REAL TIME SAFETY RISK ANALYSIS OF CONSTRUCTION PROJECTS USING BIM AND RTLS

S. Setayeshgar, *A. Hammad, F. Vahdatikhaki, and C. Zhang
Concordia University
1455 De Maisonneuve Blvd. W
Montreal, Canada H3G 1M8
*(*Corresponding author: hammad@ciise.concordia.ca)*

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ABSTRACT

The identification of potential accidents on construction sites has been a major concern in the construction industry and it needs a proactive safety plan to reduce the risk of accidents. There are no efficient methods for checking if safety measures are taken properly on construction sites. Consequently, workers on site are not given enough awareness about dangerous areas. In addition, construction sites are dynamic and on-site situations are changing in terms of permanent and temporary structures and facilities. This information can be represented using Building Information Modeling (BIM). This paper proposes the integration of BIM and safety risk analysis by considering the risk levels associated with the work spaces of different construction tasks. Work spaces are generated in a BIM model according to the Work Breakdown Structure (WBS) of the project, reference objects in the BIM, and the schedule and resources of the task. Each work space is assigned to one or more tasks or functions, e.g., work spaces for specific tasks, shared spaces (paths), storage spaces, or spaces prohibited to workers. The assignment of work spaces is based on the workers, equipment and materials involved in the task. All the work spaces are associated with a specific duration according to the schedule of the project. Then risk evaluation of the construction site is applied in order to evaluate safety risks based on their severity and the degree of exposure of workers. For example, work spaces for storing hazard materials and for heavy construction equipment have higher risks than other work spaces. The results of the risk evaluation can be visualized in a 4D BIM model.

KEYWORDS

Safety, Simulation, Real time, BIM, RTLS.

INTRODUCTION

Keeping the construction site safe is a priority for all construction companies. Safe construction sites boost the morale of the workers, which increases productivity and improves work quality. It is important to identify risks on construction sites so as to eliminate them before accidents occur. Out of the construction workers that suffer from fatal injuries, more are involved in falls than any other single cause (Huang & Hinze, 2003). Falls account for double the number of deaths caused by electrocution or being buried in trenches (ASP Construction, 2003). Therefore, it is a priority to place safety barriers and guard-rails around the hazard areas, excavations and trenches. Regulations can be used to define rules that can be used to automatically specify the location, dimensions and other important issues of fencing on a construction site, e.g., holes in the ground should have a secure lid and railing around the perimeter (Hammad et al., 2012).

Other than spaces that should be protected by physical fences, there are many spaces on site that should be identified for the safety of workers, e.g., the work spaces of construction equipment. Physical fences are not mandatory in these spaces; however, workers should be notified that those areas are dangerous and they should keep a safety distance from those areas. Work spaces represent the space used for construction activities (Guo, 2002). These spaces are reserved for the crew and their equipment, moving paths, material storage areas, etc. (Akinci, Fischer, Kunz, & Levitt, 2002). Work space analysis aims to create different types of work spaces for crews, equipment, and other required spaces in the work site, to detect conflicts between these work spaces, and then to resolve these conflicts. Heesom et al. (2003) have developed a dynamic virtual reality system for visualizing construction space usage focusing on work spaces required within proximity of the components being installed, such as work spaces for crews, equipment, and hazardous and protected areas.

Building Information Modeling (BIM) is a new approach to design, construction, and facilities management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in a digital format (Estman, Teicholz, Sacks, & Liston, 2011). Virtual 3D models can be built to represent a realistic scene of the construction site. Using BIM is changing the manner of designing and constructing buildings in the construction industry. Moreover, time information can be added to 3D BIM models to generate 4D models which contain the schedule. The relationship of space and time can be accurately described in a systematic way in 4D modeling. Several approaches have been proposed in research to analyze conflicts and to improve safety and efficiency on site based on the spatio-temporal information provided by BIM (Zhang et al. 2011). Considering the type of the project, different types of models can be used in addition to BIM, such as Bridge Information Modeling (BrIM) which can be used for bridges (Chen, Li, & Tangirala, 2006).

