Scenario-Based Construction Safety Training Platform Using Virtual Reality

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Abstract –

Learning by doing creates a marked impact on a trainee's cognitive ability. Technologies such as Virtual Reality (VR), Augmented Reality (AR) etc. aid in developing platforms to enhance the learning experience of users. These technologies can be particularly effective in construction sites which are complex and contain hazards difficult to foresee. These technologies can enable the formulation of robust safety training procedures that will enhance awareness among workers about workplace risks and help to mitigate the same. Currently, the customized development and expense in execution of these digital platforms are major deterrents in its practical deployment and optimum utilization.

In this study, a framework is proposed for the design and development of a VR platform for safety training. The proposed framework classified as Decision-Making Accident Scenario (DMAS) - produces an information skeleton which is derived out of an assessment of potential accidental situations emerging out of a functioning construction site. This skeleton works as a design document to conceptualize the accident scenario as per the identified accidental situation. In each scenario, trainees need to analyze simulated situations, identify risks, and make informed decisions about the mitigation measures which create alternate outcomes. Immersive VR experience of the scenario is built with the help of a gaming engine Unity and Google VR SDK. Smartphone-based VR platform is suggested for user interaction as it is economical to deploy. A pilot study to evaluate this proposed framework was experimentally executed by developing cases related to an ongoing project and synthesizing the different scenarios and storylines into the VR platform. This was tested on three users, and preliminary findings empirically indicated that that safety training using the aforementioned digital platform was significantly more effective in creating better understanding of safety practices on-site.

Keywords –

Virtual Reality (VR); Unity; Decision Making Scenario; Construction Safety Training

1 Introduction

The advancements made in the field of construction have facilitated the implementation of more complex projects in the sector. However, the complexity of a construction project also resulted in making the workplace more prone to accidents and injuries. Despite the industry's sustained efforts to train and educate its workforce about safety practices in the workplace, the construction industry continues to record the highest number of work-related accidents and injury. The USA Occupational Safety & Health Administration (OSHA), reports "out of every 5000 private-industry worker fatalities, 20% are in the construction industry, which means that one out of every five workers deaths is construction related" [1]. This data is based solely on officially reported injuries, and it is widely known that a majority of the workplace injuries go unreported [2]. Such statistics reveal how dangerous and potentially unsafe the construction industry is.

From the perspective of project performance, any on-site accident or injury can cause substantial project delay and cost overrun [3]. To avoid such uncalled for circumstances, the industry follows various protocols, standards, and systems established by the concerned regulatory body of the respective government of the country. The industry also ensures that basic safety training is given to its workforce and generally employs conventional methods for the same which are based on videos, presentations, lectures, and apprenticeship programs [4]. Though this approach gives an insight to the construction practitioners about risk identification and mitigation measures, its effectiveness is limited as it does not prepare them for anticipating and appropriately addressing hazard scenarios [5].

Research has shown that Virtual Reality (VR) has the potential to serve as a training platform, especially in applications that require visualization. It combines 3D vision and sound; and allows active participation by evoking a sense of the presence of the user [6]. Based on the capabilities of VR, it is proposed to develop a detailed framework to identify and analyze experiences of various accidental situations of a construction site. A platform to implement the framework that enables interactive scenario-based safety training VR application for a smartphone is also proposed. It is expected that the immersive experience of accident scenarios derived from the analysis of the accidental situation will enhance the trainee's ability of risk identification and enable suitable precaution selection.

This paper is organized into seven sections. The following section discusses the existing literature, related work and current gaps in VR based safety training. Sections 3 and 4, present the proposed solution: DMAS based VR training platform and the methodology to develop it. A pilot study to develop and apply the prototype is presented in Section 5. Section 6 shows the analysis of the results obtained after testing the prototype on users, and Section 7 presents the conclusions of the study along with the future work.

2 Related work

This section presents the methods of conventional safety training followed on-site and their limitations. It also discusses the existing VR based safety platforms along with potential and current limitations.

