

## Article

# A Hazard Identification Approach of Integrating 4D BIM and Accident Case Analysis of Spatial–Temporal Exposure

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**Abstract:** Construction sites are considered as complicated work environments. Various concurrent activities may overlap apropos to time and workspace, predisposing them to spatial–temporal exposure and repetitive accidents. Detecting the characteristics of repetitive accidents before the construction stage contributes to prevent injuries and fatalities caused by spatial–temporal conditions at construction job sites. To resolve this problem, this study proposes a novel hazard identification approach through spatial–temporal exposure analysis called HISTEA, which integrated scenario analysis of accident cases into 4D building information modeling (BIM). The proposed approach consists of three modules: (1) spatial–temporal hazard investigation (SHI) to analyze the accident cases and develop the hazard database of the spatial–temporal overlap condition of pair-wise activities; (2) spatial–temporal condition identification (SCI) to determine the conflict among different activities, considering the workspace and time overlap from the 4D BIM model; and (3) safety information integration (SII) to deliver safety knowledge to the project team through a web-based application. To illustrate and validate this approach, a HISTEA prototype for foundation work has been developed to be used at the pre-construction stage. The developed prototype is based on the analysis of 496 accident reports extracted from the integrated management information system (IMIS) of the Occupational Safety and Health Administration for the SHI module database. The proposed approach is expected to proactively aid project teams in detecting hazards that ultimately reduce repetitive accidents caused by overlapping activities.

**Keywords:** 4D BIM; hazard identification; spatial–temporal analysis; accident analysis

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## 1. Introduction

In the construction industry, health and safety (H&S) have a natural connection with sustainable development. The H&S impacts the three aspects of sustainability named as profit, planet, and people [1]. Project costs may be exceeded budget in case of accident occurred due to healthcare costs, low productivities, delays, lost working days, penalties, etc. [2]. Hollowell [3] estimated that injuries and illness had an impact on the financial results of construction companies by raising the overall cost of new non-residential buildings by up to 15%. In U.S., 20,430 of nonfatal incidents of construction labors required days away from work in 2018 [4]. The losses of H&S surpass \$1250 billion at the global level [5]. The construction collapse accidents, even due to subjective and objective causes such as human error [6], seismic or floods [7,8] have required demolition and reconstruction, which triggered construction waste and pollution. Further, 1008 of 4779 worker fatalities in 2018 were in the U.S. construction industry, i.e., one death for every five workers in construction sites [9]. Moreover, in Korea, 50% of all fatal accidents occurred in the construction industry [10]. In Europe, nonfatal injury in the construction sector ranks third, and its number exceeds the average across all industries [11]. The consequence is reduced not only quality of victims' lives, but also affecting their family, environmental

and ecological damages [1,12]. Various studies related to construction safety assert that most on-site incidents could have been minimized or even avoided through accurate risk assessment and the implementation of a proper and consistent safety management process. In particular, safety hazards should be well-identified at the pre-construction stage to allow site managers to formulate accident prevention strategies [13,14].

Prior to the construction stage, every activity's spatial and temporal conditions in the construction job site should be accurately assessed to the extent feasible, indicating where and when the activity proceeds. However, construction project sites are complex environments in which many concurrent activities occur. Activity interactions in concurrent are among the potential hazard sources that have been investigated by many researchers [15], and the construction spatial-temporal overlap has been found one of the critical endangers to the safety of workers [16]. The probability of accidents in two concurrent activities increases as compared to single or solely proceeding activities. For instance, considering the spatial-temporal conflict of activities, Sacks [17] analyzed the "loss-of-control events" through spatial and temporal exposures. Using the Delphi method, Hallowell [18] quantified the impact of pair-wise spatial and temporal interactions on the base-level risk of 25 common highway construction tasks in the United States.

The utilization of building information modeling (BIM) approach can improve occupational safety by considering the aspects of safety more closely during construction planning, such as by providing more representative site layout and safety plans [19,20]. It also provides innovative methods for visualizing current plans [21], managing site information [22], and supporting safety communication under various situations (e.g., informing the site staff of the necessity of establishing safety arrangements or warning them of safety hazards caused by the spatial-temporal overlap of certain pair-wise activities (PA)). The use of BIM also encourages the collaboration of project teams (e.g., safety professionals, designers, and schedulers) involved in both risk assessment and planning. However, the current simulation tools for building safety awareness focuses on offering general safety information without properly providing practical protection protocols and reviewing accident reports from construction sites [23]. The interoperation between the BIM model and information on past-accidents to identify hazard areas is missing [24]. Few studies have leveraged empirical data and produced results that can be used in the BIM to determine when, where, and why certain work features are dangerous to workers' safety.

Potential hazards can be identified by analyzing accidents in the past. Due to the repetitive characteristics of undesirable incidents [25], a few studies, such as [20] and [23], have proposed that project managers of design have to derive lessons from previous accidents and integrate risk management into the project creation process. In project risk management, learning from the past is a primary mechanism that aids individuals and organizations understand when, where, and why certain events occur and prevent the repetition of past errors [26]. For instance, applying the developed system in a building project, Kim [24] found the event "injury caused while loading rebar on slab form" and "death from a fall while assembling rebar" were similar to a past accident case. The details of accident information, as well as related labor information (age, occupation, safety training), were provided to the safety managers as a proactive information such as the direct and root cause of an incident and the corrective actions; thus, safety managers could avert the occurrence of a similar event. Such information analysis has assisted project teams composed of even less experienced practitioners to devise methods to prevent the repetitive incident scenarios from re-occurring, thus enhancing safety performance. However, these accident cases analysis relies on paper-based approaches to deliver safety information and does not provide visual information in BIM.

In order to overcome the above limitations, this study proposes a novel hazard identification approach through spatial-temporal exposure analysis, called HISTEA, which is an integrated scenario analysis of accident cases into 4D BIM. The objective of HISTEA

approach is to integrate hazard data with 4D BIM to improve safety planning and monitoring by enabling job site managers to visually plan, verify, control, and communicate with trade workers using spatial–temporal analysis. The current state of safety planning, accident cases analysis research, and four-dimensional (4D) BIM for spatial–temporal analysis is reviewed in Section 2. The hazard detection process of the proposed approach is elaborated in Section 3. Next, a prototype of HISTEA for building foundation work is introduced to validate the proposed approach in Section 4. Section 5 discusses the proposed system evaluation results. Finally, the conclusions and future studies are discussed and summarized in Section 6.

## 2. Literature Review

### 2.1. Current State of Hazard Identification in Construction Safety Planning

Safety planning in construction is exigent due to the inherent dynamic and complex nature of its work environment. It has been regulated following the construction regulations of many countries, such as division 292 of section 6.4 of the model Work Health and Safety Regulations in Australia, act 85 of 1993 in South Africa, regarding to division 29 CFR 1910.120(b) of OSHA regulation in the U.S., etc. Traditionally, construction safety planning starts with job hazard analysis (JHA) [27], performed by a team meeting with the site manager, safety manager, and construction manager [28]. To identify hazards proactively, the JHA focuses on the relationship among the workers, tools, and environment. However, current safety planning strategies have several problems. The plan for construction safety is usually implemented independently after project planning [29]. Furthermore, safety is generally deemed as the contractor's responsibility because accidents happen during the execution of construction activities. Hazardous conditions vary due to the dynamic nature of construction projects; hence, the integration of the time aspect with safety management is vital [30]. The current approach to safety planning does not reflect frequent schedule updates to manage changes in potential hazards [31]. Moreover, planning still relies on manually acquired paper-based regulations, two-dimensional drawings, and heuristic knowledge, resulting in a process that is labor-intensive and prone to error [32]. Accordingly, existing safety planning methods restrict the ability of planners to detect and examine construction hazards proactively. Poor safety planning usually causes accidents and consumes financial resources, which can be avoided using information technologies in the planning stage.

To resolve these issues, professionals and researchers have recently focused on design for construction safety (DfCS), which considers safety as the shared responsibility of designers and constructors [14]. Behm studied 242 fatalities in 2005 and found 40% of these were linked to design [33]. Numerous analyses of construction fatalities have revealed that the probability of accidents can be reduced by 50–60% by focusing more on the DfCS [34].

### 2.2. Accident Cases Analysis for Hazard Identification

Learning from construction accident cases is vital to prevent their reoccurrence. This includes providing stakeholders with several safety factors and values with respect to time, location, causes, and severity of accidents. For instance, OSHA provides fatality and catastrophe investigation summaries to help researchers analyze job hazards for particular activities [35]. Safety managers gain knowledge of known experiences that can enhance their capacity to identify hazards and prepare the prevention method such as installing the warning system into the scraper or training the laborers to avoid the hazard area. This also aids in identifying and mitigating project risks at the early stages of design and construction planning. To facilitate the effective use of safety factors and values derived from the analysis of accident reports, researchers have built a database of accident cases to resolve specific safety problems. For example, Kim et al. [32] suggested a framework for gathering accident data that would be able to produce queries automatically based on

tasks, site conditions. In order to aid risk management of the metro project, Zhang et al. [36] has established a database that contains 249 cases of the incident. Likewise, developing the CBR model, Goh [26] encourages the use of previous hazard and accident information to make the current hazard-identification methods more effective and sufficient. To identify the reasons for collision injuries, more than 300 accident reports from OSHA were collected and analyzed [37].

