Received October 22, 2020, accepted November 13, 2020, date of publication November 20, 2020,
date of current version December 7, 2020.

Digital Object Identifier 10.1109/ACCESS.2020.3039512

Converging Technologies for Safety Planning and Inspection Information System of Portable Firefighting Equipment

NUMAN KHAN, DOYEOP LEE, CHANWOO BAEK, AND CHAN-SIK PARK
School of Architecture and Building Sciences, Chung-Ang University, Seoul 06974, South Korea

Corresponding author: Chan-Sik Park (cpark@cau.ac.kr)

This work was supported in part by the Chung-Ang University Research Scholarship Grants in 2020, and in part by the National Research Foundation of Korea (NRF) grant funded by the Korean Government Ministry of Science and ICT (MSIP) under Grant NRF-2019R1A2B5B02070721.

ABSTRACT Many construction workers are getting injured or killed in fires and explosion accidents each year. The workers are prone to severe fatal accidents due to unavailability of permanent firefighting system in many construction sites, thus they typically rely on portable firefighting equipment (PFE) to minimize fire damage. Many occupational health and safety agencies have developed safety regulations for PFE installation and monitoring in construction. However, in the traditional construction fire safety management process, the installation spots for PFE's are visually identified in a 2D floor plan and then top-down supervisory approach is used to inspect the active availability of the PFE's. Such manually operated conventional methods of PFE installation and monitoring are expensive, prone to manipulation, and do not provide sufficient motivation for voluntarily following fire safety policies. Therefore, this research study develops a fire safety rule-based PFE installation approach and proposes an alternative method for shifting the top-down inspection approach to the bottom-up voluntarily approach for convenient, transparent, and automated safety inspection information delivery. To validate the bottom-up approach concept, a visual language algorithm is initially developed for PFE installation planning system (PFE-IPS) in BIM, followed by an optical character recognition (OCR) and blockchain -based android application for safety inspection information system (SIIS). This article also presents two case studies to evaluate the feasibility and practicality of the developed systems. The proposed approach out-turn reduces the safety manager's manual efforts and burdens of government safety auditors while enhancing efficiency and reliability.

INDEX TERMS Fire safety rule, visual languages, BIM, optical character recognition (OCR), blockchain, portable firefighting equipment (PFE).

I. INTRODUCTION

The construction industry involves numerous unhealthy activities that causes project progress delays, cost overruns, low project productivity, reputation damage, and human fatalities and injuries [1]. The construction process inherent high risk of accidents owing to the unique nature of the tasks involved, such as working at heights, exposure to severe weather, unskilled labor involvement, psychologically vulnerable working conditions, working with explosive materials [2]. The recent accident reports in construction indicate incident rates of 36%, 29.3%, and 27% in Singapore, South Korea, and the UK, respectively, that are almost twice the average incident rate in other industries [3], [4]. Over the last decade, academic researchers and industry professionals have devoted significant efforts toward enhancing construction safety, such as an extensive legislative framework for safety rules, penalties, and incentive programs. Despite these efforts, construction sites are still known to be hazardous work sites with high accident rates. Fire accidents proportions a significant share of construction site accidents. The U.S. Bureau of Labor Statistics 2018 report divulged the deaths of 66 workers each year due to fires and explosions at construction job sites [5]. Five years (2010–2014)

The associate editor coordinating the review of this manuscript and approving it for publication was Mu-Yen Chen.

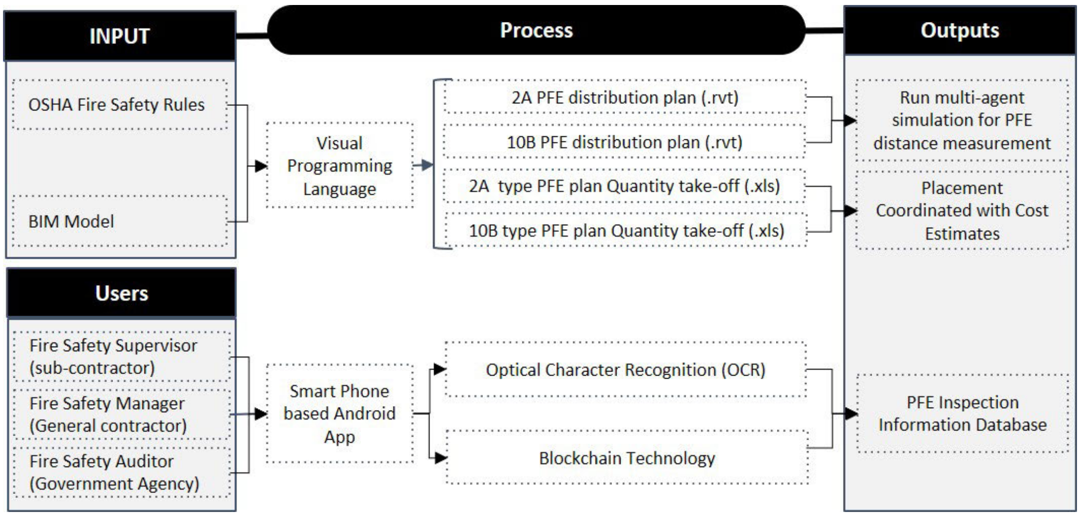


FIGURE 1. Conceptual illustration of PFE-IPS and SIIS implementation.

renovation/under-construction residential project data from the National Fire Protection Association (NFPA) reports 280 million USD in direct property damage each year [6]. Thus, a compact, advanced, and automated system is required to cope with the fire accidents at construction sites.

This applied research is initiated by assessing fire accident reports to understand the significance of fire safety management in construction and issues in the conventional system. Generally, fire safety management is a significant issue in all sectors; however, it is especially important in construction owing to numerous reasons that frequently result in fire risks. First, workers are exposed to combustible substances at numerous job sites, and the presence of wind around under-construction buildings can quickly extend the fire [7]. Second, as under-construction sites do not possess a permanent fire protection system, PFE or occasionally water tanks are the only preventive options that can be adopted [8].

Fire safety management includes two major phases: (1) fire safety planning, and (2) fire safety monitoring. The conventional fire safety planning in construction follows a site-specific planning practice to manage the fire hazards [14], [15], which required significant manual revisions with intervals [16]. Consequently, a dynamic and site-specific fire safety plan could be a labor-intensive job if done manually [17]. Several studies have focused on safe evacuation planning for existing buildings as well as under-construction buildings and tunnels [9]–[13]. However, very few studies have investigated the fire safety equipment installation. Apart from fire safety planning, fire safety monitoring is pivotal among these phases because it is the final management layer for preventing fire accidents. Extensive research has been conducted in fire safety monitoring domain, such as early detection of smoke and heat using various tools and techniques, dual infrared (IR/IR) spectral band flame detection, very early smoke detection apparatus, and fiber optic attached to distributed temperature sensing [18]–[20]. Despite this extensive research, the number of fire accidents during construction has not yet decreased significantly. Therefore, further efforts are required to strengthen fire safety management processes in construction, supported by the voluntary implementation of the industry's best practice.

The Occupational Safety and Health Administration (OSHA) stipulates that a site-specific safety plan should include a fire protection plan for every construction project. As several construction job sites rely on PFE as a preventive measure, two vital factors must be considered: (1) appropriate locations for PFE, and (2) proper maintenance to ensure active work order of PFE [17]. Therefore, intending to ensure the proper location and good working order of the PFE, this applied research study presents a rule-based visual programming approach for location optimization and a smartphone-based android app that employs optical character recognition (OCR) and blockchain technology for inspection data delivery system. The Fig 1., revealed the conceptual idea of the PFE installation planning system (PFE-IPS) and safety inspection information system (SIIS), the systems includes inputs, processes, and outputs. BIM model and OSHA fire safety rules are the inputs that are processed by using the cited tools and techniques to have the desired outputs. Contrarily, to access the android app for fire safety information system, users are defined in Fig. 1. The process layer enlisted the required tools and technologies to generate the outputs such as placement plan, quantity estimates, and inspection information database. The specific outputs and contributions to the existing knowledge are summarized as under:

- As the current PFE installation plan rely on 2D-paper based manual observation. Also, the workers in small companies with average skills do not understand the proper and correct position for the PFEs in a job site [7]. This research developed a fire safety rule-based BIM modeling for PFE installation plan, intending to automate the process and ensure appropriate location in the job site.

- The traditional inspection process is a top-down supervisory approach that comprises safety managers from the general contractor, safety inspectors from subcontractors, and the government's safety auditors. This top-down monitoring approach does not provide sufficient motivation for voluntarily following fire safety policies. Moreover, this top-down inspection is impractical due to a lack of human resources with the government as well as with general contractors. An android app supported by blockchain and OCR is developed to shift the paradigm of safety inspection from a top-down approach to a voluntary-based bottom-up method.
- Due to vigorous enforcement of the government's safety policies, many cases of forged documentation have been reported, mainly manipulating PFE tags and its records [21]. This research proposes an effective, transparent, and reliable approach as an alternative to traditional paper-based manual methods to prevent forged reporting and manipulation in inspections records, thereby reducing the safety auditor's burden.
- The conventional inspection information delivery system pertaining to PFE is prone to data loss. This research presents a convenient method to promote automation of the safety inspection information delivery through blockchain system to all the relevant stakeholders.

The findings of this study are expected to play a significant role as a benchmark for future research in technology convergence approaches for the construction industry.

II. LITERATURE REVIEW

A. LIMITATIONS OF THE CURRENT FIRE SAFETY MANAGEMENT PRACTICES IN CONSTRUCTION

In the distant past, people have typically relied on themselves or those in the neighborhood for relief and rescue operations in the event of fire [22]. The recent years have witnessed frequent fires in construction projects, and many of them have brought the enormous loss of property damage and human casualties [23]. Many countries across the globe have developed different strategies, such as upgrading fire safety codes to enforce fire safety inspections policies to overcome the critical issue of fire safety [24]. Besides, new tools and techniques have been developed over the recent decade to meet with the required fire safety rule compliance. Several concepts and their enabling technologies have been investigated to attain enhanced fire safety management [7], [17], [25]–[27], though automated rule-based fire safety planning for PFE placement is not yet achieved. Traditionally, essential inspection information related to firefighting equipment is primarily distributed among the stakeholders; however, this can occasionally lead to data loss [25]. Another significant issue associate with the current process is the falsification and forgery of PFE documentation or tags, and numerous such cases have been reported [21]. To address this issue, a BIM-based approach capable of storing necessary information related to these devices, such as device and manufacturer names, maintenance staff, equipment type, previous repair/inspection time, exterior features, and other specifications, along with the location coordinates of firefighting equipment has been proposed [28]. However, this process is mutable and requires manual inputs from the field.

