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Published in:
Proceedings of the CIBW099W123

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Speiser, K., & Teizer, J. (2023). An Efficient Approach for Generating Training Environments in Virtual Reality Using a Digital Twin for Construction Safety. In E. Fidelis, F. Sherratt, & A. Soeiro (Eds.), *Proceedings of the CIBW099W123: Digital Transformation of Health and Safety in Construction* (pp. 481-490)
https://doi.org/10.24840/978-972-752-309-2

AN EFFICIENT APPROACH FOR GENERATING TRAINING ENVIRONMENTS IN VIRTUAL REALITY USING A DIGITAL TWIN FOR CONSTRUCTION SAFETY

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Abstract

Despite investing many resources into safety planning and control in construction sites, the industry still experiences a significantly higher accident rate than other industries. Recent research introduced serious games based on Virtual Reality (VR), indicating improved safety awareness among workers. However, such scenarios often lack realism and require extensive resources in production. This work proposes a Digital Twin for Construction Safety (DTCS) linking various data sources to generate a Virtual Training Environment (VTE) automatically. The developed VTE framework integrates building information models, construction schedules and safety regulations, and convert it into a VTE prototype in the game engine Unity. The framework then allows data collection of users related to hazards and provide personalized feedback. The prototype is tested with four trainees in a railway infrastructure project with domain-typical hazards. The case study suggests the approach's viability for generating a VTE with little means and human input. The work further suggests utilizing the collected run-time data for purposes beyond safety awareness assessment, like usability studies of safe construction site layouts or machine learning algorithms for hazard prediction.

Keywords: construction safety, digital twins, occupational health and safety, safety training, safe work environment planning, virtual reality.

1 INTRODUCTION

Construction workers have one of the deadliest professions compared to other industries [1]. To address this problem, many organizations invest heavily in safety training programs, which aim to reduce the number of accidents and fatalities by improving worker knowledge and skills. Traditional training methods can be time-consuming, expensive, and not consistently effective. Recent research has introduced extended reality (XR) games as a potential solution for safety training in construction. Still, creating these games is often time-consuming and lacks realism [2]–[4]. Integrating different data sources from IoT devices, laser scans, or Building Information Modeling (BIM) may tackle these issues.

Regarding BIM, an as-planned 4D model defines how a built asset was planned in space (3D) and time (4D), and an as-built model defines how the building was actually constructed. The fourth dimension links the construction schedule to building elements. Digital twins can integrate data from various sources and represent physical assets, systems, and processes in a digital format, allowing for real-time monitoring, analysis, and optimization of their performance. A Digital Twin for Construction (DTC) generates as-performed data based on frequently updated as-built and as-performed states and does, therefore, significantly deviate from BIM models that depict a constructed asset's as-planned and as-designed states [5]. Using the data from various sources such as BIM models, Internet of Things (IoT) sensors, and other relevant information, a DTC provides a holistic view of the construction project and enables more accurate and efficient decision-making throughout its lifecycle.

With the increasing adoption of DTCs in the construction industry, the interest in leveraging them for safety training grows. Recent research introduced a Digital Twin for Construction Safety (DTCS) [6] and conceptually described a dynamic, serious game for construction safety as part of such a DTCS [7]. This paper aims to verify that a DTCS provides the required data to generate realistic virtual training environments (VTEs). Therefore, it first describes the required background knowledge. The study then depicts the method of this work and describes a prototype before discussing the first results of a case study in an infrastructure project. Finally, the authors conclude significant outcomes and propose future work.

2 BACKGROUND

The following sections provide contextual knowledge for the proposed data model. The first part introduces related work regarding novel training methods for construction safety, and the second part explains the underlying concept of close call detection.

2.1 Novel training methods

Effective construction safety training is critical for reducing accidents and improving worker safety. Traditional training methods like classroom instruction and on-the-job training may have limitations that affect their effectiveness. Particularly safety training methods must not expose trainees to hazards. Therefore, virtual training environments have been investigated as a potential solution. Immersive technologies like Virtual Reality (VR) and Augmented Reality (AR) enhance these virtual training environments, providing realistic simulations of construction tasks and hazards that can improve the effectiveness of safety training [2], [8]. Wolf et al. introduced an augmented virtuality (AV) training environment with real construction tools making the experience more realistic [3]. However, the cost and technical complexity of implementing these technologies can be a barrier to widespread adoption. Another issue is that some trainees experience cybersickness during or after immersive experiences, with at least 5% experiencing severe symptoms [4], despite improvements in hardware [9].