In addition to establishing an accident database, Kim et al. [32] mentioned the necessity of interworking among three-dimensional (3D) models and coordinating retrieved results to visualize the risk areas or factors. According to Guo [38], construction safety can be improved by collecting, analyzing, and visualizing safety data. Furthermore, Zhang [39] emphasizes that the integration of the BIM and the expert system can overcome low efficiency when extracting conventional information, reducing domain expert reliance, and promoting the exchange of knowledge and contact between customers and domain experts.

#### *2.3.4. D BIM Utilization for Safety Planning and Spatial–Temporal Analysis in Construction*

Extensive research has been performed to enhance traditional construction safety planning by employing BIM and several other information and communication technologies in the last decade. For instance, many studies have considered BIM-based safety planning specifically for temporary facilities in construction job sites [40–43]. Building information modeling has also influenced design methods, scheduling, estimating, facility operation, and monitoring for building and infrastructure. An automated rule-based approach to safety planning using the BIM technology [43] was proposed to reduce the cases of fall accidents. Moreover, the OSHA safety-based rules on different techniques were applied to excavation safety modeling using BIM and visual programming to prevent cave-ins and fall accidents [41]. An automated scaffolding risk analysis system in construction was proposed by Feng and Lu using Dynamo (a visual programming tool) and BIM [44]. Zhang et al. developed BIM-based activity level planning in construction to examine and automatically visualize the workspace using remote sensing and workspace modeling technologies [45].

Another study integrated the time aspect with the 3D models, known as 4D BIM, to deal with contemporary construction planning issues. For example, Kim et al. [46] considered construction activities and project schedules to develop the evacuation plans in 4D BIM automatically. Tran et al. [22] proposed a camera planning concept considering the construction site progress using 4D BIM and visual programming language. Choe [31] proposed a 4D construction safety planning which integrated safety data with the project schedule and 3D model for the specific activity. In addition, the spatial–temporal exposure of PA is one of the 4D BIM’s research topics, as shown in Table 1. This problem is complicated by changes in the requisites for different construction activities, parallel sequence, location, and size of the workspace [47]. Further, the spatial–temporal overlap (or conflict) among activities is difficult to eliminate in the construction industry due to other objectives, such as optimizing time and cost.

In order to solve the spatial–temporal exposure problem, many studies developed a bounding box modeling algorithm to detect the spatial–temporal overlap in 4D BIM [48–52]. Contrarily, extensive studies have been carried out to deal with the specific consequence of spatial–temporal exposure to enhance productivity and safety in construction. Mirzaei [53] focused on detecting conflicts and quantifying workspace congestion to improve productivity. Sacks [17] improved safety planning by analyzing the “loss-of-control events” through spatial and temporal exposures. Evaluating construction site collisions, Shang [16] proposed a safety assessment model based on the number of site conflicts and the portion of workspace overlap.

Although many research works have focused on the scheduling aspect to detect a conflict between two or more activities; however, integrating past accident knowledge with BIM 4D is not yet discovered. Moreover, the thorough literature review indicates

that accident reports' tacit knowledge could greatly aid the potential hazards recognition process. Therefore, integrating spatial–temporal hazard database into the 4D BIM is required to have a more efficient and robust tool for delivering safety information to construction stakeholders.

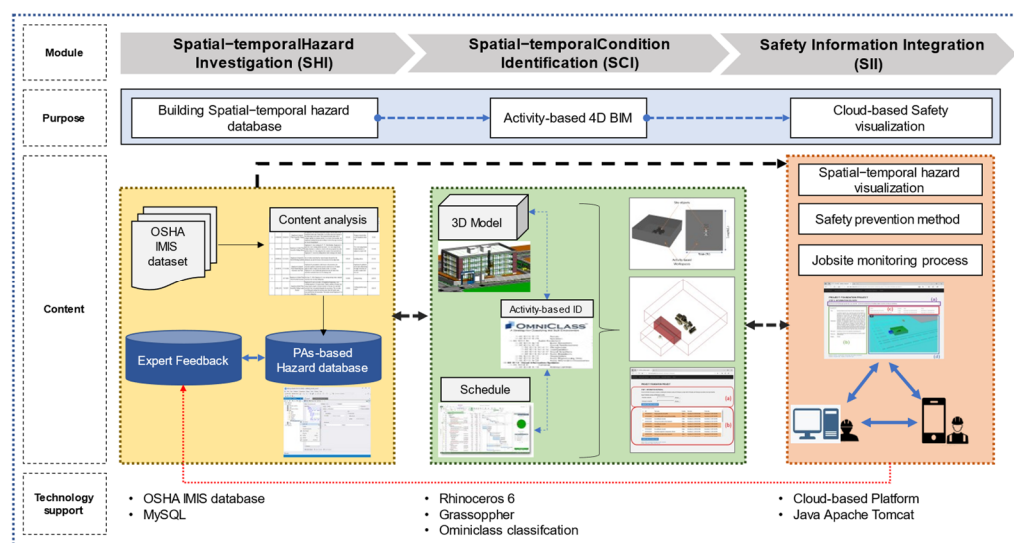
**Table 1.** Comparison between previous studies and this study.

| References               | 4D BIM | Spatial–Temporal<br>Conflict Detection | Historical Accident<br>Data Analysis | Major Concern                                                                               |
|--------------------------|--------|----------------------------------------|--------------------------------------|---------------------------------------------------------------------------------------------|
| Akinci (2002) [48,49]    | Yes    | Yes                                    | No                                   | Conflict detection                                                                          |
| Guo (2002) [50]          | No     | Yes                                    | No                                   | Conflict detection                                                                          |
| Mallasi (2006) [51]      | Yes    | Yes                                    | No                                   | Conflict detection                                                                          |
| R. Sacks (2009) [17]     | Yes    | Yes                                    | No                                   | Loss-of-control events for safety                                                           |
| M. Hallowell (2011) [18] | No     | Yes                                    | No                                   | Quantifying pair-wise spatial–temporal interactions                                         |
| Moon (2014) [52]         | Yes    | Yes                                    | No                                   | Check of workspace conflict                                                                 |
| Kim (2015) [24]          | No     | No                                     | Yes                                  | Providing similar accident cases by combining BIM and safety retrieval system               |
| Kassem (2015) [54]       | Yes    | Yes                                    | No                                   | Workspace management                                                                        |
| Zang (2016) [39]         | No     | No                                     | Yes                                  | Integrating BIM and Case-based reasoning (CBR) inference approach for hazard identification |
| Choe (2017) [31]         | Yes    | No                                     | Yes                                  | Site-specific spatial–temporal safety information integration                               |
| A. Mirzaei (2018) [53]   | Yes    | Yes                                    | No                                   | Spatial–temporal conditions for supporting productivity                                     |
| This study               | Yes    | Yes                                    | Yes                                  | PA Hazard database for supporting hazard identification                                     |

### 3. Methods and Models

#### 3.1. Proposed Approach for Safety Hazard Identification through Spatial–Temporal Exposure Analysis

The primary purpose of developing a system for hazard identification through HISTEA is to detect PA hazards caused by the working space and time overlap conditions. The structure and key features of the proposed HISTEA system are shown in Figure 1, which is composed of three modules: (1) The PA hazard database from the OSHA IMS was developed under the SHI module to understand and establish the spatial–temporal conditions that can lead to repetitive accidents and (2) The SCI module supports planners in visual identification of the spatial–temporal overlap condition using 4D BIM. (3) The SII module was designed to advise hazard prevention methods based on the retrieved information. The integrated safety information derived from the SHI and SCI modules is delivered and shared with the project team through cloud storage.



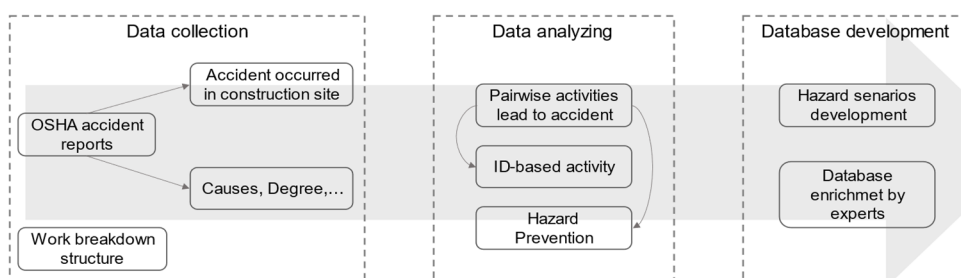
**Figure 1.** Proposed hazard identification approach through spatial-temporal exposure analysis (HISTEA).