Despite this extensive research, various workplaces, buildings, and tunnels currently employ PFE based on pre-construction 2D supported site-specific fire safety plan, and frequent inspection at specific intervals is routinely performed for PFE maintenance. Hence, an automated system is necessary to ensure optimized allocation and active working conditions of the PFE while achieving convenience, transparency, and increased reliability, which, in turn, would be valuable for the performance evaluation metrics in the bidding process.

B. BUILDING INFORMATION MODELING AND VISUAL PROGRAMMING LANGUAGES

The construction safety management includes safety planning and safety monitoring. Unexpectedly, safety planning is considered the contractor's liability and is thus ignored in the design phase [7]. However, extensive research studies have recently considered Building Information Modelling for safety integration in the design phase. Widespread research work has been presented by many authors to adopt rules in the pre-construction stage, for instance, to develop rule-based checking of building codes, BIM is applied to adopt the rules [12], automatic safety planning approach to deal with the fall risk using BIM [29], limited access zone identification and visualization using 4D BIM [30], excavation safety modeling [31], however, fire safety planning remains unexplored. In order to translate building codes of Korea from natural language into computer-readable language, the KBimCode rule interpretation plug-in has been introduced to conveniently translate the rules [32], and later adopted by many studies [7], [12], [31]. On that account, this applied research work also leverages the visual programming language for the conversion of human text language to machine-readable language; for instance, fire safety rules conversion part of the proposed system.

C. OCR AND BLOCKCHAIN TECHNOLOGIES APPLICATIONS IN CONSTRUCTION

Artificial intelligence is probabilistic, changing, and involves algorithms to guess at the reality, whereas the blockchain is deterministic, immutable, and features cryptography to record reality. The blockchain was first introduced in 2008 in the form of an underpinning technology as a verification tool for the world's first cryptocurrency transactions [33], [34]. Blockchain technology offers encrypted, distributed, and secure logging of digital transactions, exhibiting the potential to revolutionize numerous global industries [34]–[37], and the construction is no exception.

Previous efforts to explore blockchain technology for different domains can be grouped into seven categories: (1) smart homes; (2) smart cities; (3) smart government; (4) smart energy; (5) intelligent transport; (6) organizational structures and business models; and (7) construction management and BIM [37]–[45]. Even though blockchain technology-related research is still in the elementary stage in the construction management domain, the literature's scope summarized in this article is limited to studies associated with construction and buildings. This technology has the potential to address a couple of problems that discourage the construction industry from employing new technologies such as BIM; it offers features such as confidentiality, disintermediation, provenance tracking, non-repudiation, inter-organizational recordkeeping, change tracing, and data ownership [35]. A hybrid approach involving BIM and blockchain technology has been applied for energy management by measuring indoor temperature using the Internet of things (IoT)-based smart home devices [46]. Wang *et al.* (2017) presented a blockchain-based smart contract to solve one of the challenging issues of construction worker's wage payments [44]. However, to the best of the authors' knowledge, no research has been carried out to investigate the significance of blockchain technology in the inspection and maintenance process of construction equipment.

On the contrary, OCR techniques include image acquisition, pre-processing, segmentation, feature extraction, classification, and recognition [47]–[49]. Considering the OCR with a blockchain, numerous studies have focused on character recognition through optic vision. OCR technology aims to convert handwritten or typed texts within the image into texts [47]; however, handwritten text recognition is more challenging compared with typed or printed texts. Generally, handwriting styles vary depending on the individual; thus, managing these variations is vital for OCR [48]. Previous efforts have not employed OCR and blockchain technologies to inspect and record construction safety. Therefore, the proposed approach incorporating OCR and blockchain for safety inspection information system (SIIS) pertaining to PFE is presented herein.

III. NEED FOR CONVERGING TECHNOLOGIES BASED CONSTRUCTION FIRE SAFETY SYSTEM

In the construction industry, disaster prevention management focuses on fire safety equipment, escape route planning, alert or monitoring device, and educational training intended to ensure individuals' safety [25]. However, disaster prevention systems mostly depend on manual procedures that are not reliable and cumbersome. Workers with average construction skills do not understand the proper and correct position for the PFEs in a job site [7]. In the last decade, extensive research has been carried out by various researchers regarding safety planning in construction, revealing the absence of reactive tools and techniques to support designers in the pre-construction phase [50]. Surprisingly, the designer generally remains unaware of the impact of fire safety considerations in the planning and design stage [51]. However, recent fire safety developments have revealed the potential of integrating fire safety rules compliance in the planning and design stage. Therefore, fire safety equipment installation and placement planning considerations in the design stage are needed. To do so, the fire safety regulations related to the construction job site are extracted from the open-source OSHA database and translated leveraging visual language programming (VPL).

Another major issue in maintaining PFEs is proper inspection, tag catalogs, and report to the concerned department. Generally, the government safety auditor visits the construction site to check the tags of the PFEs randomly, and thus known as the top-down safety enforcement approach, and is not practically possible to control the entire region, area, and site. The general contractor's safety managers in the current system are also unable (in terms of work burden) due to the responsibility of many other tasks. Apart from that, foraged tagging and loss in the data make it more crucial, thus inevitable to have an appropriate system for the cited issues.

Artificial intelligence and blockchain technologies' rapid developments have yielded significant contributions to the current global environment [52]. This rapid advancement has resulted in a paradigm shift from the real world to a digitized world, via numerous automated devices and effective processes that enable time- and cost-savings [53]. OCR is an artificial intelligence technique that employs image acquisition, pre-processing, segmentation, feature extraction, classification, and recognition [49]. There are currently many commercial and open-source tools available in many languages to convert the image into text form. As the name indicates, the blockchain can be regarded as a series of blocks (virtual cubes) linearly aligned in a vertical structure. Each block contains a specific amount of data in the form of ciphers and codes [34], [54]. Once the block's data has been completed and validated, the block is then permanently locked and cannot be modified [55]. Previously, many researchers have used the blockchain to increase the automation of the process, reliability, and credibility through inherited functions of this technology, for instance, smart contract, transparency, and immutability. For example, to detect diamond frauds, Everledger [56] proposed a reliable blockchain verification service to generate an immutable diamond ledger for owners, law enforcement agencies, and insurance companies. Previous attempts to apply blockchain in the construction domain involve extensive research focused on smart contracts to increase payment transactions [57]. However, very few studies have focused on the conceptual blockchain framework for construction safety; consequently, this technology's potential remains unexplored. To overcome the inherited limitations in the fire safety management in construction pertaining to PFEs, thus, OCR has been chosen to support the blockchain technology for a compact system.

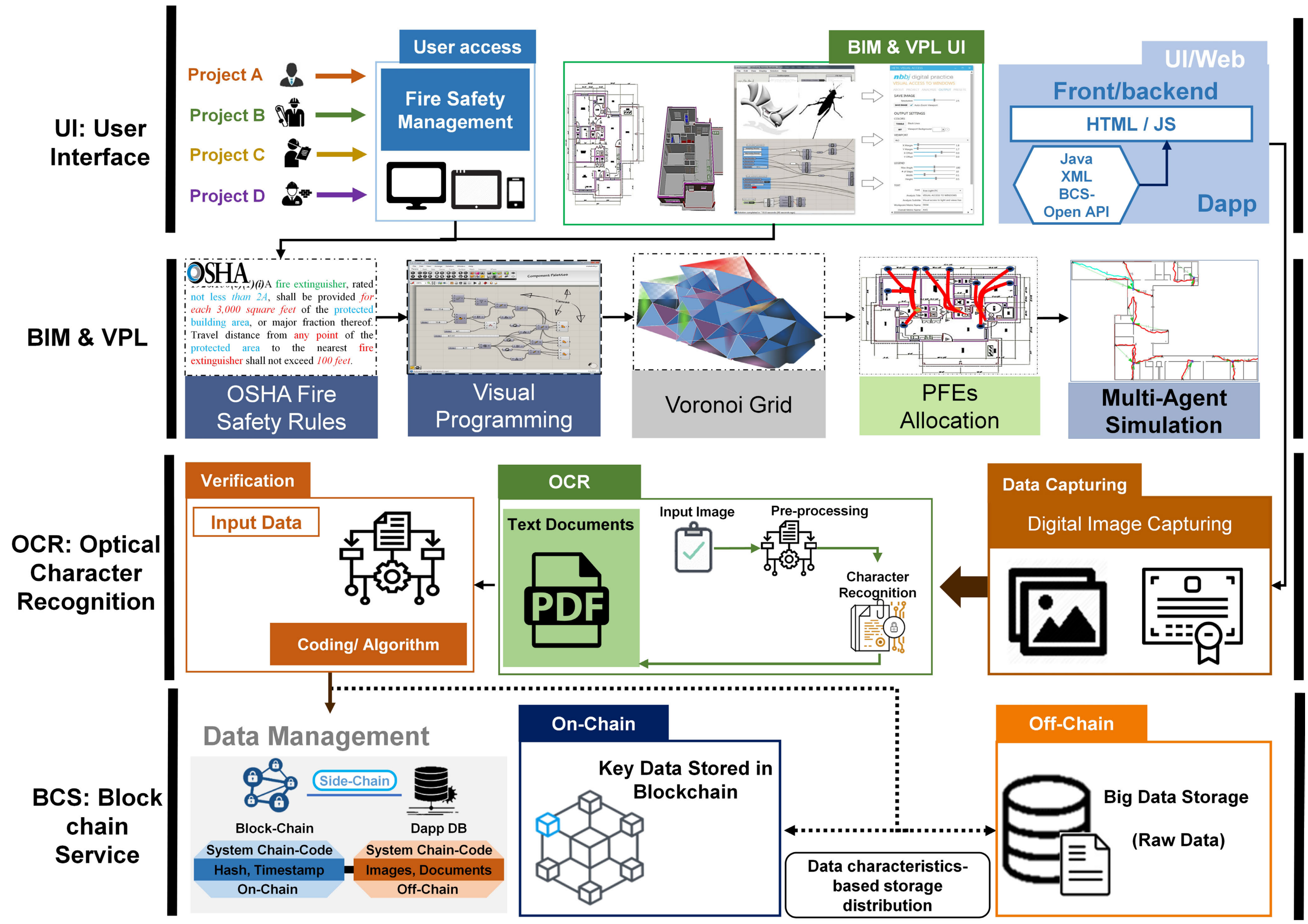


FIGURE 2. Proposed framework of PFE-IPS and SIIS.

