files. The IPFS is regarded as a complementary technical solution to the blockchain, offering a reliable platform for the secure storage and distribution of large off-chain data (Nizamuddin et al., 2019; Tao et al., 2022).

The IPFS network calculates and assigns each file a unique, 24-character hash identifier, known as the content identifier (CID) upon its uploading to the network. This CID, which is generated based on the content of the document, serves as the file's identifier and reference within the IPFS network, allowing users to access the stored file. Upon retrieval, the integrity of a file on the IPFS network is verified through the recalculation of its hash. If the calculated hash does not match the original hash, it indicates that the file has been modified. Hence, this feature grants a high degree of immutability to the IPFS file storage system. The CID, which is a 256-bit long string, is compact in size and can be easily disseminated on the blockchain network, therefore, blockchain provides an additional security layer for the data exchanged on the IPFS network. IPFS replaces the function of a centralized server with a peer-to-peer file management platform, distributing files across various storage nodes to prevent the occurrence of a single point of failure (Gao & Zhong, 2022).

This research leverages the capabilities of the IPFS system to create a secure platform for the storage and exchange of accident/incident-related photos and other supporting files. In the first module of the proposed system, ipfs JavaScript implementation (IPFS-API) is used to facilitate the exchange of documents between the system and IPFS. As presented in Fig 4., once a user submits a report and uploads proof documents, IPFS-API serves as an intermediary, transmitting the document for storage on the IPFS network and returning the generated CID to the system for access of the users. To provide an additional layer of security for the system, web3.js is used to enable the smart contract module to retrieve and store the CID of the documents within the blockchain network as a transaction. The CID changes with any modification to the document's content, allowing for the traceability of any attempts to tamper with the information. In this way, the first module ensures the security and integrity of the accident/incident evidence documents throughout the process.

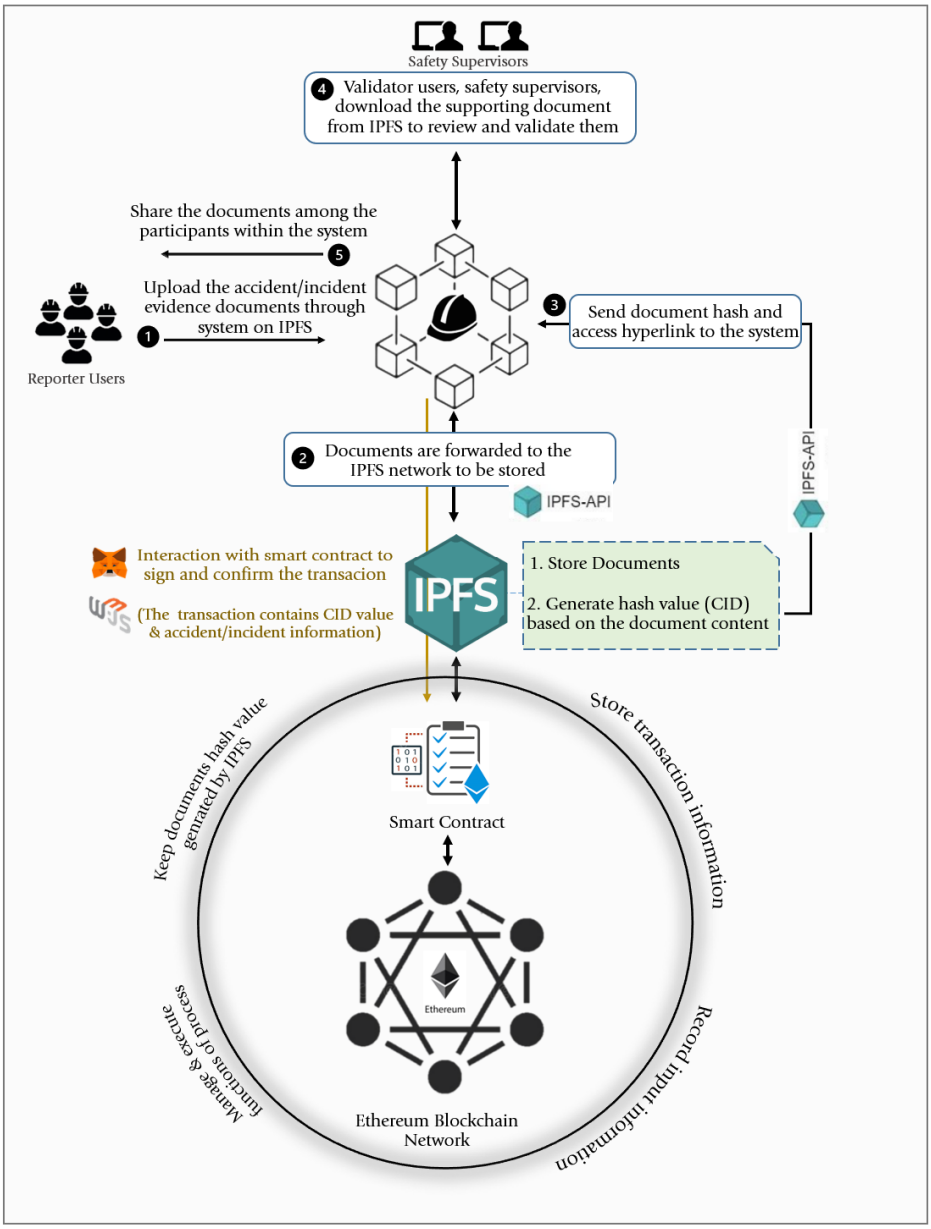


Fig.4 Blockchain-integrated IPFS module of DECAIMNG

4.3. Design and development of smart contract

To ensure the successful development and implementation of smart contract systems, it is necessary to carefully consider various technical factors, including scalability, security, privacy, maturity, cost, and data storage, when choosing a blockchain platform (J. Li et al., 2019). DECAIMNG system requires a blockchain platform that possesses the capability to execute decentralized smart contracts, seamlessly integrate with IPFS, be cost-effective, and possess the speed necessary to store and manage accident/incident information. To select the

most convenient platform for the proposed system, this study referred to the frameworks on the selection of the blockchain platforms developed by Hunhevicz & Hall (2020), Peck (2017), and Sonmez et al. (2021). As a result, the Ethereum blockchain is adopted as the platform for developing and deploying smart contract module due to its technical maturity and popularity in terms of supporting the development of smart contracts (Ahmadisheykhsarmast et al., 2020; Nizamuddin et al., 2019) as well as its efficiency in integrating with IPFS system.