Researchers proposed some approaches for safety evaluation based on simulation. Dawood et al. (2006) have introduced a Critical Space Analysis (CSA) methodology and a software tool named PECASO (Patterns Execution and Critical Analysis of Site-space Organization) that was developed to encapsulate the CSA methodology and to assist site managers in the assignment and identification of work space conflicts. Different scenarios with distinct execution patterns and sequences of tasks can be simulated using this method in order to investigate the effect of changes in patterns and sequences which will result in the minimization of work space congestions. A 3D model and a schedule were linked to visualize conflicts between different work spaces in each scenario. Doriani et al (2013) have integrated the 4D modeling and simulation techniques in the planning and scheduling phases to create a probabilistic 4D model in order to identify any potential conflicts between the construction and demolition operations.

To calculate the probability of potential victims exposed to a set of loss-of-control (hazardous) scenarios, a method has been proposed by Sacks et al. (2009) as part of the synthesis and development of the *Construction Hazard Assessment with Spatial and Temporal Exposure* (CHASTE) method. A formula has been proposed to calculate the safety risk level that is predicted for a crew exposed to a loss-of-control event caused by another crew using different parameters such as exposure in time and space, number of workers in each crew, the local managerial context, physical environment, etc. Nevertheless the accuracy of this method depends on the accuracy of the risk forecasts.

The foible of the above-mentioned methods is that they do not support real time and they only show the probability of having conflicts if a certain sequence of tasks are executed following a predefined pattern which is not guaranteed to happen. Simulation can be run to detect possible conflicts and safety issues during the project execution, although the results are not reliable enough to be considered for real-time safety management and for generating warnings.

In the execution phase of construction projects, Real-Time Location System (RTLS) can be used to track the actual locations of workers and construction equipment in order to give safety warnings. The authors of the present paper have been working on safety of equipment operations using Ultra Wideband (UWB) RTLS. In the research of Zhang and Hammad (2012) and Zhang et al. (2012), tags are attached to cranes and the pose of the crane boom is calculated in near real time. Collision detection is applied for the movement of two cranes working near each other, and real-time re-planning is applied to avoid collisions. Furthermore, the concept of Dynamic Virtual Fences (DVFs) has been proposed by the authors where the DVFs are added automatically to the BIM model and used to provide safety warnnings to workers in real time. In addition, Hammad et al. (2011) have proposed an approach to visualize data from different sources including a BIM model, video monitoring, and a UWB RTLS. The data fusion from different sources can be expected to improve quality and productivity of the project.

In this paper a new method is proposed for real time safety risk analysis of construction projects using BIM and RTLS. The main objective of this paper is to extend our previous research related to generating DVFs so that the locations and the durations of these fences are based on simulation in the planning phase and on updated real-time simulation in the execution phase in order to obtain more accurate and reliable data. A preliminary case study is used to demonstrate the feasibility of the proposed method.

METHODOLOGY

The proposed methodology has two main parts, the planning part and the execution part (Figure 1). The planning part deals with analyzing the input data, defining hazardous areas, detecting scenarios with safety risks, creating a probabilistic 4D model and generating work spaces and DVFs where needed, whiles the execution part deals with the real-time data, generating warnings and updating the simulation.

Figure 1 shows the details of the proposed method. Different sequences can be used to define the orders in which tasks can be executed. As an example for the task of pouring concrete of a foundation, it can start form the eastern sector of the foundation toward the western sector or it may start from northern sector towards the southern sector.

(1) Define work spaces: In the planning phase, work spaces are defined using data from the WBS, the schedule and the 3D model. The schedule provides information about the durations of tasks, dependency between different tasks and the sequence by which tasks should be executed. The WBS is a tree structure which divides the project into phases, deliverables and work packages. The BIM model provides a visual 3D model of the project. Data such as the dimensions of equipment and the location of each task in the model is provided by the BIM model. Figure 2 shows the work space of a scisssor lift used to install ducts. In outdoors construction projects, the site layout can be used to provide the geographical reference instead of the BIM model. For example, Figure 3(a) shows a 2D model of a loader working inside a predefined work space.
(2) Run simulation: The simulation will generate the duration information to be linked to the 3D model.