Serious games that incorporate elements such as challenges, scorekeeping, and personalized feedback are another approach for more effective learning methods. The term *serious game* implies that the game's primary purpose is beyond mere entertainment [10]. Various studies across domains indicate that gamification enhances the learning experience with more engagement [11]–[13]. Still, the effectiveness of game-based training may depend on the specific design of the game, and concerns about the transferability of skills to real-world construction environments have been raised [14].

For achieving optimal training outcomes, personalized feedback is crucial [15]. High quality should assess the accuracy of performance and provide detailed information on how students can arrive at the correct answer, improve their performance at a higher level, and align their performance with broader objectives [16]. When tailored to the individual, feedback can be more meaningful and relevant, increasing interest and enthusiasm for the task at hand.

2.2 Close calls and protective envelopes

In 2016, the Occupational Safety and Health Administration defined a "close call" or "near miss" as an incident in which an accident was narrowly avoided [17]. While such incidents may involve the risk of death or injury, chance or timely intervention prevents them. Close calls indicate that workplace hazards are not adequately controlled and require further attention to prevent future accidents. Sadly, too few near misses are identified and reported even though collecting in-depth data on close calls is essential for assessing safety planning quality and identifying measures to improve safety design [17].

To address this issue, Golovina et al. introduced a cloud-based framework for automatically detecting and reporting close calls [18]. In earlier work, they proposed weight functions that evaluate the severity of near misses by analyzing factors such as distance, duration, deviation, velocity, and orientation [19]. Their approach applies the Protective Envelopes (PE) concept visualized in Fig. 1. Human workers and construction equipment define a protective envelope based on safety regulations. For instance, ISO 5006 defines a 12 meters minimum distance for workers [20]. Once a worker collides with this sphere, violating the safety regulation is defined as a close call. From this moment, the state of the worker and equipment is stored in so-called "buffer events" every second until the worker leaves the PE of the machine. These buffer events store information about the worker and machine, including the resources' location, direction, and velocity. The previously mentioned weights are computed based on the information given in the buffer events.

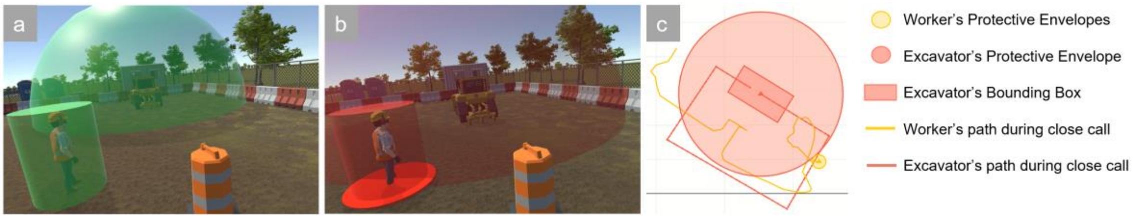


Fig. 1: (a) Worker approaches dozer, (b) close call detected, (c) one buffer event registered, incl. the trajectories of both resources during cloe call event.

3 DIGITAL TWIN FOR GENERATING VIRTUAL TRAINING

The research method includes five steps: literature review, specification, framework development, validation, and identification of further requirements. The literature review revealed that digital twins do not technically implement VTEs for construction safety. The main objective was to utilize the data provided by the DTCS to ease the generation of VTEs. The following requirements specify the goals:

- Automatically generate VTE with a minimum of user interaction.
- Allow the trainer to define parameters for the training scenario.
- Add the most recent BIM model from DTCS to the VTE for a given timestamp.
- Retrieve the construction schedule from DTCS, including tasks, resources, dates, and time.
- Provide personalized feedback based on run-time data collection.

After setting the objectives, the authors created user stories and derived crucial stakeholders. Based on existing ontologies, the authors developed a data model and implemented it into a prototype. The authors created a DTCS comprising the as-planned construction model, scheduled tasks, and involved resources such as workers and machinery. The serious game retrieves the 4D model from the DTCS. Based on a selected task from the DTCS that a player needs to perform, the serious game loads the as-planned status of the project for the specified task. The VTE always loads the latest version from the VTE. Thus, updating the scene according to new developments in the planning phase is automatic.

In the next step, the game retrieves the active resources from the construction schedule at the selected timestamp. The equipment resources, such as excavators, crane loads, or dump trucks, may represent hazards for the player. The VTE tracks the players' commands, trajectories, and close calls and sends the data to the DTCS in run-time for subsequent analyses. Existing methods developed by the authors provide personalized feedback based on the severity of the close calls. In the third phase of the research method, the authors validate the proposed framework in an infrastructure project case study. Lastly, refinements and requirements were identified to make the framework more stable and efficient.

