Automated Construction Site Safety Monitoring Using Preidentified Static and Dynamic Hazard Zones

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Abstract

Ensuring workers' safety at construction sites is complicated as protective measures often involve the tasks of planning, monitoring, and mitigation at the same time. Despite traditional methods during the pre-construction and construction phases that require time-consuming and manual efforts, poor risk assessment and situational awareness can easily lead to unplanned mishaps in detecting and eliminating risk. Semi-automated rule-based risk assessment approaches as they predominantly exist in research (ref. SafeConAI) are capable of designing out known hazards before they appear in the workplace. These, however, tend not to be interoperable with other emerging technology tasked to monitor how well safety is practiced on the construction site. This paper presents a method for enhanced safety incident analysis by fusing preidentified hazard zones that remain in construction schedules (after SafeConAI has been applied to a 4D BIM) with high-precision trajectory data (using RTK-GNSS) of pedestrian workers and heavy construction equipment. A real-life case study validates the method's feasibility yielding, aside from basic statistical spatiotemporal counting of incident numbers and precise locations between the pedestrian workforce and construction equipment, also new insights into the right size of the so-defined protective safety envelopes that should surround the construction machinery. These promising results still require further investigation into the practical applicability, for example, testing the effectiveness of sharing the detailed personalized feedback that becomes now available.

Keywords –

4D Building Information Modeling (BIM), Construction site safety planning, Construction hazards, Pedestrian workers, Proactive personalized feedback, Hazard control measures, Protective equipment envelopes, Safety risk assessment, RTK-GNSS location tracking, visualization.

1 Introduction

Of all workplaces, construction sites have the highest accident and fatality rates. As many as 20 percent of accidents and deaths are from construction sites in the European Union [1]. Construction sites are confined environments where workers are exposed to different types and sources of hazards, which can be categorized into static and dynamic hazards [2]. For instance, static hazards can come from built-in design, where pedestrian walkways transverse equipment driveways, while dynamic hazards come from workers and construction equipment interaction. One effective approach to prevent accidents is to pre-identify these hazards at the planning stage, and implement preemptive measures, such as safe path planning and guardrail installation. Nevertheless, workers are often inevitably under exposure to the hazards, e.g., when workers have to interact with construction equipment. Monitoring the movement of workers and construction equipment and detecting safety incidents, when workers are in proximity to the preidentified hazards, can prevent accidents to a further extent. Ensuring workers' safety at construction sites is complex and challenging, which involves a set of intrinsically coherent and holistic tasks across the planning and construction phases. Despite the fact that a myriad of research focuses on the digitalization and automation of individual tasks, studies on the interconnections between tasks are limited in quantity, practical implementation and consideration of hazard types on construction sites.

Therefore, the study proposes a framework for automated safety incident detection by combining safeBIM models and real-time location tracking systems. It first extracts the location data of static and dynamic hazard zones to the tracking platform. Meanwhile, the real-time locations of workers are fed into the tracking platform for safety incident detection. As a case study, this framework is tested on a real-life construction project. Aiming to bridge the research gap in the interconnection between safety planning and monitoring, this study further investigates refining safety planning with analysis results from safety monitoring.

2 Background

Traditional safety work at the construction site is manual and laborious, such as drawing hazard zones at the printed site layout [3] and conducting daily job hazard analysis by safety managers [4]. With the digitization of construction planning, extensive research has arisen in an effort to automate traditional manual methods. Hazard zone identification algorithms have enabled a more efficient identification and more accurate representation of hazard zones in BIM models. Many algorithms have been developed to identify static hazard of different categories (e.g., fall and struck-by hazards) in the design. Zhang et al. developed a rule-checking algorithm in safety planning that identifies fall hazard zones [5]. Johansen et al. designed a 4D BIM-based tool (ref. SafeConAI) to prevent two severe and frequent accidents: falls from heights and falling objects by prevention through design and planning (PtD/P) [6].