### 3.1.1. Spatial-Temporal Hazard Investigation (SHI) Module

#### Spatial-Temporal Accident Cases Collecting Process

Accident reports offer pivotal information, such as root causes, context-related severity, and recommendations for preventing future accidents of a similar nature. Extracting the root causes of past accidents provides an opportunity to understand the event's reasons for spatial-temporal exposure or any other reasons. The Integrated Management Information System of OSHA (IMIS-OSHA) provides a complete description of the incident, generally, include causative factors and events leading to the accident. The given description in the IMIS-OSHA can be easily searched using a keyword; for instance, a text of interest in the description such as critical reasons behind the accident, an event date, and an industry code (Standard Industrial Classification (SIC) code).

The IMIS-OSHA categorized the reported accidents based on the industries; Division C includes the reported accidents related to construction sectors. The following are the three broad categories of construction activities: (1) building construction, (2) heavy construction, and (3) construction activity by other specialty contractors. To limit the study's scope, the objective herein investigated was limited to buildings to reframe which consists of construction other than building, was considered out of scope for this research. Hence, this study considered parts (1) and (3) for further research. The process adopted for the database development is exhibited in Figure 2. The collected data is analyzed using the content analysis method, which enables valid inferences from textual data [48]. To identify these contents, it is necessary to recognize the patterns in written injury reports. The accident cases reported to IMIS-OSHA due to spatial-temporal reasons are considered for the PA hazard database development.

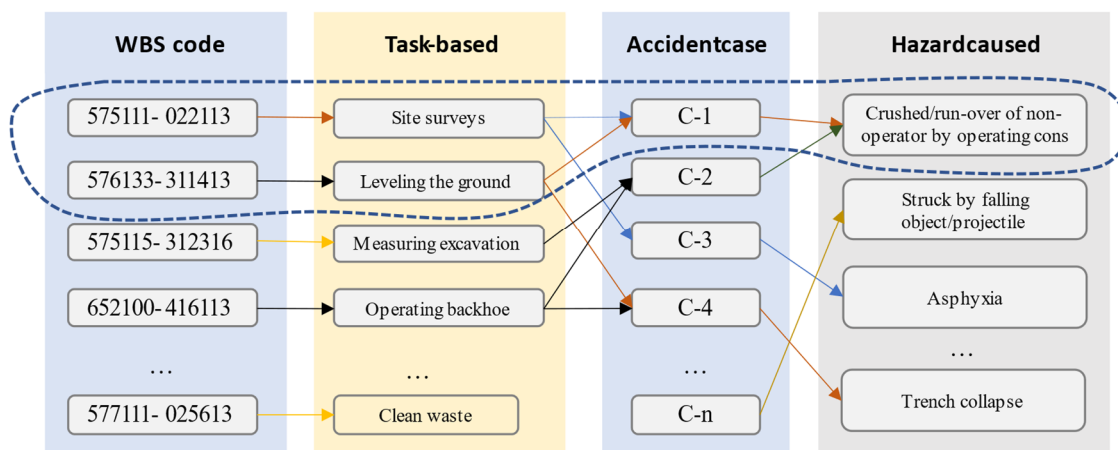


**Figure 2.** Pair-wise activities (PA) hazard database development process.

### PA-Based Hazard Database Implementation

To further elaborate on the PA hazard database, Figure 3 profoundly illustrates the development process of database establishment. As illustrated in Figure 3, the WBS codes are used as identity tags to match the given PA activities with the developed hazard database. The schedule includes action and objective as a title for each task. Moreover, the WBS code in this approach is divided into three parts separated by a hyphen (-) and includes (a) the area of the activity, (b) the number describing the action of the activity, and (c) the work results. To determine the code numbers in the WBS for (b) and (c), the OmniClass construction classification system is used. Refer to the data in “Table-22” and “Table 23” of the OmniClass in [55], the former lists the work results, and the latter one summarizes the named services for the action. For example, the activity “Fencing and gate installation around the construction site” is represented by the WBS code A-576129-323126, where:

- “A” indicates the activity location, which is usually allocated by zone.
- “576129” refers to the installation action and is obtained from “Table 32”; and
- “323126” refers to work results representing “wire fences and gates” and are obtained from “Table 22”.



**Figure 3.** The logic of hazard identification by spatial-temporal overlap condition.

The dashed curve section of Figure 3 and Table 2 exemplified the logic of hazard identification based on the spatial-temporal overlap condition. For instance, after analyzing the accident description listed in Table 2, “site surveys” and “leveling the ground” are observed as PA leading to risk. The hazard and WBS code are determined (indicated by the dashed curve). After that, the input data, including the name of the report, description, SIC code, accident extent, activity interaction, resource, WBS code, and warning, are retrieved from the entire database, as listed in Table 2.

The case study scenario was determined by evaluating the spatial-temporal overlap of the excavation work. By using the “excavation” keyword and SIC code (15 and 17), 496 accident cases were found; the contents of those reports were manually analyzed. Based on the report descriptions, the PAs leading to the accidents were identified. The accident causes were also collated to formulate prevention techniques. The analysis revealed that 57 of the 496 had PAs which could be stored in the database for hazard identification.

**Table 2.** Example of collected data for developing PA hazard database.

| Name                        | Contents                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|-----------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Title                       | Surveyor's Helper Run-Over by Scraper and Killed                                                                                                                                                                                                                                                                                                                                                                                                                      |
| Accident Date               | 09/20/2013                                                                                                                                                                                                                                                                                                                                                                                                                                                            |
| SIC code                    | 1799                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |
| Description                 | Employee #1, an assistant surveyor hired by the building contractor, performed survey activities at a residential housing construction site. Coworker #1 was operating a 627E Caterpillar and driving it in continuous circles to level the ground for creating a place pad. Employee #1 was crouched at the perimeter of the scraper's drive path on the ground and positioning stakes as part of his survey task. The scraper reached Employee #1 and was ran over. |
| Degree                      | Fatality                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
| Main Cause                  | Non-operator crushed/ran over by operating scraper                                                                                                                                                                                                                                                                                                                                                                                                                    |
| Activities that co-occurred | Site survey and ground leveling                                                                                                                                                                                                                                                                                                                                                                                                                                       |
| Prevention method           | warning                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
| Resource                    | <a href="https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=202510079">https://www.osha.gov/pls/imis/accidentsearch.accident_detail?id=202510079</a>                                                                                                                                                                                                                                                                                                     |

### 3.1.2. Spatial–Temporal Condition Identification (SCI) Module

This module is intended to detect the spatial–temporal overlap condition of activities through the 4D BIM. The module has three sub-sections: (1) the SCI begins with modeling activity in 4D BIM; Next, the necessity and sufficiency conditions of Equation (1) are explained in (2) schedule overlap detection, and (3) workspace overlap detection. The safety manager endeavors to determine the spatial–temporal overlap condition with  $n$  ( $n \in N^*$ ) activities from the planned schedule. In this study, activity  $A$  is defined using three main factors: WBS code ( $W$ ), working space ( $S$ ), and duration ( $T$ ). To detect the spatial–temporal overlap condition of these two activities,  $A_i$  and  $A_j$  ( $i, j \in I\{1, \dots, n\}$ ) are formulated as follows:

$$\begin{aligned} \vartheta(A_i; A_j) &= A_{ij} \neq \emptyset, \forall i, j \in I \\ \text{If } \begin{cases} S_i \cap S_j = S_{ij} \neq \emptyset, S_{ij} \subset \mathbb{R}^+ \\ T_i \cap T_j = T_{ij} \neq \emptyset, T_{ij} \subset \mathbb{R}^+ \end{cases} \end{aligned} \quad (1)$$

where  $A_{ij}$  is the spatial–temporal overlap portion of activities  $A_i$  and  $A_j$ . The spatial–temporal overlap condition of  $A_i$  and  $A_j$  satisfies the spatial overlap and temporal overlap conditions, as given by Equation (1).

### Activity Workspace Generation

Additionally, the SCI is also designed to generate the activity workspace modeling, as depicted in Figure 4. This study leverages the BIM aided activity workspace modeling for visualizing the construction entities (components, equipment, and materials) that are required during activities. The required workspace for activity is created from the 3D model using the concept of the axis-aligned bounding box (AABB) [52,55], which is linked to the site object and estimates the area used for each task. The interactive development and allocation of the workspace are aided using python in the visual programming. The workspace is defined by AABB's dimensions (width, depth, and length) and the coordinates are relative to the 3D model origin. For example, in Figure 4, the activity named “backfill using bulldozers” is presented by WBS code, 3D workspace, and schedule. The activity workspace includes the bulldozer object and its surrounding area. The bulldozer object's bounding box is generated. As the construction job site is dynamic, the proposed module is designed to be flexible, and the planner's decision could reflect protraction and contraction in the box if required. The WBS code “31232313-41611600” is assigned as parameters to integrate 3D and schedule to generate a 4D BIM-based activity model, as mentioned in Figure 4.

