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A framework for 4D analysis of construction safety using a Site Information Model

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Abstract:

This study introduces a comprehensive framework for 4D safety analysis in construction site layout planning (CSLP), using a Site Information Model (SIM) environment to enhance spatial hazard identification and effectively integrate it with activity-based safety management. The framework, grounded in a continuous-space layout approach, accurately positions objects to mirror temporary facilities' actual boundaries, incorporating spatial relationships and inherent safety hazards. It also features rasterization to translate layouts into a grid system. Central to this framework are three modules for spatial hazard identification: Visibility Analysis, Spatial Hazard Mapping, and Travel Path Analysis, designed to identify less visible spaces, assess spatial hazards, and simulate optimal travel paths considering safety aspects. By applying this framework to case studies of a residential complex and a commercial office project, the research demonstrates its practical utility in improving visibility and spatial hazard assessment, despite the inherently complex dynamics of construction sites. The study acknowledges challenges, such as the reliance on safety managers' experiential knowledge for setting hazard parameters and the need for further development in integrating these insights with activity-based safety management. It underscores the framework's significant potential to advance construction safety management by offering a method to preemptively recognize and mitigate spatial hazards. The approach promises not only to contribute to accident prevention but also to enhance overall project performance by incorporating spatial and temporal dimensions of safety into CSLP. This research marks a significant step toward a more holistic and integrated approach to construction safety, highlighting the importance of continuous improvement and adaptation in safety practices.

Key words: Construction safety, Site Information Model, 4D modeling, Temporary facility layout, Hazard assessment

1. INTRODUCTION

Construction sites present a challenging environment for workers, exposing them to risks of accidents such as collisions with equipment/materials, falls, and fires. The construction industry has been reported as one of the most hazardous sectors, accounting for 20% of all industrial accidents in the United States as of 2021 [1]. In response, various safety management plans are developed from multiple perspectives during the execution phase of construction projects to prevent accidents. Hazard identification is a crucial task for safety practitioners, considering the presence of temporary facilities, lifting equipment, worksites, and storage areas as potential hazards. Spatial safety management begins with the recognition that construction sites inherently contain risks due to hazardous elements, adopting strategies to maintain distance between hazardous facilities and workspaces [2]. Construction Site Layout Planning (CSLP) plays a pivotal role in this process, involving the modeling and arrangement of various temporary facilities, roads, and equipment on construction sites. Therefore, research aimed at finding the optimal CSLP also addresses safety considerations by focusing on the distance and isolation between objects [3]. Although this approach helps reduce spatial risks and prevent accidents, relying solely on layout plan has its limitations in allowing safety managers to preemptively recognize the spatial dangers on-site.

Therefore, this study proposes a framework for a 4D system that supports construction site safety management using a Site Information Model (SIM) environment that captures the spatial-temporal information of CSLP. The proposed framework focuses on complementing the spatial risk assessment aspect, which is lacking in activity-centered safety management. It aims to assess the spatial hazard within the site by applying the concept of space syntax based on a digitalized site layout in the SIM environment and integrating this with the hazard of activities that well-integrated with the schedule information.

A hidden issue in the practical application of digital modeling research for CSLP is excessive sophistication. The arrangement of temporary facility objects constrains the site's space and impacts the activities of many project organizations for a long period. In practice, such longer-term tasks require communication and negotiation with other project organizations, favoring flexible arrangements over precision [4]. Moreover, the computational methods used in studies deriving optimal placements based on precise grid environments are unfamiliar to construction industry practitioners [5]. Therefore, the evaluation of spatial aspect in CSLP often relies on the planners' empirical judgment based on approximate plans. As a result, integration of spatial hazard in safety management that focus on activity-centered hazard recognition is limited.