IV. PROPOSED SYSTEM FRAMEWORK FOR PFE INSTALLATION AND SAFETY INSPECTION INFORMATION

This study aims to develop a fire safety management system in construction that utilizes convergence technologies concepts , such as VPL, BIM, OCR, and blockchain technology for effective planning and monitoring systems pertaining to PFE. This system includes five primary attributes: (1) VPL for translating the fire safety rules from OSHA into a BIM model, (2) multi-agent simulation for virtually evaluating the PFEs installation and adding more PFEs based on the requirements described in fire safety rules of OSHA, (3) implementing OCR to determine the appropriate information generated via PFE inspection and maintenance activities; (4) leveraging a blockchain to ensure the reliability of data generated during inspection and maintenance processes by allocating a specific hash to each transaction; (5) providing accurate assessment information to stakeholders based on images of tag reports captured in the field at an elementary level by workers, technicians, or safety inspectors.

Figure 2 presents the system framework diagram of the proposed PFE-IPS and SIIS, and is schematized into user interface (UI) that enable the users to leverage the system, VPL is utilized for translating human language into computer understandable language for establishing rule-based PFEs installation in a BIM, OCR for converting digital image data into text and documents, extracting the text for verifying input data, and employing the blockchain service for ensuring data reliability through storing the generated hash on the on-chain and big data in the off-chain server. The BIM and VPL part of the proposed PFE-IPS in Construction further consists of three layers, namely: (1) Rule Extraction (RE), (2) Logic Development (LD), and (3) Fire Safety Plan Generation (FSPG), the FSPG includes Installation Plan and quantity take-off of PFEs. During the initial accident report analysis, deployment of PFEs was found as a significant preventive measure in routine under-construction works. On the contrary, the sprinkler system was perceived as a vital preventive measure for fire-sensitive construction projects such as tunnels and train-subway stations. In the second step, the OSHA safety rules database that provides lessons learned and current best practices to prevent the construction workplace accidents are investigated, and fire safety rules from the database are extracted. This scope is limited to PFEs related

TABLE 1. Construction fire safety regulations in OSHA.

1926 Subpart F Fire Protection and Prevention		
No.	Standards	Explanation
1926.150(a)	General requirements	This standard explains the roles and responsibility of fire protection plan, locations of firefighting equipment's and its periodic check to assure protection of life
1926.150(b)	Water supply	This rule discusses the fixed or enough temporary water supply requirements or either water mains installed underground.
1926.150(c)	Portable firefighting equipment	This safety rule is to determine the PFE type-based location criteria
1926.150(d)	Fixed firefighting system	Fire safety rules related to the installation of sprinkler fire protection system.
1926.150(e)	Fire alarming devices	This section is about the establishment of communication system and an alarm system with the fire department.

safety rules only because the construction sites generally use PFEs to deal with fire safety. The manually extracted fire safety rules pertaining to PFE are converted to mathematical logic because math-based logic could easily translate into computer language, leveraging visual programming.

The OSHA standard 1926 enlist construction safety and health regulations to the construction industry. The subpart-F of construction safety and health standard (1926) further include fire protection and prevention safety rules, as mentioned in the Table 1, that demonstrates the general requirements, water supply, portable firefighting equipment, fixed firefighting equipment, and fire alarm devices. The scope of this study is limited to PFEs only because the construction sites generally use PFEs to deal with fire safety.

In the first layer (RE), the following fire safety rules are extracted from the OSHA database, for instance, conferring to OSHA, "A fire extinguisher, rated not less than 2A, shall be provided for every 3000 square feet of the protected building area, or major fraction thereof. Travel distance from any point of the protected area to the nearest fire extinguisher shall not exceed 100 feet." The math-based logic from this could be as under:

- Type: rated not less than 2A, at least one PFE should be installed for the area of 3000 square feet.

$$Type\ of\ \ PFE(\leq 2A) = \frac{Total\ protected\ area}{3000ft} \tag{1}$$

- The distance from any point of the protected area to the nearest fire extinguisher should not be greater than 100 feet (ft) for the PFE type, rated not less than 2A.

$$Distance(ft)\ \leq 100ft\ for\ type \geq 2A \tag{2}$$

- The distance from any point in a protected area to the nearest PFE should be equal to or not greater than 50 ft for the type, rated not less than 10B.

$$Distance(ft)\ \leq 50ft\ for\ \geq 10B \tag{3}$$

The proposed framework of SIIS allows the categorical generation of PFE inspection information at the very bottom level, where the person performs the actual inspection. However, instead of the conventional paper-based reporting system, a smartphone-based system automatically determines and controls the reliability of generated information. Inspection information of the PFE is generated after a thorough inspection of the equipment at the job site by the contractors or subcontractors' safety inspectors. It is then recorded as evidence on the attached tag to the PFE. Additional information is reported to the concerned higher management using a paper-based method or any other tech-based method. Moreover, a fire safety auditor from a government agency randomly visits the job site to monitor fire safety management activities.The proposed system further adopts licensed protocols and appropriate stakeholders' registration procedures through a decentralized android app to limit the system's access for relevant stakeholders. This feature of the android application ensures that only authorized participants are permitted to their concerned network. The image data of the tag or the documents could be captured immediately after the thorough inspection is performed at the actual location; this process serves as a smart contract to prove that the required inspection has been accomplished. As mentioned in Fig.2, the OCR transcribes image data into text documents by utilizing optical recognition techniques; each document transaction is encrypted into a unique character string, termed as a hash, for storage in the blockchain. Based on data characteristics, the resultant data such as hashes, URLs, images, and documents are distributed into two chains: (1) the on-chain and (2) the off-chain; the former is referred to the chain for storing hashes and URLs, whereas the latter is used to store big data files, such as images and documents. The following section discusses the development of the practical system for the proposed approach.

V. TECHNICAL DEVELOPMENT OF PFE-IPS AND SIIS

On the construction job site, the PFE serves as a substantial first rapid response to fire emergencies; thus, significant attention is inevitable to ensure that the PFE is located appropriately and is in good working condition. Hence, OSHA safety rules have been extracted in the first layer for the automated PFE-IPS. In the second layer (LD), a commercially available BIM authoring platform named Rhinoceros, and a VPL tool called Grasshopper, were availed to make the visual algorithm. That visual algorithm converts the extracted math-based logic. Visual programming is employed in this research because of its comparatively simple interface and convenient use, compared with other programming languages such as Java, Python, and C++ [7]. Therefore, this study adopted the VPL approach for translating fire safety rules of sub-part F in OSHA-1926. The developed algorithm initially extracts the geometric information of the building from the 2D plan or 3D

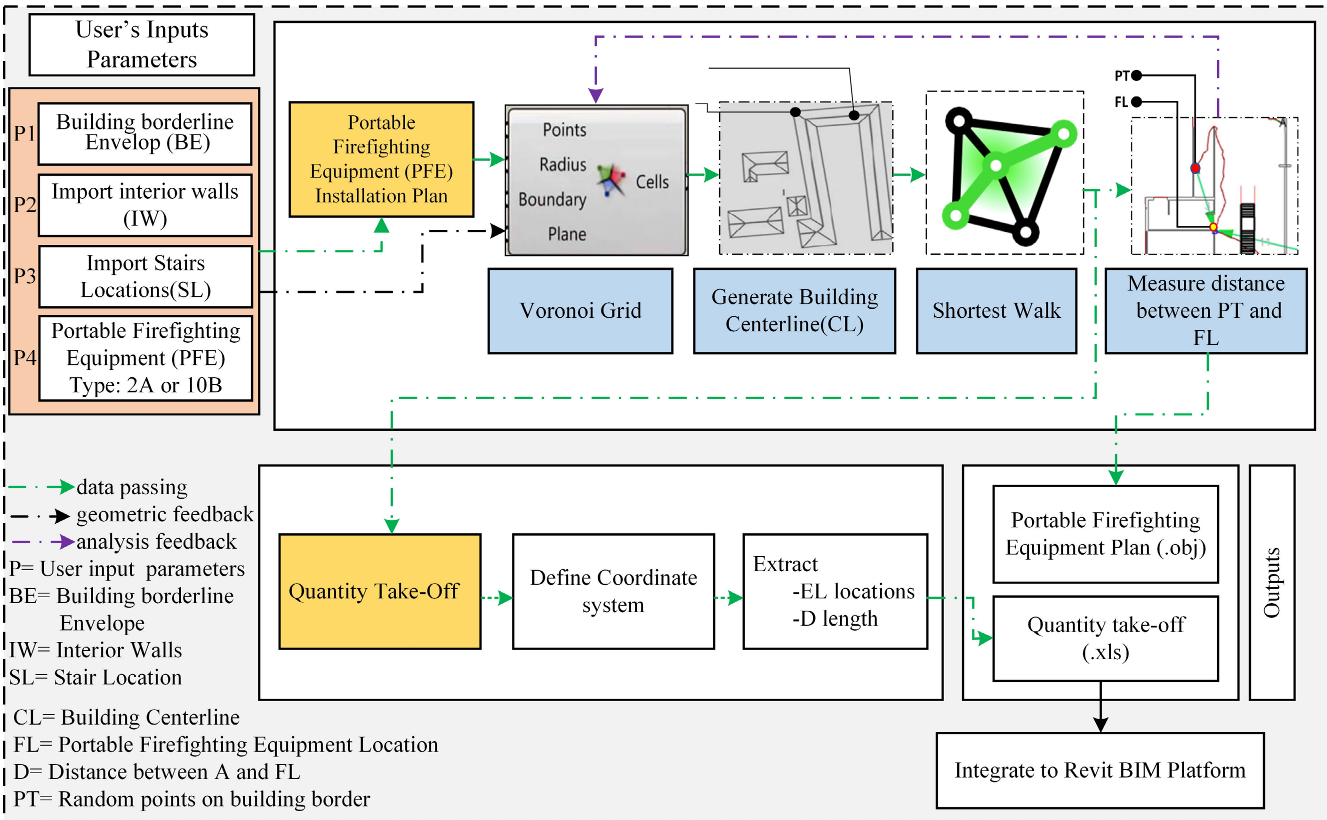


FIGURE 3. Visualization of input parameters, its processing, and corresponding outputs for PFE-IPS.

