

BIM-Based Construction Accidents Knowledge Database Management System: Centralized Accessible Information Repository for Enhanced Learning from the Past

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Abstract: Knowledge management (KM) for project safety is crucial to prevent repeated construction accidents, including fatalities, injuries, near misses, and property damage. This research examined widespread issues in managing historical accident data that impact effective learning from past accidents. Subsequently, a prototype building information modeling (BIM)-based construction accidents knowledge database management system (BIM-CAKDMS) was developed that exploits the structured database management and three-dimensional (3D) visualization capabilities of BIM and was validated using three construction accident case studies, expert interviews, and a lab experiment. The proposed system's primary innovation lies in its ability to integrate accident investigation data directly into the 3D BIM model, creating high-fidelity construction accident animations and simulations that allow stakeholders to analyze the chain of events, understand contributing factors in their actual spatial and temporal context, and internalize lessons learned through experiential rather than abstract learning. Results show that BIM-CAKDMS provides a centralized repository, standardizes data entry, and improves information accessibility. Moreover, its 3D visualization capability and the construction accident animations enhance collaboration, safety communication, and training effectiveness, and reduce the cognitive load of learning from accidents compared with text-based approaches. Overall, this study contributes to automation in construction by enabling enhanced access to accident knowledge, streamlining data-sharing among stakeholders, and learning from 3D accident animations, which potentially may lead to proactive accident prevention strategies. **DOI: 10.1061/JCEMD4.COENG-17678.** *This work is made available under the terms of the Creative Commons Attribution 4.0 International license, <https://creativecommons.org/licenses/by/4.0/>.*

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Introduction

There is a need to improve key elements of health and safety in the construction industry due to the disproportionately high number of accidents. The importance of learning from workplace accidents is significant for environmental, health, and safety reasons. The best

strategy to prevent accidents is to maintain track of their reasons and root causes and work to address these so that they never occur again (Rashid 2021). When an accident happens, a team should be put together to investigate why it happened and to create controls to stop it from happening again. The goal is to rebuild the occurrence, identify causes, and devise procedures to prevent a recurrence. A

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reverse analysis would strive to learn the reasons for the accident after reconstructing it (Morrish 2017). Recent studies have shown how companies might fail to learn despite efforts to collect data on previous minor failures and their causes to understand how to prevent more major occurrences (Maslen and Hayes 2016). Numerous studies have highlighted the barriers to learning from past incidents (LFI), such as low quality of initial reports, complex reporting systems, limited sharing of lessons learned, lack of root cause analysis, and lack of contextualizing and visual insights of the incidents, among others (Dechy et al. 2015; Drupsteen et al. 2013; Drupsteen-Sint 2014; Parker et al. 2018). Industries as diverse as oil and gas extraction, nuclear power generation, and air traffic control have embraced the concept of learning from modest mistakes with enthusiasm, which has resulted in the growth of database systems for logging and categorizing event reports. Research on organizational learning and accident reporting may benefit from focusing on collective knowledge. Many firms now recognize the significance of knowledge management (KM) and believe that accident databases can serve as source of experiential knowledge for learning from the past (Maslen and Hayes 2016). Hence, a focus on both LFI and accidents KM for enhanced safety is essential.

Safety communication is one of the crucial components of managing health and safety. Current methods to disseminate information among project teams require improvement. According to Ho et al. (2013), KM is a set of processes that govern the generation, storage, reuse, evaluation, and application of experience-based knowledge in a specific situation or problem-solving context. Construction companies frequently gather safety knowledge from a variety of internal and external sources, but their inadequate knowledge storage and transfer methods prevent their workers from acquiring the essential information they need to address pressing safety-related issues (Hallowell 2012). Construction companies must implement effective KM procedures, because their distinctive and dynamic projects frequently result in lost information owing to unrecorded ideas (Woo et al. 2004). It was discovered through exploratory case studies in the construction sector that the primary medium for information interchange between project stakeholders is paper, which is both sluggish and inefficient in retrieval, and there are no effective links between departmental systems for electronic information access (Gyampoh-Vidogah et al. 2003).

Building information modeling (BIM) is a sophisticated, three-dimensional (3D) model-based technique for developing and managing construction project information throughout a project's lifetime (Santhiya and Jagadeesan 2020). The advent of BIM as a promising visualization tool, with the ability to give a full variety of digital construction data, has improved safety performance (Zhang et al. 2013). Integration of BIM for health and safety management has been an area of interest for researchers. Zhang et al. (2015) developed an automated rule-checking framework that integrates safety into BIM effectively and provides practitioners with a method for detecting and preventing fall-related hazards. Other examples of recent and relevant efforts that integrate BIM with safety include works by Collinge et al. (2022) and Kim et al. (2024). BIM has facilitated the process of team collaboration and KM in the construction industry, and this has also been highlighted in numerous previous studies (Almarshad and Motawa 2012; Ho et al. 2013; Lin 2014). Therefore, BIM possesses the potential to positively influence the project safety KM issues on construction projects. Although systems for effective KM already exist with some caveats (existing software solutions that provide forms and databases for managing health and safety data), a parallel focus on previously mentioned barriers of LFI in construction cannot be underestimated. Therefore, exploiting capabilities of BIM to provide a BIM-based database for storing and accessing accidents knowledge that is

integrated with the 3D model could be instrumental to LFI. Additionally, integration of BIM provides a unique opportunity to utilize the as-built 3D models, that reflect the progress of work at site at the time an accident occurs, to capture the details of the accident (site environment, accident circumstances, and so forth) and the events leading to it, within the BIM environment. The idea proposed here is to use the 3D model to develop short accident simulations that can be stored within the BIM-based accidents database and used for the purpose of safety communication and training of workers. This also potentially can assist in better investigation of root causes that led to the accident. Development of such simulations would require data from accident investigation reports (site photographs, interview logs of workers, and other materials) and feedback from experts and accident witnesses upon watching the simulation, thereby assisting in collaborative and detailed investigation.

The idea of using accident simulations for construction accidents investigation and analysis, KM, and subsequent LFI is not well explored in research. The benefits of 3D visualizations for incidents, accidents, and disaster management have been recognized in other industries. Three-dimensional forensic science integrates a suite of 3D techniques to reconstruct criminal events and to support the interpretation and communication of evidentiary material (Carew et al. 2021). Ebert et al. (2014) introduced an immersive virtual reality (VR) display for forensic crime-scene reconstruction. Jiao et al. (2018) proposed a virtual-reality method that digitally reconstructs traffic accidents from video footage or still images. D'Anniballe et al. (2020) demonstrated an augmented-reality system capable of recreating a real aircraft crash scene as a three-dimensional representation. In the maritime domain, Smith et al. (2020) presented examples in which simulations and animations enhance understanding of marine accidents and outlined characteristics that make such tools suitable for litigation. Within this context, simulation and animation are employed to analyze vessel movements and operator decision pathways, including potential alternative actions, and to render visual reconstructions that elucidate complex events and systems for nonspecialist audiences. These are just some of the examples in which the value of 3D simulations has been recognized as instrumental to incident investigation and analysis and in some cases for training of those that potentially may be involved in similar incidents in the future. Surprisingly, although BIM has existed for more than 2 decades in the construction industry, it is yet to be shown how it can be adopted to assist experts in accident investigation and analysis, and to learn from the outcomes of such investigations. This research reports the first effort to utilize the visualization capabilities of BIM and its functionality as a building and construction database tool that can support construction team collaboration and KM for effectively learning from past accidents.

Although there is a plethora of published literature in the domains of construction health and safety and KM for construction (Mazher 2025), there has been little research on the function of knowledge acquisition, storage, and transfer in construction safety management, especially in terms of utilizing BIM as a central database that promotes team collaboration and from the point of view of enhancing LFI. Therefore, the aim of this research was to exploit BIM technology to create a central repository for accident investigation data and information in an attempt to neutralize the accidents KM and LFI issues. Moreover, the visualization aspect of BIM can enable project stakeholders to reimagine the past accidents using accident animations, as used in other industries, to improve construction accident investigation outcomes and to provide awareness to the management and workers regarding the safety procedures and protocols that need to be implemented at a construction project site. It also would allow the safety officers to conduct training sessions via accident simulations rather than exposing

the workers to the site itself, providing a zero-risk environment. This is achieved by proposing a BIM-based construction accidents knowledge database management system (BIM-CAKDMS) that provides better opportunities to maintain a structured and project model-oriented accident database, and allows for development of accident simulations that can potentially enhance KM and LFI. Both the development and validation of the BIM-CAKDMS are documented in this research. The methodology adopted in this research is in line with that of similar research efforts in which validated BIM-based prototypes were presented to show enhancement of certain workflows in construction project management after the integration of BIM (Ali et al. 2020; Kim et al. 2015; Shen and Marks 2016).

The significance of our contribution in this research is not only a better reporting tool, but a paradigm shift from static accident documentation to dynamic accident reconstruction. Existing tools manage safety and accident data as discrete, static artifacts: forms, checklists, photographs, and PDF reports pinned to two-dimensional (2D) drawings. They excel at answering what happened and when, but they fundamentally lack the capability to reconstruct and visualize how an accident unfolded within the complex, three-dimensional, and time-varying context of a live construction site. This inability to capture and replay the spatiotemporal dynamics of accidents is a critical gap that may prevent the needed knowledge transfer and true contextual understanding, and may be a key reason why similar accidents recur despite extensive documentation efforts. Consider a concrete example: when a worker falls from scaffolding, existing tools can efficiently record the date, location, injury severity, violated safety protocols, and even attach site photographs. However, they cannot show how the specific scaffolding configuration, the worker's movement path, the placement of materials, the lighting conditions, the proximity of other workers, and the temporal sequence of events interacted in three-dimensional space to create the conditions for the fall. This contextual, spatial-temporal information is precisely what accident investigators need to understand root causes and what workers need to internalize lessons learned. Our BIM-CAKDMS was developed specifically to fill this gap by leveraging the as-built BIM model as a "digital twin—so to speak" of the accident environment at the exact moment of the accident. Our proposed system's primary innovation lies in its ability to integrate accident investigation data directly into the 3D BIM model, creating high-fidelity animations and simulations that allow stakeholders to analyze the chain of events, understand contributing factors in their actual spatial and temporal context, and internalize lessons learned through experiential rather than abstract learning. This moves beyond static knowledge transfer to create a form of institutional memory that is both accessible and cognitively efficient.

Literature Review

KM in Construction Health and Safety

The significance of KM in modern disciplines stems from its significant impact on enhancing the value for organizations and institutions and the economy in general, by providing competitive advantage and improved decision-making with the least number of mistakes. KM also creates an environment that fosters creativity and innovation through knowledge sharing and networking with experienced individuals (Subramaniam et al. 2011). KM is motivated by the desire to exchange and transfer information, but the process encounters various challenges. Kim and Park (2003) identified noncomputerized knowledge, administration, indexing (tagging), and integration as major knowledge management difficulties. Collaboration is necessary for sharing knowledge resources, which

calls for integrated systems and technologies to enable the creation, access, and sharing of knowledge with those in need (Okere 2017). Shokri-Ghasabeh and Chileshe (2014) found that the ineffective collection of lessons learned—a crucial component of KM—is hampered by a lack of the proper tools, such as an accessible data repository.

The complex, dynamic, and temporary nature of building projects have been partially blamed for the disproportionate accident and illness rate in the construction industry. To cope with related complications, it is essential for a construction firm to recognize, capture, store, and share safety knowledge effectively (Hallowell 2012). KM is not a recent term for construction firms and its significance is well understood. However, organizations must regularly assess the performance of their KM-enabling capabilities (Okere 2017). To assess the KM strategies being implemented in the construction industry Hallowell (2012) conducted 11 case studies of general contractors. The research showed that contractor firms suffer from inadequate storage and transfer of safety knowledge that is frequently gathered from a variety of internal and external sources. This leads to workers being unable to manage safety related issues due to a lack of access to relevant essential information. Conversely, firms possessing sophisticated formal procedures, i.e., safety mentoring and data entry systems to capture tacit safety knowledge in the form of issues and their experience-based resolution strategies, clearly outperformed other firms. To identify areas in which failures in learning from accidents are occurring, Stemn et al. (2018) used bowtie analysis to organize the literature on failing to learn from accidents so that scholars and practitioners can be aware of the top priority areas. They study argued in favor of automated storage and wide transmittal of lessons learned in addition to making arrangements to provide efficient access to the workforce to be able to retrieve and utilize these lessons in a time of need. Maslen and Hayes (2016) emphasized the importance of incident-reporting systems for organizational knowledge management with the aim of avoiding undesirable events in the future.