3.1 Digital Twin framework

Based on the defined requirements, the authors created a DTCS providing the 4D BIM model, a construction schedule, and the resources (workers and equipment). Fig. 2 illustrates the implemented framework. The trainer and trainees can operate the web-based user interface (UI) that includes the VTE, personalized feedback for the trainees, and a summary of multiple game results for the trainer. Additionally, it contains a view where the trainer can create game scenarios. The UI accesses a graph-based database via an Application Programming Interface (API). The database supplies the required information from the DTCS to generate the VTE and stores the data collected during playtime.

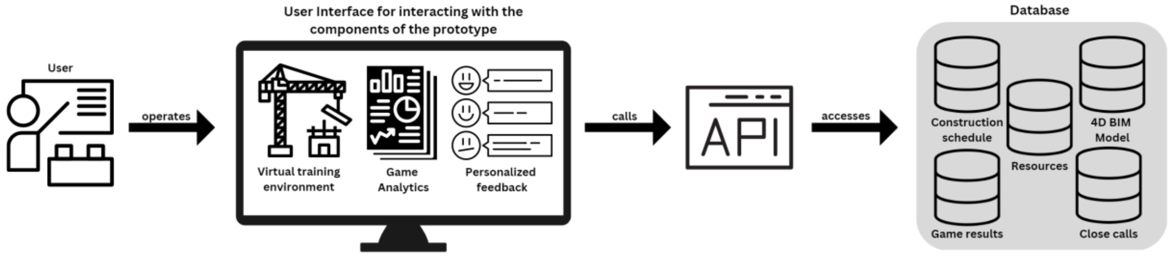
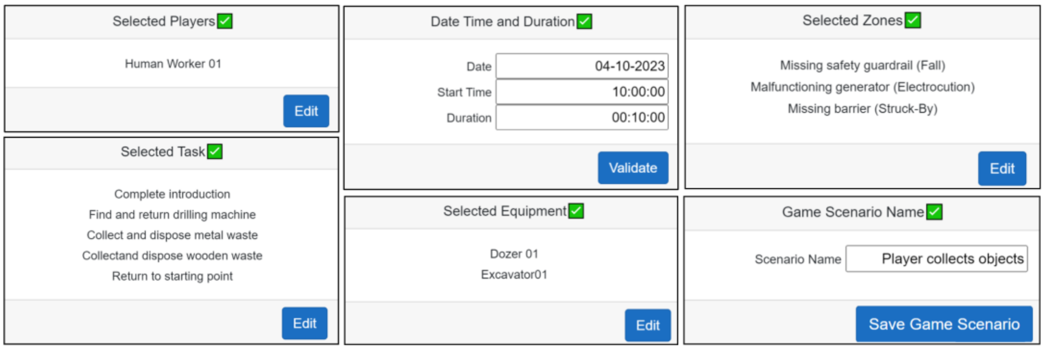


Fig. 2: Framework of the DTCS.

3.2 Game scenario specification

A game scenario defines work tasks that a construction worker should train before performing them on the real construction site. The information stored in the game scenario is input parameters for the VTE to generate the scene. Thus, these scenarios specify the tasks for the players, the date during the as-planned construction schedule, the workers, and the required resources (materials, equipment). Moreover, the trainer can select hazards for the player. Fig. 3 shows the UI and a game scenario exemplarily. In this case, one worker needs to complete three tasks. During the game, there is a dozer and an excavator, and the player is exposed to a malfunctioning generator (electrocution hazard), a missing safety guardrail (fall hazard), and a missing barrier (struck-by hazard). Once the trainer saves the scenario, the information is stored in the database and accessed by the corresponding workers.



Selected Players ☑

Human Worker 01

Edit

Selected Task ☑

Complete introduction
Find and return drilling machine
Collect and dispose metal waste
Collectand dispose wooden waste
Return to starting point

Edit

Date Time and Duration ☑

Date: 04-10-2023
Start Time: 10:00:00
Duration: 00:10:00

Validate

Selected Equipment ☑

Dozer 01
Excavator01

Edit

Selected Zones ☑

Missing safety guardrail (Fall)
Malfunctioning generator (Electrocution)
Missing barrier (Struck-By)

Edit

Game Scenario Name ☑

Scenario Name: Player collects objects

Save Game Scenario

Fig. 3: UI for the trainer to define game scenarios.

3.3 VTE scene generation

This study uses the game engine Unity to visualize the game environment. With the game scenario as input, the game scene loads the as-planned BIM model from the database. Based on the construction schedule, a script filters all active elements at the given timestamp. In this work, IfcConvert converts the provided IFC file into an OBJ, XML, and MTL file [21]. A modified version of the IFC importer asset generates a game object of the model in Unity, which includes objects, attributes, and relationships [22]. The application loads the model in run-time to ensure up-to-date information.