The smart contract module of the proposed system was implemented using Solidity 0.8.15, a well-established and widely used programming language specifically designed for developing smart contracts on the Ethereum blockchain. The Remix integrated development environment was used for the development of the module. To ensure the functionality of the smart contract module, tests were conducted by deploying it on a virtual Ethereum blockchain network provided in Ganache. This module is developed for the execution and managing the reporting and recording of accident/incident information throughout the procedure, and mainly includes encoded terms for user registration, access control, validation of authorized parties, and the recording of both on-chain and off-chain (IPFS hash of documents) data. Some of the smart contract conditions of DECAIMNG are summarized in Fig 5.

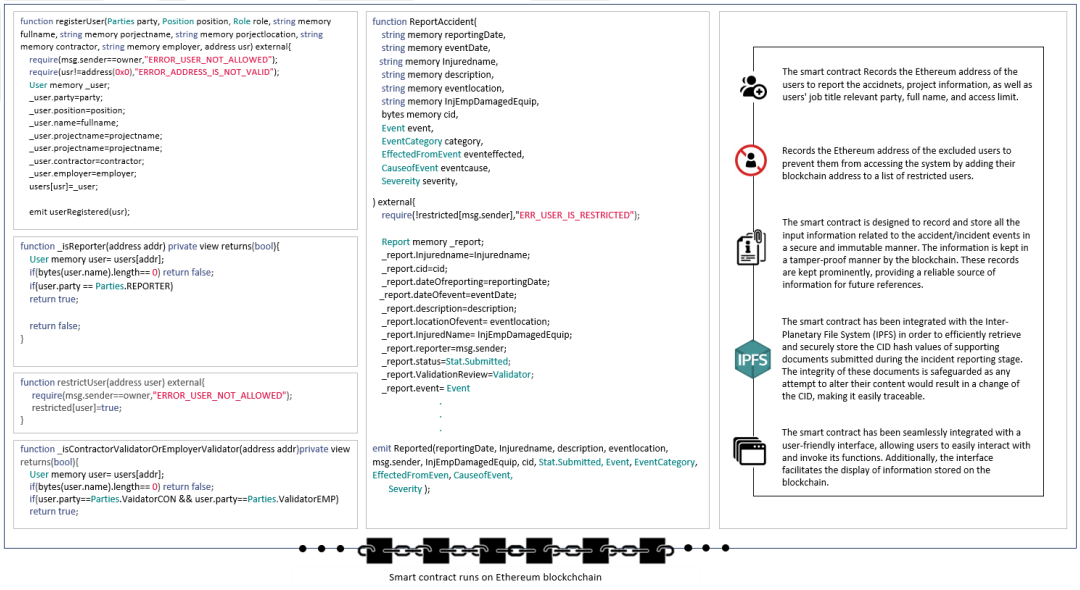


Fig.5 Summary of smart contract module of DECAIMNG

The smart contract module is developed to govern the accident/incident information procedure and manage the data and users' access to the functions. When initiating a smart contract, inputs such as; user Ethereum addresses, reporting procedures, and access limitations for participants are defined. The *registerUser* function enables the contract administrator (admin) to register new users by assigning their information and linking it to their Ethereum address. When a user submits an accident report, the *_isReporter* function verifies whether the Ethereum address belongs to a user who has been registered as a reporter in the smart contract. The function checks stored addresses within the contract to match the address provided. If the address is not listed, an error is raised to prevent unregistered users from submitting information. The *restrictUser* function allows the contract administrator (admin) to revoke access for a restricted user by adding their Ethereum address to a list of restricted addresses stored on the smart contract. This prevents the user from interacting with the system and performing any actions on the smart contract. The R*eportAccident* function allows registered reporters to input accident/incident information to the smart contract, including parameters such as the date, location, type, cause, and CID hash of documents generated by IPFS. The function retrieves and stores this information on the smart contract. The *_isContractorValidatorOrEmployerValidator* function manages the approval of information validity and verifies whether a user's address belongs to someone who has been assigned as a validator in the smart contract. The module records and maintains all information exchanged during the registration, reporting, and validation stages.

4.4. Decentralized web application (DApp)

The third module of DECAIMNG system is developed as a decentralized application (DApp) which is a web-based application that operates on a blockchain network. The DApp is the platform that provides a user-friendly interface for the users to input the accident/incident-

related information, interact with the smart contract functions intuitively, as well as upload the supporting documents on the IPFS network. JavaScript, HTML5, PHP, CSS, and JavaScript React library are used to develop the front-end web pages of DApp. For the back end of the system, the Web3.js API link is employed to enable information synchronization between the front end of the DApp and the smart contract. Moreover, IPFS-API is hired to enable the users to upload the files through the web application into the IPFS server and to access the document's CID. MetaMask, a secure web wallet, is integrated into the third module for authentication medium and account management on the Ethereum network.