BIM for KM

A building project's transient character might make it challenging to communicate, share, and reuse knowledge (Wang and Meng 2018). BIM already has been facilitating the process of KM in construction industry. Ho et al. (2013) developed a BIM-based knowledge sharing management (BIMKSM) system capable of combining all construction BIM-based KM information into a single source by incorporating outside elements, such as problem and solution descriptions, comments, and ideas. The system was applied on a case study in Taiwan and the results revealed that engineers gained a better understanding of previously captured information and experience from everyone involved in various projects based on its visual capabilities. A very similar construction BIM-based knowledge management (CBIMKM) system was proposed by Lin (2014), which utilizes both explicit and tacit knowledge of field engineers which can be shared and reused using a knowledge map built on 3D platform. For the purpose of decision-making in building maintenance, Almarshad and Motawa (2012) proposed a knowledge management of building maintenance (KMoBM) system capable of retrieving pertinent operation cases as well as their associated damaged building elements, using BIM. Based on the case studies and interviews it was concluded that the proposed system may help in establishing the history of maintenance issues within a facility and it may offer a thorough insight to enhance the decision-making process. To explore the potential enhancement of KM through the use of BIM, Wang and Meng (2018) conducted a research study in United Kingdom (UK) construction organizations

based on a quantitative questionnaire survey on the improvement of proactive KM, life-cycle KM, and KM processes. The identified KM improvements included collaboration, a database for retrieving data and knowledge, and visualization for improving knowledge representation and communication.

BIM-Based Visualization for Safety

Chiu and Russell (2011) discovered that visualizing construction data improves data cognition. Although visualization in the construction industry is used primarily to enhance communication in architectural design, its advantages can be realized at any stage of a project's life cycle (Bouchlaghem et al. 2005). The high incidence of accidents and fatalities in the construction sector necessitates carrying out more-effective and -efficient safety management practices. A compelling method for enhancing safety management in the industry is through safety training (Sawacha et al. 1999), which would allow the workers to acquire mandatory safety knowledge in a relatively shorter period in a zero-risk environment. Construction operations and the surroundings can be illustrated graphically in 3D using visualization technology, which offers a visual approach to safety instruction (Guo et al. 2017). Conventional safety trainings are teacher-student based, and are incapable of assessing both trainer and trainee performance during and after training sessions. Teizer et al. (2013) presented a novel strategy by integrating three-dimensional data visualization and real-time location tracking technologies into current iron workers' education and safety training. The proposed framework detects and visualizes unsafe practices in a training environment. Pedro et al. (2020) proposed a scenario-based evaluation framework for visualization-enhanced safety education to address the constraints of the current construction safety education assessment methods. The system was implemented with students majoring in construction management, and learner assessment is carried out using visualization-enhanced: safety theory questions, site inspection scenarios, and job safety analysis review. The findings revealed that the suggested method has a great deal of potential as a cutting-edge assessment tool for safety education by bridging the disconnect between teaching and actual workplace circumstances. According to the educators, one of the main advantages of this tool is its capacity to accommodate a variety of assessment tasks providing the opportunity for the students to showcase their safety skills. Azhar (2017) drew attention to construction site safety planning by presenting three case studies, and conducted a comparative analysis of 2D static drawings and 3D and four-dimensional (4D) dynamic tools. The results indicated that the 3D and 4D visualization technologies were more effective in communicating and implementing the site safety plans, because they accurately reflect the conditions found on a job site. A proof of concept with regards to firefighting situational awareness was presented by Chen et al. (2021) to train in-field individuals by integrating augmented reality and VR technologies with BIM. The proposed system allows firefighters to make more-informed decisions in haphazard scenarios. Shen and Marks (2016) developed a system for near-miss data collection and location-based visualization, in which near-miss data are collected within BIM and the location of the near-miss events is highlighted in the 3D model.

Construction Health and Safety and Cognitive Load

Human cognitive-behavioral studies explore the connection of the mind and body by measuring cognitive activities such as cognitive load (CL), situational awareness, perceptual processing, and information processing (Curtin and Ayaz 2017). Although there

are several definitions of CL, Brünken et al. (2016) believed that it is the mental effort expended when processing information. According to CL theory, the limitation of working memory in humans allows simultaneous handling of only seven unconnected objects (Doswell and Skinner 2014). Thus, when human working memory is forced to quickly process and absorb any greater quantities of information, it often leads to cognitive overload. As a result, the volume of information that must be managed can have a great impact on task performance. From a cognitive standpoint, information-intensive procedures are involved in every significant task in the architecture, engineering, and construction (AEC) sector. According to Kalyuga (2009), dynamic interactive animations can support cognitive processes that are critical for learning while also assisting in lowering the needless burden brought on by poorly designed instructions or difficult activities. Furthermore, a number of studies have examined the broad connection between cognitive problems and performance. In particular, it was discovered that performance problems might arise from both an excessive amount of CL (overload) and insufficient CL (underload) (Lindblom and Thorvald 2019; Paas et al. 2004). Cognitive underload can occur when a user relies heavily on a system to perform tasks, leading to a loss of interest in those tasks, which increases the likelihood of task-related mistakes. Conversely, systems can produce volumes of data that are greater than the capacity of the human mind can handle. These realizations prompted Mendel and Pak (2009) to contend that lowering CL during information-intensive activities might improve user performance.

The concept of cognitive load has substantial significance to our methodology, which involves developing an accident knowledge database system and reconstructing the sequence of events derived from accident reports to discover the underlying causes of accidents in the construction sector. During the analysis process, people may become cognitively overloaded with information retrieval, integration, and problem-solving duties. This might make it more difficult for them to pinpoint the root reasons for the incident (Paas et al. 2016). Furthermore, cognitive load affects people's ability to process safety-critical information and make wise judgments in fast-paced, high-risk work conditions, which has an impact on health and safety in the construction industry. Therefore, assessing cognitive load is critical for verifying the notion that the developed system may greatly lower the cognitive load of comprehending a past incident.

Knowledge Gap

Construction accident data continues to be managed and shared, in some cases, through ad hoc or paper-based systems, leading to significant deficiencies in how lessons learned are captured and disseminated. Although previous studies have demonstrated the potential of leveraging information retrieval systems to identify construction hazards (Kim et al. 2015) and incorporating near-miss data visualization within BIM (Shen and Marks 2016), several key gaps remain unaddressed.

First, there is no unified platform that systematically integrates all historical accident records within BIM environment. Existing approaches still rely heavily on either spreadsheet-based logs or partial digital archives, making it cumbersome for stakeholders to retrieve accident details and to contextualize them within a project's context and circumstances surrounding the accident, and this leads to difficulties in integrating this within the current BIM-driven workflows. For example, Zhang et al. (2015) developed a database for KM but did not integrate it with BIM. Second, although near-miss-related information provides valuable leading-indicator data (Shen and Marks 2016), it focuses primarily on near-miss incidents

rather than the full spectrum of accident events. This distinction is critical because near misses alone cannot capture the severity and comprehensive causes of major accidents, underscoring the need for a more holistic knowledge management system that addresses both minor and severe incidents. Moreover, little research has addressed the cognitive benefits of embedding accident simulations directly into a BIM-based environment. Although Kim et al. (2015) and Shen and Marks (2016) each proposed systems for hazards and near-miss information, their methods are still predominantly text and report based, which can prove difficult for new or less experienced workers to interpret and visualize. By contrast, developing accident simulations that recreate the chain of events in 3D offers a more immersive, context-rich experience, one that reduces cognitive load and supports better retention of critical lessons learned. Addressing these limitations, the present study utilized a mixed-methods research approach and proposes and validated a unique BIM-based system (BIM-CAKDMS) that centralizes historical accident data, enables multimedia-based re-creation of accident scenarios, and lowers the cognitive load for end users seeking to learn from past incidents. By bridging the gaps identified, this system aims to enhance accidents-related KM for promoting LFI in the construction industry.

Methodology

A three-phase modified research framework was adopted in this study that was sourced from Azhar et al. (2010) (Fig. 1). The phases

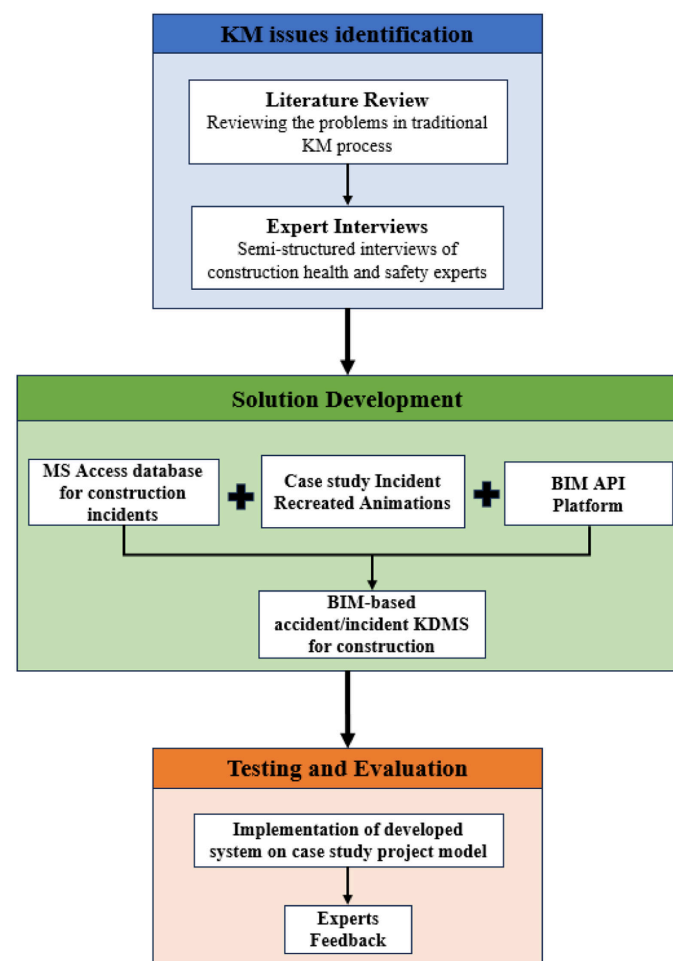


Fig. 1. Research methodology framework.

include (1) identification of knowledge management and relevant LFI issues through literature review and expert interviews; (2) BIM-based plugin development for construction accident knowledge management database in Autodesk Revit version 2023, development of a framework to create accident simulations, and creation of character animations of occurred accidents at construction sites using BIM models and Blender (a free and open-source 3D computer graphics software tool); and (3) testing and evaluation of the developed system using case studies of actual construction accidents in construction and a cognition questionnaire and expert assessments from the industry.

Identification of Barriers to Effective KM of Construction Accidents and LFI

As previously mentioned, limited research has been conducted in the KM and LFI domains in the field of construction health and safety. Therefore, challenges in KM for the construction sector initially were shortlisted after a thorough review of the extant literature. For the literature review, Google Scholar was chosen as the primary source of research articles (Mazher 2025). The keywords used to search relevant articles were “knowledge,” “knowledge management,” “effective knowledge management,” “barriers,” “critical factors,” “implicit knowledge,” “explicit knowledge,” “BIM for knowledge management,” and “KM for health and safety.” Utilizing these search keywords, nine relevant publications related to KM in the construction industry were shortlisted. Additionally, as previously discussed and emphasized in previous academic studies, there is an intrinsic relationship between KM and LFI, highlighting how the adoption of strong KM practices can significantly increase the effectiveness of the LFI process. As a result, papers focusing on learning from incidents also were included in this process. Moreover, it is arguable that enhanced KM techniques enabled by BIM technology might benefit the LFI process. Therefore, the objective is to assess how creating and deploying a cutting-edge BIM-based knowledge management system might not only remove barriers to effective KM but also deal with issues that are retarding LFI in the construction industry. After reviewing the LFI and KM papers, 16 barriers were obtained. After that, content analysis was conducted to assess the problems with overlapping concerns. In addition, the list of problems was presented to six construction health and safety specialists (Table 1) to obtain their opinions on these barriers, and they were asked to evaluate if the list contained all the potential relevant issues in construction accidents KM and LFI, and whether any elements could be added to or deleted from the list. As a result, barriers with various names but similar meanings were either combined or removed. This resulted in the identification of 13 significant KM and LFI barriers (Table 2).