Safety monitoring tracks the status and movement of workers, materials, and equipment at the construction stage. One of the goals is to detect safety incidents in static and dynamic environments before the incidents evolve into accidents [7]. Real-time location tracking is an important safety monitoring method, allowing for checking whether safety rules have been violated or conflicts exist between resources spatiotemporally. Researchers have adopted active and passive location-tracking systems for different scenarios on construction sites. For example, Costin and Teizer used passive Radio Frequency Identification (RFID) to locate workers within the indoor environment [8]. Ultra-wideband (UWB) is used to track workers in both indoor and outdoor environments [9]. Global Positioning Systems (GPS) have also been widely adopted for outdoor location tracking at construction sites [10, 11]. While GPS tracking often faces the issues of low accuracy and location drifting, Real-Time Kinematics Global Navigation Satellite System (RTK-GNSS) is developed from GPS. Via receiving signals from more satellites and corrections from static receiver, RTK-GNSS can provide an up-to-cm-level accuracy [12]. RTK-GNSS has been widely adopted on the applications requiring high accuracy, such as survey. So far, there have not been applications of RTK-GNSS in construction safety monitoring to the best of our knowledge.

Although Preemptive hazard identification and mitigation in safety planning can effectively mitigate many static hazards, it does not resolve recurring hazards. These hazards can only be mitigated by close safety monitoring and analysis. One important indicator is the observation of safety incidents, where workers enter unauthorized zones (static hazards) or the safety envelope of construction equipment (dynamic hazards). Previously, safety incident detection is inaccurate because of lacking precise static hazard zone and dynamic hazard geometry. For one thing, the static hazard zones identified in BIM are not explicitly reflected at construction sites, resulting in mitigation equipment being improperly installed and workers being unaware of the exact authorized working areas. One approach to tackle the problem is to import zone information into safety monitoring and integrate it with location tracking. Pfitzner et al. derived floorplans from BIM models and tracked the location of workers from vision data [13]. Costin and Teizer fused RFID data with BIM models for improved accuracy and trajectory visualization [8]. A challenge is to integrate as-planned models and location tracking data efficiently and accurately, which requires not only precise sensors but also accurate system alignment and integration.

For another, the tracked object is, in practice, oversimplified into a point or a circle without considering the actual geometry of the tracked object. Consequently, proximity-based safety incidents are overlooked if the proximity radius is too small or overrated if the proximity radius is too large. Teizer and Cheng define a polygonal equipment representation and warning zone around the equipment for a dynamic hazard zone [2]. Golovina et al. develop a similar polygonal resource boundary and protective envelopes [15]. In [16], we implemented a circular protective envelope to detect safety accidents, and it only provides rough results with incidents. The dynamic hazard zones have to be defined for safety monitoring for further analysis of incidents, which requires careful design of dynamic hazard zone geometries and knowledge of the location-tracking sensor installations.

3 Methodology

The section describes the methods we adopted for automated detection of safety incidents that are induced by static and dynamic hazards. Figure 1 shows the steps connecting BIM-based safety planning and RTK-GNSS location tracking. As a prerequisite, SafeBIM, where assigned and hazard zones are identified at the as-planned safety model, is generated with SafeConAI, a rule-based safety planning algorithm developed in [6].

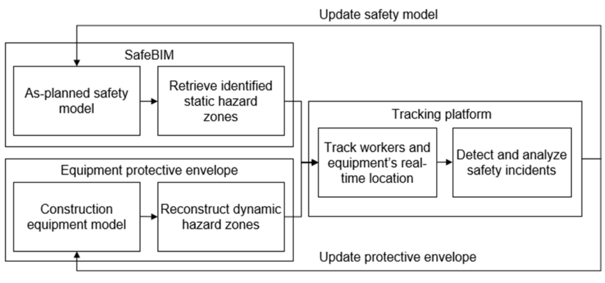

Figure 1. Workflow for connecting safety planning and monitoring.

3.1 Hazard zone retrieval from safeBIM

SafeBIM is generated from the as-planned model. Workers of different trades and equipment are only allowed to move in assigned zones. Static hazard zones, such as fall and struck-by hazard zones, are identified based on safety rules, such as leading edges and height differences in active working space. Mitigative protective equipment (e.g., guardrails) and measures are advised to be installed at hazard zones in safeBIM.