3.3.1 Workers

A script adds an avatar for each player based on the information in the game scenario. The presented framework aims to provide multiplayer training environments eventually. However, this study tests a single-player game. Each human worker represents a resource within the underlying data model. Every resource defines safety parameters for the safety envelope and the protective envelope. A worker's protective envelope is represented by a cylinder. The safety envelope is a bounding box around the avatar. Fig. 4 illustrates the concept of the *safety parameters* for a worker. The VTE triggers a close call once the protective envelope collides with a hazard (compare Fig. 1).

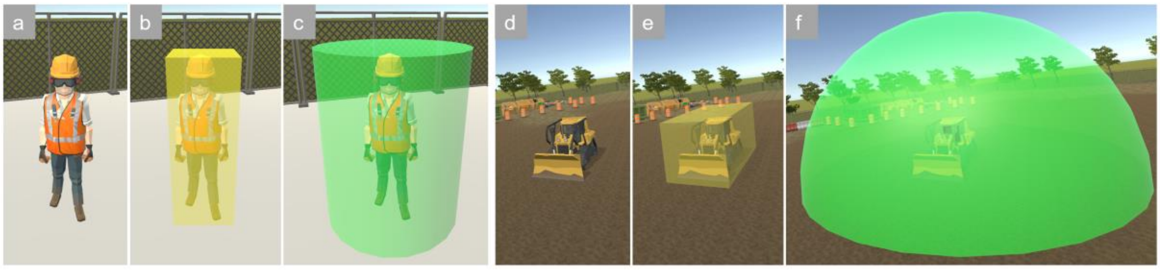


Fig. 4: (a) Worker and (d) dozer with their (b,e) safety envelopes and (c,f) protective envelopes.

3.3.2 Construction equipment

Construction equipment may cause hazard zones. For instance, ISO 5006 defines workers must keep at least 12 meters distance to earth-moving machines [20]. The developed DTCS provides this information for each resource in the form of safety parameters. Similarly to human workers, these parameters define the geometry of the safety and protective envelopes. Fig. 4 illustrates the concept of a dozer. An oriented bounding box around the equipment with an offset of 1m represents the safety envelope, and a sphere with a 12 meters radius represents the protective envelope.

3.3.3 Construction site layout and hazard zones

A successful implementation requires the provided BIM model to contain the site layout and hazard zones like the SafeConDM model describing a domain model for safety design [23] or the latest proposal of a hazard ontology [24]. This work assumes that the DTCS provides a safe 4D BIM model, including safety layout and hazard zones. We define a hazard zone as a space that workers can only enter if they are specifically permitted to. If workers enter the zone, they put themselves in danger and trigger a close call. This work focuses on the four leading hazards in construction: falls from height, electrocution, struck-by, and caught-in-between. Typically, falls from heights and electrocution are static zones, while struck-by and caught-in-between relate to moving construction machines.

The BIM model in this work contains hazards according to the ontology defined by Johansen et al. [24]. Each hazard in the model links to mitigation equipment. Fig. 5 exemplarily illustrates how such hazard zones in a BIM model may appear. As the DTCS provides a safe model with mitigated hazard zones only, a script in Unity removes mitigation equipment according to the trainer's input in the game scenario. This ensures that the player is exposed to hazards during playtime.

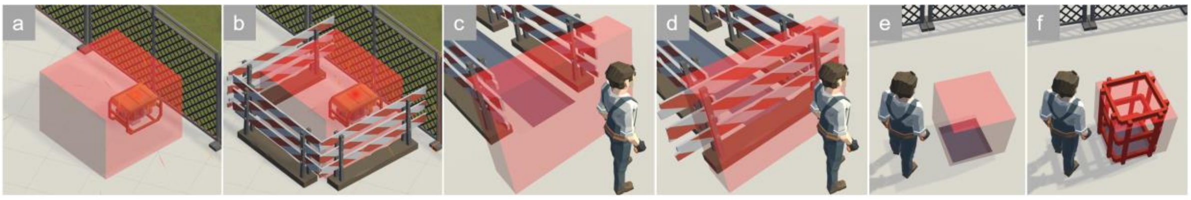


Fig. 5: (a) Malfunctioning power generator (b) with temporary mitigation equipment, (c) unprotected leading edge, (d) mitigated fall hazard, (e) unprotected manhole, and (f) mitigated by guardrails.

3.4 Data collection and analyses

The VTE collects and analyzes data throughout the game experience to evaluate the player's performance and identify behavioural patterns. This section describes the data the VTE collects and sends to the database using the API.

3.4.1 Trajectories

The trajectories of the players are an essential data source for evaluating the player's performance and retrieving valuable behavioural patterns. The implemented game tracks the location of each resource throughout playtime and continuously posts the data to the DTCS. This information allows further analysis to compute indicators such as velocity, walked distance, or proximity to equipment. Fig. 6 visualizes the collected trajectories for the trainer while the trainees play. The green line shows the player's trajectory, and the red lines indicate the player's path during a close call. The VTE also records the trajectories of the machines. In Fig. 6, the excavator in the centre moves forward and projects the trajectory in blue.