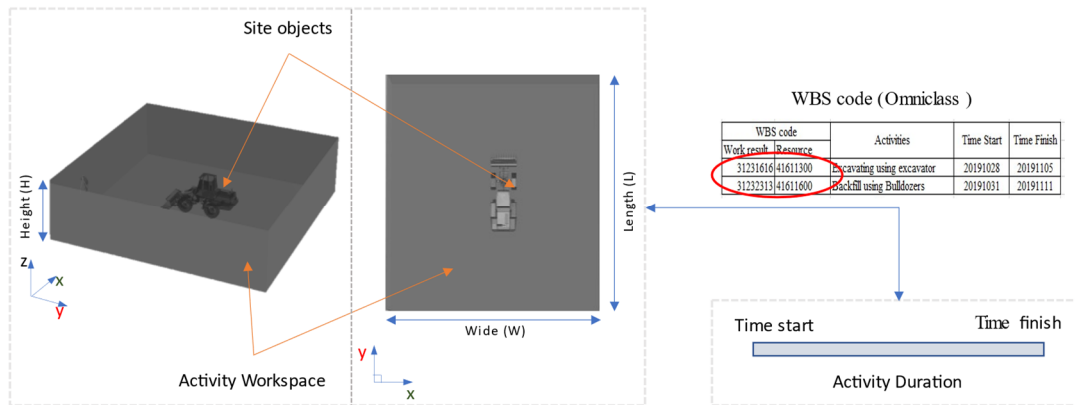


Figure 4. Activity-based modeling.

### Detection of Overlapping Schedules

During the planning stage, the activities include the start and finish times. To detect overlapping of pair-wise activities, four cases are considered for comparing the base activity with the reference activity, as depicted in Figure 5. According to Figure 5a, the base activity begins before the reference activity and terminates while the reference activity is still in progress. In Figure 5b, the overlap is noticed if both the start and finish times of the reference activity are between the start and finish times of the base activity. Overlapping occurs when the base activity's start time is between the start and finish times of the reference activity, even if the base activity finishes before or after the reference activity, as indicated in Figure 5c and d.

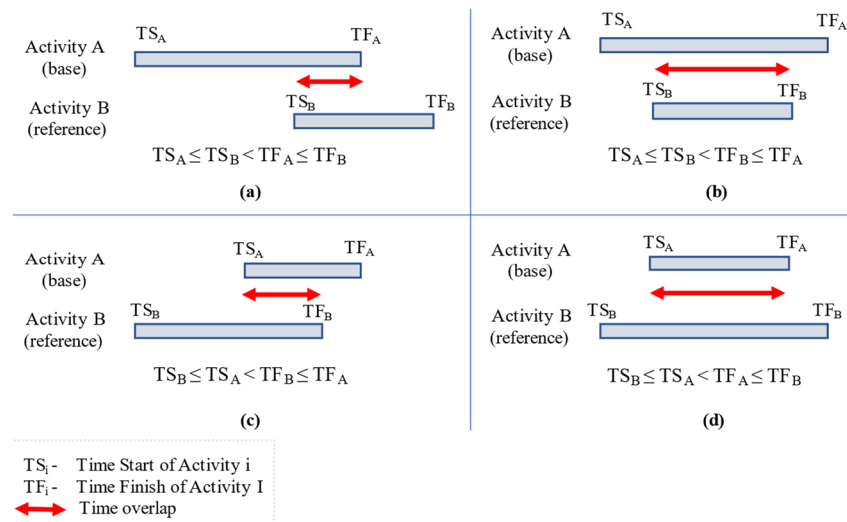


Figure 5. Cases of overlapping schedules.

### Detection of Overlapping Workspaces

The axis-aligned bounding box (AABB) intersection test is used for detecting workspace overlap. Workspace A (base) is described as  $(X_{min}^A, X_{max}^A, Y_{min}^A, Y_{max}^A, Z_{min}^A, Z_{max}^A)$ ; similarly, workspace B (reference) is described as  $(X_{min}^B, X_{max}^B, Y_{min}^B, Y_{max}^B, Z_{min}^B, Z_{max}^B)$ . The condition for the overlap to occur is given by Equation 2. The two-dimensional plane's (x-y axis) intersection of two workspaces (A and B) is simplified in Figure 6 when  $X_{min}^A$  is less than or equal to  $X_{max}^B$ , and  $X_{max}^A$  is more than or equal to  $X_{min}^B$ ; simultaneously,  $Y_{min}^A$  is less than or equal to  $Y_{max}^B$ , and  $Y_{max}^A$  is more than or equal to  $Y_{min}^B$ . Further, due to the characteristic of the 3D workspace model, the workspace intersection has to be satisfied

all together following the z-axis described by  $Z_{min}^A$  is less than or equal to  $Z_{max}^B$ , and  $Z_{max}^A$  is more than or equal to  $Z_{min}^B$ .

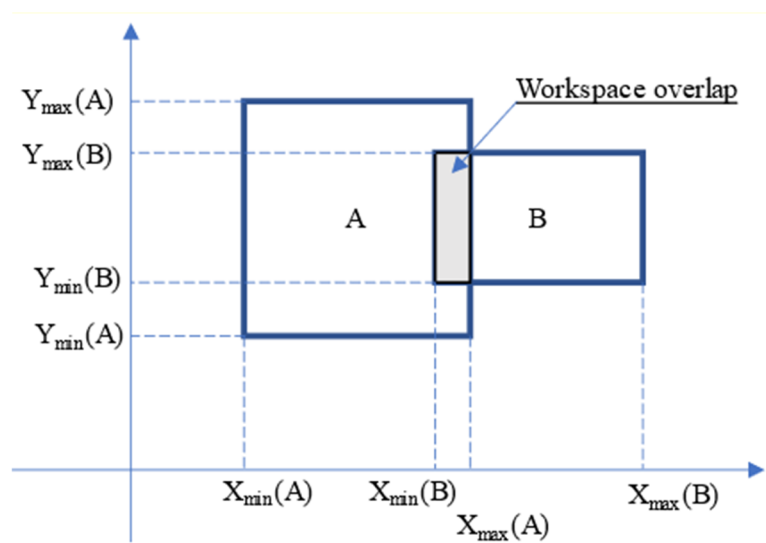


Figure 6. Workspaces overlap case.

$$\begin{cases} X_{min}^A \leq X_{max}^B \wedge X_{max}^A \geq X_{min}^B \\ Y_{min}^A \leq Y_{max}^B \wedge Y_{max}^A \geq Y_{min}^B \\ Z_{min}^A \leq Z_{max}^B \wedge Z_{max}^A \geq Z_{min}^B \end{cases} \quad (2)$$

### 3.1.3. Safety Information Integration (SII) Module

The SII module is designed to enable project teams to detect safety hazards automatically during the planning stage. The system computes PA with spatial-temporal overlap condition obtained from the SCI module and matches with the hazard database developed in SHI module. Figure 7 shows the algorithm of matching the pair-wise activities between the 4D BIM planning and hazard database. The initial input is to load spatial-temporal exposure cases from SCI module. Then each case is checked with the hazard database built from SHI module in the while loop. If the PA determined from SCI module matched with the hazard database, then it means that the given activities have an accident in the past. Moreover, it is supposed to be potentially hazardous activities for each other; hence, safety professionals have to re-define the PA's risk level. Contrarily, the safety professionals further review the PA's potential risk to convey the outcomes to other stakeholders. The resulted warning information would help to enrich the hazard database using for the upcoming projects. The PA exported from SII module are visualized in the web-based system 4D BIM simulation, as demonstrated Section 4.

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**Method:** Matching the PA between the 4D BIM and hazard database

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**Results:** Hazard information extracted from hazard database and expert inserts new hazards into the database

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Load data from spatial-temporal exposure of SCI module

Int  $i=0$ ;  $j=1$ ;  $h=0$ ;  $k=1$ ;

**While** spatial-temporal Exposure items **do**

    Connect to MySQL database

    Load WBS code from Hazard Database

    //Set WBS code of tasks in Hazard Database ( $W^H$ )

$WBS\ Hazard = |W_{i+1}^H, W_{j+1}^H|$

    //Set WBS code of tasks in the spatial-temporal exposure database from SCI module ( $W^P$ )

$WBS\ overlap = |W_{h+1}^P, W_{k+1}^P|$

**If**  $WBS-Hazard == WBS-overlap$ , **then**

        Select information from the hazard table

        Connect to at-planning model

        Print all information to the Information Delivery Screen;

**Else**

**If** Expert detect Hazard, **then**

            Input information

            Update Hazard table

**Else**

            Confirm No Hazard in case of spatial-temporal exposure analysis

**End**

**End**

$i=i+2$ ;  $j=j+2$ ;  $h=h+2$ ;  $k=k+2$ ;