As a starting point, safeBIM is generated in the safety planning stage. A 2D tracking platform is created by retrieving and mapping zones identified in safeBIM. Industry foundation class (IFC), which is an open standard used in BIM, is applied in this study for its interoperability and extensive open-source support. In particular, we use *Ifcopenshell* for reading, writing, and modifying the IFC model [17]. *Ifcopenshell.geom* allows us to efficiently query geometric elements regarding their id, information, and coordinates. We extracted the coordinates of assigned zones and hazard zones in safeBIM. The coordinates of three dimensions in the BIM local coordinate system are flattened to two dimensions at the level where workers and construction equipment move in the tracking platform. To later integrate the trajectory on the tracking platform, zones must be correctly georeferenced. The global coordinate of the origin and true north vector can be retrieved in the correctly georeferenced IFC models. For models that are not georeferenced, one approach is to survey two reference points (P_{1G} and P_{2G}) in the global coordinate system at the construction site and then map the corresponding points (P_{1L} and P_{2L}) in the local coordinate system of the model. The locations contained in the trajectory are translated and rotated using a transformation matrix (M).

$$M = \begin{bmatrix} \cos(\theta) & -\sin(\theta) & \Delta x \\ \sin(\theta) & \cos(\theta) & \Delta y \\ 0 & 0 & 1 \end{bmatrix}$$

The rotation angle (θ) is calculated from the angle between the true north vector and (0,1) in the georeferenced model or the angle between $\overrightarrow{P_{1G}P_{2G}}$ and $\overrightarrow{P_{1L}P_{2L}}$. The translation consists of two-directional movement, the distance between the origins in two systems Δx in the x-direction and Δy in the y-direction.

3.2 Dynamic hazard zone reconstruction

One source of dynamic hazards is the movement of equipment at the construction site. Workers often have to work close to moving equipment, which poses struck-by hazards to pedestrian workers. One common approach is to monitor the proximity between workers and construction equipment. According to OSHA, workers should always maintain a distance of six feet (1.8 meters) from the equipment and not enter the protective envelope. The protective envelope is created at a predefined safety distance from construction equipment, represented with a polygon in this study. On the tracking platform, the protective envelope creates dynamic hazard zones.

Due to the limited number of sensors, the construction location is only represented with one point on the tracking platform. Therefore, the reconstruction of dynamic hazard zones requires not only the location of the sensors but also the position of the sensors in the construction equipment as well as the heading direction of the equipment. As shown in Figure 2, the centroid of construction equipment is set as its origin point and the heading direction as the x-axis so as to determine the positions of the sensor (x_s, y_s) and the polygon's vertices (x_{vi}, y_{vi}). For the forklift in the following case study, the centroid of the particular equipment equals the centroid of the driver's seat, where the GNSS antenna is installed. If the heading direction ($\overrightarrow{Vh}$) is not available from the inertia measurement unit, the heading direction is calculated from the difference in consecutive coordinates in the trajectory.

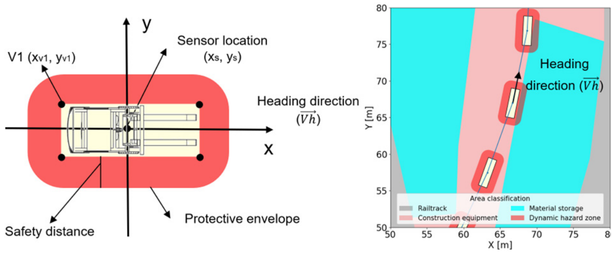

Figure 2. Simplified protective safety envelope for forklift (left image) applied to selected trajectory data (right image).