To initiate the process, the designated administrator uses the "Admin" interface of the DApp module to input the information of the users that are to be recorded on the smart contract and blockchain, as shown in Fig 6. This information includes their blockchain account address, personal details, job titles, and project-related information. The administrator also assigns a role to the users, either as a reporter or validator, which allows the smart contract to control their access to the system and information. When a user is registered as a reporter, the smart contract limits their authority to only submitting accident or incident reports and viewing the accident/incident book, a document that records information about accidents/incidents that occur on a construction site, of the project. Conversely, when a user is registered as a validator, they are granted the authority to access and verify the accuracy of the reported events. This authorization allows them to ensure the authenticity of reports, which is critical for assuring the integrity of the safety data of the project. The administrator should press the "Register User" button to invoke the smart contract module to record the input information on the blockchain. The administrator's MetaMask wallet will immediately display the required transaction fee for the user registration transaction. The transaction will then be appended into a block on the blockchain once the administrator confirms the transaction. The DApp module enables the administrator to prevent a user from accessing the system by adding their blockchain address

to a list of restricted users. This action completely revokes the user's authority to interact with the system to access the recorded information.

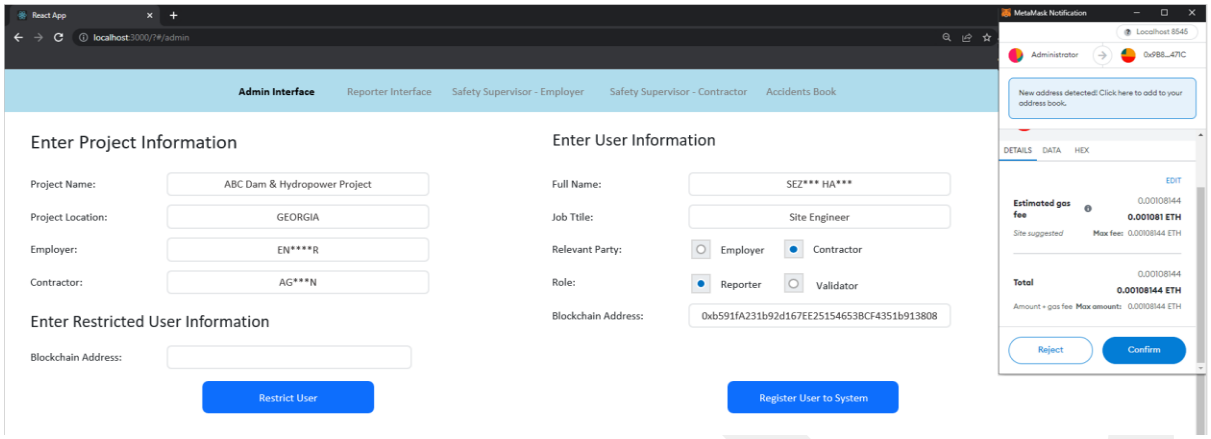


Fig.6 Admin interface to register the users

To ensure that all relevant information regarding an accident or incident that occurs at a construction site is properly reported, the proposed system has implemented a comprehensive reporting form to be filled out through the DApp module. To access this form and submit a report, users log in to the system using their MetaMask wallet. As presented in Fig 7, the reporter interface of the system is intuitively designed to capture all crucial details of the incident, including the event category, the severity of the incident, any individuals affected, any damaged machinery or equipment, any potential environmental hazards, the primary cause of the incident, the date and location of the incident, and a thorough description of the event. To gain a comprehensive understanding of the accident that occurred, reporters need to submit supporting documents such as photographs or videos of the scene, inspection reports of equipment or machinery, medical reports, and so on. To facilitate this, the DApp module allows reporters to upload these evidence documents, such as photos and videos, to IPFS storage in addition to providing information through the reporting form. This ensures that all relevant information is captured and available for the validator's review. Once the users press the "Submit Accident/Incident Report" button and confirm this transaction, the DApp module will

then display the information as well as the hyperlink/CID of the supporting documents on safety supervisors', validators, screen so that they could check the validity of the event. The smart contract module of the system securely and immutably records all information related to the accident. Additionally, it verifies the Ethereum account addresses of the reporter to ensure that only authorized users can submit reports, thus preventing any unauthorized submissions.