Table 1. Profiles of experts

Profile	Category	Frequency
Organization	Contractor	2
	Consultant	4
Experience (years)	5–10	2
	11–15	1
	15 and above	3
Job role	Health and safety supervisor	2
	HSE engineer	1
	Health and safety manager	3

Table 2. Barriers to KM of accidents and LFI in construction

Challenge	References
Disintegrated system, thereby increasing work repetition	Okere (2017)
Lack of contextualizing	Smith et al. (2015)
Inadequate resource that serves as a one-stop shop for accessing pertinent data, lessons learned, and best practices	Okere (2017), Ayatollahi and Zeraatkar (2020)
Limited dissemination of findings	Drupsteen et al. (2013), Margaryan et al. (2018)
Nonstandardization of file directories, file plans, and document templates	Okere (2017)
Complex reporting systems	Smith et al. (2015)
No communication tool to share tacit knowledge	Ayatollahi and Zeraatkar (2020) Okere (2017)
Paper-based exchange of information (slow and inefficient)	Gyampoh-Vidogah et al. (2003)
Nonexistence of efficient interfaces between departmental systems to access information electronically	Gyampoh-Vidogah et al. (2003)
Limited quality of initial reports	Drupsteen-Sint (2014), Drupsteen et al. (2013), Okere (2017)
Nonidentification of systemic causes	Drupsteen-Sint (2014)
Lack of visual insights	Parker et al. (2018), Drupsteen et al. (2012)

System Development

The proposed BIM-based construction accident knowledge database management system is composed of two subsystems.

The construction accident knowledge database and plugin integrated within a BIM platform (Autodesk Revit), and the development of character animations to recreate construction accident simulations using a BIM compatible animation software (Blender).

Development of BIM-CAKDMS Database and Plugin

During this phase, a prototype was created to address the KM and LFI concerns identified in the previous phase by following the steps shown in Fig. 2. Firstly, a template was developed for recording accident data on construction projects. For this purpose, existing templates by international bodies operating in the domain of health and safety were reviewed, and finally a template developed by the Occupational Safety and Health administration (OSHA) for accident investigation was adopted for this research. Thereafter a database was developed in Microsoft Access to record all the necessary details of an accidents (such as title, date, accident type, accident description, department, job role, and equipment details, as well as supplementary materials such as photos, drawings, and videos). Microsoft Access was chosen because of its user-friendly interface for database building and manipulation, including ease of data entry, querying, and editing.

To develop a BIM-CAKDMS, the Autodesk Revit BIM platform was utilized along with its application programming interface (API) to integrate the accident database created using Microsoft Access. The integration of Revit and Microsoft Access was chosen for a variety of reasons, each originating from the unique benefits provided by both systems. Revit is the industry's leading BIM technology, widely known and used for its strong capabilities in architectural design, modeling, and collaboration in the construction sector. One important aspect of Revit is its ability to communicate with external databases using APIs. This feature allows for smooth

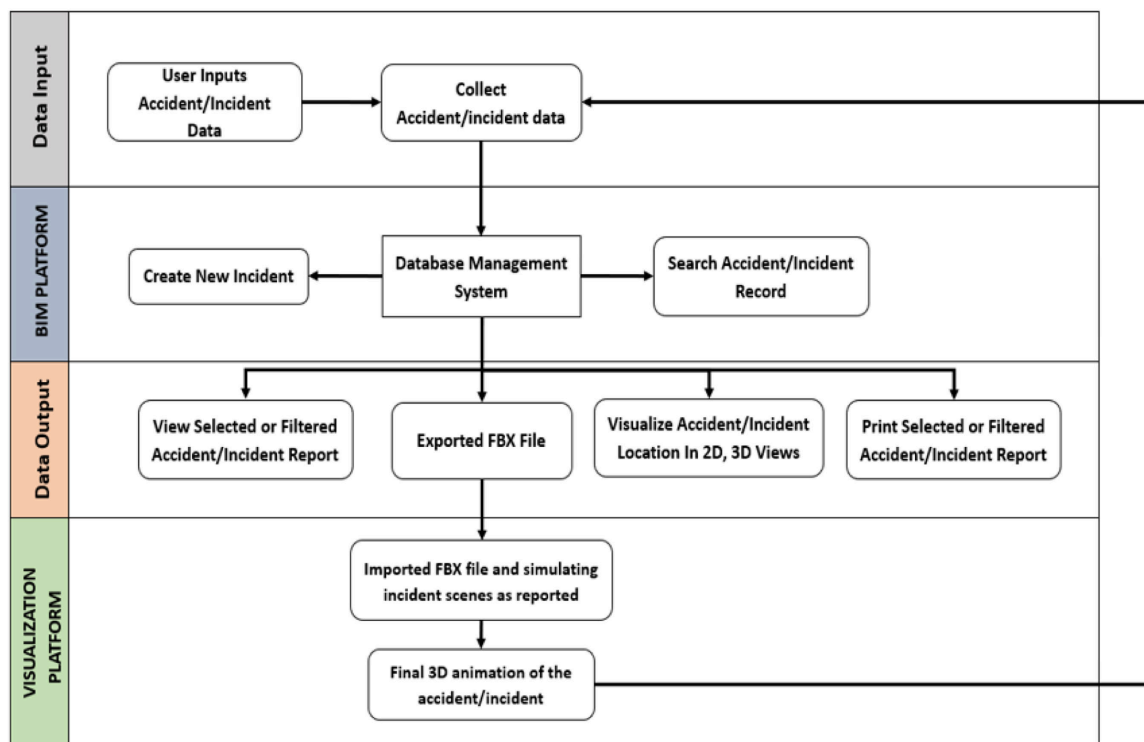


Fig. 2. BIM-CAKDMS process map.

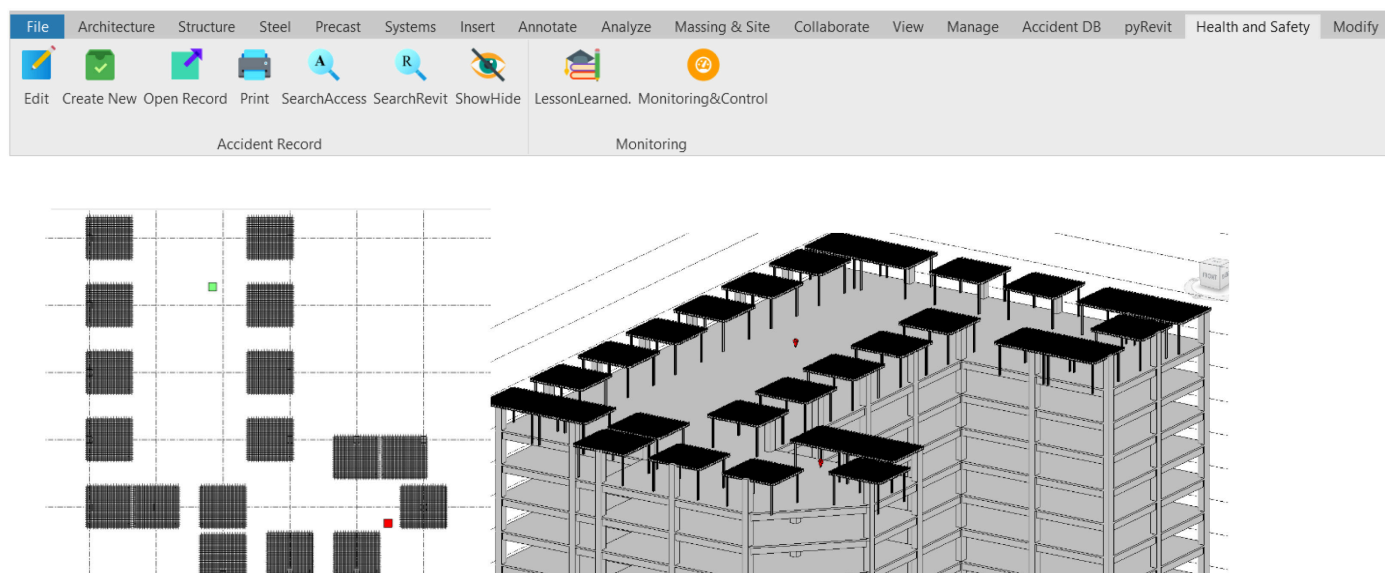


Fig. 3. Database plugin and accident locations visualization in Revit in 2D and 3D.

communication between Revit models and external databases. The accident database plugin was developed using Python programming. The PyRevit add-on facilitated the integration and upload of the code files into Revit. The plug-in constitutes the following functions: (1) create an accident report; (2) view and edit the data for existing accidents in the database; (3) view the accident report's spatial location in the BIM model; (4) filter accidents using different criteria; (5) print the accident report; (6) show or hide accident points in 3D model; (7) track, monitor, and control accident causes status; and (8) review and write lessons learned.

During the first data input step of the process map (Fig. 2), users start the accident reporting process by entering numerous data points, such as personnel and accident details into an Microsoft Access database. These extensive data guarantee that all pertinent information is collected for simple tracking and retrieval. In the following step, users may create a new accident instance within a project's BIM building model, indicating its exact position in a building's floor plan and tying it to the appropriate accident report in the Microsoft Access database. The BIM platform also supports focused searches of individual occurrences based on a variety of inputs. The output phase allows users to access and see accident records in both 2D and 3D formats on the Revit platform. Users also may print accident reports for documentation and save the project's 3D model as an FBX file for further usage in 3D animation applications. The database plugin interface and incident location points within a project's model are shown in both 2D and 3D views in Fig. 3.

In the last stage, the project's FBX file is loaded into 3D animation software to generate a detailed 3D world. Characters, locations, equipment, and scenarios are animated to create a storyboard narrative that illustrates the events outlined in the accident investigation report. The finished 3D animation film then is imported into the Microsoft Access database and connected to the related accident report, allowing users to access and see it straight from the event record in the database.

Accident Recreation

After the collection of accident data and visualizing its location within the BIM project, the next step is to simulate the scene and event of the accident based on the evidence collected. Obtaining actual accident reports was difficult given the sensitive nature of

the subject for any organization. As a result, publicly accessible data were used to gather case studies for this research. For this purpose, three published accident reports were selected as case studies, one from OSHA's Construction Incidents Investigation Reports Database [Florida Formwork Table Collapse (OSHA 2024)], and two from the Government of Alberta, Canada's, worksite fatality investigation reports [Calgary Basement wall collapse; Athabasca Fall on Steel Rebar (Alberta 2024)], to recreate the chain of events based on text and photo-based description in the selected documents. The animation software utilized for these case studies was Blender, which has capabilities such as 3D modeling, sculpting, rigging and animation, physics simulation, rendering, texturing and materials, compositing, video editing, and motion tracking.

The framework developed to recreate the accident animation is depicted in Fig. 4. Collecting detailed input data is critical for creating animations that correctly reflect an accident event's situation. Witness statements, site images, and precise accident investigation parameters such as date, time, roles, equipment, safety gear, and environmental variables are among the data collected. The animation development begins with importing an up-to-date Revit building model corresponding to the accident event, which is followed by creating a storyboard outlining pre- and postaccident events. The accident's animation characteristics then are determined, including events sequence, location information, viewing angles, and regulatory context. To guarantee realism and accuracy, the animation should be validated by comparing it with witness statements. The animation and simulation thus developed should be presented to accident witnesses (if any) and it must be reviewed by experts. Feedback obtained from witnesses and experts may help in better identifying root causes. Furthermore, team discussions supported by 3D simulations of accidents will provide an interesting opportunity to the team to analyze details of the accident, which may not be possible using traditional means of information sharing, such as photos of the site showing the location of the accident and transcribed records of witness statements. Any disparities motivate more data collection to improve the animation. After it is validated, the animation is integrated into the accident database, making it more accessible and useful for efficient analysis and communication. This iterative procedure ensures that the animation accurately represents the actual accident's occurrence.