2.1 Conventional Training Method

Safety awareness gets imbibed in workers primarily through field experience and safety training exercise among others. The construction industry has well-established systems for imparting safety training by using methods and platforms like videos, PowerPoint presentations, lectures, or safety toolbox meetings [4]. A survey was conducted on 121 construction practitioners who completed an OSHA 10-hours construction safety training course to check their perception about the efficacy of existing training programs [7]. The survey shows that most of the participants were dissatisfied with the way the training was given. Another study shows that trainees faced problems in being able to visualize construction tasks and activities. In a way, though the videos enabled visualization, the passive role of the trainee in the training procedure renders this method tedious and insufficiently engaging [8]. Thus, these conventional training platforms failed to give the desired results and time and again resurfaces and reinforces the need for a better and effective training program. The inclusion of digital advancements like VR in safety training, can go a long way in devising the potential solution to this problem.

2.2 VR Based Construction Safety Training

The use of VR in the training and education field is widespread. Its first implementation was to train the aircraft pilots by using a flight simulator. In recent years, VR has also become popular in the construction field. Many researchers have tried different ways of using VR for safety training purposes and found largely satisfactory results.

The main advantage of VR lies in the fact that it enables visualization. One study tried to verify this aspect by comparing hazard recognition and risk perception skills of two sets of test subjects: one, who worked with photographs and documents and the other who visualized the situation using VR [9]. Results show clearly that the test subjects from the VR set were able to identify most hazards correctly.

Another study tried to solve the visualization problem faced by the safety management team in risk identification [5]. In this, gaming technology was used to develop the Virtual Safety Assessment System (VSAS). This system simulated high-risk activities and asked complicated multiple-choice questions related to the activity, where the trainee had to think and observe before opting for any option. Such platforms managed to cover various aspects of general safety training. However, VR is not limited to just this. Researchers tried to train a group of students and workers about general safety training as well as task-specific safety training like safety in cast-in-situ concrete and stone cladding work [10]. Task-specific training simulation consisted of various accident scenarios that could arise because of the possible mistakes committed by the trainee while performing the assigned task. The results from the study suggests that the VR platform had a clear advantage in task-specific training, while no significant improvement was seen in the case of general safety training. It also verifies that VR training is indeed very effective as it required the trainees to maintain a high level of alertness and engagement for the entire period.

A social/collaborative VR-based framework was developed to make the workers aware of the critical elements in a collaborative task on-site. Here the students were given an opportunity to learn about construction safety measures by doing experiments on 3D virtual world space [8]. The prototype allowed the student to play an active role while collaborating with other students. The results clearly indicate that it improved the students' involvement, ability to collaborate with other students.

Although research in the field of VR has grown rapidly in the last decade; most of the existing VR platforms for construction safety training still have certain limitations. Some of these are as follows:

- Currently, existing VR platforms, while proving useful, lack a well-defined framework and methodology, which tends to generalize the process of VR based construction safety training platform development.

- Most VR simulations teach about risk identification but seldom provide scenarios on how to mitigate the risk.
- The cost associated with any VR based safety training platform is very high as a result of which deployment across construction sites gets limited.

3 Proposed DMAS Based VR Training Platform

Based on the above limitations, a Decision-Making Accident Scenario (DMAS) based VR android application platform was proposed which was economical and didn't require high-end VR devices. This platform was prompted by a requirement to focus on improving trainee's ability of risk identification as well as identifying suitable mitigation techniques. It would consist of various accident scenarios, which would be the modified replica of identified accidental situations in a real construction site.

The trainee would be introduced to these scenarios in a virtual environment. Based on observations and assessment, the trainee would need to identify the correct risks associated with the scenarios and try to mitigate those risks by suggesting appropriate precautions. After making those decisions, the trainee would need to verify the safety of that scenario's location by testing it. Identifying risks correctly and suggesting corresponding precautions accurately would be the parameters for evaluation. While testing, it might result in an incident/accident, if the trainee make errors in taking all necessary and correct precautions. These simulated accident outcomes would create a significant and much needed impact on the trainees in raising awareness about how a wrong judgment on site could lead to severe danger.