3.3 Tracking platform setup

After the RTK-GNSS system is set up at the construction site, the location data of workers and construction equipment is streamed and recorded in the global coordinate system using the World Geodetic System (WGS) format, i.e., longitude, latitude, and altitude. The data is first converted to the format of the Universal Transverse Mercator (UTM) coordinate system, a cartesian coordinate system in alignment with the BIM model coordinate system. The global coordinates are then transformed into the local coordinate system in the BIM model. The transformation matrix includes translation and rotation in the two-dimension space. The real-time location and safeBIM are combined to create a safety monitoring tracking platform. For models that are not georeferenced, reference points are required from the construction site. The transformation matrix can be retrieved.

Two types of safety incidents are detected and analyzed on the tracking platform, as illustrated in Figure

3. One is unauthorized entry to static hazard zones, i.e., when workers leave assigned zones or enter hazardous zones. The other is proximity to construction equipment, i.e., when a worker is within dynamic hazard zones. The worker is reduced to a point on the tracking platform so that the safety incident detection algorithm checks whether the point is within the polygonal area. The frequency of safety incidents by worker and location is analyzed to understand the causes of incidents regarding personalized safety performance and incomprehensive safety planning. The measures of utilizing analysis results in enhancing safety planning and training are briefly discussed as well.

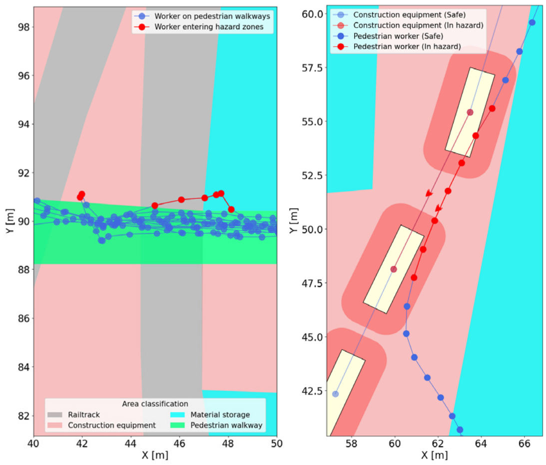

Figure 3. Two examples of safety incidents: unauthorized entry of pedestrian worker in potentially hazardous work site areas (left image), and too close proximity to construction equipment passing by (right image).

4 Case study

A case study was conducted to test the applicability of the framework and methods. The chosen site is a staging area for the rail track replacement project, where workers help equipment to load, unload, and recycle construction materials (e.g., track, sleeper, and ballast). In addition to the construction equipment, railcars also pass through the site to transport the materials to the track replacement site, increasing the complexity of the environment. A safety as-planned model is created to assign zones for different resources and activities (e.g., workers and equipment movement and material storage), based on which a safeBIM is generated to identify hazard zones. On this site, hazards mainly come from the proximity between workers and equipment.

We installed the RTK-GNSS system on the site and tracked the movement of workers and equipment. Real construction activities are monitored, where workers assist in loading and unloading materials. In addition, we also test the method with simulated scenarios in a controlled environment when there are no construction activities. In the simulated scenarios, two pedestrian workers walk inside and outside pedestrian walkways while cars drive across the pedestrian walkways.

4.1 SafeBIM and RTK-GNSS setup

The contractor provides a BIM model for site layout, where zones are assigned for different resources and activities, such as material storage, pedestrian walkways, and equipment moving zones. A safe BIM model is created on the basis of the as-planned BIM model. It identifies the junctions of the different zones for pedestrian walkways, equipment, and rail tracks. In the safeBIM, the protected areas are identified to indicate where equipment is not allowed to traverse, and railings should be installed. Zones with inevitable built-in hazards are also marked in safeBIM, for example, where construction equipment has to move across pedestrian walkways. The geometry and coordinates of identified hazard zones are retrieved on the 2D tracking platform, where location data is later integrated.