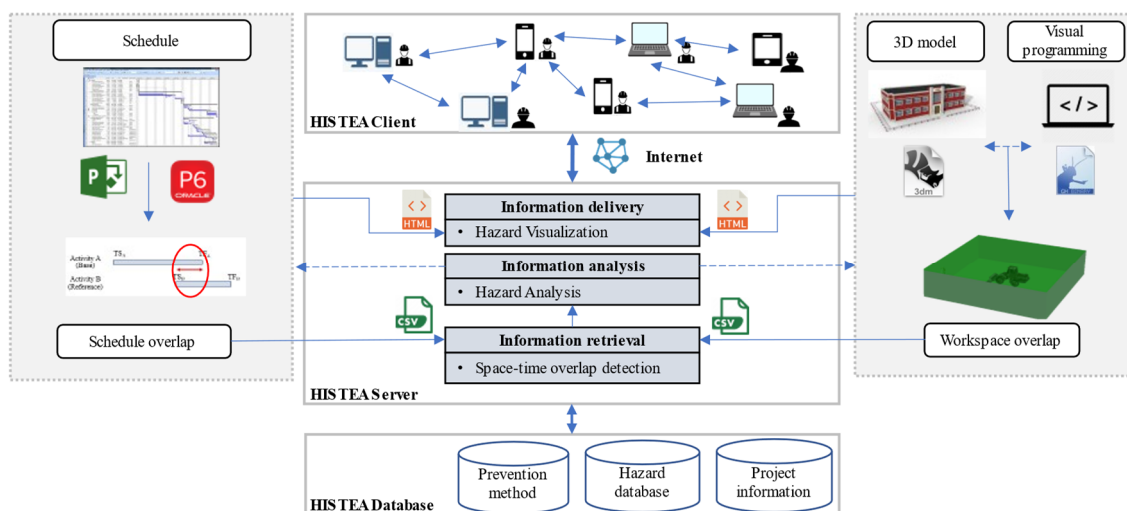
**End**

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**Figure 7.** Matching the PA between the 4D building information modeling (BIM) and hazard database

### 3.2. HISTEA System Architecture

To implement the HISTEA approach for identifying hazard of the case scenario, its architecture is designed by adopting a standard web-based environment. As depicted in Figure 8, the proposed system consists of three main components: the HISTEA client, a web service server, and a central database. The HISTEA system is formulated using the Java programming language combined with a MySQL database. The HISTEA contains two services: web and background services. The system is designed using the model-view-controller (MVC) to ensure security and flow to manage multiple access and tasks with extensive data. The web service is implemented using Apache Tomcat Servlet Container and Java Server Page technology.



**Figure 8.** HISTEA system architecture.

To connect two services, the authors choose the Apache Thrift framework. The following includes the main features of the HISTEA system: (1) It extracts information from uploaded files and analyzes it for pre-processing before it is entered into the database. (2) It employs a methodology to understand the database and a similarity algorithm to output the PA database file. (3) It allows information visualization for users in a web browser via the Java web application and Iris plugin (3D model extraction from Rhino 6 for embedding into Java Server Pages).

In the HISTEA system architecture, the project input information is derived from the project schedule and 3D model in a comma-separated values file format (.csv file); in the pre-processing, the workspace is generated using visual programming. The commercially available tool employed is Grasshopper (a plugin to Rhinoceros), which is a powerful tool for interactive workspace generation.

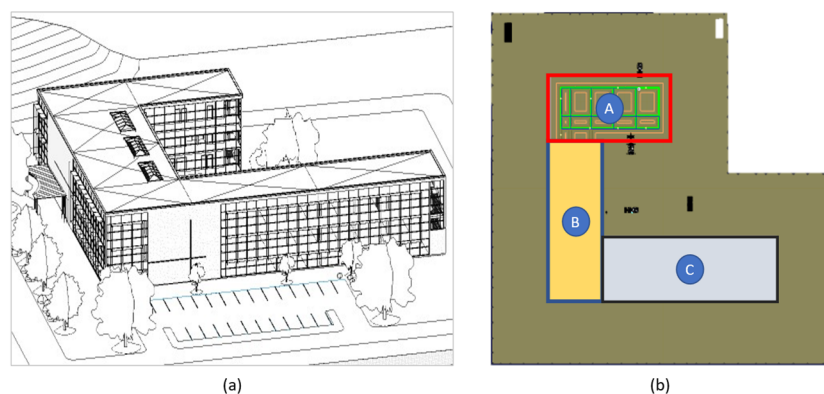
#### 4. Case Study

This section demonstrates the application of HISTEA on a typical school project obtained from the Autodesk library (see Figure 9a) to verify its performance and efficiency. The assumed schedule, format, and required libraries for the case scenario are introduced, and then the developed prototype has been implemented on the selected project.

##### 4.1. Introduction of Case Scenario

In this case study, we focus on identifying the hazard at the pre-construction stage of foundation works. The excavation work is an essential activity of foundation works; however, proper precautions are not taken, several fatal accidents can occur in this activity. Further, spatial-temporal overlap conditions always appear during this phase. For example, while the excavator is digging, laborers may be working in the trench.

The 3D model obtained from the Autodesk library is export to .3dm format to import in Rhino software. The method for excavation in this project is assumed to be open-cut excavation. The activities proposed by the project team are listed in Table 3. The schedule and 3D site layout for the experiment are provided in the MS project and Rhino software. The activities are identified using the WBS code with the format mentioned in Section 3.1.1. The project team divided the activities into work packages as a fast-tracked approach to optimize time and cost. There are three excavation zones for the foundation: A, B, and C (Figure 9b). The HISTEA is applied to detect potential hazards in zone A, as shown in Figure 9b.



**Figure 9.** Project case study.

**Table 3.** Schedule in zone A of the case scenario.

| WBS Code |         |              | Task Name                                              | Duration<br>(Day) | Start             | Finish            |
|----------|---------|--------------|--------------------------------------------------------|-------------------|-------------------|-------------------|
| Location | Action  | Work Results |                                                        |                   |                   |                   |
| A        |         |              | <b>Foundation phase</b>                                | <b>34</b>         | <b>11/13/2019</b> | <b>12/16/2019</b> |
|          |         |              | <b>Mobilize on Site</b>                                | <b>3</b>          | <b>11/13/2019</b> | <b>11/15/2019</b> |
|          | 575,123 | 015,213      | Set up a site office                                   | 3                 | 11/13/2019        | 11/15/2019        |
|          | 575,123 | 015,600      | Prepare site–laydown yard and temporary fencing        | 2                 | 11/13/2019        | 11/14/2019        |
|          |         |              | <b>Site Grading and Utilities</b>                      | <b>6</b>          | <b>11/16/2019</b> | <b>11/21/2019</b> |
|          | 576,133 | 312,213      | Rough grade site (cut and fill)                        | 4                 | 11/16/2019        | 11/19/2019        |
|          | 575,115 | 312,200      | Erect building batter boards and layout building       | 3                 | 11/19/2019        | 11/21/2019        |
|          |         |              | <b>Excavation</b>                                      | <b>14</b>         | <b>11/21/2019</b> | <b>12/4/2019</b>  |
|          |         |              | <b>Zone A</b>                                          | <b>5</b>          | <b>11/21/2019</b> | <b>11/25/2019</b> |
|          | 579,115 | 312,316      | Excavating using excavator                             | 4                 | 11/21/2019        | 11/24/2019        |
|          | 576,129 | 015,629      | Deliver supplies and manually install a safety barrier | 2                 | 11/23/2019        | 11/24/2019        |
|          | 659,100 | 312,000      | Moving of excavation soil by the dump truck            | 4                 | 11/22/2019        | 11/25/2019        |
|          | 575,115 | 312,316      | Excavation inspection & measurement of trench          | 1                 | 11/24/2019        | 11/24/2019        |
|          | 576,133 | 312,323      | Compacting                                             | 4                 | 11/22/2019        | 11/25/2019        |
|          |         |              | <b>Foundation</b>                                      | <b>21</b>         | <b>11/26/2019</b> | <b>12/16/2019</b> |
|          |         |              | <b>Zone A</b>                                          | <b>12</b>         | <b>11/26/2019</b> | <b>12/7/2019</b>  |
|          | 576,115 | 321,136      | PCC                                                    | 1                 | 11/26/2019        | 11/26/2019        |
|          | 576,129 | 032,100      | Install Rebar                                          | 3                 | 11/28/2019        | 11/30/2019        |
|          | 576,129 | 031,100      | Install Formwork                                       | 2                 | 12/1/2019         | 12/2/2019         |
|          | 576,115 | 032,000      | Pouring concrete                                       | 1                 | 12/3/2019         | 12/3/2019         |
|          | 579,123 | 031,100      | Dismantling formwork                                   | 1                 | 12/6/2019         | 12/6/2019         |
|          | 576,135 | 312,316      | Backfill                                               | 2                 | 12/6/2019         | 12/7/2019         |

First, the HISTEA begins by importing the workspace and time overlaps of PAs. Next, the HISTEA detects PAs with space–time overlaps. Then, these are compared with the hazard database to identify potential dangers. Finally, after identifying the PAs with potential hazards, the project team adjusts or proposes prevention methods to preclude undesirable incidents.

#### 4.2. HISTEA Prototype Implementation

The HISTEA begins with project creation (step 1 in Figure 10) by entering and storing the project information into the database.

