Semi-automatic Construction Hazard Identification Method Using 4D BIM

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Abstract –

The construction industry accounts for a considerable portion of work-related accidents annually. Taking appropriate pre-construction measures can significantly lessen the probability of these accidents occurring. An essential step toward achieving this goal is identifying the unsafe attributes before construction begins. This research introduces a semi-automatic method for identifying and reporting construction hazards in the early phases of the project. The presented method benefits from Building Information Modeling (BIM) object-oriented and visualization capabilities combined with the project schedule (4D BIM). An excavation and stabilization operation of an actual residential building project case is used to demonstrate the method's applicability. A hazard database is created and linked to the 4D BIM model of the project to identify the hazardous attributes causing struck-by accidents. According to feedback collected from the project team and safety experts, reducing hazard identification time and increased accuracy were considered the two most significant benefits of this method.

Keywords –

Safety; Hazard Identification; Building Information Modeling (BIM); 4D BIM; Automation

1 Introduction

The number of casualties and fatalities in the construction industry is disproportionately high. While the construction industry employed 7.2% of the US workforce in 2020 [1], 19.9% of all fatal occupational injuries occurred in this section [2]. The need to reduce the number and severity of accidents in the construction industry has caught the attention of researchers in recent years. One of the appropriate strategies is to identify the hazards in pre-construction phases and try to eliminate, reduce or manage them and their impacts. In many construction projects, the contractor is the sole responsible for the safety of the project. However, designers can also play a significant role in implementing projects with fewer safety accidents by considering the best practices and standards to achieve a safe design [3]. Identifying safety hazards in the planning phase can also considerably reduce construction accidents [4].

Advances in new technologies have provided great tools for identifying hazardous situations and eliminating or managing them in the construction industry. One of these technologies is Building Information Modeling (BIM). The increased usage of BIM in the implementation of many construction projects has provided new opportunities for greater utilization of this tool to improve the safety of projects. 4-dimensional (4D) BIM is created by integrating the 3-dimensional (3D) model of the building to the schedule of activities and can be used as a rich database with appropriate visual features to identify hazardous attributes in the project implementation process [5]. Despite its widespread applications in the safety management of construction projects, BIM's applicability, especially when integrated with the project schedule (4D BIM), has received less attention in identifying safety hazards before starting the construction phase.

Accordingly, this study introduces a semi-automatic method to identify the potential struck-by hazards in the pre-construction phases of an actual excavation and stabilization project case. This method employs 4D BIM to ease hazard identification and provide spatial insights for the safety planners. The results show that project managers can use this method to identify the potential construction hazards in pre-construction phases with high accuracy and speed, thus facilitating project planning and increasing project safety. First, the relevant literature is reviewed in Section 2. Section 3 introduces the method of identifying hazardous attributes in the early phases of the project using 4D BIM. In Section 4, the method is implemented to identify attributes that cause the struck-by accidents, one of the four most frequent accidents in the construction industry, on an actual project's excavation and stabilization operation. Finally, the research is concluded in Section 5.

2 Research Background

2.1 Hazard Identification in Pre-construction Phases

If the safety risks are not adequately identified, the analysis phase will never begin, and subsequent control measures will never be considered and implemented. Therefore, the activities will be performed without the necessary protection, and there will always be a risk of an accident for the ongoing activities. Considering safety tips and risks in the project design and planning phases can significantly impact reducing accidents [4].