We conducted a precision test for the RTK-GNSS system in comparison with stand-alone GNSS receiver. Both receivers were placed statically at the same spot with clear view to the sky, for 3 hours continuously. In total, 10800 location data points were retrieved from each receiver and a random selection of 3600 data points were plotted and analyzed, as shown in Figure 4. The test results showed that the 50 percentile of the location data falls within a radius of 0.01422 m and 0.5244 m, respectively from the RTK-GNSS receiver and the stand-alone GNSS receiver. And, for the 95 percentiles of the location data, the results were 0.03351 m and 1.2096 m. In addition, the data acquired from the standalone GNSS receiver exhibits a pronounced drift, which tends to skew disproportionately towards certain directions. The results demonstrate that the precision of RTK-GNSS is within the centimeter range, as opposed to the meter-level precision observed in the standalone GNSS solution.

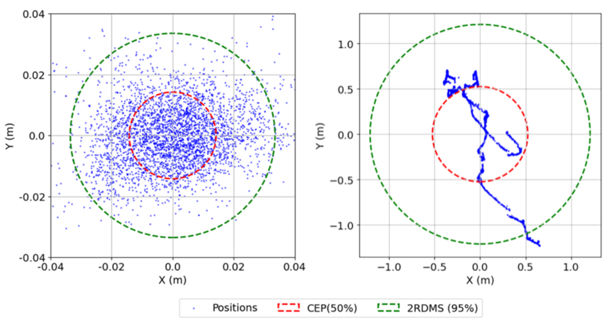

Figure 4. Circular error probable test results of rovers from 3-hour long recordings: RTK-GNSS receiver (right image), (b) Stand-alone GNSS receiver (left image).

Figure 5 shows that the setup of the RTK-GNSS system consists of a static base station and moving rovers. The base station and rovers both contain GNSS antenna and LoRa, whereas the former is used to receive GNSS signal, and the latter is used for the communication between the base station and rovers to correct the rover location. The base station is placed statically at the top of the container at the staging area, and rovers are carried by workers and installed on the construction equipment. The location data is streamed to the digital twin platform for prospective real-time hazard interference. The data is stored locally in the case study for later safety incident detection and analysis.

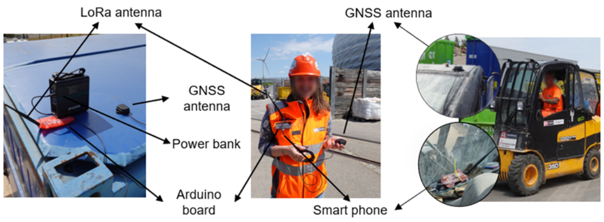

Figure 5. Setup of RTK-GNSS system on pedestrian workers and equipment.

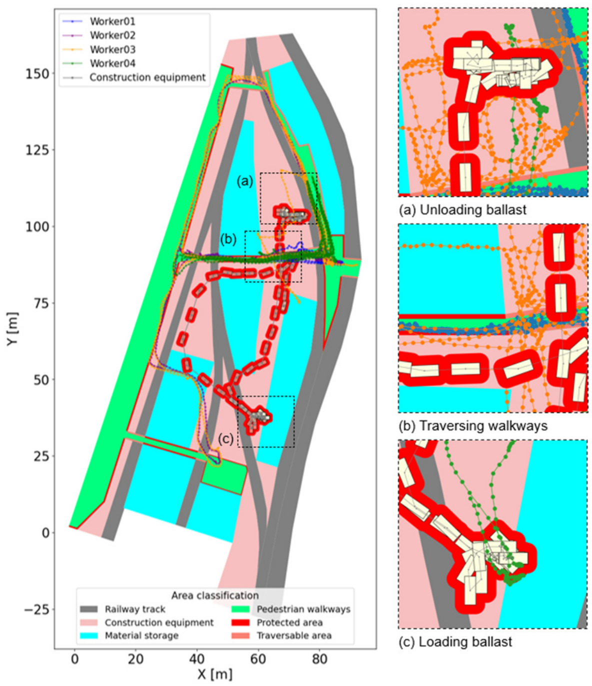

Figure 6. Monitored worker's trajectories (left image) and observed activity of forklift transporting ballast from material storage zone to railcars. (right image) on the 2D tracking platform.