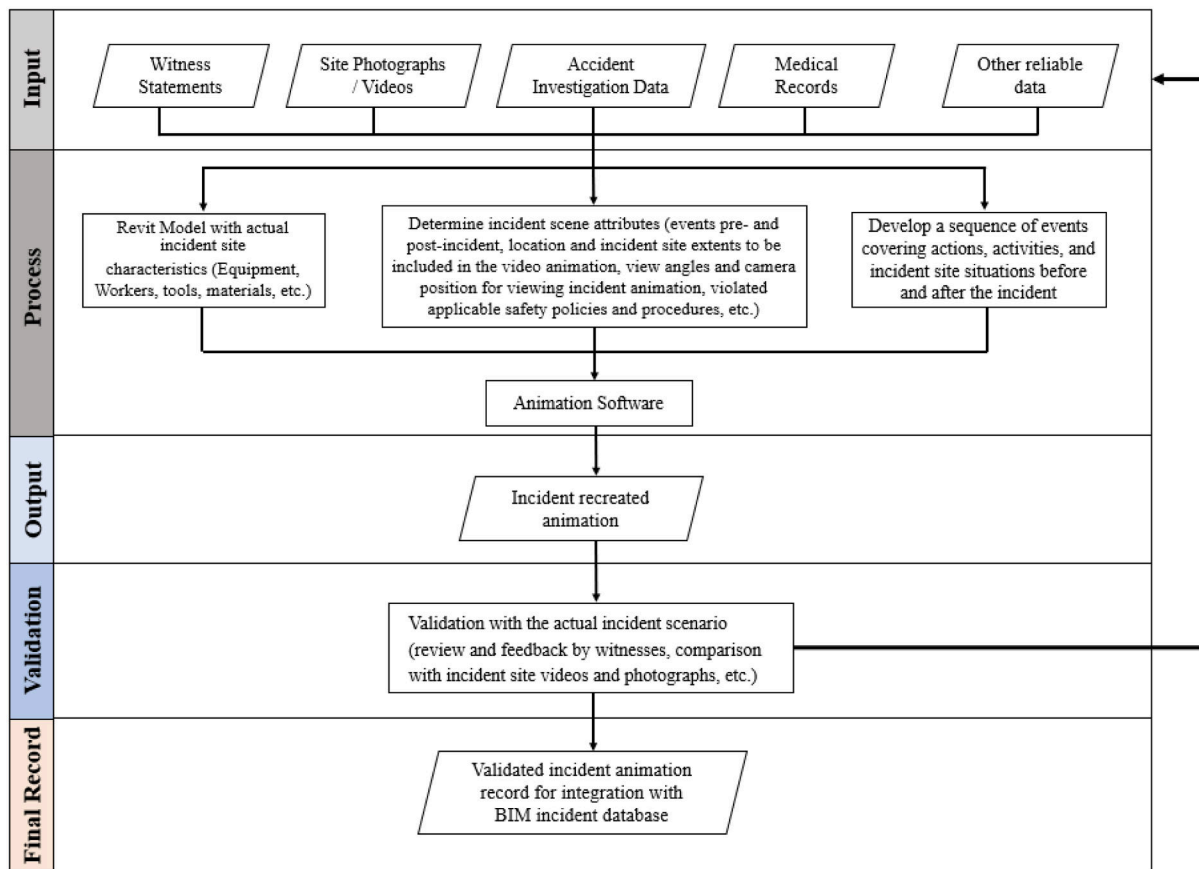


Fig. 4. Process map of incident recreation.

The three accident case studies were used to develop BIM models to reflect the building conditions in each case, and then the BIM models were exported to the character animation software Blender to recreate the accident scenario using the details provided in the case studies (Fig. 5).

System Evaluation and Validation

Questionnaire Survey

A questionnaire was developed to assess the efficacy, need, usability, benefits, and implementation of the developed BIM-CAKDMS. The questionnaire consisted of three sections. The first section was a brief introduction to the topic of the research. Section 2 collected the background information of the respondents (email, company type, company size, designation, and work experience in the respective industry). The final section of the questionnaire consisted of the final list of barriers to effective accident knowledge management and LFI. A 5-point Likert scale was used to gauge the respondents' opinions, with 1 denoting "strongly disagree" and 5 denoting "strongly agree." All safety experts received a comprehensive list of the 13 problematic issues in KM of construction accidents and LFI to assess the BIM-CAKDMS advantages. This exercise was carried out to better understand how the built system resolves the problems found throughout the accidents and LFI.

Ten health and safety specialists with expertise in the topic were chosen carefully for the review panel of experts. Although the sample size was small, it included each major category of stakeholder involved in construction health and safety (Ali et al. 2020; Shen and Marks 2016). The profiles of these experts are presented in Table 3. The experts were contacted individually in one-on-one meetings. Each participant was given the research background, an

introduction to the developed BIM-CAKDMS, and an explanation and demonstration of the tool. The key justification for choosing a more subjective method for evaluating the BIM-CAKDMS was the necessity to comprehend the views of experts in the field.

After the demonstration, semistructured interviews were conducted, and the questionnaire was administered. The relative important index (RII) approach was used to rank the created system's problem resolution capabilities. The equation to calculate the RII was (Ali et al. 2020)

$$RII = \frac{\sum W}{AxN} \quad (0 \leq RII \leq 1) \quad (1)$$

Cognitive Load Assessment

Measuring cognitive load is one of the most significant components of evaluating the effectiveness of a system to improve learning, problem-solving, and decision-making. The hypothesis given in this study emphasizes the need to decrease cognitive load to promote a better comprehension of earlier accidents, encouraging efficient transmission of lessons learned throughout the organization. According to cognitive psychology research, cognitive load has a significant impact on people's capacity to absorb and comprehend information (Sweller 1994). The cognitive load hypothesis suggests that learning and problem-solving abilities may be compromised when cognitive resources are overworked due to unnecessary processing demands (Sweller 2010). Therefore, assessing cognitive load is critical for verifying the notion that the developed system (BIM-CAKDMS) may greatly lower the cognitive load of comprehending an accident. To achieve the research goal, we performed an experiment involving two groups of participants to assess the cognitive load associated with different methods of accident-based learning. One group read the paper-based descriptive reports of accidents, and the other group used the BIM-CAKDMS and viewed animations based on the same reports.

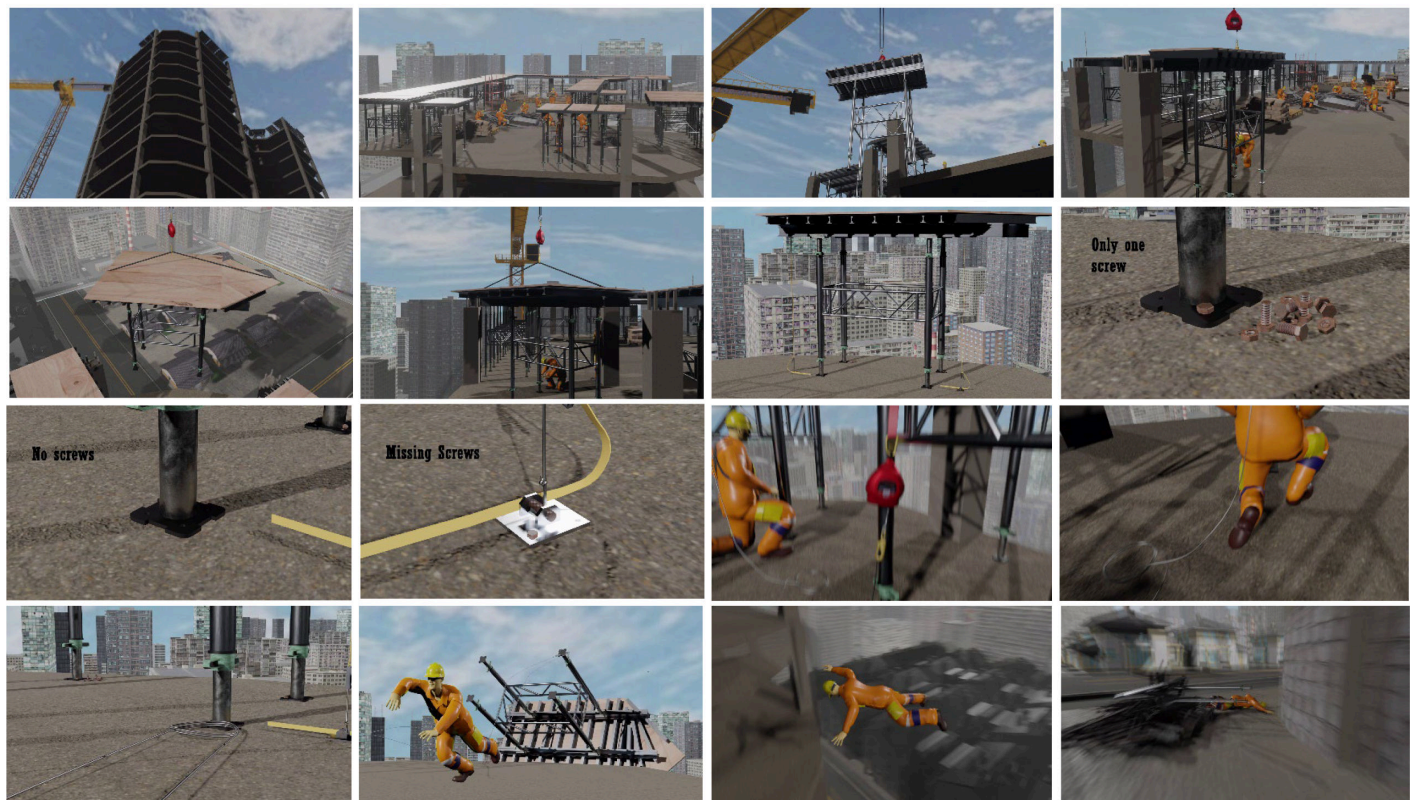
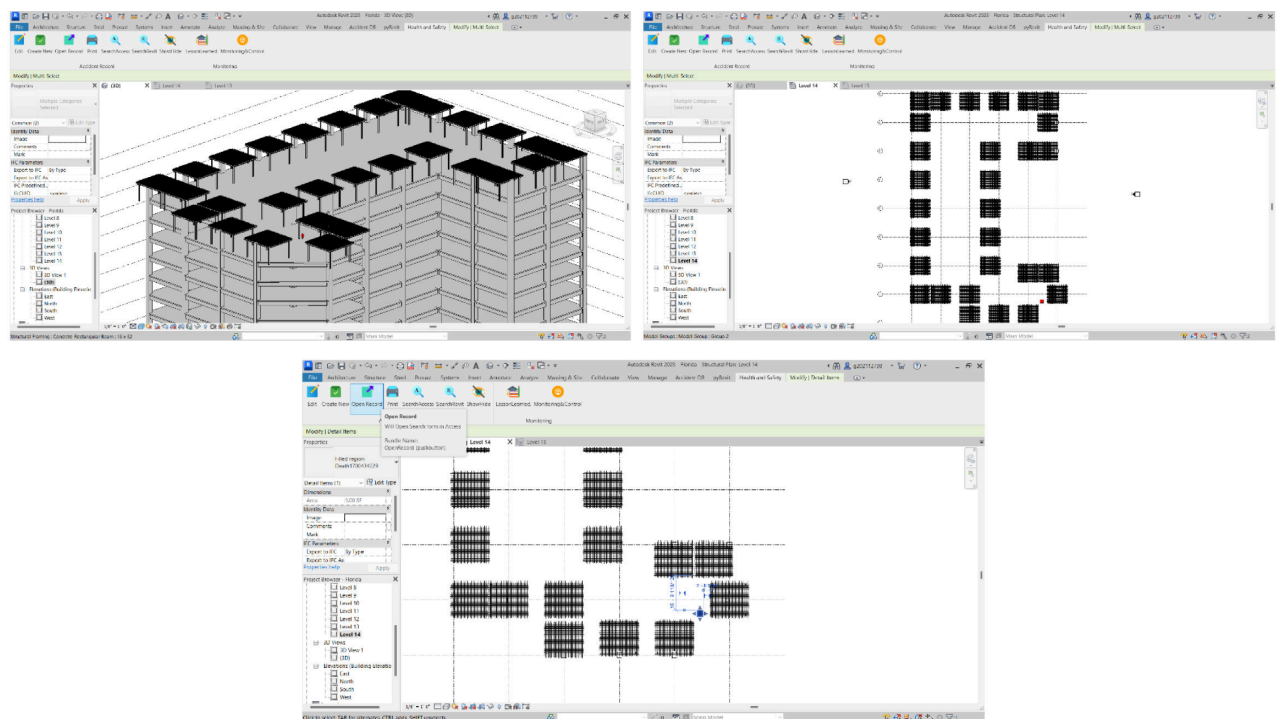


Fig. 5. Accident model and events recreation in Revit and Blender for one case study.