4 Methodology

To develop a DMAS based VR training platform, a detailed methodology, as shown in Figure 1, was designed and developed. The first step was to develop a detailed Risk Identification Framework (RIF) having the same structure as shown in the first part of Figure 1. This framework was used to classify general types of accidents that could occur on-site into standard categories (A), along with its root causes (R) and precautions (P) to mitigate it. For developing the RIF, safety manuals and accident case studies were referred.

After RIF preparation, the second step was to assess the specifics of the site and identify where training is required. The site visit was intended to identify and analyze various Accidental Situations (As), which might lead to an accident in case of negligence. The Possible Accidents (PA) in those situations were classified as per pre-classified accident categories (A), as shown in the second part of Figure 1.

The third step was to form a DMAS information skeleton. This skeleton was a design document that conceptualized the VR visualization of DMAS. As sketched out in the third part of Figure 1, there were two variables: what accidents should be framed and what corresponding precautions should be suggested for that Framed Accident (FA). The analysis of the accidental situation (As), as shown in the second part of Figure 1, would become the base for deciding the first variable as well as a storyboard (S) and surrounding environment in VR world space. The list of both the correct and incorrect precautions (CP/IP) for the other variable could be derived from RIF, as shown in Figure 1.

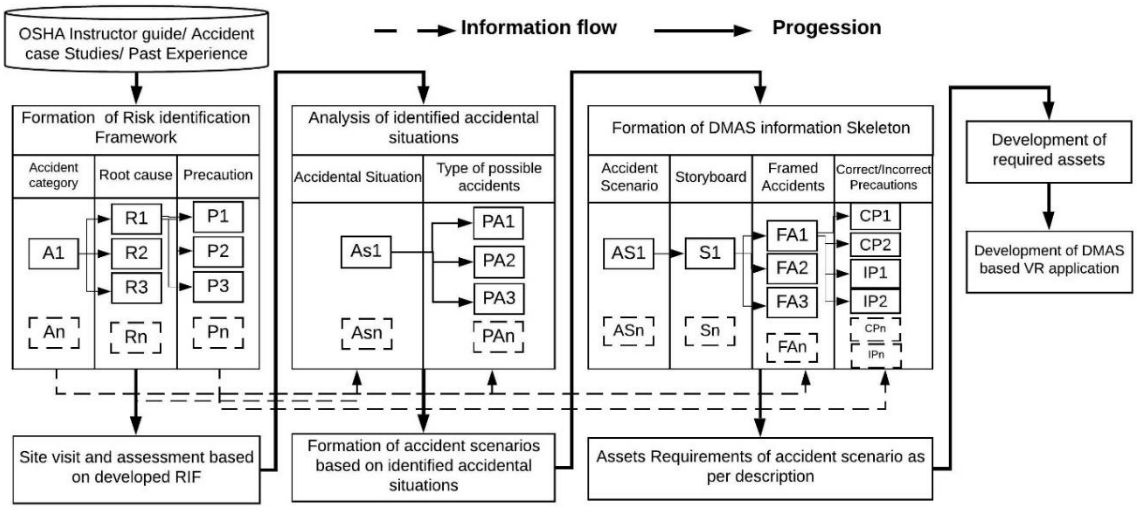

Figure 1. Framework for development of DMAS based VR safety training platform

In the fourth step, the DMAS information skeleton had specified a list of required assets (3D models, etc.). Later, these 3D models were developed with the help of modeling software. Then these all developed models were brought together on a single platform to create VR experience of DMAS where the trainee could experience the outcome of the Framed Accidents (FA).

5 Pilot Study

5.1 Risk Identification Framework (RIF)

This pilot study was executed in the sequence described in the Figure 1. This RIF was based on OSHA's four instructor guides (Construction focus four) for construction safety training [11]–[14]. The RIF output is depicted in Table 1.