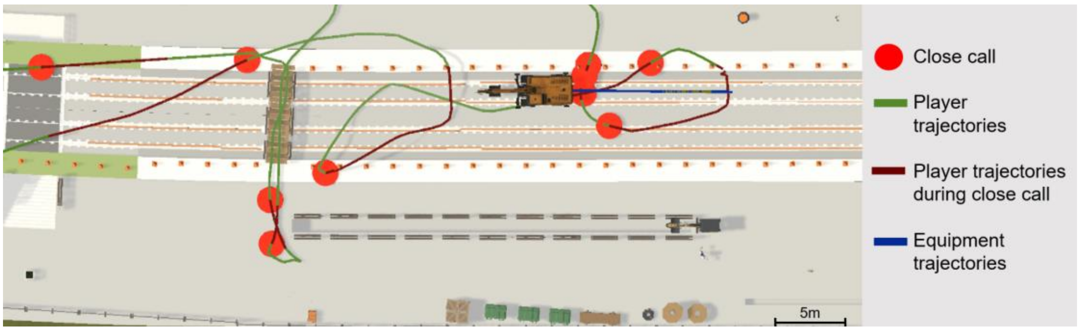


Fig. 6: Trajectories of the player and equipment and the detected close calls during playtime.

3.4.2 Proximity events and close call analysis

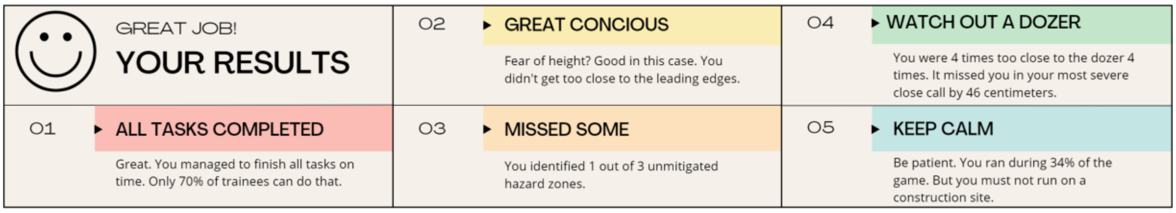
As previously described, this work uses a concept of detecting close calls introduced in previous research, where a close call corresponds to a collision between a PE of a human worker and a hazard zone [19]. Therefore, each hazard in the training environment has a script assigned that implements the two methods *OnEnter* and *OnExit*. The following code excerpt shows the methods using pseudo-code:

```
FUNCTION OnEnter(Resource endangered)
    IF endangered.InDanger:
        CloseCall cc = ActiveCloseCalls.Add(endangered)
        StartCoroutine(AddBufferEvent(cc))
    END IF
END FUNCTION
FUNCTION OnExit(Resource endangered)
    CloseCall cc = ActiveCloseCalls.Get(endangered)
    cc.PostProcess()
    ActiveCloseCalls.Remove(cc)
    Http.SendCloseCall(cc,url)
END FUNCTION
```

Once any other geometry collides with the hazard, *OnEnter* checks if the colliding resource is an endangered worker and adds a close call to the collection of active close calls (line 3). The collection is crucial because one hazard can simultaneously experience close calls with multiple resources. Line 4 initiates a coroutine to continuously insert a buffer event. The buffers contain information about the trigger and the hazard, such as their location, velocity, direction, orientation, and time. Once an endangered resource leaves the hazard zone, *OnExit* retrieves the close call with the endangered worker from the active close calls (line 8). A post-process analyzes the severity of the close call using existing methods based on the information in the buffer events (line 9). Finally, the function removes the close call from the active events and dispatches the data to the API in lines 10 and 11, respectively.

3.5 Personalized feedback

As highlighted before, personalized feedback improves the quality of the training experience. The developed prototype implements feedback for the trainee and the trainer. The trainees obtain a feedback card (see Fig. 7) summarizing their performance based on a few indicators. For further insight, a dashboard provides information on a low level. The following chapter explains the collected data for creating feedback based on the first tests. The trainer has the opportunity to overview the results from multiple game experiences and compare individual players (see Section 5).



GREAT JOB!

YOUR RESULTS

01 ▸ ALL TASKS COMPLETED

Great. You managed to finish all tasks on time. Only 70% of trainees can do that.

02 ▸ GREAT CONCIOUS

Fear of height? Good in this case. You didn't get too close to the leading edges.