The study involved 12 Master's students from a construction engineering and management program at the first author's parent university, all of whom had prior knowledge of BIM and construction health and safety. Participants were allocated randomly to one of the two groups and provided with detailed instructions on the experiment's purpose and procedures. Participants reviewed the accidents in all three case studies. A questionnaire was administered at the end of each case study to assess the quality of learning from the given accident case studies

and to record the time they took to develop a good understanding of the chain of events.

The NASA Task Load Index (NASA-TLX) (Hart 2006) was used to assess cognitive load; however, the physical demand component was excluded because it was unrelated to our research. Participants assessed their mental demand, performance, temporal demand, effort, and frustration levels on a scale of 1 (low) to 5 (high). Task performance was evaluated based on the time taken to complete

Table 3. Profile of panelists

Profile	Category	Frequency
Organization	Contractor	5
	Consultant	5
Experience (years)	5–10	5
	11–15	3
	15 and above	2
Job role	Health and safety supervisor	3
	HSE group leader	2
	HSE specialist	1
	Health and safety manager	2
	HSE engineer	2

the tasks and the accuracy of their comprehension. Participants were asked to describe the accident in their own words and provide preventative actions for future events. Responses were rated on a 10-point scale for correctness, clarity, and depth. This gave insights into participants' comprehension and cognitive processes, which assisted in identifying areas for improvement in accident reporting and prevention efforts.

Results

BIM-CAKDMS Plugin Modules

This section contains an in-depth description of each function provided by the developed database management system plugin. The Create New pushbutton in the panel pops up a small window which asks the user to select the type of incident from the drop-down list, along with its coordinates in the 2D view on the current view or floor plan (Fig. 6). The type of accidents are color-coded accordingly i.e., red indicates fatality, green indicates near miss, yellow indicates doctor visit, blue indicates first aid, and orange indicates lost time. After selecting the accident type and entering the x, y -coordinates, a Revit element ID of the particular accident instance shows the location of the accident in the project's Revit model. The Revit ID is copied by the user. When the user clicks the Okay button, a new accident record form is opened directly in the Microsoft Access database (Fig. 6). The user pastes the copied Revit ID in the Revit ID field along with other essential details of the entire accident (Fig. 6). After entering the necessary data in the form, the user can save the record, which creates a new accident report in the database as well as in the Revit model.

All accidents added to the Revit project's database can be viewed in the 3D BIM model. Selecting the accident marker on the floor plan and then clicking the Open Record pushbutton from the Health and Safety tab (Fig. 7) opens the concerned accident's report (Fig. 8). Similarly, the Edit pushbutton can be used to open a list of records in the database, and the user can query or search for any accident based on name, date, type of accident, department, and so forth. The Print pushbutton can be activated to open a list of records in the database, and based on the query by the user, any specific accident record can be printed (Fig. 9). To search for any record in the database, the Search Access pushbutton in the Health and Safety ribbon is provided, which opens the list of records (Fig. 10), and the user can search any record based on the fields in the search form. The Search Revit pushbutton in Revit can be utilized to open a pop-up window (Fig. 11) in which the Revit ID copied from the database is pasted, so that the incident point is highlighted by a

colored square Revit element at the location of the accident in the relevant floor plan.

To monitor and control the highlighted accidents, the Monitoring and Control pushbutton is provided to view the list of incidents along with multiple fields in which the senior personnel can assign responsibility to a particular individual, view the status of completion of assigned tasks postaccident, and brief the planned actions to mitigate the accident from recurrence Fig. 12.

Finally, to view the root causes and lessons learned for each accident, the Lessons Learned pushbutton is activated to open the lessons learned form in the Microsoft Access database. The list of accidents records is displayed along with their corresponding root causes and lessons learned highlighted from the report (Fig. 13). The Overall Lessons Learned field allows the health, safety and environment (HSE) manager to summarize all the key lessons learned from all the accidents throughout the entire project, which can be disseminated within the organization.

BIM-CAKDMS Plugin Evaluation

Table 4 presents the mean value, RII value, and ranking of the barriers to KM of construction accidents data and LFI that can be successfully addressed and fixed using the created BIM-CAKDMS. It is derived from the opinions of the experts, gathered on a 5-point Likert scale, where 1 denoted "strongly disagree" and 5 denoted "strongly agree."

The overall mean scores indicate that the majority of the experts provided positive ratings (agreed or strongly agree), indicating that the proposed system substantially resolves the KM and LFI issues. Ten of the 13 issues were deemed to be addressable by 80% or more compared with other issues based on RII values. Among all the highlighted barriers, disintegrated systems and lack of visual insights were the top ranked issues that can be mitigated through the developed system, indicating that the BIM platform plays an essential role in terms of integrating the scattered information. Experts also mentioned that this integration of accident information with the as-built construction drawings and accident animations would provide better insights to the users about the chain of events that caused the accident to occur. Lack of database, which includes all accident facts (description, evidence, statements, lessons learned, and so forth), was listed as the third top-ranked problem that the proposed system can solve, which suggests that the use of BIM as a central database for accidents or any other information related to the project is an effective idea. There was minimal difference in the mean scores of the barriers that the proposed system can address (Table 4). Barriers such as information inaccessibility, nonstandardization of files, paper-based data sharing, and lack of contextualizing had similar average scores which were very close to the average score of the top-listed issues, emphasizing that the developed tool is very likely to handle the majority of these concerns. Conversely, limited sharing of tacit knowledge, complex reporting systems, and nonidentification of systematic causes remained slightly troublesome, as per the experts' perceptions, and therefore were placed at the end of the list in terms of their RII values. This could be explained by the fact that the proposed system capitalizes on the visualization and data management capabilities of BIM.

No explicit effort is made in the proposed system to capture safety expert's tacit knowledge in investigating and analyzing accidents. The proposed system still depends on the quality of input obtained during the accident investigations and on the collection and documentation of lessons learned. The same barriers that hinder the capture of tacit knowledge of safety experts in accident investigation and analysis on construction projects still exist in the

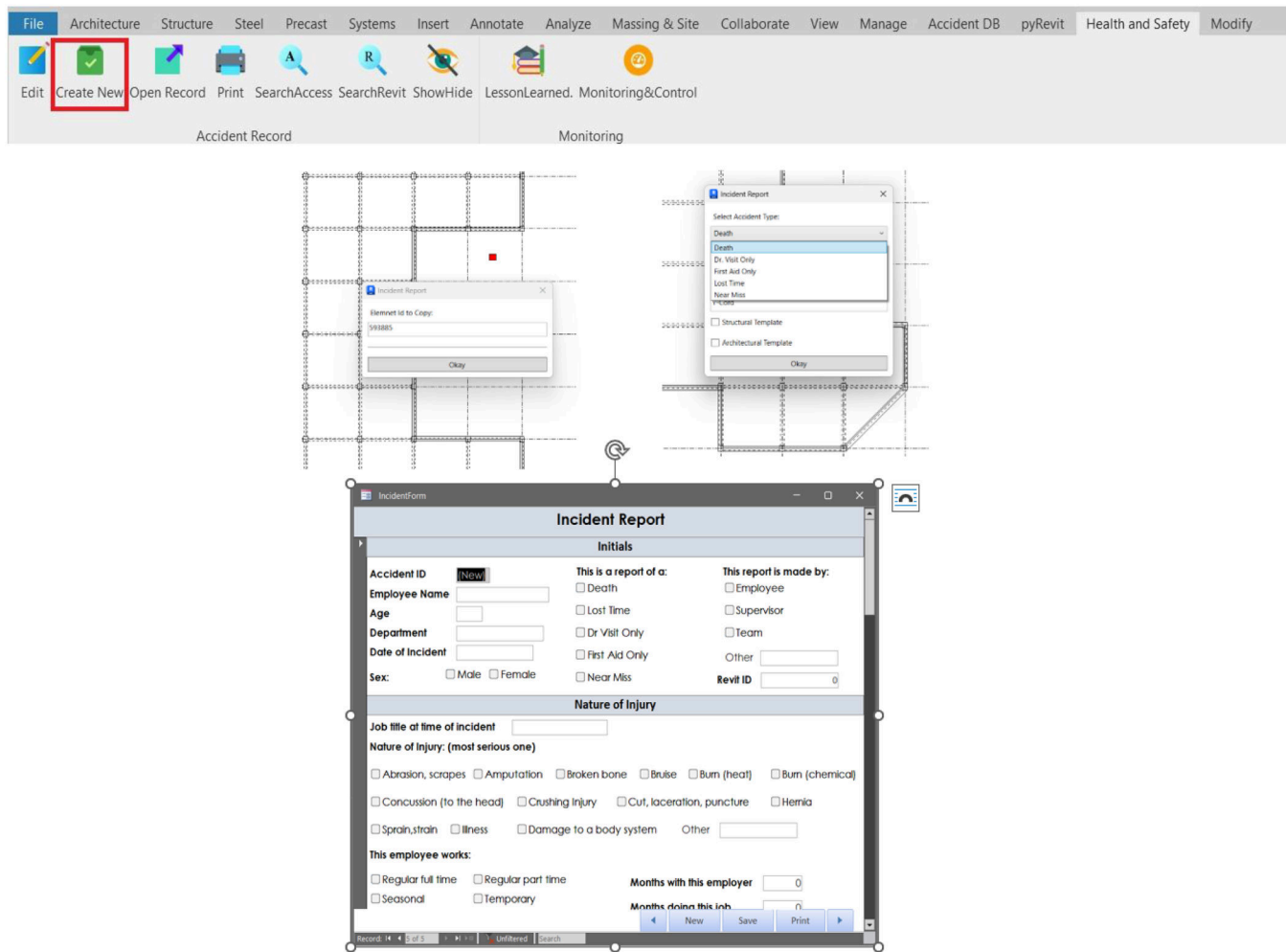


Fig. 6. New accident definition in Revit model and the Microsoft database.

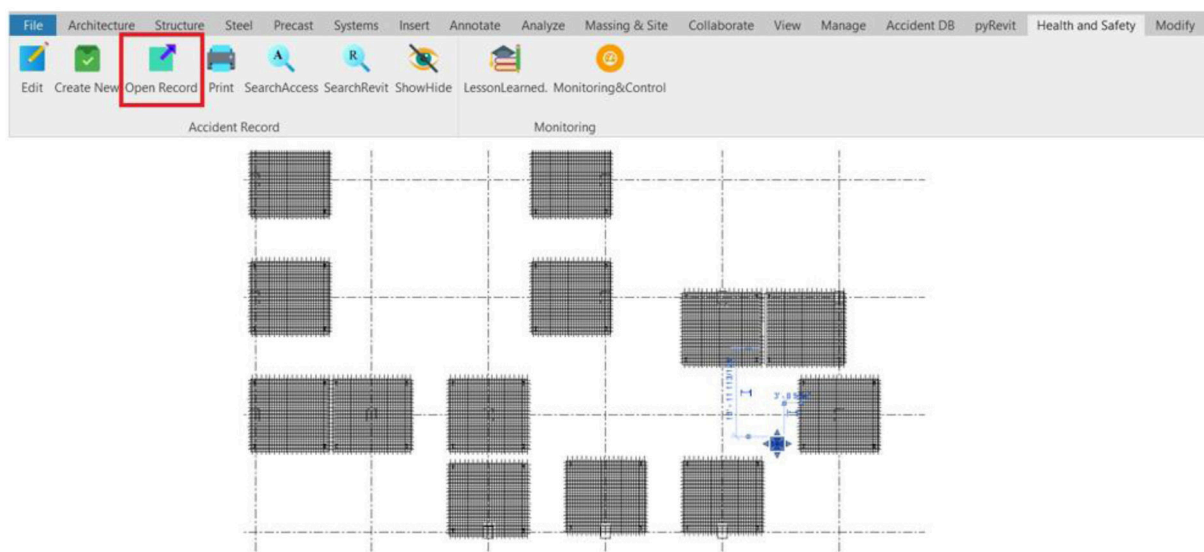


Fig. 7. Selecting accident point to open the record.

proposed system. Therefore, additional and external efforts will be required to overcome such barriers, which were outside the scope of this research. In a study of the impact of collaborative innovation activities and BIM application on innovation capability

in the construction supply chain, Qiao et al. (2021) found that BIM application can promote explicit knowledge sharing in the construction supply chain; however, it has no significant impact on tacit knowledge sharing.