In this proposed framework, the layout modeling of temporary objects starts within continuous spaces—a method particularly effective for accommodating objects of diverse sizes and shapes, as well as for sketching out approximate layouts of temporary facilities [3]. The process begins in a Graphical Information System (GIS) environment, where a library of temporary objects is utilized for the modeling phase. This is followed by the rasterization of the digital model, a first module that transitions the model into a grid system. The decomposition of the model into cells leads to the generation of a spatial hazard map, a key output of the following two modules. The second module focuses on assessing the visibility of cells that are unoccupied, the third module integrates this visibility analysis with the inherent hazards of the facilities to evaluate the overall spatial hazard of each decompose cell.

The analysis deepens with the fourth module, where the simulated travel paths of workers and equipment are integrated with activity information. This comprehensive approach allows for a detailed analysis of inherent risks that span both the schedule and space dimensions of construction projects.

Ultimately, this research offers a significant advancement in construction safety management, presenting a promising method for the identification of unsafe spaces and its integration with activity-based preliminary hazard analysis. By doing so, it aims to contribute not only to the prevention of accidents but also to the enhancement of overall project performance.

2. LITERATURE REVIEW

2.1. Safety planning and analysis in project execution

In construction projects, the role of safety practitioners involves analyzing potential hazards during project execution, quantitatively assessing those risks, and managing safety risks through activities such as worker training and job-site inspections [6]. Therefore, research supporting the planning and control of safety managements has continuously evolved with the regulatory systems such as the Occupational Safety and Health Act. Such studies have primarily focused on the workers and their activities as the safety objects [7–9].

Research from an activity-centered perspective, represented by job hazard analysis, has been consistently conducted for a long time. Such research breaks down the project execution phase activities into a series of sub-activities using a work breakdown structure, identifying hazard factors for each activity and assessing their probability of occurrence and severity [7]. Hence, studies have contributed to hazard identification by elucidating the causal relationships of accidents based on accident reports [10] and advancing risk assessment techniques [7–9]. As a result, evaluation models that assess safety risks based on the qualitative characteristics of the project and activities [8], or further refine the assessment of uncertainties through fuzzy sets [9], have been presented as outcomes that can support activity-based safety management tasks.

Such advanced activity-centered safety planning requires more detailed work packages, making it more applicable to short-term planning right before actual work execution than to initial stages of project execution, which involve long-term planning. On the other hand, the layout of temporary facilities, lifting equipment, worksites, and storage areas that constrain the site's space belongs to long-term planning. Since these facilities are not clearly associated with the safety risks of specific work packages, research on activity-centered safety planning lacks connection with spatial constraints or hazard [6].

2.2. Hazard assessment of site space based on temporary facility layout

Planning the space and environment of construction sites is known as construction site layout planning (CSLP), targeting the arrangement of temporary facilities, construction equipment, storage yards, work areas, and temporary roads. Research on CSLP aims primarily at modeling and placing these objects while analyzing the relationships of distance, containment, and visibility between them to establish an optimal layout plan [3]. Often, the primary goal of CSLP optimization is productivity, implemented through optimization techniques (e.g., linear/non-linear programming, genetic algorithm, or annealed neural network) using objective functions that minimize the transportation paths of workers and materials [11,12].

Although safety is a major consideration in CSLP along with productivity, the approach to addressing this factor differs from productivity. One method for handling safety involves setting the distance relationship between CSLP objects as a constraint, seeking layouts that maximize these distances [13]. For example, workspaces and site offices might be linked by a constraint relation and placed as far apart as possible using an objective function. Objects such as welding shops containing a high fire hazard, might be regulated by hard logic that prevents their placement too close to storage yards [12]. Another approach designates specific areas as restricted zones, prohibiting or limiting the placement of objects [14]. The congestion of construction space is deeply related to safety risks. Accordingly, some research on dynamic site layout has addressed CSLP by defining the movement and transportation distances of workers/equipment and the iteration frequency as safety factors [15]. These three approaches to addressing safety in CSLP significantly contribute to reducing safety risks in temporary facility placement. However, they are limited in providing information on which spaces within the site are more hazardous. In other words, these studies offer limited contributions to safety monitoring during project execution following the establishment of the facility layout plan.