The first column classified all possible types of accidents which could occur in any construction site into five general accidents categories (A) (fall from height, struck-by, caught-in or between, electrocution and scaffold collapse) along with its minimum basic requirements to occur.

The second column had root cause analysis (R) for each accident category with the possible reasons which might cause that particular accident. The third column had a set of common suitable precautions (P) suggested and recommended by OSHA, which could eliminate the cause as well as the risk. This given RIF in Table 1 is limited to including only those accident categories which were identified on-site and further used in VR simulation development. Shaded cells in Table 1 highlight the used elements of RIF.

5.2 RIF Based Site Assessment

The site selected for assessment was a commercial office building project. The project consisted of multiple towers which were in different stages of construction. Activities like wall cladding installation and concreting on the top floors were in progress. RIF was used to identify hypothetical accidental situations based on ongoing work.

Table 1. Risk Identification Framework (RIF)

Accidents category (A)	Root Causes (R)	Precaution (P)
Fall from height (Location's elevation higher than 6fts)	Unprotected roof edges, roof, scaffolds, and floor openings, and leading edges, etc.	Provide guardrail systems
		Provide safety net
		Wear Personal Fall Arrest Systems (harness or lanyard)
	Improper scaffold construction	Check for proper access, full planking, and guard railing.
	Unsafe portable ladders	Check for stable footing and the proper angle.
		Choose the correct ladder in good condition for the task Check for surrounding hazards,
Electrocution (Location has any electrical equipment or power lines under or above it)	Contact with overhead power lines (in case of Cranes, other high reaching equipment, Mobile heavy equipment, Ladders, and Material storage)	Maintain a safe distance from overhead power lines
		De-energize the Utility company and visibly grounded the power lines or installed insulated sleeves on power lines
		Check for Flagged warning lines installed to mark horizontal and vertical power line clearance distances
	Contact with underground power lines (in case of excavation)	Check for the markings from underground line location service before digging
		Hand dig within three feet of cable location.
		Use ground-fault circuit interrupters (GFCI)
	Contact with energized sources (live parts, damaged or bare wires, defective equipment)	Use gloves and appropriate footwear
	Improper use of extension and flexible cords	Inspect portable tools and extension cords
		Use power tools and equipment as designed
Scaffold collapse (Location has scaffold)	Improper construction	Check for safety tag (Scaffold Identification Tag)
	Use of parts manufactured in different organizations	Use same manufactured part from one organization
	Instability	Check for unsupported overall height to length of the shortest side of the base
		Check for the firmness of soil under the scaffold
		Check for weather conditions (Wind & Rain)

Figure 2. Accidental situation (As)

Even though four hypothetical accidental situations were identified, this paper focuses on the observation, illustration, and analysis of one of such accidental situations. The situation formulated is based on a new scaffold that was erected for the installation of the formwork, as shown by red arrows in Figure 2. However, the scaffold installation was incomplete and didn't have a suitable platform to work. Also, it wasn't verified by the safety engineer and hence had a red safety tag. Table 2 depicts the performed analysis of Accidental Situation (As) based on RIF. Furthermore, these observations and analysis of Accidental Situation (As) were utilized for creating Accident Scenario (AS).

Table 2. Analysis of Accidental Situation (As)

Possible Accident (PA)	Possible Worker's Negligence
Fall from Height	Workers could perform a task on that platform without any fall protection.
Scaffold collapse	Worker could perform a task on the improperly erected scaffold.

5.3 DMAS Information Skeleton

The Accident Scenario (AS) was a modified VR replica of the identified Accidental Situation (As). The analysis of the identified accident situation resulted in two possible accident types. Since there are many cases of electrocution while working on the scaffold platform, this accident type was also included in the skeleton. A list of correct and incorrect precautions was also prepared for each framed accident with the help of RIF. This was mapped into a detailed storyboard. The prepared DMAS information skeleton for this scenario is shown in Table 3.