model. As portrayed in Figure 3, the system enables the users to describe the required four parameters such as P1, P2, P3, P4; P1 is for importing building envelope (BE) as a 2D plan geometry, P2 is to define the geometry of interior walls (IW) lines in a 2D plan, P3 is to determine locations of stairs (SL) as pick points, and P4 is intended to select PFE type from the drop-down list, for instance, either type 2A or 10B. As presented in Fig. 3, the Voronoi Grid is adopted in the algorithm to generate the centerline (CL) of a building. In this research study, the centerline (CL) of a building is referred to the 2D lines positioned in the middle of a closed curve inside the building borders envelope (BE). To generate the initial installation plan for PFEs, the algorithm is designed to divide that centerline (CL) on the value gained from the division of the total building area divide by the area advised in OSHA fire safety rules (3000 ft2). To create an appropriate PFEs location (FL), since it is not practical that locations would be set in the middle, these initial allocations for PFEs are then moved to their nearest interior walls (IW). To examine the distance between BL and FL, the algorithm divides the BL into random numbers of points (PT) and leverages the shortest walk logics (a pre-designed component in the Grasshopper) to verifies the appropriate location of the PFEs. This shortest walk logic populates points in the surface geometry of the building and then establish many lines between the generated random points and PFEs location (FL) using two-dimensional proximity logics. Thus, the developed algorithm could calculate a network of the shortest path between the cluster of PFE and the nearest points (PT). The algorithm then measures the curve length (D) of the closest route between the FL and PT and assess it through if statement: If curve length D is equal or less than the distance advised by the OSHA fire safety rules that (based on the type of PFE, parameter (P4), depends on the particular type selected by users), then ignore, If curve length D is greater than P4 then divide D over P4 and round up the number, as shown in the following equation (4).

$$\begin{aligned} &if\ D(\leq P4),\\ &Return\ Null\\ &else\\ &Roundup\ \frac{D}{P4} \end{aligned} \tag{4}$$

Based on equation (4), the system is designed to add more PFEs to the existing cluster of the PFE required by the calculated paths. The program then moves the PFE to the nearest interior walls and moves-up by 3 ft in the z-direction. This PFE installation plan is visualized in the third layer (FSGP) as a (.obj) file inside the Grasshopper and rhinoceros' environment, which could also be integrated with Revit using the WIP add-on package. The algorithm also automatedly extracts the list of geolocations coordinates (x, y, and z) for each PFE and calculates the number of locations.

The algorithm generates the quantity take-off based on the number of locations and automatically saves the results in an Excel file on a local machine for cost estimation.

This segment of the technical system development section focuses on the SIIS, the second part of this research. The roles responsible for safety inspection data recording and conformance in traditional PFE inspection process were identified. OCR and blockchain technologies were adopted to develop the proposed approach. The android app was developed in an android studio using Java and Extensible Markup Language (XML). Streaming API for XML (StaX), which is considered superior to Simple API for XML (SAX) and Document Object Model (DOM), was used in Java 6.0 for parsing the XML documents. Java was used for the back-end business logic, whereas XML for the front-end design. Java is a user-friendly objected-oriented language, which is platform-independent; however, it is compiled in bytecode with the Dalvik Virtual Machine's support. To extract the PFE identity document (ID) and other relevant information from the tag, this system integrated the open-source Google OCR library, Vision API, which extracts and detects text from images. Vision API executes feature detection on an image file by transferring the contents as a base64 encoded text.

The database was designed using MySQL for storing user information and record storage. REpresentation State Transfer (REST) API was utilized to interact with the reside database and share information between them in JavaScript Object Notation (JSON). In the back-end, the REST API was developed in PHP to communicate between the app and the server (encode and decode requests/response). An open-source blockchain service TrueTimeStamp (truetimestamp.org), is used as a proof of existence for each transaction. When an image of PFE's tag is submitted, the complex mathematical formula converts the file into a string of numbers and characters. Two different submissions, even with a slight variance, would generate a different hash. The system then uploads that hash, not the image to the TrueTimeStamp Service, where it is then stored in the database. The transaction can then be verified by going to the TrueTimestamp website and putting the same hash in the verify box. The confirmation of the transaction's time and date when it was initially being updated can then be observed. The network-based location service API from Google maps, Naver maps, and kakao maps is also integrated into this app, which helps determine the location coordinates of PFE based on Wi-Fi access points or the available cell towers in the area.

VI. PROCESS DESCRIPTION OF PFE-IPS AND SIIS

This section presents the process description of PFE installation planning system (PFE-IPS) and safety inspection information system (SIIS) by converging BIM, OCR, and Blockchain for a more convenient, transparent, automated fire safety management system. The graphical demonstration in Fig. 4. illustrates six sections. In Section-1, the system allows the users to define the input parameters: building envelop, stair locations, interior walls, and PFE type. As shown in Fig. 4, Section-2 is determined to generate Voronoi grid logic. Subsequently , in Section-3, the algorithm identifies the optimized centerline in the Voronoi mesh. Section-4 divides the centerline (based on user preferences of PFE type) into several segments to generate random points. Thereafter, the system transfers the allocated PFE to the adjacent interior walls (IW). Section-4 also shows the shortest walk logic's deployment to generate the shortest path from the random points (PT) to the PFE location (FL). Moreover, Section 5 visualize the shortest walk to measures the distance between the building's envelop and PFE and highlight longer paths for the additional PFE. To verify the fire safety rule compliance of the PFE installation plan, the multi-agent crowd simulation library called PedSim is utilized and illustrated in Section-6. The system will automatically generate the required safety equipment installation plan for PFE. The developed PFE-IPS also calculates the required quantity of the PFEs for the cost estimation and export that into Microsoft Excel (Ms. Excel). Cost estimators with this powerful built-in function could conveniently develop the cost plan of the PFEs in a given project.

The process description of a decentralized android app for the SIIS pertaining to PFE is proposed herein; the SIIS leverages an integrated approach involving OCR and blockchain technologies. The process flow of the developed system is presented in the use case diagram (Fig. 5), which includes the registration required for user access, OCR for transforming images into text, and the blockchain to record transactions with their corresponding timestamps. Conventionally, for PFE inspection, two stakeholders are involved to ensure the fire safety on a given job site, such as the government safety auditor and the safety manager or an inspector from a general contractor or sub-contractor. As portrayed in Fig. 5, these responsible roles are adjusted in the developed app.

The app is designed to allow the system's functions for the registered participants based on individuals' roles. As a preliminary step, the role is responsible for investigating PFE status; for instance, the safety inspector captures the images of the attached tags or final reports to upload the data into the system. A trackable PFE ID is configured to match this ID extracted from image data using an OCR optical vision technique. During the OCR process, the image captured via the built-in camera of the smartphone traverses three phases: localization (the region where the test is located), segmentation (extraction of each symbol), and recognition (reconstruction of words and numbers using contextual information). Subsequently, the system extracts the ID of the observed PFE and matches it with the corresponding input ID for submission to the database. Matching the extracted and input IDs will ensure accurate images of the tag for a given PFE; this will help reduce false reporting and forgery.

The submission process can be smoothly accomplished if both IDs are identical, and a hash value is allocated to the uploaded image using the Secure Hashing Algorithm (SHA-256). This hash value is a digital signature that provides cryptographic proof to avoid any modification

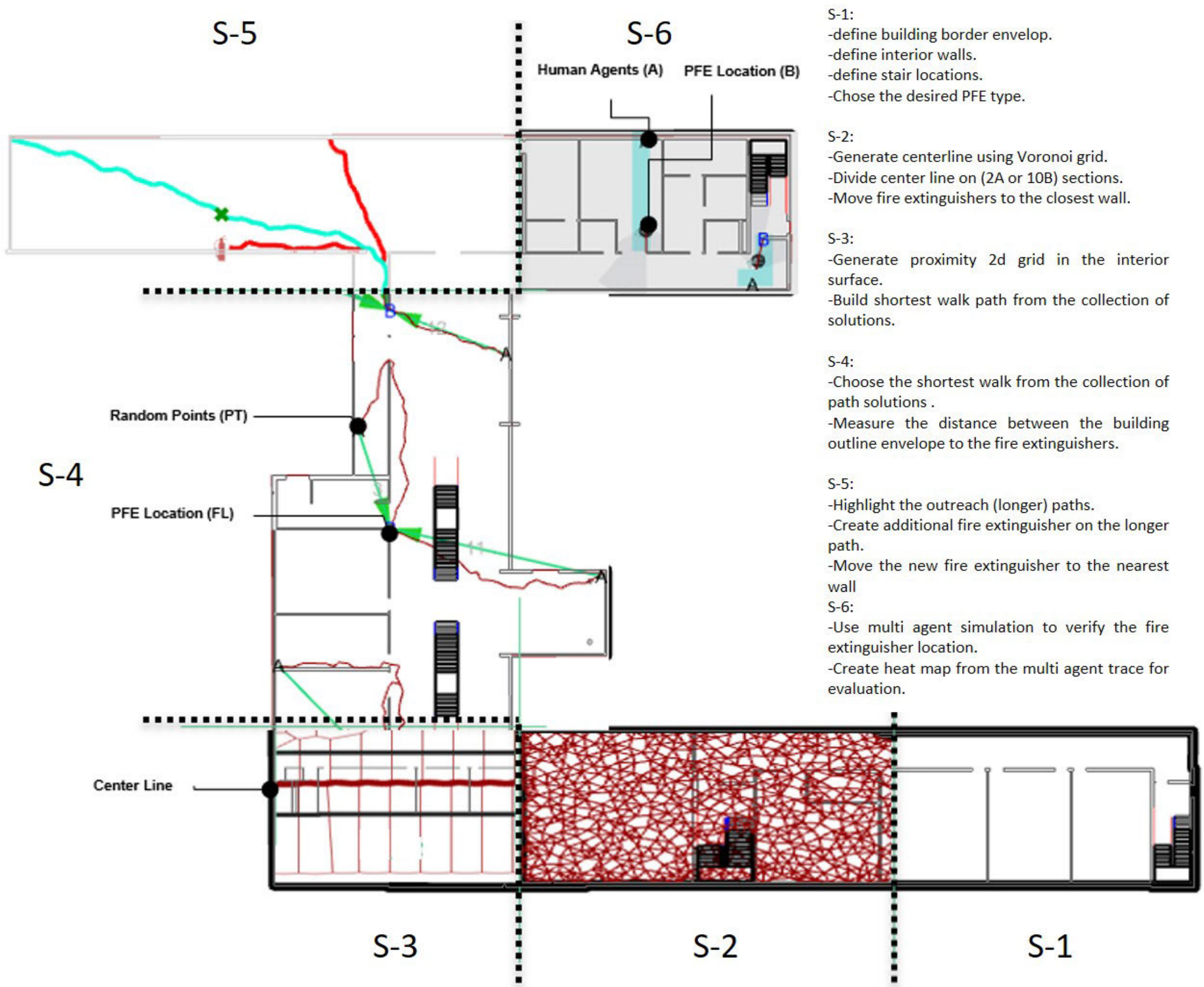


FIGURE 4. Illustration of the process steps for PFE-IPS.