The figure displays three screenshots of the 'IncidentForm' application, showing different sections of an accident report for a selected incident point.

Top Left Screenshot: Initials

- Accident ID:** [Blank]
- Employee Name:** Worker1
- Age:** [Blank]
- Department:** Formwork
- Date of Incident:** 01/09/2016
- Sex:** ☒ Male ☐ Female
- This is a report of a:**
 - ☒ Death
 - ☐ Lost Time
 - ☐ Dr Visit Only
 - ☐ First Aid Only
 - ☐ Near Miss
- This report is made by:**
 - ☐ Employee
 - ☐ Supervisor
 - ☒ Team
 - ☐ Other [Blank]
- Revit ID:** 583490
- Nature of Injury**
 - Job title at time of incident:** [Blank]
 - Nature of injury: (most serious one)**
 - ☐ Abrasion, scrapes
 - ☐ Amputation
 - ☒ Broken bone
 - ☐ Bruise
 - ☐ Burn (heat)
 - ☐ Burn (chemical)
 - ☐ Concussion (to the head)
 - ☐ Crushing injury
 - ☐ Cut, laceration, puncture
 - ☐ Hernia
 - ☐ Sprain, strain
 - ☐ Illness
 - ☐ Damage to a body system
 - ☐ Other [Blank]
- This employee works:**
 - ☒ Regular full time
 - ☐ Regular part time
 - ☐ Seasonal
 - ☐ Temporary
- Months with this employer:** 0
- Months doing this job:** 0

Top Right Screenshot: Incident Description

- Exact location of the incident:** 3 THIRTY THREE DOWNTOWN at 333 Fern Street, West Palm Beach, FL, 33401
- Exact time:** 7:00 am
- What part of employee's workday?**
 - ☐ Entering or leaving work
 - ☒ Doing normal work activities
 - ☐ During meal period
 - ☐ During break
 - ☐ Working overtime
 - ☐ Other [Blank]
- Name of witnesses:** [Blank]
- What personal protective equipment was being used?** Miller Falcon MP20G-27/20FT cable lifeline
- Describe, step by step the events that led up to the injury:** On the day of the incident, the table-setting crews arrived at the site around 6:30 a.m. They held a planning meeting for about half an hour, and
- Attachments:**
 - Written witness statements [Blank]
 - Video [Blank]
 - Photographs [Blank]
 - Maps / Drawings [Blank]
- Incident Causes**
 - Unsafe Workplace Conditions (Check all that apply)**
 - ☐ Inadequate guard
 - ☐ Unguarded hazard
 - ☐ Safety device is defective

Bottom Screenshot: Corrective Actions

- What changes do you suggest to prevent this incident / near miss from happening again?**
 - ☐ Stop this activity
 - ☐ Guard the hazard
 - ☐ Train the employee(s)
 - ☐ Train the supervisor(s)
 - ☐ Redesign task steps
 - ☐ Redesign work station
 - ☐ Write a new policy/rule
 - ☒ Enforce existing policy
 - ☐ Routinely inspect for the hazard
 - ☐ Personal Protective Equipment
 - ☐ Other [Blank]
- What should be done to carry out the suggestions checked above?** [Blank]
- Written and Reviewed By**
 - Written by:** [Blank] **Title:** Team Lead
 - Reviewed by:** [Blank]
 - Department:** Formwork **Written Date:** 15/09/2016 **Reviewer Title:** H&S Manager
 - Review Date:** 30/09/2016
 - Names of investigation team members:** [Blank]
- Lessons Learned**
 - Root Causes:** 1. Inadequate fastenings of formwork legs.
 - Lessons Learned:** 1. Critical importance of continuous monitoring of weather

Fig. 8. Accident record of the selected accident point.

When commenting on the BIM-CAKDMS system, the expert respondents stated that their organizations use complex reporting strategies to record accident information in their databases. Although the fields in the accident report of the developed system are compliant with international templates, experts found these fields less informative and fairly basic compared with the systems deployed within their enterprises.

Cognitive Load and Task Performance Evaluation

The purpose of this experiment was to compare the possible impacts of visualization-based versus paper-based accident event comprehension on participants' CL. An in-depth understanding of the accidents is essential in various aspects of employee health and safety training and communication. Compared with conventional paper-based approaches, research has demonstrated that visualization aids, such as animations and simulations, can improve learning and retention of knowledge (Mayer 2005). Organizations may enhance safety communication by using visualization techniques to make complicated material more accessible and interesting. This eventually will lessen cognitive strain and increase employee knowledge retention (Alessi and Trollip 2000).

Three incident case studies were chosen for this exercise. The first incident report was lengthier and more complex than the others, the second was moderately complex, and the third event was the simplest of the three. A thorough analysis of the NASA-TLX data average scores for each of the three case studies was conducted. For the first incident, paper-based comprehension was the most cognitively demanding in terms of mental demand, temporal demand, effort, and frustration levels (Table 5). Participants' performance in the paper-based approach was marginally better than that in the visualization approach in terms of understanding the incidents based on their performance satisfaction level. The same pattern was observed for the other two cases—all the CL characteristics proved to be more demanding, except the performance parameter, for which the difference between paper-based comprehension and visualization-based comprehension of the accidents was quite small. The difference between the other four characteristics (mental demand, temporal demand, effort, and frustration) was rather considerable (especially for the second case) (Table 5). In addition, the case reporting Incident 1 was more challenging in terms of the series of

Incident Report

Initials

Accident ID: 1 This is a report of a: ☒ Death ☐ Last Time ☐ Dr Visit Only ☐ First Aid Only ☐ Near Miss

Employee Name: Worker1 This report is made by: ☐ Employee ☐ Supervisor ☒ Team ☐ Other

Age: Department: Formwork Date of Incident: 01/09/2016 Sex: ☒ Male ☐ Female

Nature of Injury

Job title at time of incident: Nature of Injury: (most serious one)

☐ Abrasion, scrape ☐ Amputation ☒ Broken bone ☐ Bruis ☐ Burn (heat) ☐ Burn (chemical) ☐ Concussion (to the head) ☐ Crushing injury ☐ Cut, laceration, puncture ☐ Hernia ☐ Sprain, strain ☐ Illness ☐ Damage to a body system ☐ Other

This employee works:

☒ Regular full time ☐ Regular part time ☐ Seasonal ☐ Temporary Months with this employer: 0 Months doing this job: 0

Incident Description

Exact location of the incident: 33THIRTY THREE DOWNTOWN at 333 Fern Exact time: 7:00 am

What part of employee's workday

☐ Entering or leaving work ☐ Doing normal work activities ☐ During meal period ☐ During break ☐ Working overtime ☐ Other

Attachments

Written witness statements: ☐ Video ☐ Photographs ☐ Maps

Incident Causes

Unsafe Workplace Conditions (Check all that apply)

☐ Inadequate guard ☐ Unguarded hazard ☐ Safety device is defective ☐ Tool or equipment defective ☐ Workstation layout is hazardous ☐ Unsafe lighting ☐ Unsafe ventilation ☐ Lack of needed personal protective equipment ☐ Unsafe clothing ☐ No training or insufficient training ☒ Lack of appropriate equipment / tools ☐ Other

Unsafe acts by people (Check all that apply)

☐ Operating without permission ☐ Operating at unsafe speed ☐ Unsafe lifting ☐ Servicing equipment that has power to it ☐ Making a safety device inoperative ☒ Using defective equipment ☐ Using equipment in an unapproved way ☐ Taking on unsafe position or posture ☐ Distraction, teasing, horseplay ☐ Failure to wear personal protective equipment ☐ Failure to use the available equipment / tools ☐ Other

Why did unsafe conditions exist? Why did unsafe acts occur?

Were the unsafe acts or conditions reported prior to the event? ☐ Yes ☒ No Have there have been incidents or near misses prior to this one? ☐ Yes ☒ No

Is there a reward that may have encouraged the unsafe conditions? ☐ Yes ☒ No

Corrective Actions

What changes do you suggest to prevent this incident / near miss from happening again?

☐ Stop this activity ☐ Guard the hazard ☐ Train the employee(s) ☐ Train the supervisor(s) ☐ Redesign task ☐ Redesign work station ☐ Write a new policy/rule ☒ Enforce existing policy step ☐ Routinely inspect for the hazard ☐ Personal Protective Equipment ☐ Other

What should be done to carry out the suggestions checked above?

Written and Reviewed By

Written by: Title: Team Lead Reviewed by: Department: Formwork Written Date: 15/09/2016 Reviewer Title: H&S Manager Review Date: 30/09/2016

Names of investigation team:

Lessons Learned

Fig. 9. Print preview of the accident report.

Accident ID	Revit ID	Employee Name	Department	Date of Incident	Death	Lost Time	Dr Visit Only	First Aid Only	Near Miss
1	593490	Worker1	Formwork	01/09/2016	☒	☐	☐	☐	☐
2	593552	Worker2	Formwork	01/09/2016	☐	☐	☐	☐	☒
3	593623	worker3	Finishing	02/09/2018	☐	☐	☐	☒	☐
4	593705	worker	Excavation	05/05/2020	☐	☒	☐	☐	☐
5	593885	worker5	Site works	08/12/2021	☐	☐	☐	☒	☐
(New)	0				☐	☐	☐	☐	☐

Fig. 10. Accident records list for searching.

events that led to the accident. The second case (Incident 2) was less complex, and the third case (Incident 3) was the simplest. This leads to the conclusion that accidents that contain more contextual aspects (site conditions, weather,

workers or team at the site, construction equipment and tools being used, and so forth) are more demanding from a CL perspective, and therefore the proposed system will be most beneficial for learning from such complex accidents.

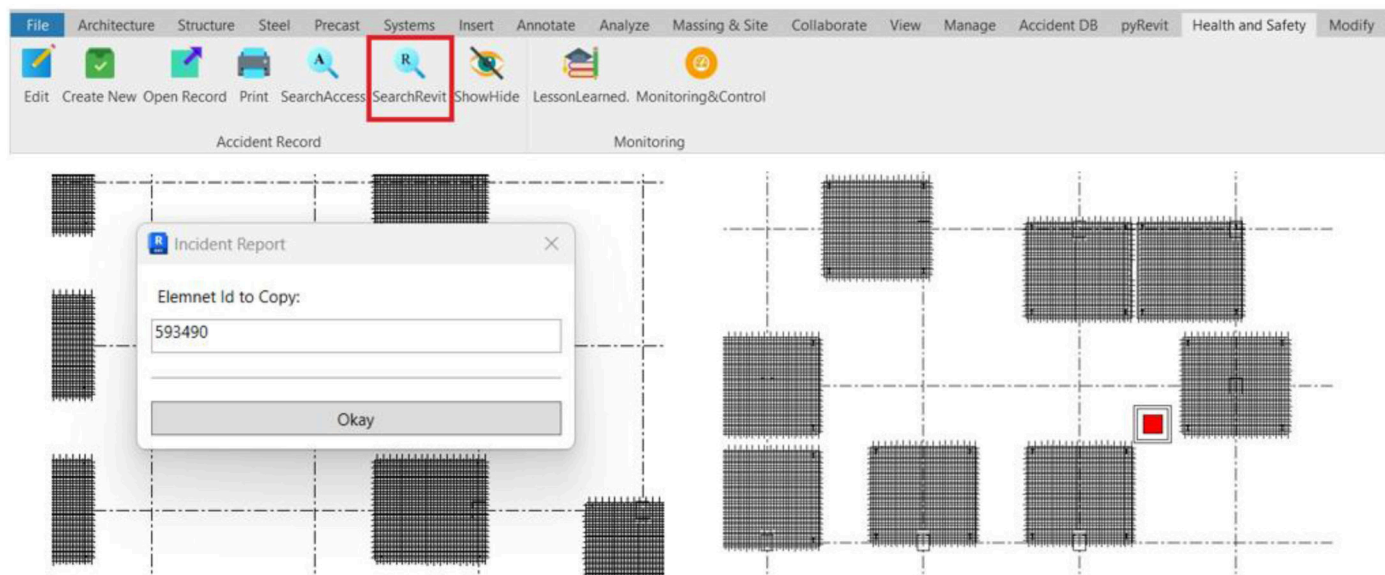


Fig. 11. Revit search for accidents.