4.2 Tracking platform integration

The 2D tracking platform is created with the input of the safeBIM model, from which we extracted the zone coordinates and created the polygons. Figure 6 (left) shows that four assigned zones and two hazard zones are created on the tracking platform. The origin (0, 0) of the safeBIM model of the site is located at (694697,534392, 32, U) in the UTM system, and the true north of the site model is (0, 1). The RTK-GNSS system receives location data in WGS. These location data are converted to local coordinates and then mapped on the tracking platform.

To reconstruct the protective envelope of the forklift, we took a measurement of its length (4 m including fork length), width (1.2 m), and the installed location of the GNSS antenna. The protective envelope of the forklift is set at 1 m offset from the polygonal boundary of the construction equipment when it is not driving, and the driving orientation is calculated from the trajectory. Figure 6 (right) shows the observed activities of the forklift transporting ballast from the material storage zone to railcars. The red zone surrounding the forklift indicates the dynamic hazard zones.

4.3 Safety incident detection and analysis

4.3.1 Unauthorized entry

In the simulated scenarios, pedestrian workers were required to walk within and outside the area of pedestrian walkways while one car carrying the RTK-GNSS sensor traveled across the transversal area. Figure 7 shows the result of unauthorized entry incidents from four workers. The causes of the incidents are related to safety planning and workers' safety behavior. From Figure 7(a), it can be seen that worker 03 violated predefined pedestrian walkways more frequently than others. The causes of worker 03 need to be investigated on the actual construction site, which can be due to a lack of sufficient safety training or missing authorization of entry to specific zones. Personalized feedback and training are envisioned to be further provided in the training environment devised.

Other than incidents due to individual-related reasons, some incidents can result from safety planning that fails to reflect the construction site in time. As shown in Figure 7(c), locations with lighter colors have higher safety incident occurrences. Besides, some routes chosen by workers deviate substantially from the safety planning in the BIM model, such as the route connecting the pedestrian walkway and container office, as shown in Figure 7(b). The coordinates of the spots with high incident occurrence are extracted and included in the safety planning model, as the 1x1 meter cells where the occurrence of safety incidents exceeds the average 8 times in this study are marked out in Figure 7(d).

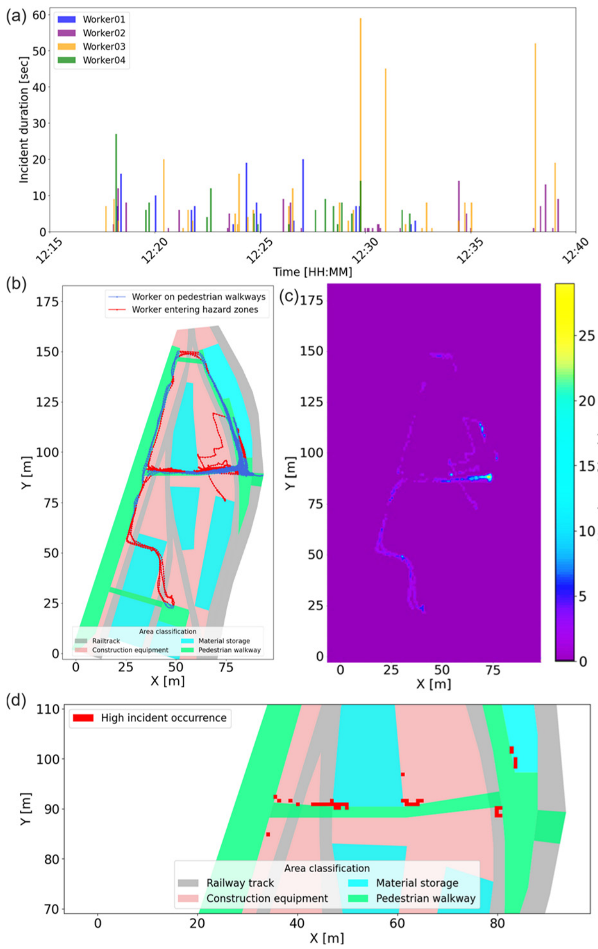

Figure 7. Safety incidents of workers entering unauthorized zones in the simulated scenario: (a) safety incidents count and duration by workers, (b) locations where pedestrian workers leave pedestrian walkways, (c) incident frequency over the construction site, and (d) marked locations with high incident occurrence.