or reproduction. As shown in Fig. 5, the uploaded image is stored in the database, while the generated hash value is recorded on a server using the TrueTimeStamp service. All associated stakeholders, particularly the government agency safety auditor, can view these stored records and verify any transaction through the server.

Figure 6 presents the login protocol process for users to register and access the developed application functions. Associated stakeholders must also be registered in the system before they can use this application. The registration process is initiated with a sign-up form; users need to fill in the required information on this form and save it to the MySQL database. To further illustrate the method in terms of user login functionality, Fig. 6 also depicts the ''User Login'' case. Users Users enter their personal information, such as e-mail IDs, usernames, and passwords, and system verifies the entered information. If the entered information is valid, the system grants access to that user and proceeds to a new ''Main Dashboard'' session.

In this dashboard, the safety manager or safety inspector adds project details and the ID assigned by the government department. Similarly, the government safety auditor repeats the same process for registration and functional access; this would enable the auditor to remotely view and verify submitted PFE inspection records along with their location coordinates. The following section focuses on simple case studies to validate the PFE-IPS and SIIS.

VII. CASE EXAMPLES FOR PROPOSED SYSTEM IMPLEMENTATION

This segment of the study presents two case studies carried out to validate the practical implementation of the proposed systems. Due to the current situations of COVID-19, one case study is validated using virtual humans leveraging

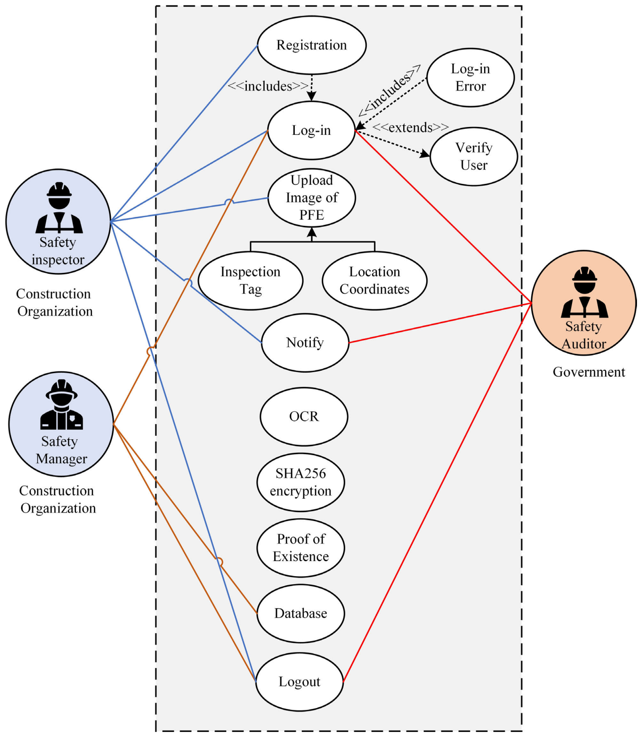


FIGURE 5. Use case diagram for developed SIIS.

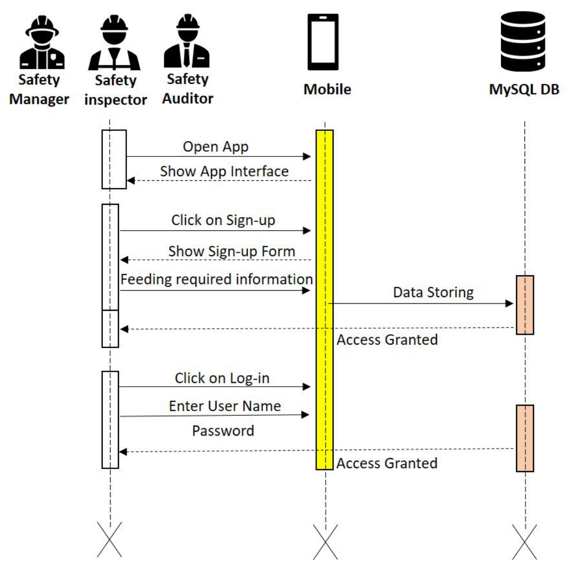


FIGURE 6. Sequence diagram for user registration.

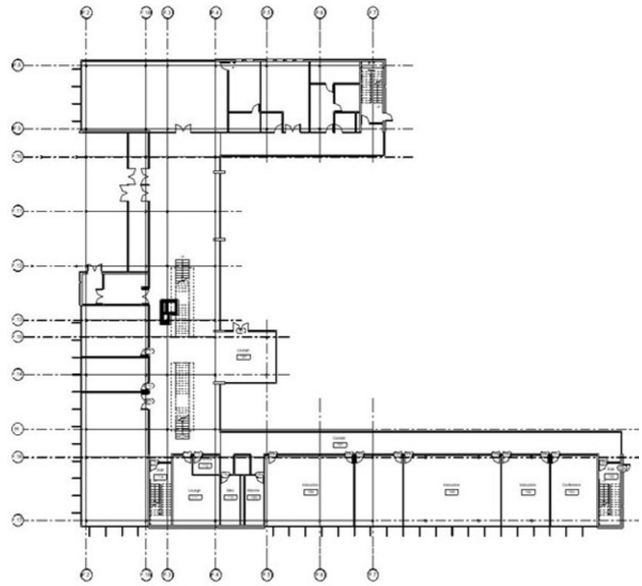


FIGURE 7. 2D plan of simple case example from Revit family.

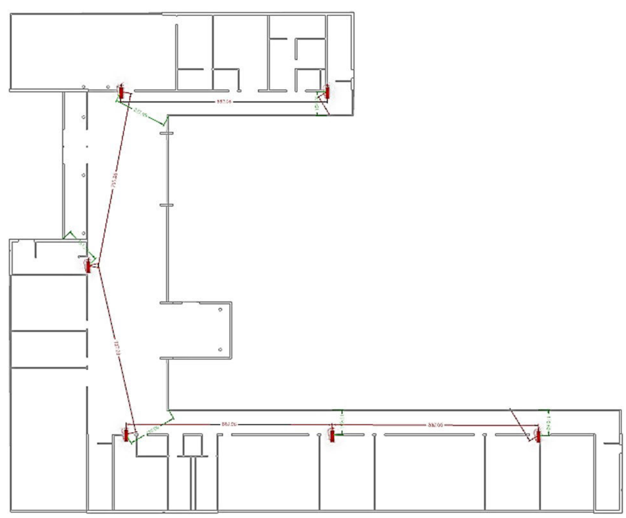


FIGURE 8. Initial PFE installation by the proposed system.

multi-agent approach in the grasshopper environment. The other case study has been carried out inside the campus. However, the research team tried their best to reflect the real scenarios in both examples.

A. CASE 1

This case intended to implement the developed PFEs installation safety planning system and bill of quantities estimation approach. To do this, a sample from the Autodesk Revit (see Fig. 7) is selected, and the 2D plan with the exclusive property's information is imported into the Grasshopper and Rhino environment. The system needs various kinds of predefined conditions to fulfill the required parameters, such as importing building envelope (BE) as a 2D plan geometry, the geometry of interior walls (IW) lines in a 2D plan, locations of stairs (SL) as pick points, and selection PFE types from the dropdown (2A or 10B) and then run the algorithm. The algorithm initially converts exterior walls into a closed curve, and a point object highlights stair locations (SL). As mentioned earlier, the user could select the desired PFE types from the top-down list, for instance, 2A or 10 B. We selected 2A, and the algorithm was simulated, accordingly. The optimized building centerline is generated through

Number	Travel Distance (Inches)
1	1311.8
2	618.9
3	752.4
4	726.7
5	835.0
6	488.1
7	350.4
8	570.0
9	357.8
10	559.5
11	690.2
12	378.6
13	139.9
14	752.4
15	550.6

FIGURE 9. Multi-agen simulation for verification of the proposed PFE-IPS.