Malekitabar et al. [6] examined 363 accident reports and found that a significant number of the risk factors causing these accidents could be identified at the design phase. Design for Construction Safety was introduced as a concept to address this importance. Another concept that points to the importance of safety at the design stage is Prevention through Design (PtD). This concept encourages project stakeholders to consider project safety from the design stage to eliminate or control hazards [7]. Due to the complexity and uncertainty of the construction industry, the designers and safety planners have used new technologies and tools to identify as many risks and predictable situations as possible in the construction process. The use of project simulation tools is an example of these. Baniassadi et al. [8] suggested a framework for concurrent safety and productivity assessment of different work scenarios before the construction activity begins to choose the best scenario in terms of safety and productivity. They used project simulation tools and expert judgment to identify the risks. Using new technologies with proper visualization capabilities can also improve hazard identification capability in the project's planning phase [9]. Esmaeili et al. [10] presented a method of identifying and analyzing safety risks based on safety attributes (called Attribute-Based Safety Risk Assessment) and the lessons learned from past events and injury reports. With this method, safety risks can be identified and modeled independently from specific activities or building components. This theory believes that any injury or accident results from an interaction between a worker or a group of workers and a limited number of hazardous work environment attributes. By analyzing injury reports, a database of past accidents can be created, including the hazardous attributes, which are the cause of the accident, and the outcome of each event [11]. The database generated can predict accidents caused by these hazardous attributes in future projects [12], [13].

Current methods for identifying hazards during pre-construction phases rely heavily on expert judgment or consider the project schedule without visualizing how the operational tasks are implemented. These issues seriously complicate construction safety analysis. Using new technologies such as 4D BIM, which combines scheduling with a 3D model, could provide greater accuracy in identifying hazards, but little attention has been paid to them so far.

2.2 BIM and Project Safety

Malekitabar et al. [6] proposed using BIM capabilities to identify safety hazards and risks at the design stage. Bansal [14] combined BIM and GIS technology to help workers visually observe the sequence of activities and the environment around each of them in the pre-construction stage. This allowed them to better understand the interactions between activities and the safety points and issues associated with these activities. Ciribini et al. [15] used BIM to monitor the progress of ongoing activities. Their research showed that by comparing the BIM model and the executed map obtained from laser scanners, the project manager could effectively identify and modify safety components forgotten in the structure, such as guardrails or safety nets. Ganah & John [16] researched the use of BIM to improve workers' training. Their research examined the effectiveness of this technology in increasing the understanding of workers and stakeholders of the project to safety challenges during construction.

By connecting the 3D BIM model to the activity schedule, the 4D BIM model is created. Many people involved in the construction industry believe construction accidents can be eliminated or lessened using 4D BIM. Collins et al. [17] investigated the impact of 4D BIM in assisting safety managers in implementing preventive strategies for scaffolding activities in construction projects. This study used the experts' opinions and safety risk factors in conjunction with the 4D BIM model. Zhang et al. [4] used 4D BIM to identify and eliminate the risk of falling from a height in the early stages of the project planning phase. Their goal was to automatically detect unsafe conditions during project construction and locate them in a 3D model. Then, solutions to reduce the identified hazards were provided interactively with the opinion of safety experts or automatically. Jin et al. [7] proposed a tool for assessing construction risks during design phases of projects at an activity level and in a 4D environment. In this study, safety risk quantification for design elements is based on survey results from construction field personnel and expert judgment to assess construction risks. Abed et al.

[18] used 4D BIM simulation to help the safety managers understand the details and sequence of work. They demonstrated the effectiveness of this technique in hazard identification by relying on the opinions of safety experts.

Based on the literature reviewed, 4D BIM is an appropriate tool for identifying hazards in the pre-construction phases. Regulation rule checking and using expert opinion are the most common approaches to identifying hazards. These can be upgraded using safety experiences from past safety incidents. Considering the hazardous attributes identified from past incidents, identifying these attributes with the help of 4D BIM can complement past research.

3 Semi-automatic Hazard Identification Method

This method primarily aims to identify safety hazards in the early stages of construction projects with less time and more accuracy. This goal is achieved by using the capabilities of the 4D BIM model and the automatic processing power of computers. Figure 1 shows the different parts of the method