4.3.2 Proximity to construction equipment

For workers working in proximity to construction equipment, we detected the safety incidents from the observed activities of one worker assisting the forklift in transporting ballasts. We compared the detection results using two protective envelopes, circular and polygonal safety envelopes. The protective envelope's safety distance (the radius to the sensors) is set as 3.2 meters long (1m offset from a 2.2 m wide envelope). Figure 8 shows that 11 incidents are detected with the polygonal envelope and 20 incidents with the circular envelope. Figure 9 (left) shows that the circular envelope overlays the polygonal envelope. Hence, the incidents detected with the polygonal envelope are expectably all included in the incidents with the circular envelope.

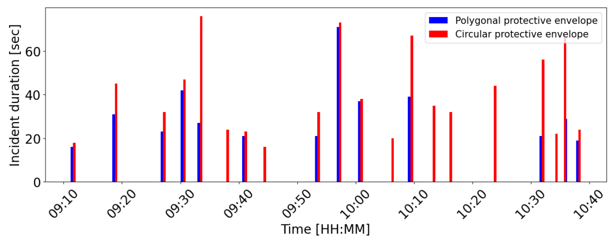

Figure 8. Frequency and duration of a worker in proximity to equipment using the polygonal and circular protective envelope of the forklift.

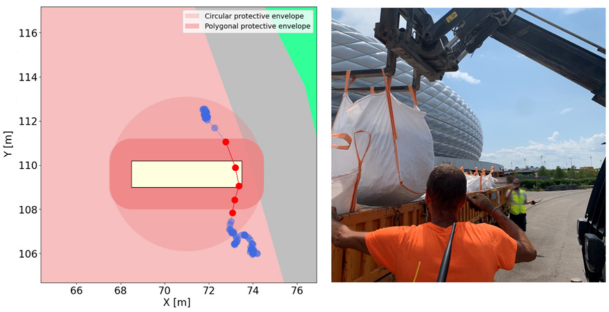

Figure 9. Construction worker walking underneath the forks of the telehandler, as detected on the tracking platform (left image) and as about to be observed on the site (right image).

On the other hand, a circular shape overlooks the geometry of the equipment and identifies incidents even when workers work one meter away from the equipment. A polygonal shape more precisely represents the contour of the equipment and makes the investigation of the incidents more informative. Figure 9 shows an example of a safety incident investigation. It can be seen in Figure 9 (left) that the spotter worker guided the forklift to load the ballast onto the railcar and walked underneath the telehandlers, which is also observed in Figure 9 (right). In comparison, such detailed safety incident investigation is difficult to retrieve with oversimplified equipment geometry and protective envelopes.

The safety distance of the protective envelope is relevant to workers' working distance to the equipment and site compactness. We set different safety distances for the protective envelope and observed the occurrence of proximity safety incidents. The results are displayed in Figure 10, which shows that with the increase in safety distance, the total duration that workers are involved in safety incidents also increases. However, with the safety distance to the forklift increasing from 0.5 meters to 5 meters, the occurrence of safety incidents first increases and then decreases, reaching the highest at 2 meters. The result indicates that the worker mostly works within a 2 m protective envelope to assist the forklift in loading and unloading materials. While at the 1m protective envelope, the occurrence increases drastically, showing that workers mostly keep a 1-meter distance from the forklift.

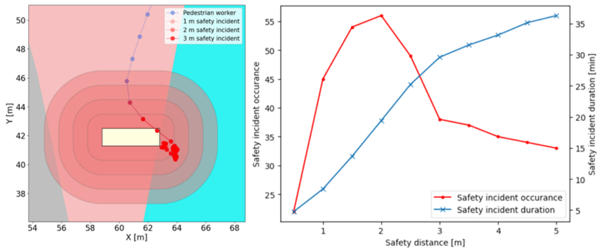

Figure 10. Worker within the protective envelope of different safety distances (left image), frequency and total duration of safety incidents (right image).