5.4 DMAS Based VR Application Development

Figure 3 shows the followed system architecture and its information flow for VR application development. As shown in Figure 3, the first step for developing a VR application representing DMAS was to create all required 3D models, shown in Table 3.

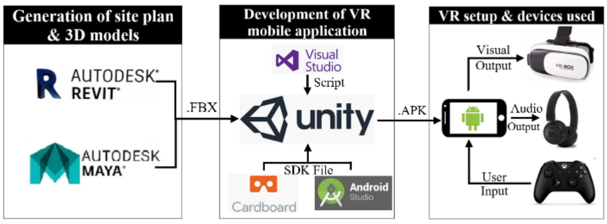

Figure 3. System architecture and technical integration

Autodesk Revit was used for creating models such as under-construction building, transmission tower etc. However, models like a safety net, harness etc., required more flexibility in modeling their shapes. Since Revit was not a non-uniform rational B-spline (NURBS) modeler, which generally helped in manipulating 3D curves and surfaces of any object, it couldn't be used for creating these models. For these models, Autodesk Maya (a NURBS modeling software) was used. After creation, these models were exported into .fbx format

Figure 4. Visual representation MainScene of DMAS

As shown in the second step of Figure 3, these 3D models were imported into Unity where it was navigable. In the Unity environment, all models were located as on-site, so that the overall view of the GameScene (MainScene - Figure 4) could present the prepared Accident Scenario (AS). Animation and user-controlled movement of the character were added to make the static GameScene functional. The dynamics of these models were customized, and conditions were levied on the models, by adding scripts created in Visual Studio using C#. Multiple outcomes for the framed accidents (fall from height, Electrocution, Scaffold Collapse), were also developed in a similar way in various GameScenes. Physics engine, visual effects in the form of Particle System Prefab, and audio effect in the form 3D sound were added to augment the reality quotient of these Outcome GameScenes. The options of correct/incorrect risks and precautions, were empanelled in the form of buttons inside User Interface (UI).

The MainScene was then interlinked with the Outcome GameScene, so that the trainee could be directed to the respective Outcome GameScene based on his responses in MainScene. The Plain visual output of the MainScene was converted in stereo screen format by using Unity Package - Google VR SDK. It was decided to use a smartphone-based VR platform as this is economical to deploy. Android SDK was utilized to process the Unity output for a smartphone-compatible application in .apk format.

Table 3. DMAS Information Skeleton of the accident scenario

Description	A scaffold having a platform higher than 24 feet will be erected. It will be having red safety identification tags with some unprotected platform openings without any fall protection system. A power cable from the transmission tower will be going just above the scaffold platform in proximity to the workplace.
Storyboard (S)	A workforce is going to start work on the newly erected steel scaffold platform. Its tasks include welding and reinforcement fixing. Look carefully and identify the possible accidents and suggest suitable precautions.

Framed Accident (FA)	Correct Precaution (CP)	Incorrect Precaution (IP)	3D Model Required
Fall from Height	Provide edge protection Provide safety net Cover scaffold's opening Wear harness	Do nothing Clean the area Wear safety shoes Wear eyeglasses Wear safety gloves Deny to work	Wooden plank to cover scaffold openings Edge protection Safety nets Harness Under-construction building
Scaffold Collapse	Check for safety-identification tag Call the supervisor	Wear harness Wear safety gloves Work and walk slowly	Scaffold with openings Safety tags
Electrocution	De-energize the cable Wear safety gloves Wear safety shoes	Wear eyeglasses Clean the area	Transmission tower Power cables Safety Gloves Safety Shoes

As shown in the third part of Figure 3, the visual output and audio output of the application were received by Google Cardboard and headphones, respectively, and a gaming pad was used to give user input for controlling the character's movement in 3D world space.

5.5 System Evaluation

Feedback from users was obtained on the basis of their experience of using the platform in order to enable an evaluation of the application. For the evaluation, the user was first introduced in the form of an avatar at a predefined location in virtual space. Within this space, the user explored the site with the aid of navigation options and made informed decisions regarding potential hazards and ways to mitigate it as per options available in UI. The scenario got modified depending on the user response. Figure 5 showed how users could mitigate fall from height risk by selecting the options such as provide edge protection, provide safety net, and provide cover for scaffold openings in UI of the MainScene.