The 3D BIM model of the project and the schedule of activities provide input for the method. A 4D BIM model for the project is made by connecting the 3D BIM model with the schedule of activities. A 4D BIM model typically contains spatial and geometric data, as well as the schedule of activities. For the safety analysis, further assumptions and details are also needed to be provided. In most cases, these details are not added to the model by default because the project owners may not see a need for them, or protocols are not defined for providing them. For example, to identify the struck-by hazards in an excavation project, as discussed in Section 4, the user should include some additional information such as the safe distance from the material storage place on the project site, the safe distance from the material transport route, the safe distance from the roadway, and the rotation radius of boomed vehicles. The user enters this additional information into a separate database, which is created based on the data extracted from the 4D BIM model. A specific identification algorithm is then designed and developed for identifying each of the hazardous attributes. Next, appropriate queries are written on the prepared database to examine its content according to the developed algorithms and identify hazardous activities and attributes. Once the hazardous attributes are identified, they are transferred to the 4D BIM model to create the 4D+ BIM model. The 4D+ BIM model is the 4D model of the project enhanced with safety information resulting from this method.

4 Method Implementation

To demonstrate the method's capabilities presented in Section 3, the researchers implemented it on an excavation and stabilization operation of a real project. In this sample implementation, struck-by accidents, one of the four most frequent accidents in the construction industry, were selected as a sample category of construction accidents. The implementation process of the method is described as follows.

4.1 Identification Algorithms

By reviewing 1,812 struck-by accident reports, Esmaeili et al. [10] introduced a group of hazardous attributes leading to the occurrence of this type of accident. Eleven of these attributes were selected as samples to create the construction hazard database of this study. The following are 11 selected hazardous attributes:

1. Working in the swing area of a boomed vehicle
2. Working with heavy equipment
3. Working in a material storage zone
4. Working in a material-transportation zone (horizontally)
5. Working near an active roadway
6. Workers on foot with moving equipment
7. Driving heavy equipment, falling out
8. Driving vehicle
9. Working with a nail gun
10. Working with power tools/large tools
11. Working in falling objects zone

The researchers determined the identification algorithms for each of these eleven attributes. The algorithm for identifying the hazardous attribute no. 1 (working in the swing area of a boomed vehicle) is described in detail as a sample.

4.1.1 Hazardous attribute no. 1 (working in the swing area of a boomed vehicle)

The following algorithm was taken to identify activities in which there is hazardous attribute no. 1.

1. First, consider the activities in which the boomed vehicle has been allocated as a resource. Then consider the time planned for the implementation of these activities as a period of risk.
2. The hazard zone with a risk of occurring the struck-by accident is determined based on the minimum and maximum coordinates of X and Y of the boomed vehicle's location in the model and considering the maximum rotation radius of the machine (R). The range of the hazard zone is determined by summing up R with the maximum coordinates and subtracting R from the minimum coordinates of the boomed vehicle's location. As

shown in Figure 2, the hazard zone is estimated as a cube.