(3) Probabilistic 4D: Appending the defined work spaces to the results of the simulation, the probability of having collisions between different crews can be calculated which results in a probabilistic 4D model (Doriani, Mawlana, & Hammad, 2013).
(4) Extract information with spatial aspects from the safety code: For example, the Quebec Safety Code for the Construction Industry (ASP construction 2003) has been reviewed and information that has spatial aspects has been extracted by the authors to either indicate problems or provide solutions (Hammad, Zhang, Setayeshgar, & Asen, 2012).
(5) Evaluate Safety risk: Safety rules and regulations are used alongside the probabilistic 4D model in order to detect work spaces with safety hazards and to assign the severity level of that hazard.
(6) Generate dynamic virtual fences: As a result of the previous step, areas having hazards are detected and DVFs are generated in order to prevent hazard.
(7) Capture Near real-time data: In the execution phase, near real-time data are used along with the data form the planning phase. UWB tags are attached to physical fences monitored in real time and to workers and equipment.
(8) Check work spaces: The locations of the workers and equipment are monitored in real time to prevent approaching dangerous areas and to ensure that they are working in the work space assigned and predicted based on the schedule. In cases where workers are late or ahead of the schedule and they are not in the expected area, the real-time data are used to calibrate simulation in order to have a real-time simulation.
(9) Check real fences: Mapping the physical fences with their corresponding virtual fences is applied to check if they are installed at the proper locations with the proper dimensions. If any physical fence is missing, the corresponding virtual fence in the model is highlighted and a reminder is sent to the manager.
(10) Trigger warnings: A warning is triggered when a worker or equipment approaches a virtual fence to notify of the potential danger. The project manager and/or the safety manager will also get a signal indicating that there is an inconsistency between real-time data and the simulation results. Figure 2 shows the concept of sending warnings to workers-on-foot. Two dynamic virtual fences are created based on the workspace of a scissor lift and an opening in a slab. When a worker approaches the virtual fence, he/she will receive a warning alert. When the task of the scissor lift is finished or the opening is covered, the virtual fence associated with these tasks is removed.
(11) Update simulation: the simulation is updated based on real-time data.

Figure 3(b) shows a loader which is moving out of its defined path but it is still inside the reserved work space. No warning is generated so far since the equipment is still located inside the defined work space. In Figure 3(c) a new work space is defined for the loader knowing that a loader needs to relocate itself after approximately 25 cycles. Having the duration of each cycle, the approximate time of relocation can be calculated. However if the loader leaves its current work space within the calculated time limit a new work space will be assigned to the equipment. Figure 3(d) shows a loader which is out of the defined work space so a warning is triggered to notify the operator and nearby workers of the arising hazard.

It is critical to detect when to send warnings to equipment operators and workers. In order to make the proposed method more flexible, i.e. to accommodate different scales of time and a space, different levels of work spaces can be defined.

(1) Weekly work space is generated based on data from the WBS and the schedule. This work space reserves an area for the tasks which are going to be done within a week and will be updated every week;
(2) The next level is the shift work spaces which cover tasks that should be done within a work shift and will be updated hourly;
(3) The third level is the cycle work spaces. It shows work spaces assigned to tasks which are going to be done within minutes, e.g. the work space in Figure 3 for multiple cycles of the equipment. The cycle work space will be updated every minute; and
(4) The sub-cycle work spaces, e.g. actual real time poses of a crane which are updated continuously (Zhang & Hammad, 2012). A safety buffer can be added around work spaces to consider RTLS location errors, low update rates as well as the diversions of predefined work spaces.