After the user had taken all the precautions to secure the situation, he/she was asked to verify the efficacy of the selected precautions. If all correct precautions were taken for the identified potential risks, then work should progress as planned, with minimal chances of any untoward incident occurring in the virtual space. However, if the user happened to miss one or more of the recommended precautions for a risk in hand, then the user would have faced the accident outcome linked to the missed precautions. The VR accident experience-of typical framed accident (scaffold collapse) is shown in Figure 6.

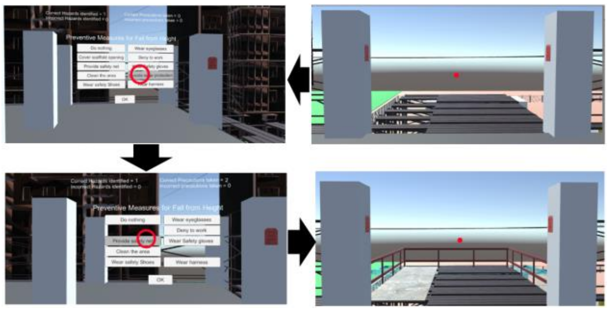

Figure 5. Modification of scenario as per the options selected by the trainee

The scenario presented to the three users had a total of 3 correct, 2 incorrect risk situations, and 9 correct and 11 incorrect precautions. The user responses to the scenario experience is recorded in the four outcomes:

- Number of correct risks identified
- Number of incorrect risks identified
- Number of correct precautions taken
- Number of incorrect precautions taken

This prototype application was evaluated based on feedback collected from three students of the civil engineering department. Each of these students had already worked in a construction site before and had taken a course on construction safety thereby having an introductory understanding of the safety practices to be adhered to on-site.

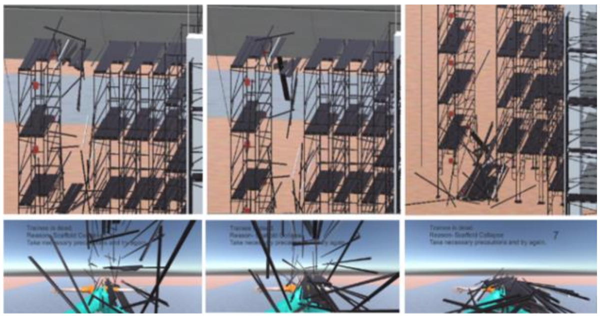

Figure 6. VR experience of scaffold collapse accident

6 Results & Discussions

The results of the training test and the feedback survey are presented in Table 4 and Table 5.

Table 4. User response records of training test

User no	Risk Identified		Precautions Taken	
	Correct	Incorrect	Correct	Incorrect
1	2 of 3	0 of 2	4 of 9	1 of 11
2	2 of 3	1 of 2	3 of 9	4 of 11
3	3 of 3	0 of 2	6 of 9	4 of 11

Observations of Table 4 show that only user 3 was able to identify all risks. User 1 and 2 were not able to identify all the risks, specifically electrocution. The conversation after the training test revealed that these users neglected the electrical hazard near the scaffold as they were not anticipating this. This confirms that though VR could definitely help in visualization it doesn't necessarily improve risk identification ability, as this ability requires site experience as well.

Table 4 also shows that there were many events where even after identifying the correct risks, users had failed to identify the appropriate precautions recommended for the same. An analysis of two similar events post their occurrence are discussed further. User 1 and 2 failed to take two precautions from the list of recommended precautions to mitigate fall from height as listed in Table 3. They missed covering the scaffold openings because they thought wearing the harness and providing edge protection with safety net would be sufficient to ensure safety. In the event of electrocution, two potential sources of this risk were framed. The first one was emanated from the power cable coming from the transmission tower, the second from the welding task assigned to the trainee as per the storyboard of the scenario. User 3 verified the effectiveness of the selected precaution just after de-energizing the power cable, but he forgot to wear safety shoes and gloves which were essential for the welding task.