5 Discussion

The results validate the applicability of the framework and demonstrate the prospective applications in safety monitoring. The output from safety planning can be efficiently extracted for safety monitoring, thus improving safety incident detection accuracy.

The precision of the framework is dependent on several aspects, including the precision of georeferenced BIM model, location-tracking technology and geometrical measurement of construction equipment. In the case study, we investigated the precision of RTK-GNSS, which can reach cm-level accuracy if there is no obstruction to the receivers to clear sky view. While the precision of the BIM model is not at the scope of this study, there has been research on increasing the georeferencing precision of BIM model. Zhu and Wu devised an approach to geo-reference BIM models with reference points and transformation matrices in the geographic information system (GIS) [17]. Reversely, locations tracked in a global coordinate system can also be converted back to BIM models as described in our method. However, further tests still need to be conducted on the precision of the framework and the methods it adopted, such as validation with other monitoring methods. In addition, the framework is dependent on the availability of as-planned models and the precision is subject to the quality and granularity of the model. Regarding the methods that we adopted in the case study, there are also limitations on the applicable scenarios while alternatives exist for different methods. For instance, although RTK-GNSS is limited to outdoor location tracking, other tracking systems (e.g., Ultra Wideband (UWB), Bluetooth-Low Energy (BLE)) can substitute it when it comes to indoor tracking scenarios.

As a starting point, the framework shows the positive impact of imposing safety planning output on safety monitoring. Compared to other attempts in using BIM-based safety plan for safety monitoring on construction sites, the framework also investigates how safety monitoring results can provide feedback to safety planning and training in return as a further step. Locations with recurring safety incidents are marked as hazard zones in the safeBIM, while workers with high safety incident rates may be advised to receive safety training. Further investigation can be conducted to understand the causes of safety incidents. Despite better performance in safety incident detection and investigation, the forklifts' geometry and protective envelope can further be enhanced with consideration of driving velocity and the movement of telehandlers. In addition, the protective envelope can further consider blind spots, where hazard risks are higher than in other places. We only studied forklifts in the case study, while other construction equipment can have higher degrees of movement freedom. For instance, excavators can also rotate which creates a more sophisticated protective envelope. When reconstructing the dynamic hazard zone for such equipment, polygons with higher degrees of movement freedom are needed to reflect all components' motion, which also requires consideration of where the sensors should be installed on the machine. As an outlook, the framework should provide a platform where additional (and even robotic) human-machine interaction can be further studied [18-19].

6 Conclusion

This paper presented a framework that automates safety incident detection and monitoring based on technologies that were originally purposed for tasks in detailed model-based safety planning and resource location tracking. The first technology (ref. SafeConAI) generated a model of a safe construction site layout plan based on the construction project's BIM model at a given time in the construction schedule (aka. 4D BIM). Here, the scope was limited to finding and modeling the geometry of simplified objects of so-defined 'static hazard zones' where pedestrian workers' entry is – by following an existing safety rule – restricted. These in reality three-dimensional spaces, for simplicity in this paper reduced to two-dimensional zones, were later in field trials fused with real-time location tracking data of both multiple construction workers and equipment. Small wearable RTK-GNSS tags were designed to function as part of smart safety protective equipment and additional tags were also deployed on the heavy construction equipment that were present in the highly congested work environment. The combination permitted a basic but live safety status monitoring in partially simulated experimentation on a real construction site. Further computational data analysis focused on successfully detecting two particular types of incidents: workforce entering restricted work areas and their proximity to construction equipment. The achieved results give good reasons to conclude that detecting such incident types, including a timely report of their safety information (i.e., respective locations and frequency) on a first of a kind BIM-based safe construction site layout model, is technically feasible. Furthermore, this work created much-desired information on the parameters of the so-defined (virtual) protective safety envelopes (e.g., size and shape) of construction equipment. These, in future work, might be used to surround the construction equipment and allow generating autonomous and automatic warnings or alerts before mishaps occur and the equipment can seriously harm a pedestrian worker.

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