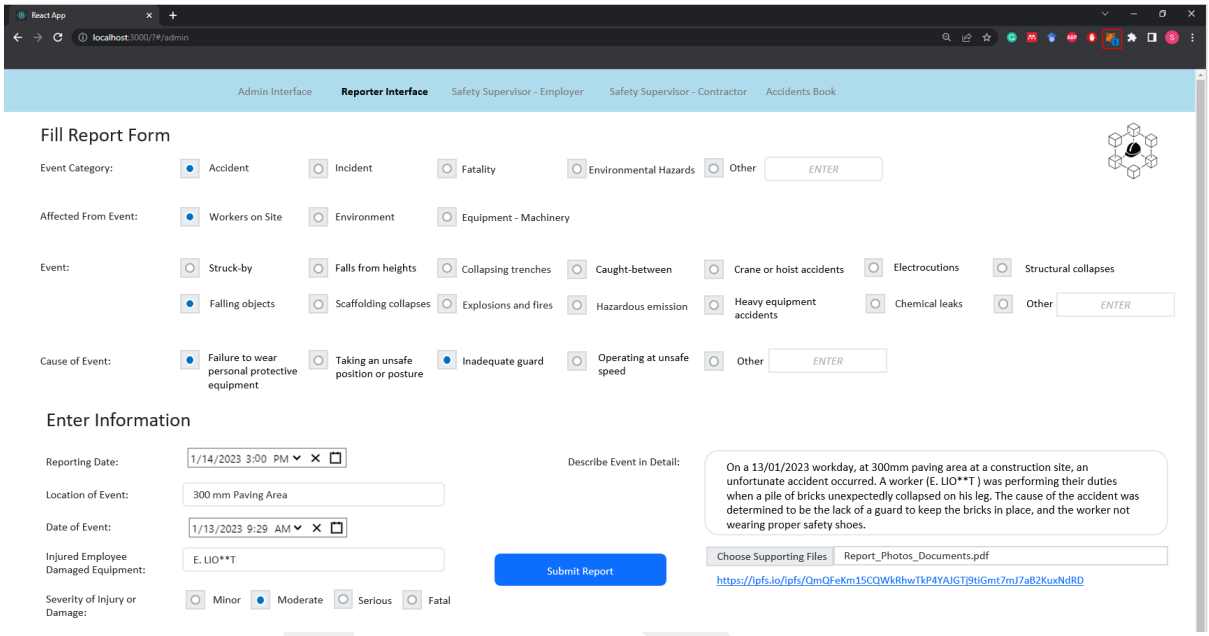


Fig 7. Reporter's interface to submit the report

Upon completion of the reporting process, the DApp module will transmit the accident/ incident information, along with hyperlinks or CIDs of any supporting documents, to be displayed on the screens of both the "Validator (Contractor)" and "Validator (Employer)" as depicted in Fig 8. Safety supervisors will meticulously review the reported accident to ensure its veracity. They will then have the discretion to press the "Approve" or "Reject" button to finalize the process. The smart contract module will verify the blockchain addresses of the validator users to exert control over access and deter any unauthorized confirmation of data. Additionally, all the accident reports and relevant contents are appended to the block and recorded in the Ethereum blockchain network, and distributed among the participants, ensuring a decentralized, transparent and immutable record of the accident/incident.

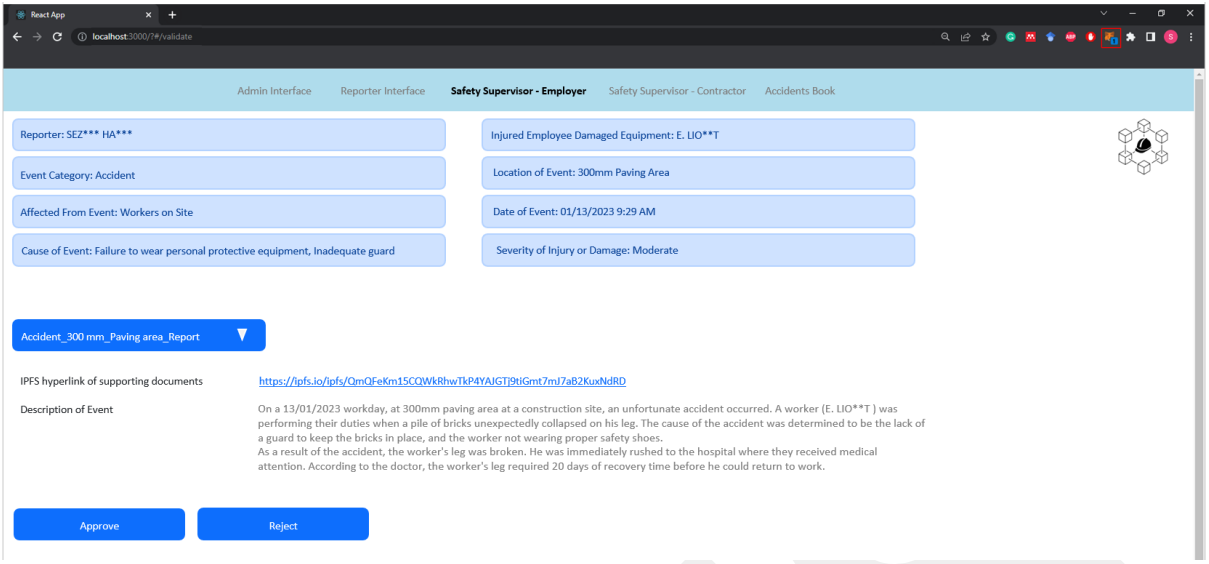


Fig 8. Safety supervisors' interface to approve the report validity

5. Implementation of the proposed system on a real construction project

Following completion of design and development of the fully decentralized DECAIMNG system to illustrate its use in practice and to examine its benefits and limitations, real construction accident information of an actual construction case project is used to simulate the proposed system. Since the main objective of this research is to design and develop a blockchain-based system to provide a decentralized, secure, traceable, and transparent method for accident/incident information management of construction projects, a construction project is selected as the case project. The case project was a 185 MW Hydropower Plant and Dam under construction in Georgia. To initiate the process, the smart contract module was deployed on Ethereum virtual blockchain provided by Ganache, as depicted in Fig. 9. To initiate the process, the MetaMask wallet was used to create 12 Ethereum accounts for the reporter users and two validators, and then 10 Ether was assigned for each account. The reporter users included two safety site engineers and one safety supervisor from the employer organization, and two safety site engineers and one safety supervisor from the contractor organization, to report the accident through the system in parallel to the conventional method. The safety

supervisor of each party was designated as the validator user within the procedure. The IPFS Desktop application was used to establish the IPFS local node to facilitate adding files and accessing the documents stored on the network through the system. IPFS local node is a node that is running on a local computer or on a local network to add and retrieve files from the IPFS network.