03 ▸ MISSED SOME

You identified 1 out of 3 unmitigated hazard zones.

04 ▸ WATCH OUT A DOZER

You were 4 times too close to the dozer 4 times. It missed you in your most severe close call by 46 centimeters.

05 ▸ KEEP CALM

Be patient. You ran during 34% of the game. But you must not run on a construction site.

Fig. 7: Feedback card for the trainee.

4 PROTOTYPE VALIDATION

A study with four trainees was conducted based on a railway infrastructure project to validate the proposed approach. In the first game scenario described in Fig. 8, a player needs to perform five tasks: (1) Complete an introduction to the game's objectives and controls (Fig. 9), (2) find a drilling machine and bring it to storage, (3) find a wooden piece and dispose it at the correct recycle container, (4) find a recycle bag and bring it to the correct container, and (5) return to the initial position. Visuals highlight the locations where a player should go, as the game scene is rather large. However, there are different paths a player can choose. The player has the main objective of not exposing themselves to hazards. This game scenario comprises the hazards defined in the game scenario from the previous section: two dynamic hazards in the form of moving machinery and three static hazards: a malfunctioning generator, an unprotected leading edge, and a missing barrier (compare Fig. 5).

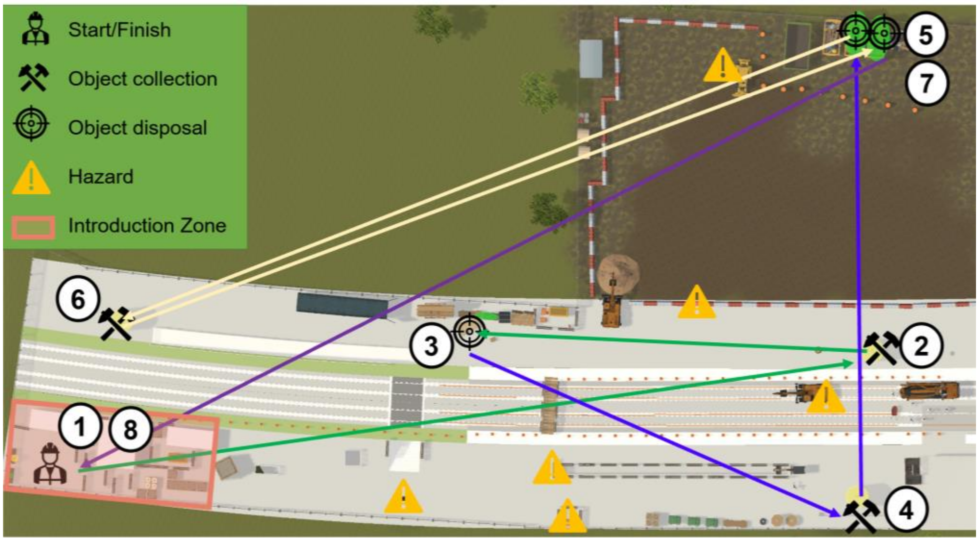
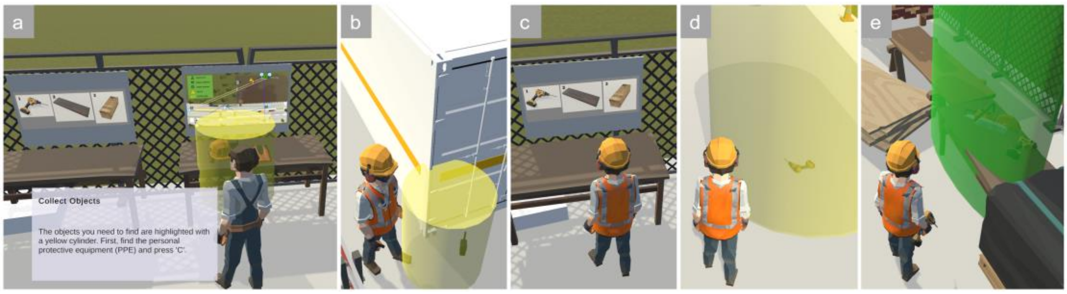


Fig. 8: The players get introduced to the controls (1), handle three objects (from 2 to 3, 3-4-5, and 5-6-7, respectively, shown are the shortest and potentially unsafe pathways), and return to the start (8).



Collect Objects

The objects you need to find are highlighted with a yellow cylinder. First, find the personal protective equipment (PPE) and press 'C'.

Fig. 9: Entrance of user to VET: (a) Instructions to the game controls by selecting PPE, (b) detecting a pick-up location in form of a transparent yellow cylinder, and (c) task preparation through visuals, (d) in-game pick-up location, and (e) drop-location in form of a transparent green cylinder.