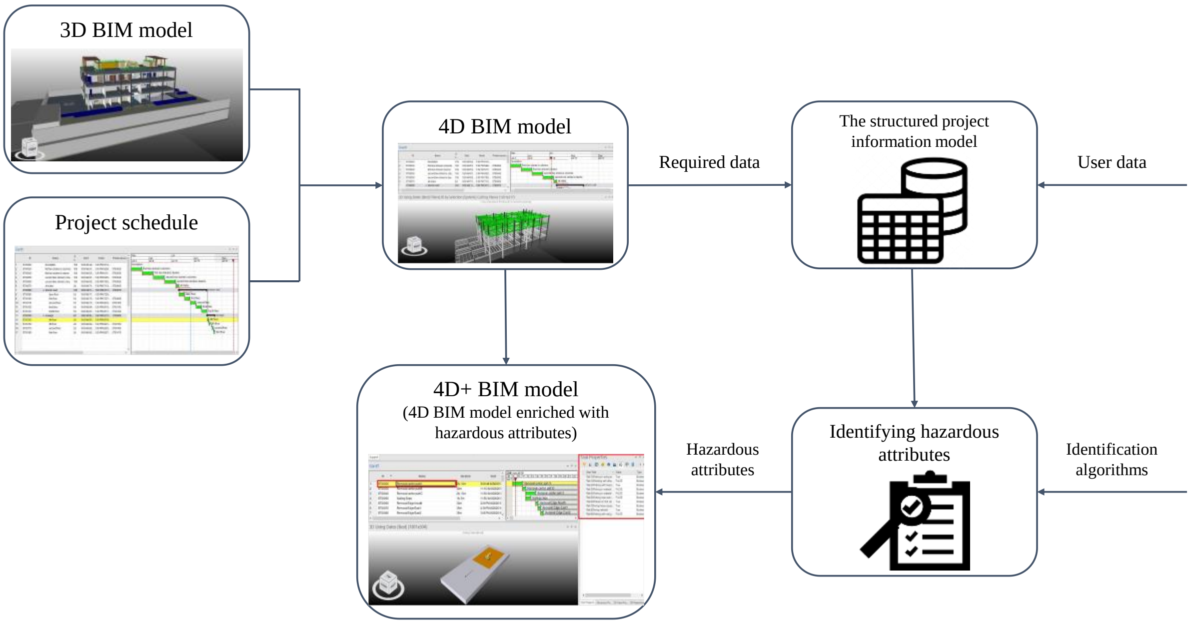

Figure 1. Semi-automatic hazard identification method

3. Activities that, at the time of operation of the boomed vehicle (specified in step 1), their resources are located in the hazard zone (determined in step 2) are identified.

4.2 Project Description

The project is an 8-story residential building located in Tehran, Iran. This case study is limited to some of the activities related to excavation and stabilization of the pit walls.

4.2.1 Steps of the Excavation Operation

The excavation operation was executed in six general steps as follows.

1. Excavating the middle of the pit and moving the nails to the side of the pit
2. Excavating the side of the pit
3. Smoothing the walls around the pit, straightening it, and making it parallel to plumb line
4. Drilling of piles and injection of concrete into the nails
5. Installation of steel network bases by workers and then installation of steel networks
6. Shotcrete walls

Figure 3 displays each of these execution steps.

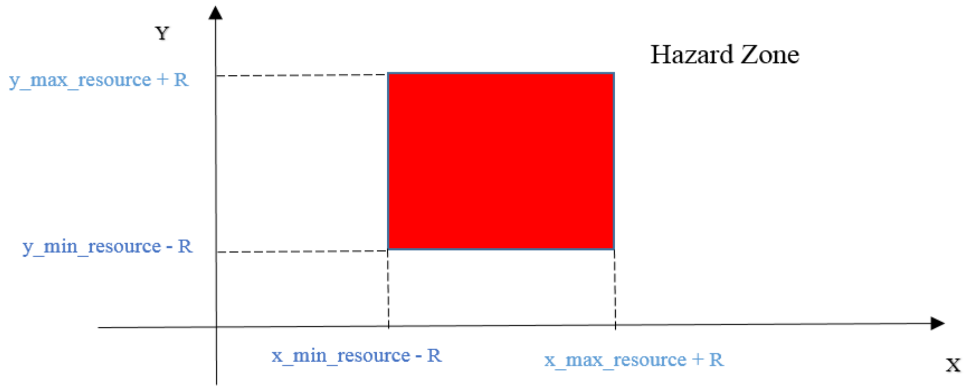

Figure 2. Determining the hazard zone in an activity where a boomed vehicle is used

Figure 3. The execution steps of the excavation

4.3 4D BIM Model

First, the 3D BIM model of the project was created. The schedule for excavation and stabilization of the pit was then connected to the model elements. Therefore, a 4D BIM model of the project was developed. Figure 4 shows a view of the generated 4D BIM model.

4.4 Structured Hazard Information System

In this study, an independent database was created to store the safety hazards knowledge. Although this database is linked to the information model of the project under study, its independent nature allows it to be used to identify risks of future projects as well. The researchers designed the database's structure, tables, the properties of each table, and the connection between them. Figure 5 shows the tables, the relationship between them, and the characteristics of each. The desired data was then extracted from the generated 4D BIM model and stored in the created database. Additionally, some data, as explained in Section 3, is also taken from the user.