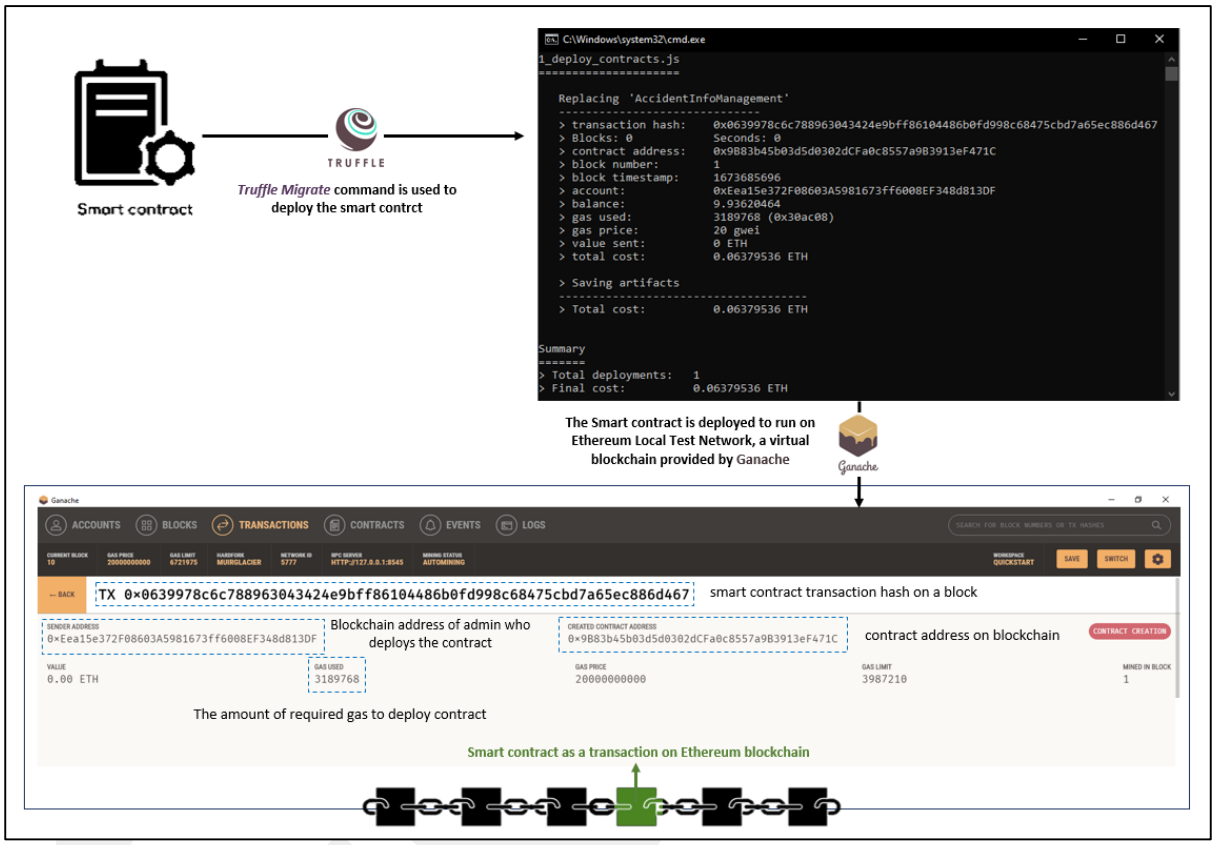


Fig. 9 The smart contract deployment and relevant information on the block

On December 20, 2022 the DApp module was executed to register the Ethereum account addresses of users as well as project information into the system. During the system execution, two minor incidents and one moderate accident were reported through DECAIMNG. The details of the accidents are summarized in Table 1. The MetaMask account of the reporter was used to execute the DApp to submit the accident report. The evidence photos of the accidents were also submitted as blockchain integrated IPFS module of the system enables the uploading and storing of the documents. It should be noted that during the report

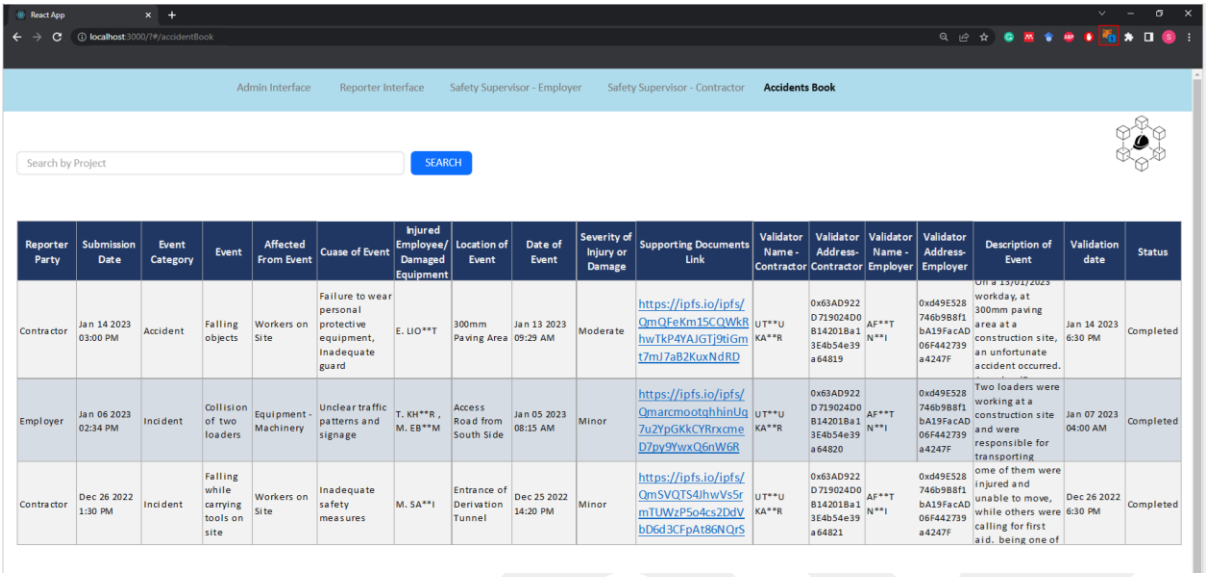
submission stage, some unregistered Ethereum accounts were tried to execute the DApp. However, the smart contract module denied access to these accounts and prevented them from logging into the system.

Table 1. Details of the case accident and incidents

Date of Event	Accident Event	Affected From Event	Severity of Injury or Damage	Cause of Event	Injury/Damage
Jan 14 2023 03:00 PM	Falling objects	Workers on Site	Moderate	Failure to wear personal protective equipment, Inadequate guard	Broken Leg, 1 month off for recovery
Jan 06 2023 02:34 PM	Collision of two loaders	Equipment - Machinery	Minor	Unclear traffic patterns and signage	Minor damage to the vehicles
Dec 26 2022 1:30 PM	Falling while carrying tools on site	Workers on Site	Minor	Taking an unsafe position or posture	Twisted Ankle, 5 days off for recovery

The safety supervisors' MetaMask was used to log into the system and execute the DApp to validate the submissions. The CID hyperlink of the documents was used to access and retrieve the files stored on the IPFS. The transaction of report validation was signed and approved using the safety supervisors' accounts. After mutual approval of the validators, the smart contract module recorded the information on the blockchain and distributed them among all the participants within the network. The DECAIMNG system is designed to facilitate the tracking of accident/incident information and reports on the blockchain. To accomplish this, the system includes a separate interface called "Accidents book", which is accessed through the DApp. The "Accident Book" retrieves stored accident information from the blockchain and provides a comprehensive historical list of all submitted and validated accident records. All users are authorized to access the records, ensuring the distribution and transparency of the data in the

proposed system. As demonstrated in Fig 10, all recorded accident events for the project are transparently accessible to participants.