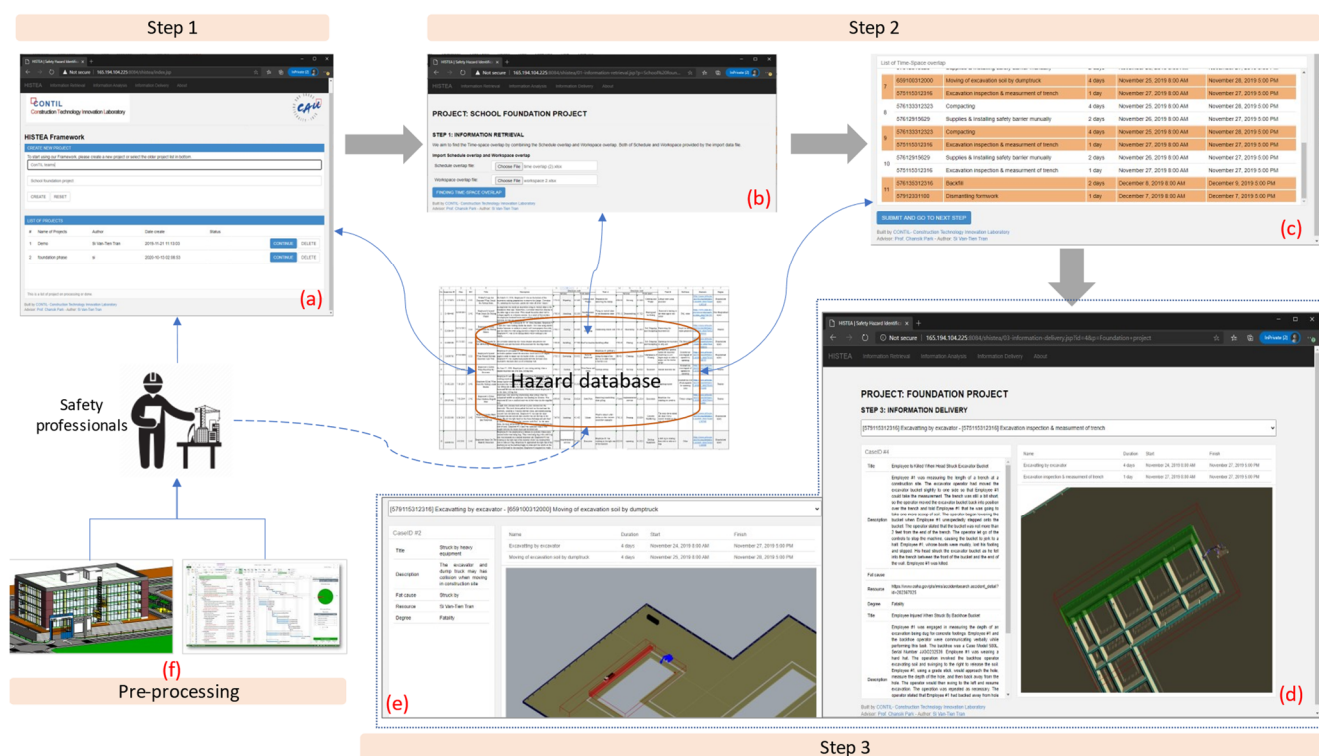


Figure 10. Case study implementation.

#### 4.2.1. Information Retrieval

After creating a project, the HISTEA moves to a new tab; this step involves importing the workspace overlap and time overlap of PAs. The input template is provided; it requires the project team to enter the requested information. As illustrated in Figure 10b and f, the pair-wise activities (PA) of spatial-temporal overlaps are selected. In this case, 14 pairs of time overlap, and 18 pairs of workspace overlaps are analyzed. As shown in a new window (see Figure 10c), there are 11 PAs with spatial-temporal overlaps (Figure 10c). Before the next step can be performed, the project team must input these results into the HISTEA stored in the database.

#### 4.2.2. Information Analysis

The pair-wise activities selected in step one are compared with those in the hazard database. After comparison, 11 cases are identified. (1) Two pairs have matches in the database, i.e., there are recorded historical accidents when these activity pairs are implemented at the same time in the same workspace. (2) Nine pairs are manually analyzed by the safety professional. Thereafter, the information is entered into space, as shown in Figure 10d and e, because the analysis information can be reused for the next project. To specify for the case at hand, eight of the nine pairs had potential hazards; hence, these eight pairs were added to the hazard database. Moreover, safety information, such as description, main cause, and sources, is entered with the eight pairs as shown in Figure 10e.

#### 4.2.3. Information Delivery

Ten pair-wise activities were identified as having potential hazards. To obtain adequate information, it is necessary to provide a visual of this hazard for the client. In the HISTEA, ten PAs are delivered to the 3D platform to highlight the intersecting workspaces. Figure 10 visualizes the result of the pair-wise activities as “Excavating using excavator” and “Excavation inspection & measurement of the trench.” The screen displays four types of primary information that are delivered to the project team: (a) the pair-wise activities that have a potential hazard, (b) the previous accident report including accident

description, primary causes, resource, and extent, (c) the schedule of pair-wise activities, and (d) the exported workspace information from the 3D model.

## 5. Results

Following the development of the HISTEA system prototype, its potential practicality and applicability have been validated through a survey which participants related to the construction industry. The interviewee conducted to use of the web-based system and feedback on their experience to the research team.

The research team prepared a video to explain the HISTEA system functions and features and how the hazard identification of spatial-temporal conditions was delivered, providing the participants an overview of how the HISTEA supports safety improvement in the pre-construction stage. The survey participants answered questionnaires and were interviewed to determine whether the HISTEA system satisfied usability criteria. These criteria were formulated to evaluate the system characteristics that are beneficial to project members; moreover, relevant control variables, such as gender, education background, and experience, are identified. Due to the Covid-19 pandemic, the research team recorded the survey instruction (approximately 5 min), prepared questionnaires using Google form tools, and was sent to potential survey participants using electronic mail. The evaluation criteria were graded on the Likert scale from 1 to 5, indicating the respondents' satisfaction level. Twenty-one individuals responded, from which nineteen were considered for evaluation, as two of the responses encompass incomplete information and did not achieve the authors' criteria. Table 4 summarizes the relevant details on these participants. Table 5 summarizes the questions and their results. Six questions are stated to evaluate the criteria of HISTEA, including understandability, ease to use, the effectiveness of visualization, applicability, feasibility, and potential [23,28]. In addition, the questionnaire also elicited additional comments and feedback from the participants for improving the HISTEA.

**Table 4.** Descriptive statistics of control variables.

| Control Variables         |                    | Percentage of Participants | Number of Participants |
|---------------------------|--------------------|----------------------------|------------------------|
| Gender                    | Male               | 100%                       | 19                     |
|                           | Female             | 0%                         | 0                      |
| Education background      | High school        | 32%                        | 6                      |
|                           | University         | 42%                        | 8                      |
|                           | Graduate school    | 26%                        | 5                      |
| Current position          | Student            | 32%                        | 6                      |
|                           | Engineer/Architect | 53%                        | 10                     |
|                           | Researcher         | 16%                        | 3                      |
| Experience                | < 1 year           | 42%                        | 8                      |
|                           | 1–5 years          | 32%                        | 6                      |
|                           | >5 years           | 21%                        | 4                      |
| Current city of residence | Seoul              | 26%                        | 5                      |
|                           | Other              | 74%                        | 14                     |

**Table 5.** Means and standard deviations of dependent variable satisfaction scores.

| Number | Statements                                                                           | Mean<br>(Standard Deviation) |
|--------|--------------------------------------------------------------------------------------|------------------------------|
| 1      | The interviewees understand the instructions of the HISTEA approach                  | 4.37<br>(0.60)               |
| 2      | The HISTEA prototype is easy to use                                                  | 4.26<br>(0.65)               |
| 3      | The HISTEA improves the ability to identify the hazards of spatial-temporal overlaps | 4.53<br>(0.51)               |
| 4      | Knowledge on safety is delivered                                                     | 3.95<br>(0.85)               |

|   |                                                                        |                |
|---|------------------------------------------------------------------------|----------------|
| 5 | The HISTEA has potential for integration with construction methods     | 4.32<br>(0.58) |
| 6 | The integration of 4D BIM model and hazard identification is effective | 4.21<br>(0.63) |

As the results, questions 1 and 2 measure the understandability of the instructions regarding the approach and usability of the HISTEA prototype during the survey. Most of the participants responded with positive feedback, scoring 4.37 and 4.26, respectively. Questions 3, 4, and 5 were designed to measure the HISTEA potential for effectively delivering safety information. The project team's efforts to identify the hazards under spatial-temporal overlap condition, the retrieval of past accident information became automatic. Most of the participants preferred the integration of the 4D BIM model visualization into the hazard identification. The participants suggested enhancing the HISTEA with the 4D BIM plugin; the input necessary for step 1 is the PA information obtained from planning. They also look forward to the development of a HISTEA system that applies to the construction phase.