4.5 Hazardous Attributes Identification

The algorithms determined to identify each hazardous attribute were implemented with the help of information systems capabilities to write queries. The hazardous attributes for each planned activity are identified and stored in the activity risk table by implementing these algorithms. The output of the developed information system is the risk table of activities, which shows the identified or non-identified hazardous attributes for each activity. Figure 6 illustrates a sample form designed to display the information stored in the table after analyzing the case study project.

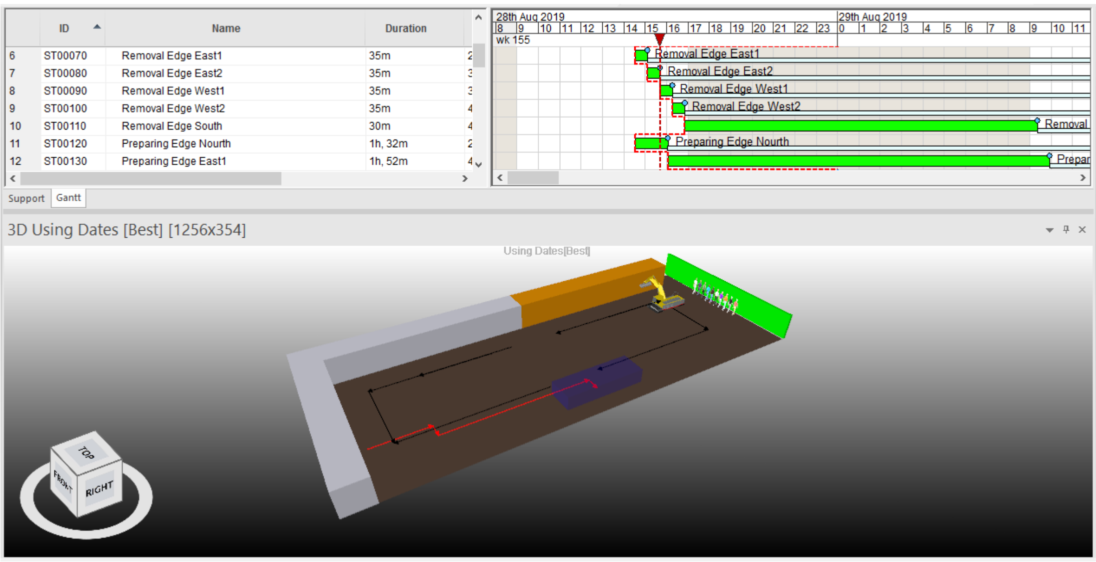

Figure 4. The project's 4D BIM model

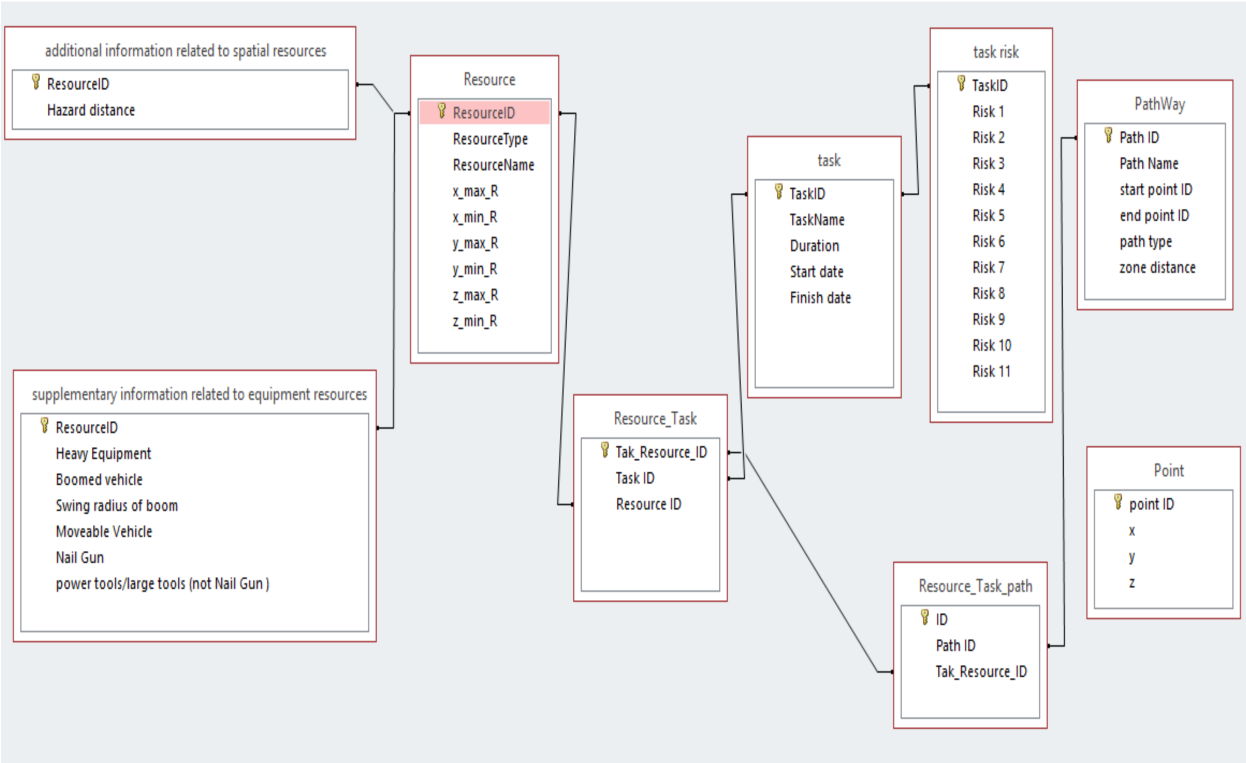

Figure 5. Database structure designed to analyze the information to identify hazardous attributes

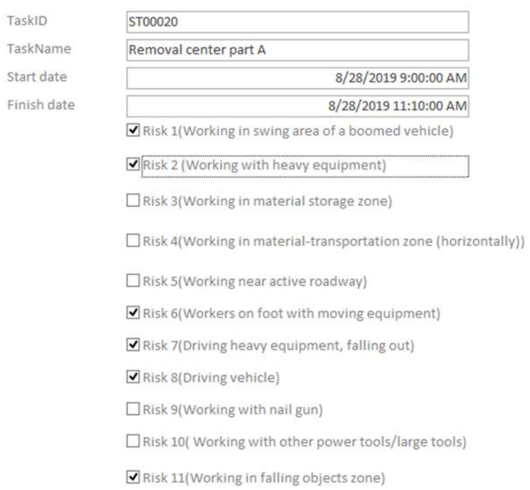

Figure 6. Designed form to view the identified hazardous attributes of each activity in the project's 4D+ BIM

The results from the previous step were integrated with the 4D BIM model of the project to create the 4D+ BIM model. Figure 7 shows a view of the resulted 4D+ BIM model of the project. As shown in Figures 6 and 7, 6 hazardous attributes have been identified for the activity titled "Removal center part A." As shown in Figure 7, an excavator has been used as a resource for this activity. This resource has increased the presence of hazardous attributes in this activity, so it is necessary to consider appropriate strategies in project planning for its safer implementation

4.6 Expected Benefits and Future Works

Based on the case implementation and feedback from the project team and safety experts, the method's benefits are as follows.

1. The 4D BIM made it possible to use computer tools and, consequently, to automate the hazard identification process. The automation of hazard identification allows the process to be performed more straightforwardly, more quickly, and less costly.
2. Due to the consideration of the relationships between elements and activities, the hazardous attributes are identified with higher accuracy compared to conventional methods.

Even though the proposed method has received positive feedback from safety experts, it is still necessary to quantify and compare its results with conventional methods. In addition, future research needs to address further automatization of the method, including minimizing the user's role and standardizing the database so that it can apply to a variety of construction projects.