Conversely, research on evaluating the risk of unoccupied space on construction sites or identifying unsafe spaces is rare. [16] assesses the risk of unoccupied space based on the assumption that workers instinctively avoid hazardous spaces, considering the composition and location of work teams. [17] and [15] introduced an approach using the concept of space syntax. They commonly distribute the hazard associated with placed objects to unoccupied space and interpolating the gaps, based on the assumption that the inherent risk of a temporary facility decreases inversely with distance. While these efforts have made progress in identifying risks in site spaces based on CSLP, the discussion on how this can be integrated with activity- and schedule-centered safety management is insufficient.

A potential link between these two could be the issue of planning travel paths within the site space. Research dealing with CSLP utilizes various pathfinding techniques (e.g., calculation based on rectilinear distance, visibility graph and evolutionary algorithms) to simulate the travel paths of workers/equipment, but such simulated path showed considerable differences compared with the actual movement. The main reason makes such gaps is the spatial risk perception of managers/workers [18]. Therefore, simulating travel paths based on spatial risk not only contributes to the accuracy of efficiency predictions in CSLP but also enables the assessment of inherent risks in those paths. Since the decision of departures and destinations for the movement of workers/equipment on site is closely linked to the workface scheduling, representing spatial hazard-based travel paths can provide useful information for activity-centered preliminary hazard analysis.

3. FRAMEWORK FOR 4D SAFETY ANALYSIS

The construction site layout framework presented in this study, aiming for 4D safety analysis, starts by placing site objects, linked to an object library and scheduled activity class, within a continuous spatial environment. The placed site objects are then rasterized into a grid space environment. The analysis related construction safety is conducted based on the decomposed individual cells. In this SIM environment, individual cells have attributes beyond X-Y coordinates; they include the information related to occupancy status, occupied object, cell invisibility, and cell hazard. Once the site objects are rasterized, individual cells in the X-Y coordinate system gain values for occupancy status and the types of objects occupying them. Linked to this information, three spatial hazard identification modules can be operated.

The Visibility Analysis Module calculates the visibility value for each cell and stores the inverse of this value as the cell invisibility within the cell. The Spatial Hazard Mapping Module combines the inherent hazard information of the site objects with the cell invisibility to compute and store the cell hazard values. The Travel Path Analysis Module is a component that simulates travel paths between designated start and destination points, or two points associated with the scheduled activities, based on cell hazard values. The list of cells generated by this module's travel path holds the path's hazard information, as it receives the cell hazard values. This information is integrated with the inherent hazard of activities, enabling the operation of the 4D safety analysis. The diagram in Fig. 1 organizes the conceptual explanation, and the two major axes of this framework are detailed below.