The results demonstrate the effectiveness of HISTEA system in supporting hazard identification in the course of safety planning, and the project team could adequately define and identify safety hazards using the system. The specific contributions of this article are listed as follows:

1. A hazard identification approach using 4D BIM and accident cases analysis from the OSHA database is proposed. The developed system would be valuable in identifying potential hazards caused spatial-temporal exposures through computing and matching the repetitive nature of the given activities from the past accidents data.
2. The excavation activity related cases reported to IMIS-OSHA in 20 years (2000–2020) is extracted and analyzed for the hazard database development. This study found 496 cases related to excavation activity, whereas 57 number of accidents are reportedly happened due to spatial-temporal exposures.
3. A web-based BIM-4D application is developed and integrated with a hazard database to demonstrate the proposed concept. Moreover, the developed prototype on the proposed concept is validated by a case study as an example.
4. Additionally, the developed prototype is evaluated with stakeholders from the construction industry and academia; 19 members participated in the ranking of the proposed system based on the Likert scale of 1–5.

Nevertheless, this research has certain limitations: (1) The study focuses on identifying PA's potential hazards. However, even though more than two activities can co-occur in the same workspace, it only considers the combination of two activities and does not comprehensively represent the interaction of more than two activities with a spatial-temporal overlap. (2) The database scale for this case study is small. Hence, it is necessary for safety professionals to evaluate the rest of the PA with their experience. However, more cases will be added to the database to have a compact and universal hazard database. (3) The 4D BIM level of details is among the problems in the HISTEA framework. During the accident investigation, the authors have found many interacting job steps (tasks) leading to accidents. For example, an accident report in the OSHA database (inspection identification: 317176873) described that a worker was struck by a falling object while preparing to remove the clamps.

## 6. Discussion

This research developed the HISTEA system to enhance construction safety planning and reduce repetitive accidents of PAs. The main goal was to integrate hazard data with 4D BIM to improve hazard identification of pair-wise activities caused by spatial-temporal overlap. A thorough literature review depicts that previous efforts found the significance of construction accident case analysis and BIM-based approaches in determining

the potential hazards for enhancing construction safety planning. Furthermore, the hazard caused by spatial–temporal exposure could be identified early by combining the advantages of accident case analysis and 4D BIM.

The 3D CAD system and a visual programming tool (Grasshopper) was employed to detect workspace overlap (spatial conflict). Moreover, the workspace overlaps of the corresponding activities are compared with the time aspect using the scheduling tool (MS Project) to identify the schedule overlap (temporal conflict). The spatial–temporal conflict of PAs was visualized in a web-based 4D BIM environment. The HISTEA system can detect potential hazards of PAs by matching them with the hazard database developed from IMIS-OSHA. A simple project obtained from the Autodesk library was used in this research to demonstrate the functionality and applicability of the HISTEA.

The survey was conducted to demonstrate the potential integration of 4D BIM and accident analysis into the HISTEA to support hazard identification. Its respondents gave positive feedbacks and indicated the HISTEA potential. In addition, the HISTEA could enable job site managers to visually plan, verify, and communicate between stakeholders. As construction progresses, the HISTEA could be used to identify potential hazards, making it possible to modify the construction process to ensure safety. Further, the web-based 4D BIM visualization has potential not only in the planning phase but also in the construction stage. It is a valuable graphical tool for architects, engineers, contractors, subcontractors, and suppliers. Through a web-based environment, project stakeholders can access the web viewer system anywhere and whenever to determine potential hazards and review them before proceeding with construction. Each party can deliver the appropriate information for real construction sites. Accident prevention measures can then be implemented for construction safety improvement. The SII module provides an efficient safety hazard identification technique for PAs with a spatial–temporal overlap and is presumed to afford project teams intuitive approaches. Furthermore, the hazard database is enriched by this module, allowing its applicability to various construction projects.

For future research, the following aspects are under consideration: (1) the enrichment of the hazard database by deriving information from additional resources, such as the IMIS and historical data from other countries; expert analysis can also contribute to such enrichment. (2) After the HISTEA has identified the hazards, it would be better to adjust the schedule or workspace automatically if the system suggests accident prevention methods. Concurrently, such adjustments must ensure that the efficiency of the project. Further, (3) the worker's density involved in pairwise activities, which usually did not analyze from accident reports, could affect the level of potential hazards. The density may be considered as one of the parameters in future hazard calculation caused by pairwise activities. (4) In addition to the spatial–temporal overlap, other overlap conditions, such as the “safety clash” term [56], will be analyzed and integrated into BIM.

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## References

1. Mohandes, S.R.; Zhang, X. Developing a holistic occupational health and safety risk assessment model: An application to a case of sustainable construction project. *J. Clean. Prod.* **2021**, *291*, 125934, doi:10.1016/j.jclepro.2021.125934.
2. Statistics - Costs to Britain of workplace injuries and new cases of work-related ill health. Available online: <https://www.hse.gov.uk/statistics/pdf/cost-to-britain.pdf> (accessed on 6 February 2021).
3. Hallowell, M.R. Risk-based framework for safety investment in construction organizations. *J. Constr. Eng. Manag.* **2011**, *137*, 592–599, doi:10.1061/(ASCE)CO.1943-7862.0000339.
4. Employer-Reported Workplace Injuries and Illnesses (Annual) Available online: <https://www.bls.gov/news.release/osh.toc.htm> (accessed on 6 February 2021).
5. Amponsah-Tawiah, K. Occupational health and safety and sustainable development in Ghana. *Int. J. Bus. Adm.* **2013**, *4*, 74–78.
6. Xu, F.Y.; Zhang, M.J.; Wang, L.; Zhang, J.R. Recent highway bridge collapses in China: Review and discussion. *J. Perform. Constr. Facil.* **2016**, *30*, 04016030, doi:10.1061/(ASCE)CF.1943-5509.0000884.
7. Ruggieri, S.; Porco, F.; Uva, G.; Vamvatsikos, D. Two frugal options to assess class fragility and seismic safety for low-rise reinforced concrete school buildings in Southern Italy. *Bull. Earthq. Eng.* **2021**, *19*, 1415–1439, doi:10.1007/s10518-020-01033-5.
8. Ruggieri, S.; Tosto, C.; Rosati, G.; Uva, G.; Ferro, G.A. Seismic vulnerability analysis of masonry churches in piemonte after 2003 valle scrivia earthquake: Post-event screening and situation 17 years later. *Int. J. Archit. Herit.* **2020**, doi:10.1080/15583058.2020.1841366.
9. Commonly Used Statistics|Occupational Safety and Health Administration. Available online: <https://www.osha.gov/data/commonstats> (accessed on 3 August 2020).
10. 971 S. Korean Workers Died on the Job in 2018, 7 More Than Previous Year : National : News : The Hankyoreh. Available online: [http://english.hani.co.kr/arti/english\\_edition/e\\_national/892709.html](http://english.hani.co.kr/arti/english_edition/e_national/892709.html) (accessed on 3 August 2020).
11. Accidents at Work Statistics—Statistics Explained. Available online: [https://ec.europa.eu/eurostat/statistics-explained/index.php/Accidents\\_at\\_work\\_statistics](https://ec.europa.eu/eurostat/statistics-explained/index.php/Accidents_at_work_statistics) (accessed on 3 August 2020).
12. Nawaz, W.; Linke, P.; Koç, M. Safety and sustainability nexus: A review and appraisal. *J. Clean. Prod.* **2019**, *216*, 74–87.
13. Hadikusumo, B.H.W.; Rowlinson, S. Capturing safety knowledge using design-for-safety-process tool. *J. Constr. Eng. Manag.* **2004**, *130*, 281–289, doi:10.1061/(asce)0733-9364(2004)130:2(281).
14. Gangolells, M.; Casals, M.; Forcada, N.; Roca, X.; Fuertes, A. Mitigating construction safety risks using prevention through design. *J. Saf. Res.* **2010**, *41*, 107–122, doi:10.1016/j.jsr.2009.10.007.
15. Zhang, S. Integrating safety and BIM: automated construction hazard identification and prevention, Georgia Institute of Technology, 2014. Available online: <https://smartech.gatech.edu/handle/1853/52235> (accessed on 3 August 2020).
16. Shang, Z.; Shen, Z. A framework for a site safety assessment model using statistical 4D BIM-based spatial-temporal collision detection. In Proceedings of the Construction Research Congress 2016, San Juan, Puerto Rico, 31 May–2 June 2016; pp. 2187–2196.
17. Sacks, R.; Rozenfeld, O.; Rosenfeld, Y. Spatial and temporal exposure to safety hazards in construction. *J. Constr. Eng. Manag.* **2009**, *135*, 726–736, doi:10.1061/(ASCE)0733-9364(2009)135:8(726).
18. Hallowell, M.; Esmaeili, B.; Chinowsky, P. Construction management and economics safety risk interactions among highway construction work tasks. *Taylor Fr.* **2011**, *29*, 417–429, doi:10.1080/01446193.2011.552512.
19. Khan, N.; Khairadeen Ali, A.; Van-Tien Tran, S.; Lee, D.; Park, C. Visual language-aided construction fire safety planning approach in building information modeling. *Appl. Sci.* **2020**, *10*, 1704, doi:10.3390/app10051704.
20. Zou, Y.; Kiviniemi, A.; Jones, S.W. A review of risk management through BIM and BIM-related technologies. *Saf. Sci.* **2017**, *97*, 88–98, doi:10.1016/j.ssci.2015.12.027.
21. Wu, Z.; Chen, C.; Cai, Y.; Lu, C.; Wang, H.; Yu, T. BIM-Based visualization research in the construction industry: A network analysis. *Int. J. Environ. Res. Public Health* **2019**, *16*, 3473, doi:10.3390/ijerph16183473.
22. Tran, S.; Ali, A.K.; Khan, N.; Lee, D.; Park, C. A Framework for camera planning in construction site using 4D BIM and VPL. In Proceedings of the 37th International Symposium on Automation and Robotics in Construction (ISARC); International Association for Automation and Robotics in Construction (IAARC): Kitakyushu, Japan, 27–28 October 2020.
23. Pham, H.C.; Pedro, A.; Le, Q.T.; Lee, D.Y.; Park, C.S. Interactive safety education using building anatomy modelling. *Univers. Access Inf. Soc.* **2019**, *18*, 269–285, doi:10.1007/s10209-017-0596-y.
24. Kim, H.; Lee, H.-S.; Park, M.; Chung, B.; Hwang, S. Information retrieval framework for hazard identification in construction. *J. Comput. Civ. Eng.* **2015**, *29*, 04014052, doi:10.1061/(ASCE)CP.1943-5487.0000340.
25. Abudayyeh, O.; Federicks, T.; Palmquist, M.; Torres, H.N. Analysis of occupational injuries and fatalities in electrical contracting industry. *J. Constr. Eng. Manag.* **2003**, *129*, 152–158, doi:10.1061/(ASCE)0733-9364(2003)129:2(152).
26. Goh, Y.M.; Chua, D.K.H. Case-based reasoning approach to construction safety hazard identification: Adaptation and utilization. *J. Constr. Eng. Manag.* **2010**, *136*, 170–178, doi:10.1061/(ASCE)CO.1943-7862.0000116.
27. Zhang, S.; Boukamp, F.; Teizer, J. Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Autom. Constr.* **2015**, *52*, 29–41, doi:10.1016/j.autcon.2015.02.005.
28. Park, C.S.; Kim, H.J. A framework for construction safety management and visualization system. *Autom. Constr.* **2013**, *33*, 95–103, doi:10.1016/j.autcon.2012.09.012.