Reporter Party	Submission Date	Event Category	Event	Affected From Event	Cuase of Event	Injured Employee/ Damaged Equipment	Location of Event	Date of Event	Severity of Injury or Damage	Supporting Documents Link	Validator Name - Contractor	Validator Address- Contractor	Validator Name - Employer	Validator Address- Employer	Description of Event	Validation date	Status
Contractor	Jan 14 2023 03:00 PM	Accident	Falling objects	Workers on Site	Failure to wear personal protective equipment, Inadequate guard	E. LIO**T	300mm Paving Area	Jan 13 2023 09:29 AM	Moderate	https://ipfs.io/ipfs/QmQFeKm15CQWkRhwTkP4YAJGTj9tiGmt7mJ7aB2KuxNdRD	UT**U KA**R	0x63AD922D719024D0B14201Ba13E4b54e39a64819	AF**T N**I	0xd49E528746b9B8f1bA19FacAD06F442739a4247F	On a 15/01/2023 workday, at 300mm paving area at a construction site, an unfortunate accident occurred.	Jan 14 2023 6:30 PM	Completed
Employer	Jan 06 2023 02:34 PM	Incident	Collision of two loaders	Equipment - Machinery	Unclear traffic patterns and signage	T. KH**R , M. EB**M	Access Road from South Side	Jan 05 2023 08:15 AM	Minor	https://ipfs.io/ipfs/Qmarcmootqhhinuq7u2YpGKkCYRrxcmeD7py9YwxQ6nW6R	UT**U KA**R	0x63AD922D719024D0B14201Ba13E4b54e39a64820	AF**T N**I	0xd49E528746b9B8f1bA19FacAD06F442739a4247F	Two loaders were working at a construction site and were responsible for transporting	Jan 07 2023 04:00 AM	Completed
Contractor	Dec 26 2022 1:30 PM	Incident	Falling while carrying tools on site	Workers on Site	Inadequate safety measures	M. SA**I	Entrance of Derivation Tunnel	Dec 25 2022 14:20 PM	Minor	https://ipfs.io/ipfs/QmSVQTS4JhwVs5rmTUWzP5o4cs2DdVbD6d3CFpAt86NQrS	UT**U KA**R	0x63AD922D719024D0B14201Ba13E4b54e39a64821	AF**T N**I	0xd49E528746b9B8f1bA19FacAD06F442739a4247F	ome of them were injured and unable to move, while others were calling for first aid. being one of	Dec 26 2022 6:30 PM	Completed

Fig. 10 Accident book interface of the system

In the Ethereum blockchain, transaction fees are referred to as "gas" and are paid in Ether (ETH), to power all transactions and smart contract executions on the network. The cost-performance of Ethereum systems execution could be mainly impacted by several factors such as network congestion, gas price, smart contract functions complexity, storage requirements, and computational complexity (Rosic, 2017). Table 2 presents the transaction cost in gas, for deploying the smart contract of the case project along with the major functions, as revealed through the deployment of the smart contract on the Ethereum local test network. The deployment cost of the smart contract for the case project was 0.06379536 ETH or $77.21 at an exchange rate of 1210.30 ETH/$. The highest transaction cost was revealed for the execution of the report submission function (0.009014ETH or $11.91), as the smart contract records full information related to the accident/incident event and controls the access limit of the users in this stage.

Table 2. Deployment and transaction cost of the proposed system

Function	Gas	Transaction cost (ETH)	Transaction cost ($)	Average ETH/$ Rate
Deployment of smart contract	3189768	0.06379536	77.21	1210.3
User Registration	54072	0.00108144	1.31	1210.3
Submission of the accident report	450700	0.009014	11.91	1321.2
Approve/Reject the validity of the report by the safety supervisors	70224	0.00140448	1.86	1321.2

Applying the proposed system to real accident cases revealed that the total cost of $15.08 for the reporting and recording of the accident/incident events is insignificant compared to the advantages it provides. The IPFS.io gateway, which is utilized for storing and accessing large-size supporting documents, is free of charge and serves as a valuable alternative to costly centralized storage solutions.

6. Interviews with the Project Participants

Structured interviews were conducted to obtain further feedback and to reveal opinions of the parties involved in the case project about the proposed decentralized accident/incident information management system. The interviews followed the structured interview procedure outlined by (Fowler Jr, 2004), wherein the questions, and in some cases, the answer categories, are developed and organized in an interview schedule prior to the interviews. Four safety site engineers and two safety supervisors who had participated in the case project were interviewed. All of the interviewees were acquainted with blockchain technology, two interviewees had a limited understanding of smart contracts, and four had limited knowledge about decentralized storage as shown in Table 3. A brief 10-minute introduction to smart contracts and decentralized storage was provided to inform the six interviewees who were not familiar with the subjects before the interview.