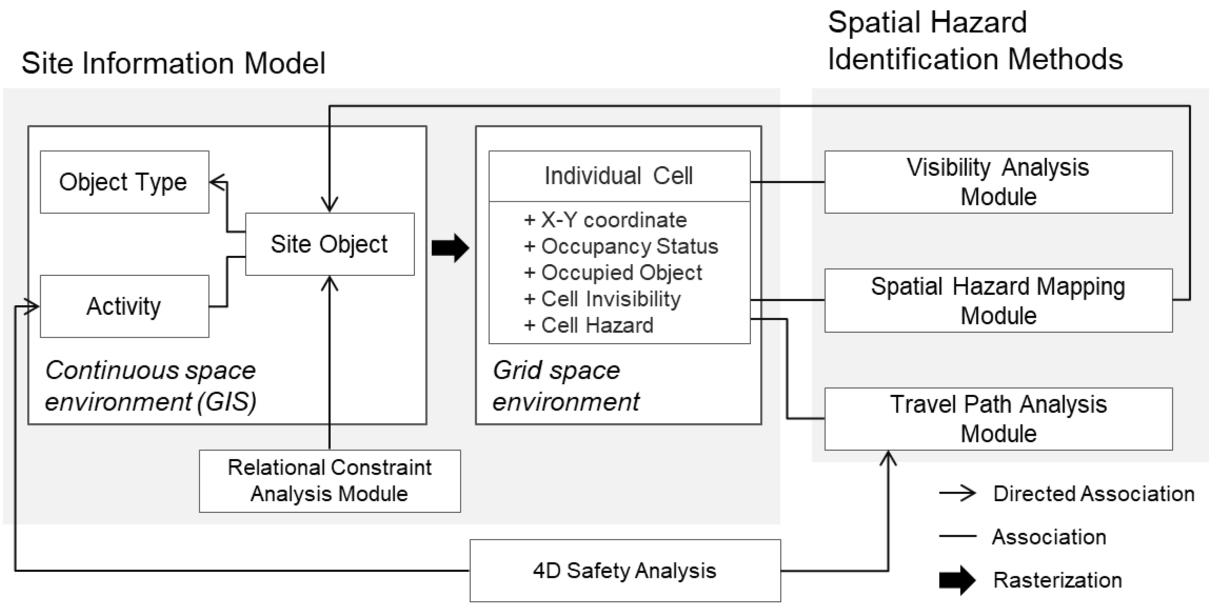

Fig. 1. 4D safety analysis framework based on SIM

3.1. Site information model

The framework proposed in this study begins with the represented site layout within a SIM environment. In practice, planners utilize tools (e.g., AutoCAD or MS PowerPoint) that provide an environment without constraints on the representation of objects or boundaries to establish approximate site layout plans. Thus, the environment for modeling the site space should be easily integrated with current work processes while being capable of converting layout planning work into location information alongside the placement of temporary facilities. Therefore, a GIS with an Open Application Programming Interface [19] is designated as the environment for modeling site space.

This setting, which we define as the SIM environment, allows for the use of a site object library to draw site objects integrated with work schedules and to rasterize them, enabling individual cells to interact with modules related to spatial hazard identification, providing necessary information, and storing results. The major attributes of a Site Object are 1) the vertices created by the planner's drawing, 2) the object type, 3) the attributes obtained by referencing the object library (which defined by Object Type), and 4) the related and demolished activities referenced from the planner's scheduling.

For each Object Type, the object library defines geometry, facility-inherent hazard variables (i.e., hazard- distribution, distance(D), severity(S) and sensitivity(n)), and relational constraints with other types of objects. Relational constraints are defined as information such as a certain range inside/outside between two facilities (i.e., *Within_d_Of, NotWithin_d_Of*). This object library is based on preliminary study on typology of temporary facilities [20]. Fig. 2 is an example centered around tower cranes, illustrating the relational constraints and facility-inherent hazard attributes defined in the library. These relational constraints can be reviewed based on vertex information formed while placing site objects in the GIS environment. Activities are set to interlock with modeled site objects by the planner scheduling start and end times, establishing related/demolished activities, thereby holding the same information.

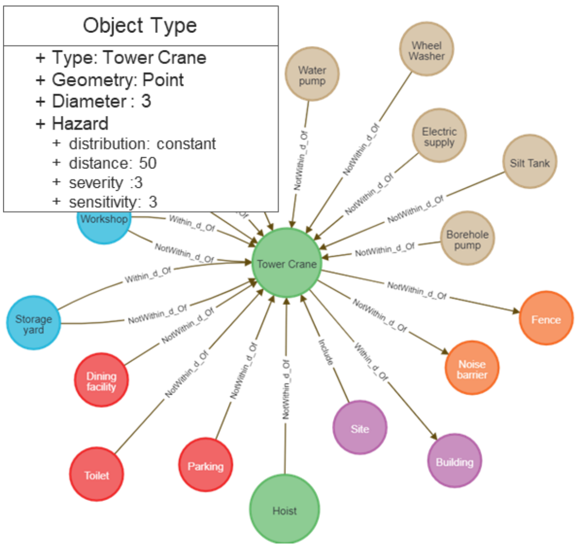

Fig. 2. An attribute example of Object Type (Tower Crane) with relational constraints