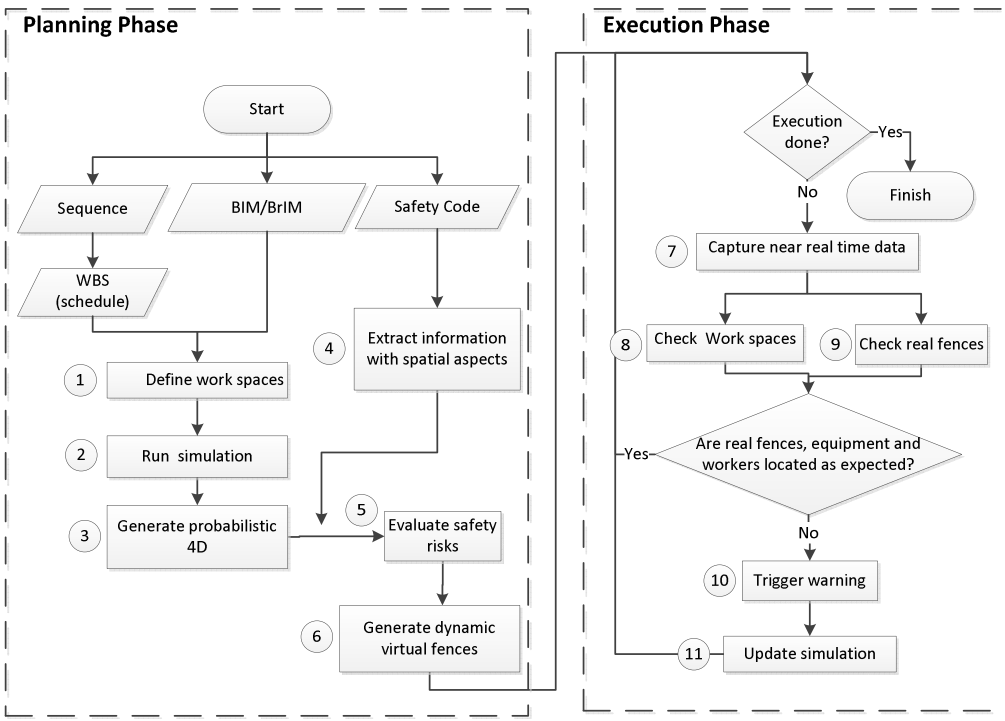


Figure 1 – Proposed Method

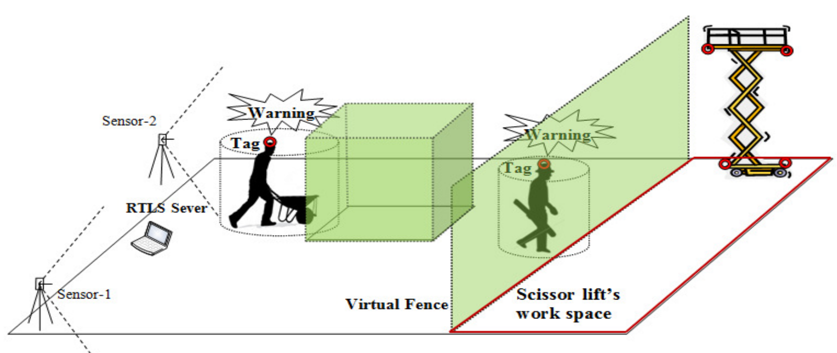
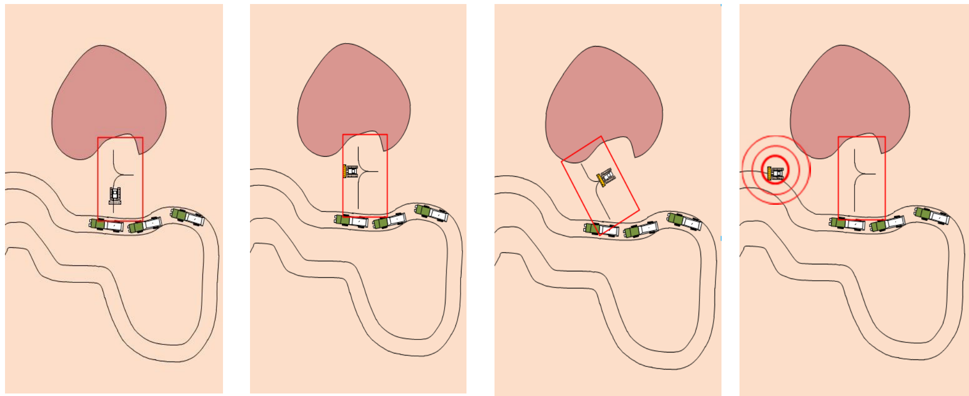


Figure 2 - Concept of sending warnings to workers on foot



(a) Located in predicted work space | (b) Out of path | (c) New work space | (d) Out of work space

Figure 3 – Example of Work Space and Location Real-time Updating

In order to use real-time data for safety purposes, two important parameters should be considered, the accuracy of the data and the update rate. Since warnings are generated and the simulation is updated based on the location information, it is important to have accurate data. The more accurate the data is, the more reliable the results will be. Safety can be improved by giving the workers more awareness of the environment and using the real time simulation to predict potential hazards more precisely.