Table 3. Information of interviewees

ID	Organization	Position	Level of knowledge		
			Blockchain	Smart Contract	Decentralized Storage
EM1	Employer	Safety Supervisor	High	Medium	Medium
EM2	Employer	Safety-Site Engineer	Medium	Low	Low
EM3	Employer	Safety-Site Engineer	Medium	Low	Low
CO1	Contractor	Safety Supervisor	Medium	Medium	Low
CO2	Contractor	Safety-Site Engineer	High	High	Medium
CO3	Contractor	Safety-Site Engineer	Medium	Medium	Low

The interviewees were asked four pre-worded questions in the same order. These questions focused on the advantages and disadvantages of DECAIMNG, their opinion on using the proposed system for safety information management of construction projects, and their suggestions regarding DECAIMNG. The responses to the first question, regarding the advantages of DECAIMNG, were classified into five categories: 1) Improved data security, 2) Elimination of data manipulation, 3) Enhanced information sharing, 4) Improved data accessibility, 5) Increased transparency. The advantages of the DECAIMNG, based on the perspectives of the interviewees involved in the case project, are summarized in Table 4. Among the interviewees, four mentioned data security, three interviewees identified transparency as the advantages of the proposed system, two stated that the proposed system eliminates data manipulation and improves information sharing, and one interviewee mentioned the potential of DECAIMNG to enhance data accessibility.

Table 4. Question 1: What are the advantages of DECAIMNG?

Interviewee	Response	Category
EM1	It ensures that accident data is accurately recorded and stored in a tamper-proof manner. This is a crucial step towards improving safety management in the construction industry	1,2
EM2	It has the potential to eliminate the majority of the limitations of traditional safety information management systems; such as inefficient information sharing and data security risks.	1,3
EM3	The system can provide a single source of truth about the safety performance of companies, which is required in the bidding stages of construction projects.	1,2
CO1	This application will expedite the reporting process, as users can access the application and report events immediately. It also increases the accessibility, transparency, and security of safety data.	3,4,5
CO2	The DECAIMNG system is a much-needed solution to the challenges faced by safety management in the industry. The use of blockchain technology provides a secure and transparent platform for managing accident information, which is crucial for improving safety data management.	1,5
CO3	The system ensures that all parties have access to the information. It also prevents manipulation risk of safety data.	2,5

Four categories are used to classify the responses to the second question on the disadvantages of DECAIMNG, which are: 6) Unfamiliarity of the project participants with the new technology, 7) Lack of IT personnel to develop and manage the proposed system, 8) Cost of developing and managing the system, 9) Lack of legal infrastructure for the proposed system. Three interviewees identified unfamiliarity of the project participants with the new technology as the disadvantage of the DECAIMNG, as shown in Table 5. Lack of IT personnel to develop and manage the proposed system, cost of developing and

managing the system, and lack of legal infrastructure for the proposed system were mentioned among the disadvantages of the proposed system by a single interviewee.

Table 5. Question 2: What are the disadvantages of DECAIMNG?

Interviewee	Response	Category
EM1	Blockchain technology is relatively new, and using its integrated applications requires a vast understanding of the parties involved in the technology. Additionally, there are few experts available to resolve any technical problems that may arise in the system.	6,7
EM2	The majority of the construction safety personnel may not be familiar with blockchain. Hence, a training may be required for the system.	6
EM3	The system is well aligned with the reporting procedures in the industry and does not have any significant limitations.	-
CO1	Currently, blockchain systems require interaction with a wallet for transaction confirmation, which may be a limitation for some users who are not familiar with this technology. However, as the system becomes more common in the industry and more users become familiar with it, this limitation may be eliminated over time.	6
CO2	Despite its advantages, organizations may not be willing to pay transaction fees. Additionally, developing such systems may be more expensive compared to traditional ones, so organizations may avoid setting it up.	8
CO3	Insurance companies often require history of safety reports from companies. However, since there is no legal justification for this technology, insurance companies may not accept blockchain records.	9

Both safety supervisors from the employer and contractor organizations, as well as two safety site engineers from the employer organization, expressed their intention to use DECAIMNG for managing accident/incident information in construction projects. However, two safety site engineers from the contractor organization had reservations about using the DECAIMNG. One engineer replied that he might consider using DECAIMNG

once the legal infrastructure is in place, while the other engineer stated that he would not use DECAIMNG due to the additional costs associated with its development and operation.

The safety supervisor of the employer organization suggested that the proposed accident/incident information management system could be extended to include all of the safety information to achieve a decentralized safety information management system for construction projects. The safety supervisor of the contractor organization highlighted the importance of integrating DECAIMNG to the existing safety information management systems. One of the safety site engineers of the contractor organization recommended that blockchain based rewards (such as cryptocurrencies or non-fungible tokens) could be provided to workers who report the accidents or incidents. The other safety site engineer of the contractor organization proposed using the data compiled by the system to determine the conditions that may result in potential accidents or incidents.

7. Discussion

In this section, the contributions and limitations of the proposed system as well as suggestions for its further improvement are provided.

7.1. Contributions

The proposed system offers a secure approach for creating a decentralized and transparent record of accidents/incidents that occur on construction projects. In order to comply with legal requirements, companies need to maintain accident records as the reference of companies' safety performance for both completed and ongoing projects. Therefore, by providing an immutable and trustworthy source of accident information, the system will enable improved evaluation of the safety performance of companies involved in the construction industry. DECAIMNG system will serve as a single source of truth of construction safety performance, as it includes all accident information of projects, and can be considered as a single reference

of companies' safety performance which is one of the important criteria that is generally required during the pre-tendering stage of the construction contracts.

As a core technology underlying the system, blockchain offers a secure and trustworthy method for maintaining accident information records through its decentralized and distributed ledger system. This architecture ensures that data is recorded across multiple nodes in the network, making it virtually impossible for a single point of failure or tampering. Hence, the permanent record of accidents is assured. Furthermore, the implementation of cryptographic techniques, such as hashing and digital signatures, guarantees the authenticity and immutability of records, meaning that once a record has been added to the blockchain, it cannot be altered or deleted, thereby ensuring the integrity of the data. This feature is of paramount importance in the context of accident information records, as it guarantees that the records are accurate, tamper-proof, and easily verifiable, which is essential for maintaining trust and accountability in the event of accidents.