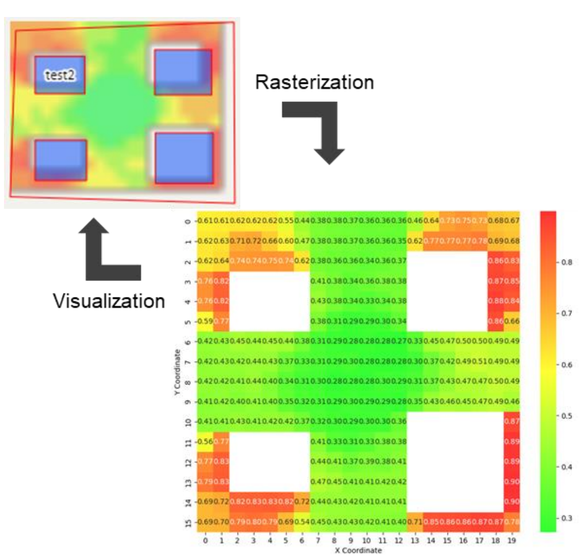

Fig. 3. Front- and back-end information in SIM environment

Fig. 3 illustrates the format in which individual cell information interconnected with spatial hazard identification is stored, using the example of the Invisibility (IV) value. Once the drawn site object rasterized, X-Y coordinate values and occupancy status for each cell are generated in the back-end. Also, other information is calculated and stored through interaction with the spatial hazard identification modules. However, for user convenience in the front-end, the result is provided as color-based visual information added to the GIS environment where the drawing was performed.

3.2. Spatial hazard identification modules

Research that evaluates planned site layout from the perspective that the placement of temporary facilities changes spatial hazard quantifies the safety risk of a plan based on the idea that each temporary facility has its inherent risk, and that risk increases as the distance between facilities decreases [15]. The approach of space syntax, which more directly quantifies space, assumes that the hierarchy of space changes due to the arrangement of objects [21]. In studies applying space syntax to the arrangement of temporary facilities, visibility, which is well-seen from the surroundings, and connectivity between facilities are transposed to spatial hazard based on the perspectives that they are associated with evacuation [17]. Furthermore, it has been observed that the actual movement of workers on site is based on a latent rule of avoiding danger within their line of sight [18]. Building on studies above mentioned, the modules of spatial hazard identification calculate spatial hazard (H_S) the following flow and transpose it into a form that can be integrated with the schedule.

The Visibility Analysis Module employs the concept of Isovist lines from space syntax to determine the visibility for each decomposed cell. Fig. 4(a) depicts the visibility derived through Isovist lines, and Fig. 4(b) delineates the process of mapping this visibility onto the cells. As Fig. 4(a) shows, virtual lines extend from a specific point to all cells within the analysis range. If many lines are unobstructed by objects, similar to the green point, the cell is assigned a high visibility value (V); conversely, if many lines are obstructed, as with the red point, a lower V is given. The calculation process, as illustrated in

Fig. 4(b), yields *V* values between 0 and 1 for all unoccupied cells, with the Invisibility (*IV*) value, computed as *2-V*, subsequently stored.

The Spatial Hazard Mapping Module calculates the cell hazard score (H_S) using the *IV* values from each cell, in conjunction with four parameters related to the facility's inherent hazard (H_F)—namely distribution, distance (*D*), severity (*S*), and sensitivity (*n*)—which are associated with the Site Object. Fig. 5 provides a concise summary of the H_S calculation procedure. The H_F reaches its peak value, denoted as S^n, when the distance to a particular cell is zero. Moreover, the effect of H_F on adjacent cells is acknowledged to vary according to both distance and the specific type of hazard distribution. For example, the fire risk from a welding shop diminishes with increasing distance, whereas the risk of falling objects from a tower crane remains consistent within its boom range. In Fig. 5's scenario F_1, both sensitivity and severity are set to 1, indicating a facility with a constant hazard distribution over a distance of 1, resulting in identical H_{F1} values for the surrounding cells. The impact of a similarly computed H_{F2} is accounted for in cells situated between two facilities. The final hazard score (H_S) is ascertained by multiplying the *IV* weight by the cumulative H_F values, as demonstrated in Fig. 5.