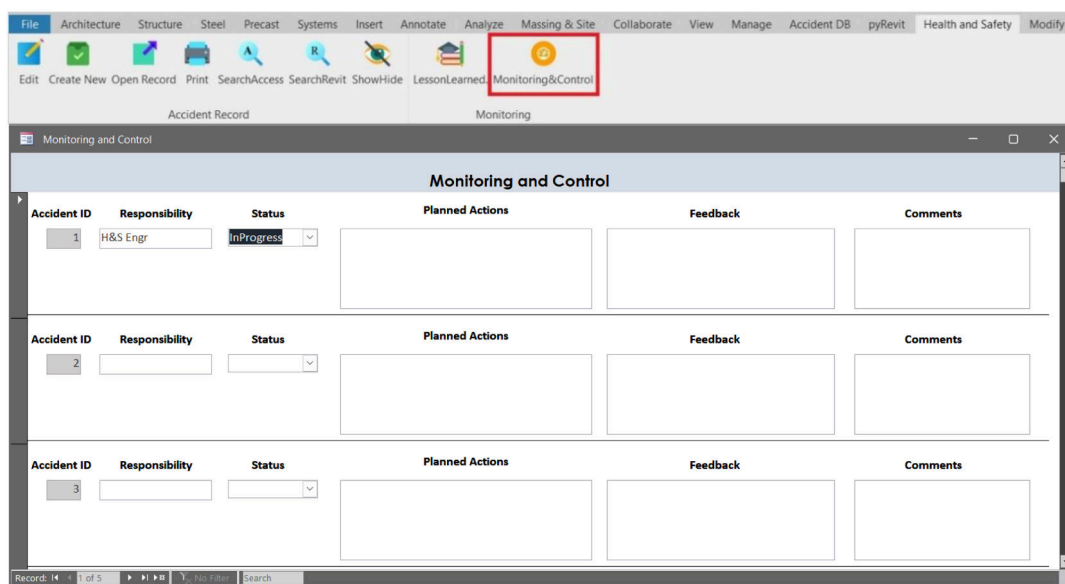


Fig. 12. Monitoring and control interface.

As described in the previous section, the experimental task involved participants divided into two groups, one using paper-based reports and the other using BIM models and character animation videos to assess and understand the details of the incident presented in their respective formats. Two metrics were used to evaluate task performance: the time participants needed to complete the activity, and the accuracy with which they grasped and summarized the chain of events as described in the reports. Table 6 presents the completion times of the participants for all three case studies and the performance scores. For the first instance, the paper-based group required 41 min to do the job, considerably longer than the visualization-based group's 18 min. The group that understood the accident by seeing the BIM model and the accident video animations had the highest task score (6.08) of the two groups. Similarly, the visual-based group finished reviewing the second accident case study in 11 min, 6 min faster than the paper-based group. They also scored higher than the paper-based group, 6.2, in terms of their understanding of the chain

of events in the subject accident. Both groups completed the third incident's work in the same amount of time, but the visual-based group received a higher task score, 6.75, than the other group. In conclusion, there were considerable differences among the paper-based and visual-based groups' completion durations and performance ratings across three event situations. The group that utilized visual aids demonstrated a constant ability to complete tasks more quickly and with higher learning and comprehension scores, highlighting the value of visualization-based methods for improving task performance and accident comprehension.

Discussion

Based on the experts' opinion, the suggested system (BIM-CAKOMS) is expected to reduce the strength and influence of many of the identified barriers to proper accidents KM. It may also

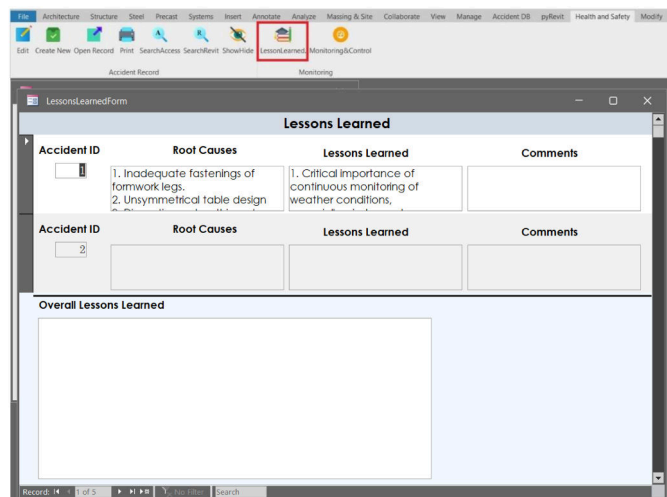


Fig. 13. Lessons learned interface.

help in mitigating some of the issues in learning from past accidents. Research emphasizes the importance of teamwork in enhancing construction safety, and that it promotes a culture of shared ownership and accountability for safety, with each team member actively contributing to ensuring a safe working environment (Hinze and Gambatese 2003). According to Fargnoli et al. (2011), this collaborative approach supported by an integrated KM system reduces the need for redundant communication efforts and ensures that ideas are communicated quickly. Utilizing the BIM-CAKDMS facilitates efficient information sharing and collaborative safety management, thereby embodying the principles of teamwork and integrated knowledge management. According to the experts, issues such as lack of a database, inaccessibility of information, nonstandardization of files, and paper-based exchange of information can be addressed by using the developed BIM-CAKDMS, because it is a centralized repository in which all the information regarding the incident is stored and can be accessed and retrieved easily at any time. KM consists of three techniques: preserving existing knowledge, disseminating and applying knowledge, and making knowledge usable (Kim and Park 2003). Lin and Tserng (2003) stated that having the necessary knowledge at the appropriate time will favor lean building, eliminating waste, decreasing mistakes, enhancing performance, and increasing productivity. In the present research, the experts concurred that the proposed system would resolve problems such as inadequate information exchange and ineffective departmental system interfaces that prevented electronic information access. This makes sense because all the relevant accident information is in one system, making it easier to convey all of the information at once and reducing the need to evaluate the material in a fragmented way.

Effective communication is crucial for establishing a secure working environment by sharing information about risks and risk management techniques. (Vecchio-Sadus 2007). Researchers have discovered that using an integrated system improves information exchange and cooperation (Dave and Koskela 2009; McInerney and Koenig 2011). Additionally, if an organization adopts the proposed system for their project's accident KM, over time the structured database of accidents across all projects undertaken and the knowledge captured as lessons learned and mitigation strategies could be utilized effectively in future projects. The major benefit of the proposed system is the availability of all the accident information in a structured digital format that can be queried easily and that is communicable via the project's common data

Table 4. Effectiveness of BIM-CAKDMS in resolving KM and LFI issues

No.	Effectiveness of BIM-CAKDMS in resolving issues	Evaluation scores		
		Mean score	RII	Overall rank
1	Disintegrated system, thereby increasing work repetition	4.5	0.9	1
2	Lack of visual insights	4.5	0.9	2
3	Lack of a database that serves as a one-step shop for accessing incidents and accidents data, lessons learned, and best practices	4.4	0.88	3
4	Inaccessibility of information anytime and anywhere	4.3	0.86	4
5	Nonstandardization of file directories, file plans, and document templates	4.3	0.86	5
6	Paper-based exchange of information (slow and inefficient)	4.3	0.86	6
7	Lack of contextualizing	4.3	0.86	7
8	Limited quality of initial reports	4.1	0.82	8
9	Limited dissemination of findings	4.1	0.82	9
10	Nonexistence of efficient interfaces between departmental systems to access information electronically	4	0.8	10
11	No communication tool to share tacit knowledge	3.9	0.78	11
12	Complex reporting systems	3.9	0.78	12
13	Nonidentification of systemic causes	3.7	0.74	13

environment (CDE). Here, each stakeholder, including the client, consultants, contractors, and subcontractors can access the safety information of a project in terms of any fatality, injury, near miss, and/or property damage instance, and they can educate themselves in a timely manner to avoid similar instances in the future. Similarly, other interested stakeholders such as governmental health and safety regulatory bodies and insurance companies can be provided access to the CDE that holds the digital BIM models Microsoft Access databases, and the safety records of past accidents, which can facilitate on-demand and instant access to information for conducting accident investigations and for determining compliance with health and safety codes and policies.

One of the core purposes of employing BIM on any project is to enhance team collaboration. The proposed system exploits BIM as a preferential database for KM of accidents because a BIM model holds information about all other aspects of a project, thereby approaching the concept of having a single source of truth for all project related matters. Additionally, the opportunity to utilize BIM models to animate the chain of events leading to an accident allows safety experts and other relevant stakeholders to capture the contextual knowledge of the site and its environment at time of the accident. The process of animating the chain of events (as per the framework proposed in Fig. 4) requires the relevant stakeholders to provide feedback to make corrections to the developed animations and to bring the accident simulation exactly in line with the collected accident investigation data from the accident site. The ensuing mutual discussions among the relevant stakeholders, while they provide feedback on the visual accounts of the accident recreation in the simulation and while they try to match the simulation with what has been recorded in investigation data, allow for a unique form of collaborative interaction which may help in analyzing the accident in more details. This may not be possible with the same efficiency only by reading accident investigation

Table 5. Cognitive load measurements of paper-based group and visual-based group

Dimension	Incident 1		Incident 2		Incident 3	
	Video animations	Paper-based reports	Video animations	Paper-based reports	Video animations	Paper-based reports
Mental demand	2.33	4	2.33	3.2	2.67	3.6
Temporal demand	2.5	4.2	2.17	3.4	2.17	3.8
Performance	3.7	3.8	3.33	3.6	4.17	4.4
Effort	2.5	3.6	1.83	3	2.67	2.8
Frustration	2.5	3.4	1.67	2.4	2.33	2.4

Table 6. Task performance assessment of paper-based group and visual-based group

Measured parameter	Incident 1		Incident 2		Incident 3	
	Video animations	Paper-based reports	Video animations	Paper-based reports	Video animations	Paper-based reports
Time duration	18	41	11	17	12	12
Task score	6.08	4.8	6.2	4.3	6.75	4.7

reports, questioning bystanders, and reviewing after-the-fact site photographs showing the scene of the accident. This argument is supported by the fact that accident simulations recently have been used in crime scene investigations and to communicate the accident chain of events in courts of law.

Our findings also show that a visual-based method to understanding causes and sequence of events leading to construction accidents requires much less cognitive burden than a typical paper-based approach. This conclusion is consistent with previous research that investigated the association between cognitive load and learning from experiences. Mayer and Moreno (2016) found that visual aids improve cognitive processing, increasing learning efficiency. Our findings support this notion, because individuals who used the visual-based strategy displayed faster understanding and better memory of accident data. This implies that including visual features in accident reports can improve the learning process by reducing cognitive strain and allowing for more-effective event analysis and memory (Mayer and Moreno 2016; Sweller 2010). Therefore, the materials generated from accident investigations including reports and character animations detailing the scenarios can be used organization-wide for several purposes.

The most important of these purposes is the investigation to determine the root cause of the accident in question, and the second most important purpose is the use of these digital reports and animations for training construction labor and a project's health and safety personnel on past accidental events. This will be more effective than simply displaying accident statistics on notice boards on project sites and sharing the accident reports as written documents that may not be easily understandable and that may be ignored by receiving individuals due to the inherent difficulty in understanding and the lack of interest in reading lengthy reports. Usman et al. (2025) explored the barriers to learning from incidents in the construction industry of Saudi Arabia. Among the most critical barriers, those of interest to this research include lengthy investigation reports, difficulty identifying broader lessons, lack of visual insights, and lack of contextualizing. These barriers point to issues that potentially can be resolved via visual means to review and learn from past accidents. Visual simulations can provide benefits that can partially or completely mitigate these barriers by overcoming the need for reviewing lengthy investigation reports and by providing a detailed account of all the events and circumstances leading to an accident, thus aiding in contextualizing and drawing lessons from past accidents and therefore learning better from them.

