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A Project Framework to Introduce Virtual Reality in Construction Health and Safety

KEYWORDS: Health and Safety, Virtual Reality, BIM, Workers' Training

Building construction is considered a complex, dynamic and highly hazardous process which embraces many factors that are potentially dangerous to workers. Many studies proved that the improvement of preventive and proactive measures -dynamically included in the building design, planning and construction- could reduce site accidents as well as increase the site productivity.
In this context, process management models and information visualization techniques such as Building Information Modelling (BIM) and Virtual Reality (VR) seem to be devoted to strongly contribute to the advancement of the current safety management practices. For this reasons, the presented contribution starts with a short review of the adoption of BIM and BIM-related digital technologies for risk management together with VR application for Construction Health and Safety which aim to generate immersive environments from which workers can experience safe insights into the way the real construction site works.
The main objective of this contribution is to review existing proposals in this field of construction health and safety as related to ICT technologies, especially BIM and Virtual Reality, in order to propose, at the end, a project framework able to guide future researches and applications on the use of BIM-enabled Virtual Reality for Safety purposes for site design validation and related workers' training.

INTRODUCTION

OHS in building construction

Even now, construction Occupational Health and Safety (OHS) remains a worldwide problem in terms of workplace injuries and fatality statistics as is shown from OpenData 2018 of the Italian National Institute for Insurance against Accidents at Work (INAIL) (INAIL OpenData 2018) with an increase by 1,6% to 20.039 reported accidents and 682 fatal ones.
In this context, what is important is to look at the root causes in order to develop appropriate research and innovative applications able to realistically influence and increase safety culture throughout the project life-cycle, from the design phase to maintenance. Such causes may be inferred from the findings of the "CNCPT 2017 Report" (Activity Report CPT 2017) about safety in construction sector where CNPT has monitored 23.117 construction sites with 48.294 site inspections amounting to 14.987 construction companies involved. The instances of non-compliance in the application of the Italian HS regulation in the aforementioned inspections can be classified as follow in order of decreasing amount:

1. extensive lack of warning signals for the identification risk zones,
2. lack of site personell having specific safety tasks;
3. lack of education in terms of site planning and coordination;
4. shallow risk analysis inconsistent with the specific construction site.

What emerges from this report is an important lack of contents, quality and details in the safety plans with negative safety implications in the entire construction execution that is often delegate to the foremans' improvisational capabilities and their on-site experience. This is also due to the fact that most of those plans are usually provided with a set of instructions in the form of texts or two-dimensional drawings often difficult to be fully understood by site technicians and even more by site workers.
Nowadays, as reflected in literature (Martinez-Aires et al. 2018), there are many proposals that use new models and technologies to assist safety management tasks and, more specifically, Building Information Modelling (BIM) and BIM related technologies seem to be to the most advocated to increase safety performance.
Given these circumstances, the main objective of this contribution is to review existing proposals in this field of construction health and safety as related to ICT technologies, especially BIM and Virtual Reality (VR), in order to propose, at the end, a project framework able to guide future researches and applications on the use of BIM-enabled Virtual Reality for Safety puroposes for site design validation and related workers' training.

BACKGROUND

Increasing use of ICT for safety purposes

Several studies show that Information and Communication Technology (ICT) is often advocated to contribute to safety and risk management. In the following section, an overall view of the research trends and applications is provided:

1. Knowledge based systems: systems and models that take into account data and experience from previous projects in order to support decision making for risk assessment. The integration with BIM in terms of information source (Motamedi et al. 2014) and a digital environment to share knowledge among site managers and engineers has been proposed (Qi et al. 2011).
2. Automatic rule checking: design assessment based on the use of computer programs to asses a design and objects configuration with regulations via specific algorithms and BIM-compliant platform (Eastman et al. 2009) (Getuli et. al 2017).
3. 4D BIM: Construction schedule information integrated into a 3D BIM to increase dynamic visualization of safety procedure.
4. Clash detection: for a safety desing purpose, clash detection is monstly used for construction workspaces planning and management which includes three main research objectives:
    a. generation and allocation of workspaces by using 2D/3D modelling environment able to simulate construction activities' workspaces by using mark-up;
    b. detection of congestion and spatial temporal conflicts in terms of physical conflict among workspaces, temporal overlap between tasks and site congestions;
    c. workspaces conflict resolution by using different approaches as mathematical algorithms, artificial intelligence methods or rule-based heuristic approaches.

All the aformationed models has been classified as Reactive IT-based safety systems that are able to provide simulation virtual prototyping to assist safety risk identification and safety planning.