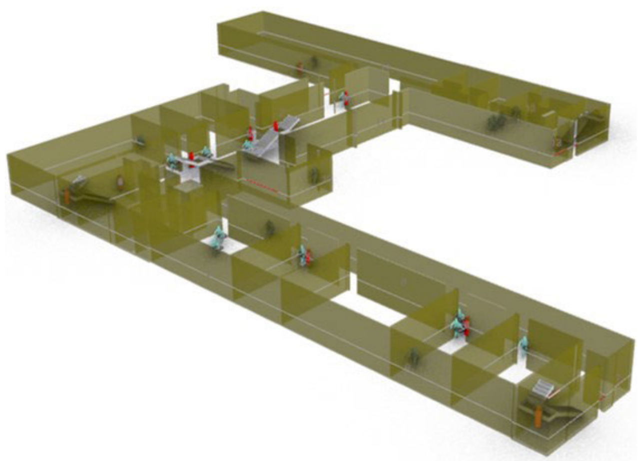
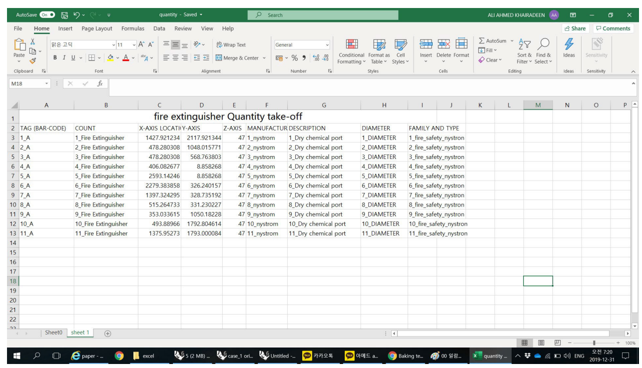


FIGURE 10. 3D BIM model of multi-agent Simulation.



fire extinguisher Quantity take-off

TAG (BAR-CODE)	COUNT	X-AXIS LOCATI	Y-AXIS	Z-AXIS	MANUFACTUR	DESCRIPTION	DIAMETER	FAMILY AND TYPE
1_A	1_Fire Extinguisher	1427.921234	2117.921344	47	1_nystrom	1_Dry chemical port	1_DIAMETER	1_fire_safety_nystron
2_A	2_Fire Extinguisher	478.280308	1048.015771	47	2_nystrom	2_Dry chemical port	2_DIAMETER	2_fire_safety_nystron
3_A	3_Fire Extinguisher	478.280308	568.763803	47	3_nystrom	3_Dry chemical port	3_DIAMETER	3_fire_safety_nystron
4_A	4_Fire Extinguisher	406.082677	8.858268	47	4_nystrom	4_Dry chemical port	4_DIAMETER	4_fire_safety_nystron
5_A	5_Fire Extinguisher	2593.14246	8.858268	47	5_nystrom	5_Dry chemical port	5_DIAMETER	5_fire_safety_nystron
6_A	6_Fire Extinguisher	2279.383858	326.240157	47	6_nystrom	6_Dry chemical port	6_DIAMETER	6_fire_safety_nystron
7_A	7_Fire Extinguisher	1397.324295	328.735192	47	7_nystrom	7_Dry chemical port	7_DIAMETER	7_fire_safety_nystron
8_A	8_Fire Extinguisher	515.264733	331.230227	47	8_nystrom	8_Dry chemical port	8_DIAMETER	8_fire_safety_nystron
9_A	9_Fire Extinguisher	353.033615	1050.18228	47	9_nystrom	9_Dry chemical port	9_DIAMETER	9_fire_safety_nystron
10_A	10_Fire Extinguisher	493.88966	1792.804614	47	10_nystrom	10_Dry chemical port	10_DIAMETER	10_fire_safety_nystron
11_A	11_Fire Extinguisher	1375.95273	1793.000084	47	11_nystrom	11_Dry chemical port	11_DIAMETER	11_fire_safety_nystron

FIGURE 11. Quantity take off for portable firefighting equipment.

VORONOI logic. The developed algorithm finds the appropriate locations for PFEs utilizing the shortest walk logic's and computes the length between the closest PFE with the building border envelope. Thus, supplementary PFE is added in the area if protracted than required; in this case, the system did not identify any long distance (see Fig. 8). To evaluate the system's real performance and to have diversity in the shape of the building, one big room is added to the existing model. The multi-agent simulation is in Fig. 9 and Fig. 10, that works on the concept of social forces model algorithm (PedSim in Grasshopper), In which a persons move from Point (A) to Point (B) using the shortest route, avoiding walls or other barriers and obstacles, as in shown Fig. 9. After running the algorithm on the modified model, the travel distance to PFE in that room comes-up greater than the desired length directed by OSHA safety rules. Hence, the system allocates an additional PFE on a longer path and moves the added PFE to the nearest wall. In this case study, the 14 paths among 15 paths traveled by the generated human agents are in the safe range of 1200 inches (100feet), excluding the highlighted number in the table of Fig. 9, which is 1311.8 inches. Consequently, a new PFE is added to the existing PFE cluster, as depicted by a teal color path in Fig. 9. In addition to this, the program automatically generates the quantity-take-off for the cited case study. In order to get the quantity take-off (see Fig. 11), a layer of PFE family is established , and the coordinates (X, Y, Z) are extracted and counted.

B. CASE 2

To further illustrate the second motive of the proposed research, safety inspection information system (SIIS), this section presents a case study for the OCR and blockchain-based inspection data recording and delivery system

FIGURE 12. Case study for testing the proposed SIIS.

FIGURE 13. Sign-up process for system user registration.

pertaining to PFE. The second-floor corridor of the Department of Architectural Engineering building (208) in Chung-Ang University, Seoul was considered for this purpose (Fig. 12). As mentioned earlier, the current practice for fire safety management includes two primary participants; therefore, two major participant roles and one sub-participant role, such as a government agency safety auditor, manager, or inspector, is incorporated in the designed app. Figure. 13 demonstrates the cases created to test the

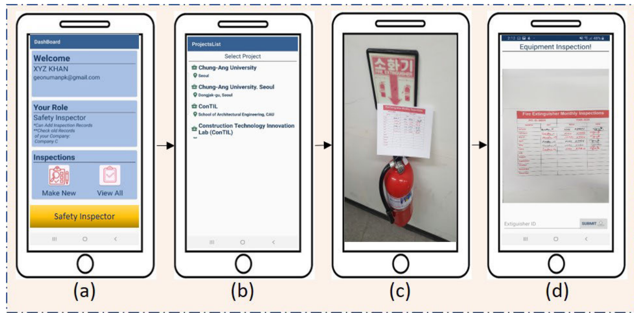


FIGURE 14. Example of portable firefighting equipment inspection recording.

functionality of the registration process in Fig. 6, which explains the incorporated roles and the sign-up process for registering users in the database. After completing the registration, the process is initiated through the android client by registering three emails against the corresponding roles. As depicted in Fig.13, the authorized users then enters their usernames or email IDs along with the corresponding passwords. The system verifies this entered information and generates another session (main dashboard) for the valid users. Through this dashboard, the safety inspector can create a new project and work on it or view previous history been already made for other projects. Fig. 14 presents the categorical process required to record the PFE tag information after a thorough inspection. The information tags for enlisting the safety inspection evidence were assigned to each PFE (Fig. 14-c) to achieve the demonstrated scenario. As the app is designed to enhance the bottom-up reporting approach instead of a top-down enforcing approach, a new project named as "Construction Technology Innovation Lab (ConTIL)" under the company name "company c" is created in the project list menu by using the safety inspector role, as shown in Fig. 14-b. This role is assigned to the person who is actually responsible for assessing the maintenance and monitoring of PFE. The safety inspector could submit the record via two sources: (1) a captured image, or (2) images imported from local storage. For this instance, the tag images were captured using the camera and uploaded to the database with the ID of each PFE, as depicted in Fig. 14-d. The system uses REST API to communicate between the front-end android app (client) and the back-end database (server) over HTTP protocols.

The embedded OCR technology in the app extracts the ID from the image and matches it with the manually entered ID. To overcome fraudulent submissions and ensure absolute proof that the inspection was performed at a certain date, an open-source blockchain service, named TrueTimeStamp (truetimestamp.org), is used for each transaction. All the timestamps are decentralized and do not depend on any other third party. When the image of a PFE tag is submitted, TrueTimeStamp API automatically converts the file into a unique hash and generates a certificate proving that the data was created at a certain point and time. This process

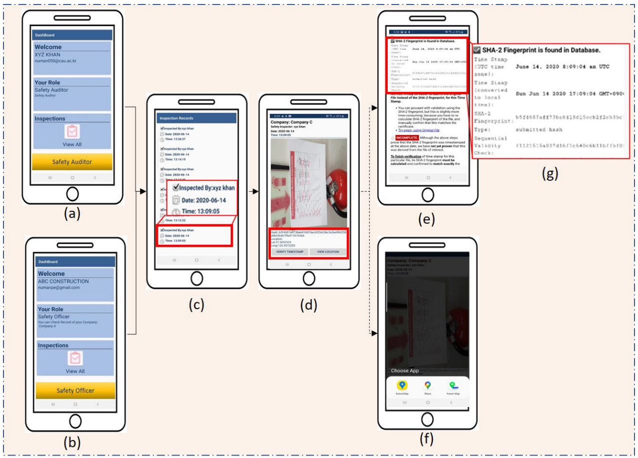


FIGURE 15. **Android application screenshots depicting functions and data verification.**

employs a cryptographic data fingerprint in a public blockchain, which makes the regeneration of original data impossible; thus, the submitted data is immutable and no one would ever get their hands on the data. In our case, several images have been uploaded; the blockchain-based proof of existence service allocates a unique hash value (a digital signature) to each record and stores them on the server. An example of such tag image is presented in Fig. 14-c, and 14-d, the digital signature generated for this specific inspection is presented in Fig. 15-d, that is "b5f4687aff 73ba6418d15ecb2f2eb3bc3a3ea90d358a0b036d67f9e91057 64b6." As depicted in Fig. 15, the safety auditor from the government agency (see Fig. 15-a) or the safety officer from the company (see Fig. 15-b) could remotely view and verify the inspection conducted by a safety inspector through logging-in to their respective accounts. As mentioned, the transaction can then be verified from the TrueTimeStamp website by inputting the same hash in the verify box. Alternatively, the safety auditor from the government agency or the safety manager from the concerned company could double-check inspection-related data by clicking on relevant transactions. Confirmation regarding the time and date, when these data were originally updated can also be observed. For instance, in our case, the respective transactions of each PFE inspection associated with this project can be verified by clicking on the "VERIFY TIMESTAMP" button on the dashboard. The inspection performed by xyz khan dated 2020-06-14 at 13:09:05 is verified, and the results associated with this record are presented in Fig. 15-c, d, and e; this indicates that "SHA-2 Fingerprint is found in the database," with the same hash, date, and time. In addition to transaction's verification, locations can also be traced using different maps services such as Kakao, Naver, or Google. The network-based location service API from the entire three sources are also integrated into the proposed app, which helps determine the location based on Wi-Fi access points or through other internet sources, such as the available cell towers in the region.