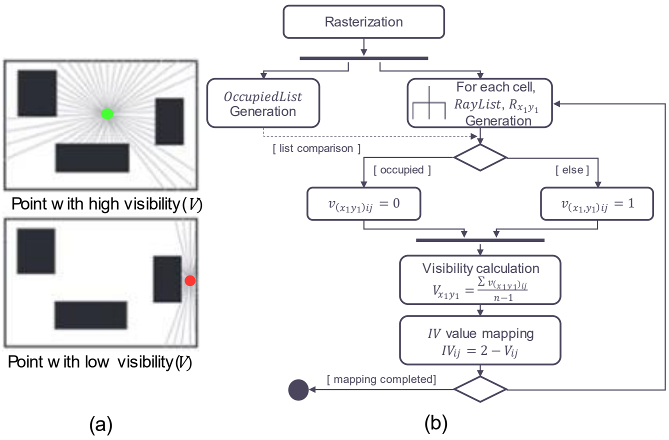

Fig. 4. (a) Concept of visibility derivation and (b) Process of invisibility mapping

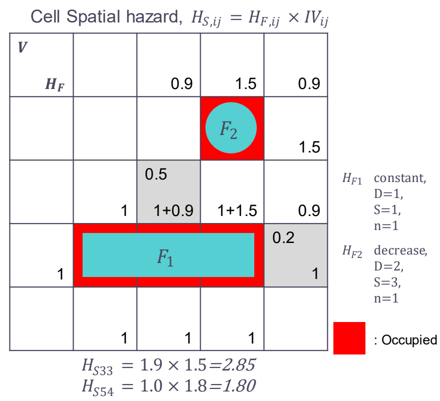

Fig. 5. A scenario of cell hazard score (H_S) calculation

The Travel Path Analysis Module is a component that utilizes the mapped H_S values for each cell to simulate the optimal travel path between two points. This module employs the A* algorithm, a heuristic graph search algorithm that finds the most efficient path under given conditions. It identifies the path with the lowest cumulative H_S value that connects the start and destination points without obstruction from objects, thereby determining the anticipated path of workers/equipment. Therefore, this module not only simulates a travel path that reflects the real movements of workers but also calculates the sum of H_S for the cells along the path, which can be interpreted as path's hazard score. Additionally, the module supports the simulation of paths for related activities modeled by the planner when drawing objects. Hence, it is designed to combine the hazard of the activities with the spatial hazard encountered by workers during their movement for that task.

4. SITE LAYOUT REPRESENTATION

Utilizing the system that applies the proposed framework, we evaluated CSLP representations and the corresponding identification of spatial hazards through practical case studies. Fig. 6 presents the results from a residential complex construction case (Case A), while Fig. 7 showcases an example from a commercial office project (Case B). Figs. (a), (b), and (c) illustrate the visualization outcomes obtained through the Visibility Analysis, Spatial Hazard Mapping, and Travel Path Analysis modules, respectively.