29. Kim, K.; Cho, Y.; Zhang, S. Integrating work sequences and temporary structures into safety planning: Automated scaffolding-related safety hazard identification and prevention in BIM. *Autom. Constr.* **2016**, *70*, 128–142, doi:10.1016/j.autcon.2016.06.012.
30. Yi, K.-J.; Langford, D. Scheduling-based risk estimation and safety planning for construction projects. *J. Constr. Eng. Manag.* **2006**, *132*, 626–635, doi:10.1061/(ASCE)0733-9364(2006)132:6(626).
31. Choe, S.; Leite, F. Construction safety planning: Site-specific temporal and spatial information integration. *Autom. Constr.* **2017**, *84*, 335–344, doi:10.1016/j.autcon.2017.09.007.
32. Kim, K.; Cho, Y.; Kim, K. BIM-driven automated decision support system for safety planning of temporary structures. *J. Constr. Eng. Manag.* **2018**, *144*, 04018072, doi:10.1061/(ASCE)CO.1943-7862.0001519.
33. Behm, M. Linking construction fatalities to the design for construction safety concept. *Saf. Sci.* **2005**, *43*, 589–611, doi:10.1016/j.ssci.2005.04.002.
34. Hossain, M.A.; Abbott, E.L.S.; Chua, D.K.H.; Nguyen, T.Q.; Goh, Y.M. Design-for-Safety knowledge library for BIM-integrated safety risk reviews. *Autom. Constr.* **2018**, *94*, 290–302, doi:10.1016/j.autcon.2018.07.010.
35. Fatality and Catastrophe Investigation Summaries | Occupational Safety and Health Administration. Available online: <https://www.osha.gov/pls/imis/accidentsearch.html> (accessed on 12 December 2020).
36. Zhang, X.; Deng, Y.; Li, Q.; Skitmore, M.; Zhou, Z. An incident database for improving metro safety: The case of shanghai. *Saf. Sci.* **2016**, *84*, 88–96, doi:10.1016/j.ssci.2015.11.023.
37. Esmaeili, B.; Hallowell, M. Attribute-based risk model for measuring safety risk of struck-by accidents. In Proceedings of the Construction Research Congress 2012: Construction Challenges in a Flat World, Proceedings of the 2012 Construction Research Congress: West Lafayette, Indiana, 21–23 May 2012; pp. 289–298.
38. Guo, H.; Yu, Y.; Skitmore, M. Visualization technology-based construction safety management: A review. *Autom. Constr.* **2017**, *73*, 135–144.
39. Zhang, L.; Wu, X.; Ding, L.; Skibniewski, M.J.; Lu, Y. Bim-based risk identification system in tunnel construction. *J. Civ. Eng. Manag.* **2016**, *22*, 529–539, doi:10.3846/13923730.2015.1023348.
40. Zhang, S.; Teizer, J.; Lee, J.K.; Eastman, C.M.; Venugopal, M. Building Information Modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Autom. Constr.* **2013**, *29*, 183–195, doi:10.1016/j.autcon.2012.05.006.
41. Khan, N.; Ali, A.K.; Skibniewski, M.J.; Lee, D.Y.; Park, C. Excavation safety modeling approach using BIM and VPL. *Adv. Civ. Eng.* **2019**, doi:10.1155/2019/1515808.
42. Ji, Y.; Leite, F. Automated tower crane planning: Leveraging 4-dimensional BIM and rule-based checking. *Autom. Constr.* **2018**, *93*, 78–90, doi:10.1016/j.autcon.2018.05.003.
43. Zhang, S.; Sulankivi, K.; Kiviniemi, M.; Romo, I.; Eastman, C.M.; Teizer, J. BIM-based fall hazard identification and prevention in construction safety planning. *Saf. Sci.* **2015**, *72*, 31–45, doi:10.1016/j.ssci.2014.08.001.
44. Feng, C.W.; Lu, S. Using BIM to automate scaffolding planning for risk analysis at construction sites. In Proceedings of the Annual International Symposium on Automation and Robotics in Construction (ISARC), Taipei, Taiwan, 28 June–1 July 2017; Volume 34.
45. Zhang, S.; Teizer, J.; Pradhananga, N.; Eastman, C.M. Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning. *Autom. Constr.* **2015**, *60*, 74–86, doi:10.1016/j.autcon.2015.09.009.
46. Kim, K.; Lee, Y.-C. Automated generation of daily evacuation paths in 4D BIM. *Appl. Sci.* **2019**, *9*, 1789, doi:10.3390/app9091789.
47. Wu, I.-C.; Chiu, Y.-C. *4D Workspace Conflict Detection and Analysis System*. In Proceedings of the 10th International Conference on Construction Applications of Virtual Reality, CONVR 2010, 4–5 November 2010, Sendai, Japan.
48. Akinci, B.; Fischen, M.; Levitt, R.; Carlson, R. Formalization and automation of time-space conflict analysis. *J. Comput. Civ. Eng.* **2002**, *16*, 124–134, doi:10.1061/(ASCE)0887-3801(2002)16:2(124).
49. Akinci, B.; Fischer, M.; Kunz, J. Automated generation of work spaces required by construction activities. *J. Constr. Eng. Manag.* **2002**, *128*, 306–315, doi:10.1061/(ASCE)0733-9364(2002)128:4(306).
50. Guo, S.-J. Identification and resolution of work space conflicts in building construction. *J. Constr. Eng. Manag.* **2002**, *128*, 287–295, doi:10.1061/(ASCE)0733-9364(2002)128:4(287).
51. Mallasi, Z. Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualisation. *Autom. Constr.* **2006**, *15*, 640–655, doi:10.1016/j.autcon.2005.08.005..
52. Moon, H.; Dawood, N.; Kang, L. Development of workspace conflict visualization system using 4D object of work schedule. *Adv. Eng. Informatics* **2014**, *28*, 50–65, doi:10.1016/j.aei.2013.12.001.
53. Mirzaei, A.; Nasirzadeh, F.; Parchami Jalal, M.; Zamani, Y. 4D-BIM dynamic time-space conflict detection and quantification system for building construction projects. *J. Constr. Eng. Manag.* **2018**, *144*, doi:10.1061/(ASCE)CO.1943-7862.0001504.
54. Kassem, M.; Dawood, N.; Chavada, R. Construction workspace management within an Industry Foundation Class-Compliant 4D tool. *Autom. Constr.* **2015**, *52*, 42–58, doi:10.1016/j.autcon.2015.02.008.
55. OmniClass®—Construction Specifications Institute. Available online: <https://www.csiresources.org/standards/omniclass> (accessed on 19 January 2021).
56. Tixier, A.J.P.; Hallowell, M.R.; Rajagopalan, B.; Bowman, D. Construction safety clash detection: identifying safety incompatibilities among fundamental attributes using data mining. *Autom. Constr.* **2017**, *74*, 39–54, doi:10.1016/j.autcon.2016.11.001.