4.1 Instructions

The game first introduces the user to the objectives and the game controls. The worker in this prototype is navigated in a third-person view on a screen. Still, the authors expect the proposed concept also to work with immersive VR solutions. To familiarize players with the game controls, they must first find their personal protective equipment. In the second step, the player must find a walkie-talkie and put it on a desk. This exercise introduces the player to how to collect objects. Before the training starts, the player can see a map of the game environment indicating hazards and objectives (Figure 9a).

4.2 Safe and unsafe paths

The player can freely navigate through the game scene to complete the tasks. The safe construction site layout comes from the BIM model and provides safe paths for the workers. However, the game removes mitigation equipment to expose the player to hazards. Fig. 10 depicts two examples. The trainee should cross the railways using the safe bridge instead of risking proximity with the excavator. In another example, a portion of the barrier has been removed, but a stop sign next to a hole should indicate to the player that they should not enter and instead find a safer path.

Fig. 10: (a) A secure bridge to the left offers a safe path for crossing the railway under construction, (b) a gap between the barrier may lead a user to enter a restricted work zone, and (c) a safe alternative.

4.3 Feedback

After the game, the players get forwarded to a website for in-depth insight into their performance (see Fig. 11). The first element indicates the severity and location of individual close calls. The second element provides an overall grade. The authors have not yet developed the grading as more tests are required. Component 3 provides mean values for each weight of the near misses, and component 4 lists the number of close calls caused related to the different hazards: struck-by, fall, and electrocution.

5 DISCUSSION

Table 1 and Fig. 12 overview the results of the first training experiences in a table and a dashboard, respectively. All four trainees completed the five tasks within the given time limit. Player 3 was the slowest and walked the longest distance, while Player 2 was the fastest. In this context, fast is not necessarily good as it may lead to inattentive behaviour. On average, Player 1 experienced 9 close calls. Despite being the fastest, Player 2 has the lowest value with 5 close calls, and Player 4 has the highest with 16. However, Player 2 has the highest average weight for the close calls. Fig. 12 indicates that Player 4 never used the bridge for crossing the railway and always crossed the work zone of the dozer instead of taking the alternate safe path. Only the third player detected and used the designated path to avoid the hazard of the traversing dozer. As previously stated, this work does not yet implement a holistic method to evaluate the performance quantitively. However, based on the results shown in Table 1 and Fig. 12, Player 3 would probably receive the best grade concerning safety awareness.

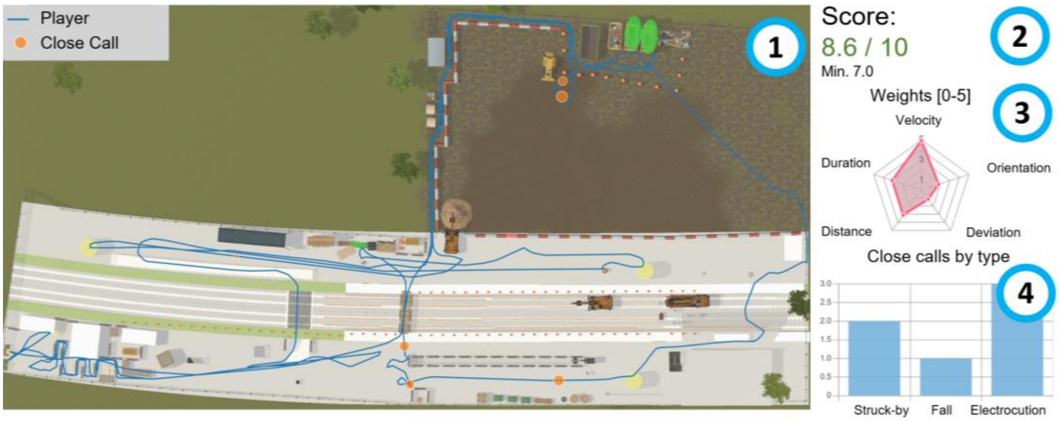


Fig. 11: Web-based dashboard for trainees provide some of their personalized feedback.

Table 1: Comparison of crucial indicators for the performance of the four trainees.