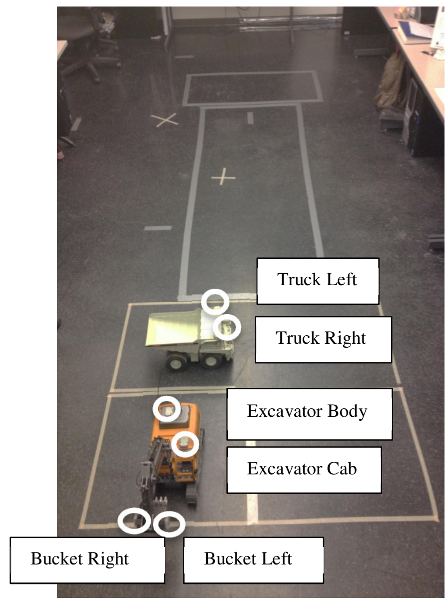
CASE STUDY

In order to test the feasibility of the proposed approach, a case study is carried out in the laboratory. Two radio-controlled (RC) models of a truck and an excavator (Hobby Engine, 2013) are used. The truck has two motors that allow the movement of the body (drive forward/backward, turn right/left) and the bed of the truck (up/down). The excavator has five motors that allow the movement of the body (drive forward/backward, turn right/left) and the boom and stick (turn up/down). Both models can be controlled using a remote control that allows the movement of one Degree of Freedom (DoF) at a time. An excavator has three joints which provide DoFs for the movement of the boom, the stick and the bucket. However, the model used for the case study has only two DoFs for the rotations of the boom and the stick. More details related to the equipment are given in Table 1.

Table 1 – Specifications of equipment

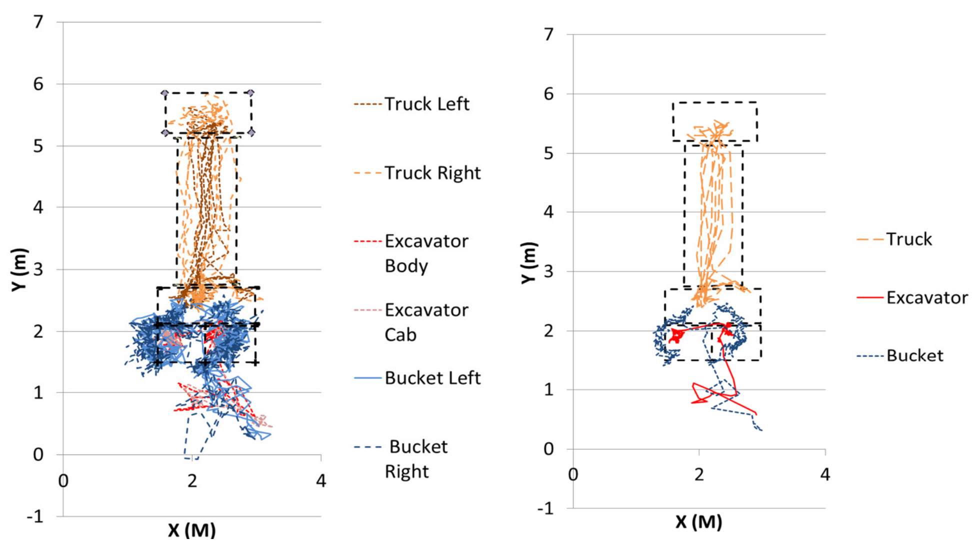
Specification / Equipment	Dimensions	Moving Forward Speed	DoFs	Range (°)	Angular speed
Truck	445 × 220 × 330 mm	0.58 m/s	Bed rotation	[0, +40]	10 °/s
Excavator	743 × 222 × 490 mm	0.23 m/s	Body swing	[-180, +180]	8 °/s
			Boom rotation	[+40, +80]	10 °/s
			Stick rotation	[-70, -30]	10 °/s

Ubisense UWB system (Ubisense, 2013) was utilized to locate the model equipment. Four UWB tags were attached to the excavator and two were attached to the truck to monitor their movement. Sensors are installed at the locations providing the best coverage of the monitored test area. The nominal update rate of the system was set to 10 Hz while analyzing the results of the test showed an actual update rate of about 8 Hz.



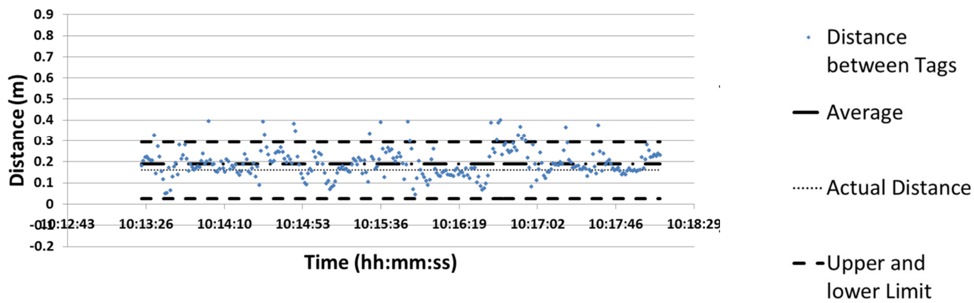
(a) 2D model of the case study   (b) A picture of the actual case study