To provide a more rigorous articulation of the system's theoretical underpinnings, it is useful to define the spatial-temporal

contextualization framework that BIM-CAKDMS operationalizes. This framework is built upon three core components: (1) spatial contextualization, (2) temporal contextualization, and (3) an integration mechanism that enables experiential learning (Fig. 14). Spatial contextualization involves leveraging the as-built building information model as a high-fidelity digital twin of the physical environment at the moment of an accident (Eastman et al. 2011). This goes beyond simple 3D visualization by preserving the complex network of spatial relationships such as proximity between workers and equipment, visibility constraints, and access and egress routes that are critical for understanding causality but are abstracted away in traditional 2D drawings and text-based reports. By capturing the precise 3D configuration of the site, this component provides the foundational canvas upon which accident dynamics can be accurately reconstructed, addressing a key barrier in LFI in which lack of context prevents effective knowledge transfer.

Temporal contextualization comprises the representation of the accident as a sequence of events unfolding over time. This involves capturing not just the final state, but the dynamic state changes of objects and actors involved in the incident (e.g., a guardrail moving from a secure to an insecure state, the trajectory of a falling object, or the movement path of a worker). This component addresses a fundamental limitation of static accident reports by reintroducing the dimension of time, allowing for the analysis of the chain of events and contributing factors as they evolved, which is essential for effective root cause analysis. Finally, the integration mechanism is the core of the BIM-CAKDMS, linking the spatial and temporal data within a unified data structure. This integration enables the creation of dynamic, interactive simulations. By binding the temporal event sequence to the spatial digital twin, the framework transforms abstract, declarative knowledge (what happened) into procedural, experiential knowledge (how it happened). This transformation is critical for reducing cognitive load and enhancing learning, as demonstrated in our experimental results, by allowing stakeholders to experience the accident sequence rather than merely reading about it.

Further enhancement of this framework could be achieved through formalization using an ontology-based approach (Gruber 1993), such as developing a dedicated construction safety ontology using Web Ontology Language (OWL) or proposing extensions to the existing Industry Foundation Classes (IFC) schema (Pauwels and Terkaj 2016; Beetz et al. 2009). A formal ontology would provide a machine-readable, standardized vocabulary for describing accident knowledge, which would significantly enhance interoperability between different safety management systems and enable automated reasoning capabilities, such as

be used for training across all projects organization-wide, providing economies of scale. Finally, as BIM becomes the default platform for construction project management (progress monitoring, cost estimation, procurement, and facility management), integrating safety knowledge management into this ecosystem ensures that accident learning evolves with, rather than remains isolated from, the industry's digital transformation.

From an operational perspective, standard database maintenance activities (backups, user access management, and software updates) are handled by the company's IT department as part of routine organizational IT operations, similar to maintaining other enterprise databases. Data entry effort scales with accident frequency and organizational decisions about which accidents warrant simulation development. This is comparable to existing effort that organizations already invest in documenting accident investigations and developing training materials. Ongoing activities include user training for corporate health and safety personnel, access management as personnel change, and periodic content curation to ensure relevant accidents are highlighted for training purposes.

Importantly, these maintenance requirements are comparable to existing burdens, e.g., for OSHA compliance systems and training material development. The BIM-CAKDMS consolidates and streamlines existing maintenance activities rather than adding entirely new burdens. Organizations already maintain accident databases, training material libraries, and BIM models for other purposes. The system leverages and integrates these existing investments rather than creating wholly new maintenance obligations.

To address the practical viability of BIM-CAKDMS and demonstrate that the principle of zero additional data entry is achievable, it is important to detail the conceptual framework for integration with existing enterprise systems and OSHA regulatory reporting platforms. This framework is based on a one-way data flow from existing enterprise safety management systems to BIM-CAKDMS, leveraging standard data exchange formats. The proposed integration would utilize an application programming interface to pull data in a known format from existing enterprise safety platforms. Most modern enterprise safety management systems (e.g., Procore, Autodesk Construction Cloud, and HammerTech) provide APIs for data extraction, and these systems structure their data according to OSHA reporting requirements to facilitate regulatory compliance. The core of this integration is a field mapping that translates data from standard OSHA forms (such as Form 301, Injury and Illness Incident Report) to the corresponding fields in the BIM-CAKDMS database, ensuring that all necessary information is captured without requiring manual re-entry.

The BIM-CAKDMS data resides in a structured access database that can be easily modified to suit any structure or template. Therefore the zero additional data entry workflow would involve an incident being recorded on-site using the company's existing enterprise system, with a corporate safety manager subsequently initiating a data pull in BIM-CAKDMS. The system then would make an API call to the enterprise system, retrieve the data, and automatically populate the BIM-CAKDMS database using the field mapping. The safety manager then would link the imported case to the relevant as-built BIM model. This workflow demonstrates that all descriptive data are entered only once into the primary system of record, and BIM-CAKDMS enriches this data rather than requiring redundant data entry.

An important consideration is the rapid advancement in AI-powered automation, which offers a clear pathway to overcoming the implementation bottleneck of animation production cost. Emerging agentic AI systems, which are autonomous AI agents capable of complex, multistep tasks, have demonstrated remarkable capabilities that can be structured into a conceptual three-stage

pipeline. The first stage, automatic script generation, would leverage large language models (LLMs) such as GPT-4 to parse unstructured investigation narratives and witness statements into a formal, machine-readable script. This script would define the event sequence, actors, and objects involved, effectively translating human language into a structured format for animation. The second stage, model slicing and scene generation, would use this structured script to programmatically prepare the 3D environment. This involves automatically slicing the as-built BIM model to isolate the relevant accident area and using text-to-3D generative models, such as Shap-E (Jun and Nichol 2023), to populate the scene with any necessary non-BIM assets. This automates the creation of a precise digital twin of the accident scene. The final stage, automated animation and rendering, would use the script and the generated scene to animate the event sequence, intelligently suggesting optimal camera angles and lighting based on the narrative, and iterating simulations based on feedback without manual re-animation. Recent work in retrieval-augmented video generation provides a strong precedent for this capability (He et al. 2023). Although our current proof-of-concept uses manual animation workflows, the framework we have developed positions organizations to leverage these emerging AI capabilities as they mature. This means that the resource concerns (cost), although valid for current manual workflows, are likely to diminish substantially as AI-assisted animation becomes more accessible.

To summarize, this research enhances LFI and accident KM by introducing a spatial-temporal contextualization framework that addresses a critical gap. Existing research on KM and LFI in construction safety treats accident context as descriptive metadata (date, location, and project type), but our BIM-based framework demonstrates that context must be preserved as experiential, reconstructible information to enable effective accident KM and to improve LFI. This theoretical contribution advances understanding of how spatial-temporal complexity affects knowledge transfer in construction safety, with implications for other domains in which incidents unfold in 3D space over time (e.g., manufacturing, mining, and oil and gas).

The claims regarding the contribution of the proposed system are supported by the following observations:

1. The proposed system facilitates efficient information sharing and collaborative safety management by providing a centralized database, which can be made accessible to relevant stakeholders in and outside of a construction organization, to enhance explicit accident knowledge capturing and sharing in a structured format. It provides a persistent, accessible repository of accident knowledge that transcends individual projects and personnel turnover.
2. The system also facilitates collaboration among stakeholders by utilizing the visualization capabilities of BIM. Maintaining accident records and animations and simulations within BIM models provides a centralized repository of safety related project information, in addition to other types of project information.
3. The system promotes team collaboration during the accident analysis phase by allowing the team to view different progressive versions of accident simulations that incorporate their feedback in each version, thus allowing the team to better contextualize the events and project circumstances that lead to the accident. Integration of BIM here provides a unique opportunity to capture the as-built state of the project and the unique circumstances at the time of each accident. The system facilitates deeper causal analysis through spatial-temporal reconstruction rather than relying solely on text-based descriptions.
4. The proposed system reduces the CL required to understand the recorded accidents, thus potentially making it easier for construction organizations to use past accident simulations and

cases for dissemination of safety knowledge and for training of workforce. This has been proven to be a more efficient approach for the purpose of learning from past accidents than using (after-the-fact) site photographs, interview logs of witnesses, and summary reports. It improves communication of accident findings across diverse audiences (management, workers, sub-contractors, and clients) through visual simulations.

Conclusions

To enhance accidents KM and organizational learning from past accidents, the goal of this study was to exploit the visualization capabilities of BIM and proposed a relevant BIM-based solution. Initially, a literature review was conducted to identify KM and LFI barriers in construction safety. Subsequently, a BIM-CAKDMS was designed to efficiently handle construction accident data and to address the identified barriers. In addition, three published accident case studies were turned into relevant BIM models and character animations to develop a centralized accidents project database and to exploit the visualization features of BIM and enhance the learning element from past occurrences. The developed BIM-CAKDMS acts as a central repository for all the accidents (including fatality, injury, near miss, and/or property damage) in a project including all the necessary details of the accidents (date, time, description, and so forth) along with the reconstructed accident animations and additional visual proof. Specialists in construction health and safety assessed the developed system to determine whether the developed tool was feasible. Additionally, an experiment was carried out with 12 construction engineering and management students to evaluate the impact of the system on the ability to quickly and efficiently acquire knowledge and understanding of how the events happened, and their associated CL was assessed. The developed system's results showed that problems such as a disintegrated system, a lack of a database, nonstandard file formats, paper-based information exchange, restricted information sharing, and limited accessibility mostly could be rectified. According to the findings of the CL and task performance evaluation, paper-based comprehension of the accidents was the most cognitively demanding, time-consuming, and had a poor performance score in terms of the comprehension of the accidents compared with the proposed system, thus providing confidence in the capabilities of the proposed system. The proposed BIM-CAKDMS serves as a prototype to demonstrate the effectiveness of BIM as an effective platform to enhance health and safety in construction firms by promoting accidents KM and learning from past accidents. BIM is rapidly becoming the default platform for construction project management, driven by standards such as ISO 19650 that mandate BIM usage across the entire supply chain. Our system positions safety management within this digital transformation, ensuring that accident knowledge management evolves in parallel with other project functions (design coordination, cost estimation, and progress monitoring) rather than remaining siloed in legacy systems.

Limitations

Despite the promising outcomes in enhancing KM for construction accidents and thus the LFI, several limitations exist in this research that must be acknowledged. Barriers related to spatial-temporal representation, centralization, and standardization align well with BIM's inherent strengths, whereas barriers related to human judgment and organizational culture do not. The proposed system does not resolve all identified problems to the fullest extent, and residual

effects of the identified barriers may remain due to persistent challenges. It improves contextualization through 3D representation, but workers still must interpret relevance to their specific work (users still require domain expertise to interpret accident scenarios and apply lessons to their specific contexts). Although simulations reduce cognitive load, they supplement rather than replace detailed reports needed for regulatory and legal purposes, and therefore the significance of detailed documentation and record keeping efforts remains. As discussed in this study, tacit knowledge resists codification; the system provides richer experiential learning but cannot directly transfer tacit expertise. Moreover, technology alone cannot change organizational willingness to share knowledge or learn from failures; the system enables sharing but requires organizational commitment to utilize it (knowledge sharing, adequate resources for simulation development, and integration into training and planning workflows). Future work can focus on integrating expert commentary features where experienced safety professionals can annotate accident simulations with contextual insights and judgment calls. More work is required to develop case-based reasoning approaches that link similar past incidents to help transfer pattern recognition expertise. Augmented reality and AI applications need to be explored that could provide just-in-time tacit knowledge for potential accident prevention during actual work activities. There is a need to define metrics to track system usage and learning outcomes, providing evidence to reinforce organizational commitment.

The number of experts consulted during the system development and validation stages was relatively small, which may restrict the generalizability of the findings. Although these experts possessed extensive health and safety expertise, a broader stakeholder representation, such as additional construction managers, regulatory officials, and technology specialists, could yield more-comprehensive insights. Additionally, the system demonstration relied on partially public, published accident case studies, given the sensitive nature of proprietary organizational data. Consequently, real-time industry contexts and complexities may introduce factors not fully captured by the selected case studies. In addition, only three case studies were considered. Third, the BIM-CAKDMS prototype was tested under controlled conditions (a lab experiment and limited pilot projects), meaning that large-scale longitudinal deployment and its integration with other project management platforms remains unassessed. Fourth, the creation of 3D animations in this study was labor-intensive, requiring manual modeling, rigging, and rendering; however, emerging generative AI tools could automate this process with minimal cost and time, thus lowering barriers to widespread adoption. Finally, some organizations have more-complex internal databases with highly specialized reporting fields; incorporating all these idiosyncratic requirements into a standardized BIM-based system may require further customization and ongoing refinement.

Data Availability Statement

Some or all data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request.

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