Player	Duration [m:ss]	Distance [m]	No. of close calls [-]	Average weight [-]
1	3:49	703	9	2.79
2	3:40	782	5	2.91
3	5:02	1045	6	2.80
4	4:24	843	16	2.62

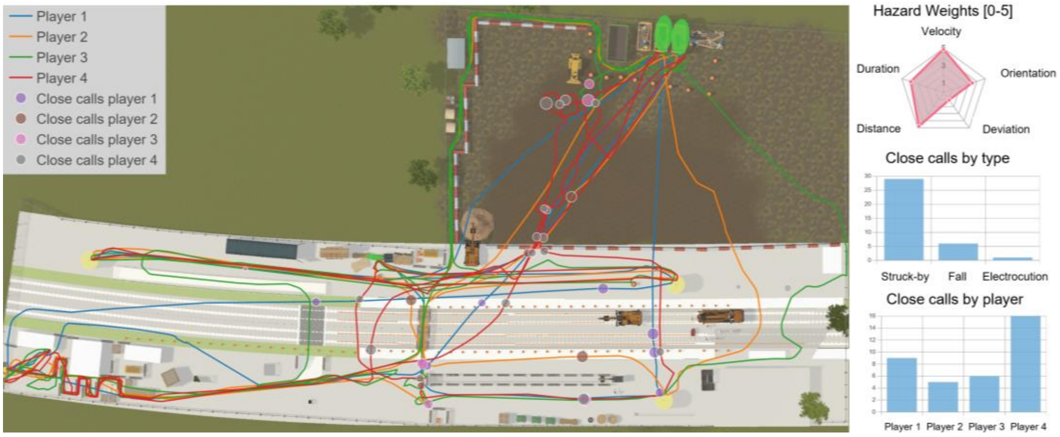


Fig. 12: Dashboard for the trainer overviewing all game results.

The severity of the hazards is rather high. The observed 36 close calls have an average weight of 2.7. While the velocity and the distance weights are high, with 4.9 and 4.8, respectively, the deviation weight has the lowest value (1.1). These results raise the question whether the weight formulas require adjustments. However, most close calls relate to moving machinery, as expexted these are one key concern in railway construction, where the exposure to velocity contributes most to the total weights.

Fig. 12 shows that no trainee solely used the safe paths, perhaps because no signage was provided. All players crossed the railways and the work zone of the dozer at least once. This fact highlights one of the significant advantages of this novel training method. In on-the-job training, the trainer would need to intervene immediately once the worker enters such a hazardous area as the risk of an injury is too high. In the VTE, however, the trainer can expose the workers to such situations and evaluate their behaviour. The VTE allows trainees to learn and experience potential hazards under both safe and controlled conditions, and the safety trainer can collect valuable information about workers' behaviour once they find themselves in a hazardous situation. This information is yet available but primarily in accident reports where the damage already occurred. Another advantage is that decision-makers can retrieve valuable information regarding the usability of their safety design by simulating the tasks in such a VTE. Future work will investigate how the results can contribute to improving the site layout regarding usability and safety in an automatized way. For instance, how can algorithms determine that the players did not use the designated safe paths, and how can these algorithms propose adequate improvements?

6 CONCLUSION

This paper verifies that a DTCS provides the required data to generate realistic VTEs for construction safety with little manual means. We implemented a data framework based on existing ontologies into a prototype for a DTCS. The prototype integrates a VTE in a web application where the trainer can create game scenarios, and the trainees play a serious game to train their safety awareness. The prototype utilizes the 4D BIM model from the DTCS for generating the VTE and storing game results in a database. Algorithms process the results on the DTCS and provide personalized feedback. A dashboard summarizing the game results for all trainees allows the trainer to compare the performances. Based on the first results, we conclude the following three theses that require further investigation.

1. Accurate information about the location of materials and equipment makes VTEs more realistic.
2. The construction schedule requires more detail than current practice provides.
3. VTEs, as part of a DTCS, generate valuable data for purposes beyond pure safety awareness evaluation of construction workers.

First, the construction site in the case study was too tidy. Thus, the DTCS requires more knowledge about materials and the project status to make the VTE more realistic. Otherwise, a specialist must improve the scene with manual effort. Second, the construction schedule for the railway project links elements to tasks. The construction schedule must provide information about as-planned trajectories for the automatic generation of VTEs, purely based on such tasks. The construction industry is not yet at a point where, for instance, a crane follows a predefined path for locating objects. However, using as-performed trajectories of machinery from IoT devices could solve this issue. Lastly, the first results in a test with four trainees indicate that such a game generates valuable information beyond pure awareness evaluation. For instance, decision-makers can identify flaws in the safety design or simulate the usability in such a VTE before the construction starts.

Based on the main conclusions, the authors suggest future work investigating the impact of a DTCS providing advanced information regarding the placement of materials and as-planned trajectories of equipment. Furthermore, future research should study how the collected data in VTEs can contribute to improved safety design. One approach is to develop models that can automatically propose better site layouts regarding productivity and safety. The collected data could also train machine learning models for predicting hazards during construction based on the results from the training. Additionally, future research can integrate real-time sensor data and other data sources to improve the accuracy and relevance of the virtual training environment, resulting in improved safety outcomes.

ACKNOWLEDGEMENT

The research presented in this paper has been funded by the European Union Horizon 2020 research and innovation program under grant agreement no. 958310 and 95398.

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