In the risk scenario of scaffold collapse wearing harness was one of the incorrect precautions chosen by the users. Similarly, for fall from height - safety shoes and gloves were incorrectly identified as a precaution. Committing such mistakes however made the user reflect on his knowledge gaps and raised awareness about chances of negligent behavior in such situations.

The feedback survey in Table 5 evinces that DMAS based VR training significantly enhanced responsible behavior and improved decision-making ability of the user. This is largely because the simulation of the vivid accident scenario gave the user an opportunity to experience the accidents and hence take cognizance of negligent behavior that causes the same in a graphically visual form. Besides this, the experientiality of these virtual scenarios helped to create a deep and long-lasting impression on the user, thereby enhancing their decision-making ability in the face of such situations at the site in future.

Further, the survey evinces that the VR training boosted the user's confidence and significantly enhanced their safety knowledge and awareness. This can be attributed to the real-time scenario that the platform was capable of simulating, which was crucial to reinforcing the importance of applying the correct precaution and gave the user a chance to witness and realize immediately why his selection of precautions were incapable of mitigating the risk completely. Thus, this platform helped to identify and bridge the gaps in the user's knowledge thus enabling him to make more informed and confident decisions.

The main limitation of the smart-based VR platform was its unpleasant experience as the user felt VR sickness during the test. Despite this limitation, all users agreed that this training would go a long way in helping them to avoid accidents on site and strongly recommended the importance of such training in the future also.

7 Conclusion and Future Work

It was found that of all the steps in the proposed methodology, RIF preparation was the most crucial and time-consuming step. The high level of detail involved in developing RIF enhances its efficacy to identify a sizeable range of accidental situations on-site and also ensures that a high quality of training is maintained. The RIF used in this study is limited to general safety training, but it can be extended to develop site-specific or task-specific training.

Site assessment or analyzing the identified accidental situation is also another vital step. The analysis of the accidental situation should be done rigorously, and all possible outcomes need to be identified and taken into account as it formulates the scope of DMAS information skeleton.

Table 5. Feedback of the users

Questions	User 1	User 2	User 3	Avg
To what extent this training affected your knowledge about safety?	8	9	9	8.7
To what extent will you remember what you've learned a year from now?	9	7	9	8.3
To what extent will training affect your behavior on a construction site?	9	8	9	8.7
To what extent was learning a pleasant experience?	4	3	1	2.7
To what extent, this training improved your confidence in identifying risks on the construction site?	9	9	10	9.3
To what extent, this training improved your decision-making ability?	10	8	10	9.3
Will the training help you avoid accidents on the site?	Yes	Yes	Yes	*
Do you want to have similar training in the future?	Yes	Yes	Yes	*

The skeleton of this study is based on only one accidental situation, but it can be expanded and made more informative by merging various accidental situations of multiple sites thus opening up significant scope for a wider range of training.

The study concludes that the proposed framework made the development process of VR application-based training platform more intuitive, perspicuous, and pragmatic. Moreover, unlike the existing literature on the safety training using VR, the proposed framework isn't limited to this presented scenario, but the same can be further utilized to develop various other scenarios covering all broader aspects of general safety training.

Furthermore, the final product architecture and the prototype VR platform performed well in terms of giving a virtual experience of accidents, identifying gaps in existing knowledge, teaching the immediate applicability and thereby reinforcing the significance of the precautions recommended, and enhancing the confidence of users. However, extended usage may cause VR sickness, and this may be addressed by sophisticated technological improvements.

The DMAS based VR training platform is presently limited to general safety training. This study could be extended to encompass and develop a safety training module for task-specific and site-specific training as well. Further, these DMAS related to task-specific training can be prepared for multi-user environments also. Such environments will enable the participants to play collaborative roles on site and bring the virtual experience even closer to the real scenarios.

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