VIII. DISCUSSION AND LIMITATIONS

The primary goal of this study was to develop a novel approach for PFE installation plan, maintaining reliability and overcoming forged tag reporting through bottom-up inspection approach and by leveraging the convergence of BIM, VPL, OCR, and blockchain technologies, to ultimately ensure that the PFE is in the appropriate place and good working condition. The conventional fire safety plan in construction follows the site-specific plan [11] and is a 2D based cumbersome process. Modeling safety facilities in BIM is significant for quantity estimation, cost calculation, and visualization [7]. With this regard, a novel system named as PFE-IPS to sort out this challenging issue is presented. Based on the complexity and the scale of the project, the tedious modeling process generally needs hours, days, or even weeks [29].

Case-1, in this study, disclosed that the proposed approach could deliver an advanced and inclusive evaluation for the fire safety rule-based planning. The developed semi-automated approach has successfully generated the PFE installation plan (see case-1). In addition, this research presented an expedient approach for visualization and calculated the quantities for actual cost with regards to just on time approach. Therefore, the vagueness of overestimate or underestimate could be eradicated, and the acquired cost estimation would be shared with certainty.

Previous studies on fire safety monitoring and inspection data recording failed to consider a blockchain-based method to shift the top-down approach into a bottom-up voluntary approach. The proposed method integrates OCR and blockchain technologies to develop a decentralized android app to automate the inspection data recording process. The developed app is expected to be beneficial and could serve as an alternative for government inspection agencies and the safety managers and inspectors from contractors/subcontractors responsible for fire safety in construction. This approach provides reliable, transparent, and verified information required to ensure conformance to construction fire safety policies. The integration of advanced technologies, such as image recognition, image matching, and IoT-based sensors, with blockchains, could help determine accurate and secure information pertaining to safety conformance. As evidenced by the case study, the system designed to capture the required information and upload it to the server was implemented successfully.

Moreover, the developed method was also suitable for viewing and analyzing the stored inspection information. This feature makes the stakeholders powerful in terms of information access and data deliveries. The results generated via this approach are advanced, transparent, and more effective than the conventional paper-based reporting and recording method. The submitted inspections are recorded with enhanced reliability and the relevant stakeholders can verify each transaction. This verification feature in our approach is validated in Case-2. A blockchain is a digital ledger for storing and recording transactions. Once a transaction has been performed and validated, the block's information is cryptographically sealed, providing immutability. Therefore, this technology offers a reliable verification service to generate an immutable ledger of any interesting domain in construction, which is significantly beneficial for owners and insurance companies as well as during the bidding process. The model developed in this study could be extended in terms of construction safety and quality by considering safety checklists and material supply chains. The proposed app could be integrated with a coin reward system or other appreciation systems to motivate the bottom managers. For instance, the Hyper-ledger fabric protocols and IoTs could be utilized to store critical information regarding quality-related events and activities on job sites by using blockchain technology, thereby ensuring quality conformance. Additionally, the integration of artificial vision intelligence with blockchains is expected to increase safety monitoring effectiveness on construction job sites.

Similar to other research studies, this applied research is also deprived of some limitations; for instance, the inputs parameters such as 2-D plan, selection of stair location and interior walls required manual efforts, detection of 2D plan elements could be automated leveraging space family in BIM, then the user does not require the selection of 2D plan, manually. Incentives in coins or an appreciation system are necessary to promote the bottom-up approach and encourage workers or bottom-level managers. Thus, by employing an appropriate reward system, the proposed method can be further enhanced. Moreover, the ID of a given PFE needs to be input manually, constituting another limitation of the approach. However, this manual effort can be minimized through QR coding, which will also improve the automation and efficiency of this process.

IX. CONCLUSION

This study introduced an automated PFE installation planning system (PFE-IPS) and a smartphone-based application for a bottom-up reporting approach named as safety inspection information system (SIIS) to replace the existing PFE installation and monitoring process. The outcomes were achieved by converging Building Information Modeling (BIM), Optical Character Recognition (OCR), and Blockchain technologies. Two case studies validated the implementation of the developed approach for construction fire safety management pertaining to PFE. The developed systems provided an optimized PFE installation plan and reliable safety inspection data. A multi-agent simulation in PFE-IPS demonstrated that the proposed system would be an effective tool for practical fire safety planning at construction sites. In addition, the successful implementation of SIIS revealed reliability in-terms of data recording and improved access to fire safety inspection information. Based on these case studies, the authors are convinced that PFE-IPS and SIIS can address the limitations of the current construction fire safety management procedures to a greater extent. The presented research will promote construction 4.0, enhance transparency, minimize the use of paper, decrease the burden on concerned stakeholders, and reduce the visits of physical safety auditors/managers, that is also beneficial during the current COVID-19 pandemic.

In future research, a comprehensive system will be developed by integrating the PFE-IPS with the schedule (BIM 4D) to have dynamic planning based on the construction site changes. In order to make a comprehensive safety performance system, an extension of SIIS to evaluate concerned contractors' fire safety performance required in the bidding process would be developed in the future.

REFERENCES

[1] S. Kumar and V. K. Bansal, "Construction safety knowledge for practitioners in the construction industry," *J. Frontiers Construct. Eng.*, vol. 2, no. 2,pp. 34–42, 2013.
[2] C. Vigneshkumar, *Nature of Fall Accidents in Construction Industry: An Indian Scenario*, no. 2277, 2014, pp. 144–146.
[3] S. Moon, T. Kim, B.-G. Hwang, and S. Chi, "Analysis of construction accidents based on semantic search and natural language processing," in *Proc. 35th Int. Symp. Autom. Robot. Construction (ISARC)*, Jul. 2018, pp. 1–6.
[4] M. A. Hossain, E. L. S. Abbott, D. K. H. Chua, T. Q. Nguyen, and Y. M. Goh, "Design-for-Safety knowledge library for BIM-integrated safety risk reviews," *Autom. Construct.*, vol. 94, pp. 290–302, Oct. 2018.
[5] Bureau of Labor Statistics. *Census of Fatal Occupational Injuries (CFOI) Current and Revised Data*. Accessed: Oct. 3, 2018. [Online]. Available: https://www.bls.gov/iif/oshcfoi1.htm
[6] R. Campbell, "Fires in structures under construction, undergoing major renovation or being demolished fact sheet," Nat. Fire Protection Assoc. (NFPA), Quincy, MA, USA, Tech. Rep., Feb. 2017. [Online]. Available: https://www.nfpa.org//-/media/Files/News-and-Research/Fire-statistics-andreports/Building-and-life-safety/osFiresInStructuresUnderConstruction.pdf
[7] N. Khan, A. K. Ali, S. Van-Tien Tran, D. Lee, and C. Park, "Visual language-aided construction fire safety planning approach in building information modeling," *Appl. Sci.*, vol. 10, no. 5, p. 1704, Mar. 2020.
[8] U. Rentals. "Fire extinguishers on construction sites: What's required | United Rentals," United Rentals, Incorpotaion, Edmonton, AB, Canada, Tech. Rep., Feb. 2018. Accessed: Jan. 30, 2020. [Online]. Available: https://www.unitedrentals.com/project-uptime/safety/fire-extinguishers-constructionsites-whats-required#
[9] F. S. A. Services, "Fire safety plan for construction, renovation and demolition sites background information," Tech. Rep., 2017.
[10] S. Choe and F. Leite, "Construction safety planning: Site-specific temporal and spatial information integration," *Autom. Construction*, vol. 84, pp. 335–344, Dec. 2017.
[11] K. Kim and Y.-C. Lee, "Automated generation of daily evacuation paths in 4D BIM," *Appl. Sci.*, vol. 9, no. 9, p. 1789, Apr. 2019.
[12] H. Kim, J.-K. Lee, J. Shin, and J. Choi, "Visual language approach to representing KBimCode-based korea building code sentences for automated rule checking," *J. Comput. Design Eng.*, vol. 6, no. 2, pp. 143–148, Apr. 2019.
[13] Y.-Y. Chen, Y.-J. Chuang, C.-H. Huang, C.-Y. Lin, and S.-W. Chien, "The adoption of fire safety management for upgrading the fire safety level of existing hotel buildings," *Building Environ.*, vol. 51, pp. 311–319, May 2012.
[14] M. Kumm and A. Bergqvist, "Fire and rescue operations during construction of tunnels," in *Proc. 4th Int. Symp. Tunn. Saf. Secur.*, Sep. 2010, pp. 383–394.
[15] P. Yang, C. Shi, Z. Gong, and X. Tan, "Numerical study on water curtain system for fire evacuation in a long and narrow tunnel under construction," *Tunnelling Underground Space Technol.*, vol. 83, pp. 195–219, Jan. 2019.
[16] M.-Y. Cheng, K.-C. Chiu, Y.-M. Hsieh, I.-T. Yang, and J.-S. Chou, "Development of BIM-based real-time evacuation and rescue system for complex buildings," in *Proc. 33rd Int. Symp. Autom. Robot. Construct. (ISARC)*, Jul. 2016, pp. 999–1008.
[17] H. Jiang, "Mobile fire evacuation system for large public buildings based on artificial intelligence and IoT," *IEEE Access*, vol. 7, pp. 64101–64109, 2019.