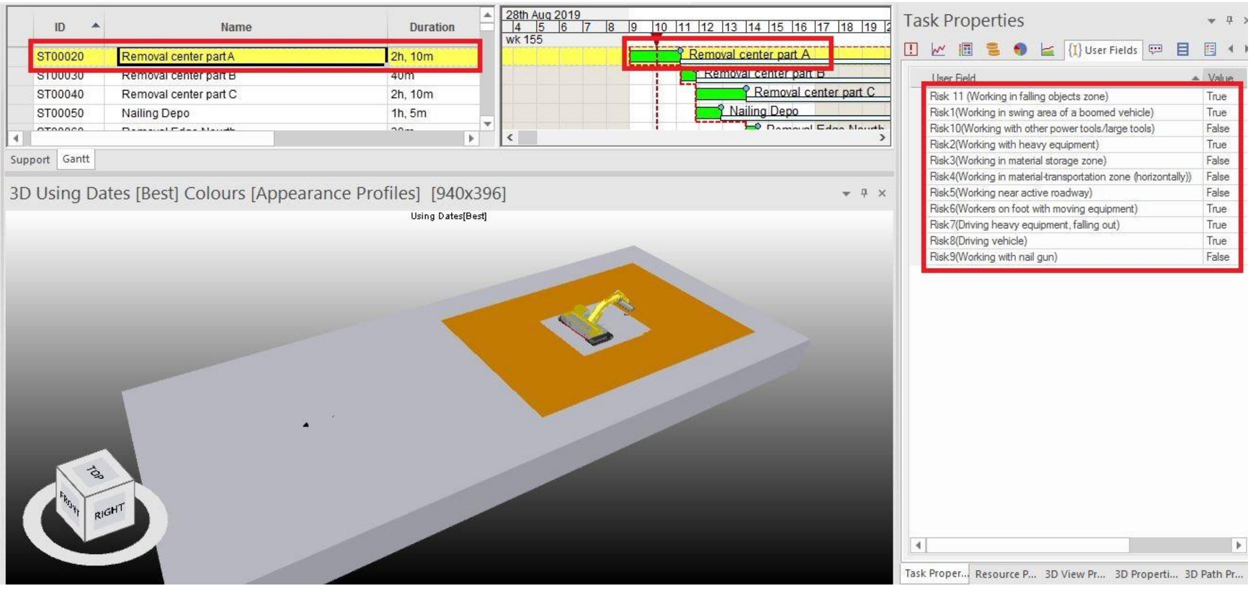

Figure 7. A view of the project's 4D+ BIM model representing the presence or absence of the hazardous attributes in the activity's property menu

5 Discussions and Conclusions

The most important way to control hazards in construction projects is to identify them before occurring. The object-oriented nature and interoperability with other databases of BIM have provided the ability to review conditions and check rules in a short time, low cost, and high accuracy. Therefore, BIM allows the automation of the risk identification process. As a result, 4D BIM was used in this study to identify hazardous attributes in the pre-construction phase of a project. Accordingly, the conceptual method was presented. The method was then implemented on a real project to identify the hazardous attributes causing struck-by accidents in the planning phase. Finally, the expected benefits of the implemented model were presented. Faster and more accurate hazard identification than traditional methods were mentioned as the main benefits of the implemented method.

The method can be used as an efficient tool for Job Hazard Analysis (JHA) procedure. Job Hazard Analysis (JHA) is usually implemented before performing each activity to identify the risks and hazards that threaten its implementation in the project. Using this method in the JHA procedure, risk factors can be quickly identified at the project's planning phase.

Nowadays, toolbox meetings are among the new and effective methods used to express the safety challenges during construction in the project site. The implemented method can help improve the quality of these meetings. It is possible to simulate all activities performed daily, weekly or monthly, along with the risks and hazardous attributes affecting each of these activities in this period.

Another advantage of the implemented method is that it helps maintain and transfer project knowledge. Information about the resources used in the project can be stored in the designed database. This database could then be used in subsequent projects and collectively store project experiences. Modular construction and using robotics in construction are the two most expanding concepts in construction management. This research can help to expand these concepts by taking a step towards automating the hazard identification process. Investigating the effects of using the method implemented in this research on reducing accidents and increasing productivity in projects using robots in the construction and modular construction projects can be considered a subject for future research.

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