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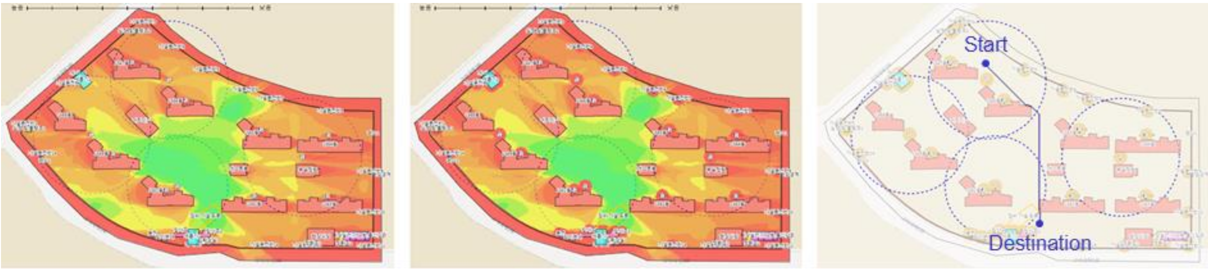
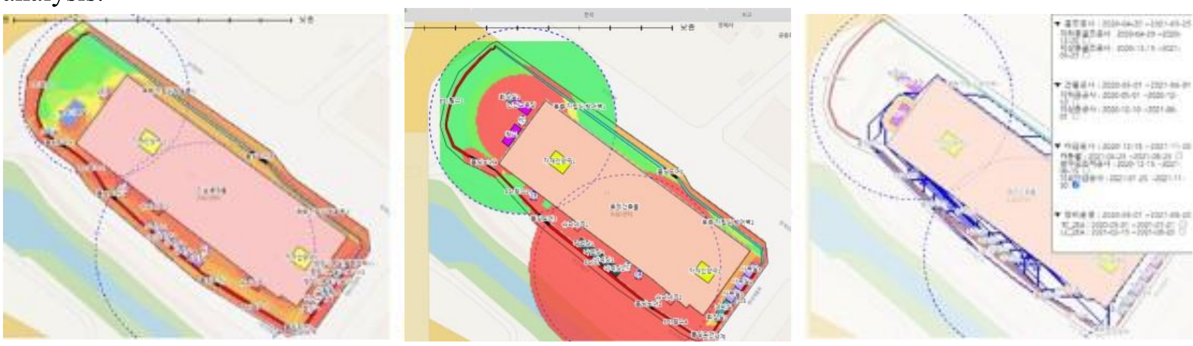


(a) (b) (c)

Fig. 6. Analysis results of three spatial hazard identification modules (Case A)

Compared to Fig. 6(a), the visibility results in Fig. 7(a) reveal that the site office is positioned in an area lacking sufficient visibility due to the project's high building-to-land ratio. This demonstrates that, in both instances, visibility-related safety considerations are not a priority in CSLP practices. Fig. 6(b) displays results derived from the default hazard parameters set in the object library, whereas Fig. 7(b) shows outcomes after adjusting parameters for two tower crane objects, validating the Spatial Hazard Mapping Module's algorithm implementation. Nonetheless, the reliance on safety managers' experiential knowledge for setting hazard parameters persists as a future challenge. Figs. 6(c) and 7(c) present the Travel Path Analysis Module's results, based on two-point and related activity analyses, respectively. This enables planners to not only assess the safety aspects of worker movement but also to lay the groundwork for integrating these aspects with activity hazard levels, scheduling and 4D safety analysis.



(a) (b) (c)

Fig. 7. Analysis results of three spatial hazard identification modules (Case B)

5. CONCLUSION

This study introduced a comprehensive framework for 4D safety analysis using a SIM environment for CSLP, to enhance spatial hazard identification and integrate it with activity-based safety management. Through the application of Visibility Analysis, Spatial Hazard Mapping, and Travel Path Analysis modules, we demonstrated the framework's ability to identify unsafe spaces and simulate travel paths with a focus on safety aspects, thereby facilitating a more holistic approach to safety management. The case studies of a residential complex and a commercial office project highlighted the framework's practicality, showcasing its potential to improve visibility and spatial hazard assessment despite construction sites' complex dynamics. Reliance on safety managers' experiential knowledge to set hazard parameters presents a future challenge. Furthermore, advancing integration with activity-based safety management remains an area for future development. Ultimately, this framework represents a significant advancement in construction safety management, promising to contribute to accident prevention and enhance overall project performance by integrating spatial and temporal dimensions of safety into CSLP.

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