[18] T.-N. Guo and Z.-M. Fu, "The fire situation and progress in fire safety science and technology in China," *Fire Saf. J.*, vol. 42, no. 3, pp. 171–182, Apr. 2007.
[19] P. Johnson, C. Beyler, P. Croce, C. Dubay, and M. McNamee, "Very early smoke detection apparatus (VESDA), david packham, john petersen, Martin cole: 2017 DiNenno prize," *Fire Sci. Rev.*, vol. 6, no. 1, pp. 1–12, Dec. 2017.
[20] D. Cram, C. Hatch, S. Tyler, and C. Ochoa, "Use of distributed temperature sensing technology to characterize fire behavior," *Sensors*, vol. 16, no. 10, p. 1712, Oct. 2016.
[21] En-Gauge. (2014). *Security Officers Arrested For Tampering With Fire Extinguisher Records*. En-Gauge Fire and Life Safety Blog. Accessed: May 29, 2020. [Online]. Available: https://www.engaugeinc.net/life-and-fire-safety-blog/security-officers-arrested-for-tampering-with-fire-extinguisher-records
[22] M. Kobes, I. Helsloot, B. de Vries, and J. G. Post, "Building safety and human behaviour in fire: A literature review," *Fire Saf. J.*, vol. 45, no. 1, pp. 1–11, Jan. 2010.
[23] L. Hui, W. Yongqing, S. Shimei, and S. Baotie, "Study on safety assessment of fire hazard for the construction site," *Procedia Eng.*, vol. 43, pp. 369–373, Jan. 2012.
[24] W. K. Chow, "Fire safety in green or sustainable buildings: Application of the fire engineering approach in Hong Kong," *Architectural Sci. Rev.*, vol. 46, no. 3, pp. 297–303, Sep. 2003.
[25] K.-C. Wang, S.-Y. Shih, W.-S. Chan, W.-C. Wang, S.-H. Wang, A.-A. Gansonre, J.-J. Liu, M.-T. Lee, Y.-Y. Cheng, and M.-F. Yeh, "Application of building information modeling in designing fire evacuation—A case study," in *Proc. 31st Int. Symp. Autom. Robot. Construct. Mining (ISARC)*, Jul. 2014, pp. 593–601.
[26] M. Shokouhi, K. Nasiriani, Z. Cheraghi, A. Ardalan, H. Khankeh, and H. Fallahzadeh, "Preventive measures for fire-related injuries and their risk factors in residential buildings: A systematic review," *J. Inj. Violence Res.*, vol. 11, no. 1, pp. 1–14, 2019.
[27] Y.-J. Chen, Y.-S. Lai, and Y.-H. Lin, "BIM-based augmented reality inspection and maintenance of fire safety equipment," *Autom. Construct.*, vol. 110, Feb. 2020, Art. no. 103041.
[28] S.-H. Wang, W.-C. Wang, K.-C. Wang, and S.-Y. Shih, "Applying building information modeling to support fire safety management," *Autom. Construct.*, vol. 59, pp. 158–167, Nov. 2015.
[29] S. Zhang, K. Sulankivi, M. Kiviniemi, I. Romo, C. M. Eastman, and J. Teizer, "BIM-based fall hazard identification and prevention in construction safety planning," *Saf. Sci.*, vol. 72, pp. 31–45, Feb. 2015.
[30] S. Zhang, F. Boukamp, and J. Teizer, "Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)," *Autom. Construct.*, vol. 52, pp. 29–41, Apr. 2015.
[31] N. Khan, A. K. Ali, M. J. Skibniewski, D. Y. Lee, and C. Park, "Excavation safety modeling approach using BIM and VPL," *Adv. Civil Eng.*, vol. 2019, pp. 1–15, Apr. 2019.
[32] J. Lee, *The Automated Design Rule Checking System*, vol. 1, 2019, pp. 795–804.
[33] J. Song, J. Kim, and J.-K. Lee, "Converting KBImCode into an executable code for the automated design rule checking system," in *Proc. Intell. Informed 24th Int. Conf. Comput.-Aided Architectural Design Res. Asia (CAADRIA)*, vol. 1, 2019, pp. 795–804.
[34] T. M. Fernandez-Carames and P. Fraga-Lamas, "Towards post-quantum blockchain: A review on blockchain cryptography resistant to quantum computing attacks," *IEEE Access*, vol. 8, pp. 21091–21116, 2020.
[35] Z. Turk and K. Robert, "Potentials of Blockchain technology for construction management," in *Proc. Creative Construct. Conf.*, 2017, pp. 638–645.
[36] H.-Y. Paik, X. Xu, H. M. N. D. Bandara, S. U. Lee, and S. K. Lo, "Analysis of data management in blockchain-based systems: From architecture to governance," *IEEE Access*, vol. 7, pp. 186091–186107, 2019.
[37] K. Tsoulias, G. Palaiokrassas, G. Fragkos, A. Litke, and T. A. Varvarigou, "A graph model based blockchain implementation for increasing performance and security in decentralized ledger systems," *IEEE Access*, vol. 8, pp. 130952–130965, 2020.
[38] H. Mason, J. and Escott, "Smart contracts in construction: Views and perceptions of stakeholders," in *Proc. FIG Conf.*, İstanbul, Turkey, May 2018, pp. 2006–2009. [Online]. Available: http://eprints.uwe.ac.uk/35123/
[39] M. Kassem, J. Lia, and D. Greenwood, "Blockchain in the built environment: Analysing current applications and developing an emergent framework," Diamond Congr. Ltd., Budapest, Hungary, Tech. Rep., Jul. 2018, pp. 59–66.
[40] S. Nanayakkara, S. Perera, G. T. Weerasuriya, and J. Ayoub, "Blockchain technology and its potential for the research methodology blockchain," Tech. Rep., 2017, pp. 662–672.
[41] S. Nanayakkara, S. Perera, and S. Senaratne, "Stakeholders' perspective on blockchain and smart contracts solutions for construction supply chains," in *Proc. CIB World Build. Congr.*, Jun. 2019, pp. 17–21.
[42] J. A. F. Castellanos, D. Coll-Mayor, and J. A. Notholt, "Cryptocurrency as guarantees of origin: Simulating a green certificate market with the Ethereum Blockchain," in *Proc. 5th IEEE Int. Conf. Smart Energy Grid Eng., SEGE*, Apr. 2017, pp. 367–372.
[43] H. R. Hasan, K. Salah, R. Jayaraman, M. Omar, I. Yaqoob, S. Pesic, T. Taylor, and D. Boscovic, "A blockchain-based approach for the creation of digital twins," *IEEE Access*, vol. 8, pp. 34113–34126, 2020.
[44] J. Wang, P. Wu, X. Wang, and W. Shou, "The outlook of blockchain technology for construction engineering management," *Frontiers Eng. Manage.*, vol. 4, no. 1, p. 67, 2017.
[45] A. A. Hijazi, S. Perera, A. Alashwal, and R. N. Calheiros, "Blockchain adoption in construction supply chain: A review of studies blockchain adoption in construction supply chain: A review of studies across multiple sectors," in *Proc. CIB World Build. Congr.*, Jun. 2019, pp. 1–11.
[46] A. Dorri, S. S. Kanhere, and R. Jurdak, "Towards an optimized BlockChain for IoT," in *Proc. 2nd Int. Conf. Internet Things Design Implement.*, Apr. 2017, pp. 173–178.
[47] Q. Lu, L. Chen, S. Li, and M. Pitt, "Semi-automatic geometric digital twinning for existing buildings based on images and CAD drawings," *Autom. Construct.*, vol. 115, Jul. 2020, Art. no. 103183.
[48] N. S. Rani, V. T, C. M, and M. N, "2D morphable feature space for handwritten character recognition," *Procedia Comput. Sci.*, vol. 167, pp. 2276–2285, Jan. 2020.
[49] A. F. Mollah, N. Majumder, S. Basu, and M. Nasipuri, "Design of an optical character recognition system for camera-based handheld devices," *IJCSI Int. J. Comput. Sci. Issues*, vol. 8, no. 4, p. 1, Jul. 2011.
[50] S. Zhang, J. Teizer, J.-K. Lee, C. M. Eastman, and M. Venugopal, "Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules," *Autom. Construct.*, vol. 29, pp. 183–195, Jan. 2013.
[51] C. Maluk, M. Woodrow, and J. L. Torero, "The potential of integrating fire safety in modern building design," *Fire Saf. J.*, vol. 88, pp. 104–112, Mar. 2017.
[52] J. Li, D. Greenwood, and M. Kassem, "Blockchain in the construction sector: A socio-technical systems framework for the construction industry," in *Advances in Informatics and Computing in Civil and Construction Engineering*, I. Mutis and T. Hartmann, Eds. Cham, Switzerland: Springer, 2019, doi: 10.1007/978-3-030-00220-6_7.
[53] N. O. Nawari and S. Ravindran, "Blockchain and building information modeling (BIM): Review and applications in post-disaster recovery," *Buildings*, vol. 9, no. 6, p. 149, 2019.
[54] B. W. Munich, *BIM and Blockchain (Part 1): Basics of Blockchain*, vol. 11, 2019, pp. 26–27. [Online]. Available: https://www.bim-world.de/bim-blockchains-part-1-basics-blockchain/
[55] Z. Dakhli, Z. Lafhaj, and A. Mossman, "The potential of blockchain in building construction," *Buildings*, vol. 9, no. 4, p. 77, Apr. 2019.
[56] Everledger. (2020). *Tech for Good Blockchain Solutions*. Accessed: Jul. 17, 2020. [Online]. Available: https://www.everledger.io/
[57] N. O. Nawari and S. Ravindran, "Blockchain technology and BIM process: Review and potentialapplications," *J. Inf. Technol. Constr.*, vol. 24, pp. 209–238, May 2019.

NUMAN KHAN received the B.S. degree in civil engineering, and the M.S. degree in engineering management from the Ghulam Ishaq Khan Institute of Science and Technology (GIKI), Topi, Pakistan, in 2015. He is currently pursuing the Ph.D. degree with the Construction Technology Innovation Laboratory, Chung-Ang University, Seoul, South Korea.

His research interests include BIM, computer vision, construction quality, rule-based modeling, construction fire safety, human safety in construction, and construction 4.0.

DOYEOP LEE received the master's degree in architectural engineering, and the Ph.D. degree in construction engineering and management from Chung-Ang University, Seoul, South Korea. His research interests include construction automation, computer vision, job hazard analysis, construction safety, construction quality, blockchain, and BIM.

CHANWOO BAEK received the B.S. degree from the Department of Architecture, Joongbu University, Goyang, South Korea. He is currently pursuing the master's degree with the School of Architecture and Building Science, Chung-Ang University, Seoul, South Korea. His research interests include safety policy development in the construction job-site, block chain for construction management, and BIM.

CHAN-SIK PARK received the B.E. and M.E. degrees in architecture from Chung-Ang University, Seoul, South Korea, the M.S. degree from the University of Colorado at Boulder, and the Ph.D. degree from the University of Florida with the major in construction management.

He has been a Professor with the School of Architecture and Building Science and the former Dean of the Graduate School of Construction Engineering, Chung-Ang University, since 1995. He is one of the founders and the former President of KICEM, the Founder of ICCEPM, and the Vice President of Building Smart Korea.