The traditional methods of storing accident information have relied on centralized databases, which poses significant security and data tampering concerns. To mitigate these risks, the proposed system employs the integration of blockchain technology with decentralized storage (IPFS) for the storage of large off-chain data for achieving decentralized management of accident/incident information. Upon uploading a document to the IPFS network, the document is encrypted using the SHA-256 hash algorithm, generating a unique Content Identifier (CID). The generated CID is then recorded on the Ethereum blockchain. The implementation of IPFS in the proposed system effectively addresses the issue of data manipulation that arises from centralized cloud service providers as any alteration in the document's content will result in a change of its CID, which can be tracked within the network. As an alternative, Yang et al. (2022) also implemented smart contracts to compare data in the block to verify the inputted information, and used an off-chain database and SHA-256 to store

data. While some features of the present system may partly resemble those found in Yang et al. (2022), decentralized storage has not been employed by Yang et al. (2022) to record large off-chain data. This is a significant element distinguishing the system proposed herein which features a decentralized storage for accident information management from the previous ones. Decentralized storage assures security, transparency, authenticity, and immutability of the accident/incident data. Additionally, the distributed nature of IPFS and blockchain technology ensures the perpetual availability and integrity of data throughout the process. The proposed system presents a transformative solution for construction safety accident information management as it presents a new fully decentralized approach for accident/incident information management of construction projects.

Smart contracts incorporate function modifiers that are utilized to limit access and execution of functions to authorized participants only. These modifiers enhance the security of smart contracts against unauthorized access. Function modifiers are appended to smart contract functions to perform preliminary validation checks prior to executing a function (Frantz & Nowostawski, 2016). If the function does not meet the requirements set by the modifier, an exception is thrown, and the execution of the function is halted. The proposed system, for instance, employs this feature by allowing only authorized validators to validate accident reports and restricting reporter users from performing this task. Additionally, the smart contract in the proposed system also verifies the user's account addresses to prevent unauthorized access to the system.

7.2. Limitations and future studies

DECAIMNG revealed the potential of blockchain and decentralized IPFS storage technologies to enable a secure, transparent, immutable, and trustworthy environment for the management of accident information in construction projects. Despite its advantages, the proposed system requires further investigation.

The proposed system for managing accident information in construction projects was demonstrated through its implementation in real-world accident scenarios. However, the practicality of the system from the perspective of stakeholders remains to be evaluated. In order to gain a comprehensive understanding of the system's feasibility, it is recommended that professional surveys and interviews be conducted with the participants involved in the construction projects. Despite the potential benefits, the construction industry may be reluctant to adopt new technologies such as blockchain due to the additional costs, time, and effort required to understand the underlying concepts. Therefore, future studies should include an economic analysis of the proposed system to demonstrate that the additional costs are minor in comparison to the system's benefits.

Analyzing and resolving potential vulnerabilities in the execution of smart contract codes before deployment of the contract is crucial to ensure that the contract is secure and free of vulnerabilities. To address these issues posed by smart contract programming and other blockchain systems, there is a definite need for blockchain engineering since poor programming practices during contract development lead to these issues. Therefore, testing smart contracts for detection and solving vulnerability issues would increase the reliability and security of the proposed system.

The proposed system leverages the Ethereum blockchain to run the smart contract module of the system. Ethereum blockchain is known for its scalability issues, which can lead to slow transaction speeds and high fees. Therefore, it is recommended that future studies investigate other blockchain networks such as EOS or TRON, as they are specifically designed to handle high transaction volumes. Doing so will provide better scalability and performance for managing accident information in construction projects. In order to identify the most efficient blockchain platform for the proposed system, it is essential to conduct a thorough examination of the potentials and limitations of various blockchain platforms.

8. Conclusions

The construction industry is acknowledged as one of the most dangerous industries, accounting for the highest rates of fatal and non-fatal accidents compared to other industries. Recording information related to these accidents is legally necessary for the companies since these records present their safety performance and help prevent similar events in future projects. However, the traditional paper-based approach or centralized systems are insufficient, and the security, transparency, immutability, and traceability of the information are not assured in these methods.

To address these issues, this paper presented a blockchain-based system that employs blockchain and decentralized storage technologies to address the aforementioned issues that exist in traditional methods. a novel decentralized blockchain-based system is designed and developed for the management of accident/incident information of construction projects leveraging; (i) smart contract to govern the accident information management steps and securely store the information, tackling security, transparency, and immutability problems. (ii) blockchain-integrated IPFS storage to exchange and store proofing documents related to the accidents, addressing data distribution and traceability issues, and (iii) decentralized application to facilitate the participants' interaction with the system during the process and access to the information.

The proposed system replaces centralized systems with blockchain and decentralized storage technologies to create a secure, transparent, traceable, and accessible platform for accident information management in construction projects. The new decentralized system is immune to manipulation since any single modification in the database will change the hash of the original record. Accordingly, one can easily trace the tampered data as the computed hash will not match the original value. The proposed framework excludes the involvement of intermediaries, resolves the data storage problem for real-world projects, and ensures that

authentic safety data is recorded in an immutable, transparent, and traceable manner, which in turn makes performing a healthy accountability analysis possible. The effectiveness and applicability of the proposed system for managing accident information were demonstrated by simulating the system using construction accident data of a real-world construction project.

The proposed system enables a decentralized, secure, and trustworthy alternative for safety performance evaluation of a contractor, by guaranteeing security, transparency, authenticity, immutability, availability, and integrity of the accident/incident data. The contractor, their employee, or any other third party would not have any control on the accessed accident/incident information stored in the system. Hence, the foregoing properties of the proposed system provide the basis for the employers to perform safety performance evaluations of the contractors in an objective manner. In addition, this system can consequently lead to compilation of reliable, tamper-proof, secure, and transparent accident/incident data; so that, a company can effectively use the data for self-evaluation, to learn from the mistakes of the past, and thereby to prevent potential future accidents.

The proposed system provides a secure and transparent alternative for ensuring security and achieving a decentralized accident information management process for construction projects. Although the system provides an advancement over the conventional methods, it still relies on manual entry and validity checks of accident information. Future research focusing on the integration of sensors and artificial intelligence into smart contracts to automatically capture accidents could enable a fully autonomous and decentralized accident information management system.

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