Figure 4 – The setting of case study

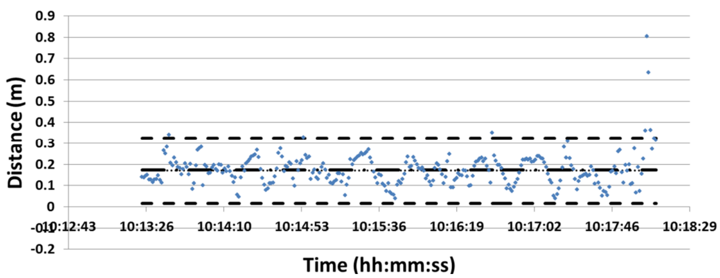


(a) Raw data   (b) Processed data

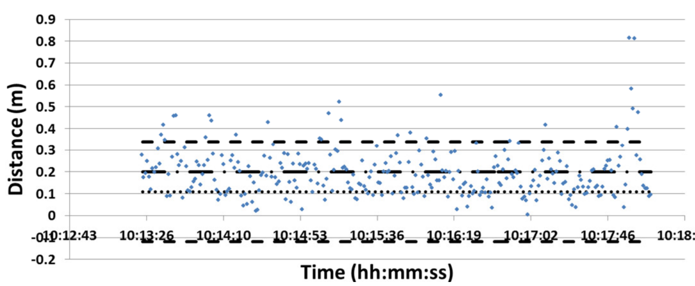
Figure 5 - Operation's processed data



(a) Distances between the two tags on the truck



(b) Distances between the two tags on the excavator body



(c) Distances between the two tags on the bucket

Figure 6 – Filtering inaccurate data based on the acceptable level of errors

Figure 4 shows the setting of the case study which contains four main parts namely, the excavation area, loading area, hauling area and the dumping area. The truck is loaded in the loading area by the excavator; it moves to the dumping area and dumps its load. Traces of movement for different tags are shown in different colors in Figure 5. The raw data gathered from the site require a multi-step processing before it can be used for data analysis. The processing is required to compensate for the missing or erroneous data. The data processing includes the following steps: (1) The tag IDs are identified and grouped according to their geometric relationship with respect to the objects to which they are attached to (e.g., tags attached to the body of excavator); (2) tags' locations are averaged over a period of time, i.e. 1 second; (3) the location data are filtered based on the geometric constraints, i.e. the fixed distance between the two tags assigned to the same object. The acceptable error related to this distance is set to (±2σ); and (4) the location of an object is calculated by averaging the locations of the two tags attached to it. Figures 5(a) and (b) show how the data processing helps increase the accuracy of the data. These steps are the minimum requirements for the identification of the location data and further processing is required if the poses of the machines are to be identified too. This simple data-processing can be further improved through the consideration of additional constraints, e.g. velocity constraints (Zhang, Hammad, & Rodriguez, 2010). Figure 6 shows the upper and lower boundaries for the distribution of the distances between tags attached to different objects based on the acceptable level of error of ±2σ. The actual distance and the average value of all the distances are marked in Figure 6. The points below and above the boundaries are filtered out as explained above in step (3) of the data processing.

The traces of movement in Figures 5(a) and (b) also show that the excavator left the defined workspace and entered an unexpected area. In this case a warning is triggered immediately when the excavator approached the virtual fence at the edge of the workspace to notify the driver of a potential danger. The project manager also receives a warning since the excavator was not supposed to leave the workspace according to the schedule.

SUMMARY AND FUTURE WORK

This paper has proposed a new method for the integration of BIM and safety risk analysis by considering the risk levels associated with the work spaces of different construction tasks. Work spaces are generated in a BIM model according to the WBS of the project, reference objects in the BIM, and the schedule and resources of the task. Each work space is assigned to one or more tasks or functions. The assignment of work spaces is based on the workers, equipment and materials involved in the task. All the work spaces are associated with a specific duration according to the schedule of the project. Future work will consider the details of the probabilistic risk evaluation and the mechanism for generating and updating the work spaces based on the project data and real-time location updates.

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