5. Moreover, due to the fact that construction projects have a habit of changes during the execution phase, a second group of models, classified as Proactive IT-based safety systems have been proposed in literature. These models, somehow integrated with BIM environments, are able to collect real-time data from the sites for futher analysis and give immediate warning or feedback to the site personells. They are mostly used for:
    a. materials, workers and machines' real-time dynamic position tracking during

construction activities;

b. safe machines' navigation in the construction site due to automatic obstacle detection system;

c. positioning sensors such as Radio frequency identification (RFID), Global positioning system (GPS) etc. embedded into Personal Protective Equipments to track workers real time and warn when they enter a hazard space;

d. other proactive technologies such as laser scanning, remote sensing and actuating technology, wireless communication.

6. Virtual Reality (VR) and related technologies that are mainly used for construction education and training which consist of an interactive computer environment able to introduce an external user in a real-time animation simulating the real works. These application can be classified as follow:

a. Desktop-Based VR that displays a 3D virtual world of the construction site environment on a desktop screen without any tracking equipment to support. It relies on the workers' spatial and perception abilities to experience what happens around them. Most of the tasks can be conducted through the use of mouse and keyboard.

b. Immersive VR that relies on the use of special hardware, such as the head-mounted device (HMD) and sensor gloves, to withdraw users from the physical world and provide an environment more immersive and interactive than others techonologies.

c. 3D Game-Based VR. It is an engine able to produce a computer-based video game that provide a interactive virtual-reality of the site environmt also using a multi-user operating technology.

d. BIM-Enabled VR. BIM-enabled VR relies on the model, emphasizing on the data binding and connections behind other VR categories, to simulate construction processes and operations. For example, BIM-enabled VR allows user to take building design into a 3D virtual environment with all relevant building information, experiencing the BIM model in a virtual environment without the restrictions of peering into a 2D drawings, and actually inspecting the designed space.

e. Augmented reality. It uses sensory technology to provide a live direct view of a physical environment with overlapped virtual information.

All the aformentioned technologies have been used for safety training to improve construction site operation safety.
From the above-mentioned background it has been emerged that, despite of considerable development work, most of their focus has been developed for testing or developing new technologies to mitigate safety risks. In addiction, another knowledge gap is that there are nearly no studies investigating how BIM and VR can be simulataneosuly integrated in real projects for site safey management by using a coherent and linear methodological workflow.
For these reasons, in the following

AN HS PROJECT FRAMEWORK

The research assumption, extensively codified in literature on which the proposed framework is based, is the use of BIM both as a systematic construction management tool and as a data source with the object to fill the role of an input driver for others BIM-enabled tools (IFC-compliant) able to run further site simulation or analysis (e.g. 4D BIM simulation). Furthermore, as regards VR technologies, a BIM-based approach has been widely adopted to develop immersive VR experiences for validation purposes at different project stages (Lin et al. 2018) (Du et al. 2018).
Starting from these evidences, a project framework for planning HS workers' training by using immersive VR, integrated in a coherent BIM-based design workflow -which embraces the design, planning and construction stage-, is proposed. The reason for that is twofold:

a. Design efficiency: a BIM model that stores the information required for the Health & Safety management (site phases, layouts, site paths, risk zones, etc.) together with the 3D building geometry and data, is precisely what is needed to generate virtual scenarios and to plan VR training sessions;
b. Process repeatability: once determined a robust BIM-based framework and workflow for delivering immersive VR training experiences, it can be exentesively adopted and repeated in other real construction projects.

As shown in Figure 1, the proposed project framework is composed of three different macro-phases: (1) building design, (2) construction planning and (3) construction execution that are those of a standard project life-cycle. For each one of them a BIM-process HS-oriented and a VR application is set. Their description is reported below:

- Phase 1: Building design

The standard Building Information

Models (BIMs) -architectural, mep and structural- are first amalgamated into a Federated Model. This model is the one dedicated to being validated in a collaborative multi-user VR sessions in which contractor, project manager together with the design team, virtually walking into the building, will be able to examine design solutions from the different perspectives and requirements on functions, work environments, safety and emergencency signs. In order to be ale to use the BIM model as the basis of the VR Model, the IFC Data Format is recommented; otherwise great uncertainty will ensure as the result of an interoperability bottleneck when passing data from BIM to VR applications.

- Phase 2: Construction planning

Having validated and stored the Building Design, it is time to start with the construction site planning. At this step the BIM is enriched with the information required to simulate and analyse the construction process in terms of site progression. According to the H&S Manager experience, the construction schedule, in terms of construction phases and the activities with the relevant Health and Safety data and site objects (e.g. facilities, machineries' position, equipments, scaffolds, labor crews, site paths, etc.) concur to build a complete Site Information Model (SIM). The given SIM is now ready to being exported in a 4D BIM simulation environment in order to visualize the activities progression proposed. In the same way as the previous phase, the HS Manager and others involved practitioners can validate the site plans for each layout in a collaborative multi-user VR session having an immersive experience of the site environment. This "first-person" experience of the virtual site allows to evaluate its feasibility in terms of position of facilities, equipments and machineries; storage areas, materials' input/output paths and workspaces management and risk zones.

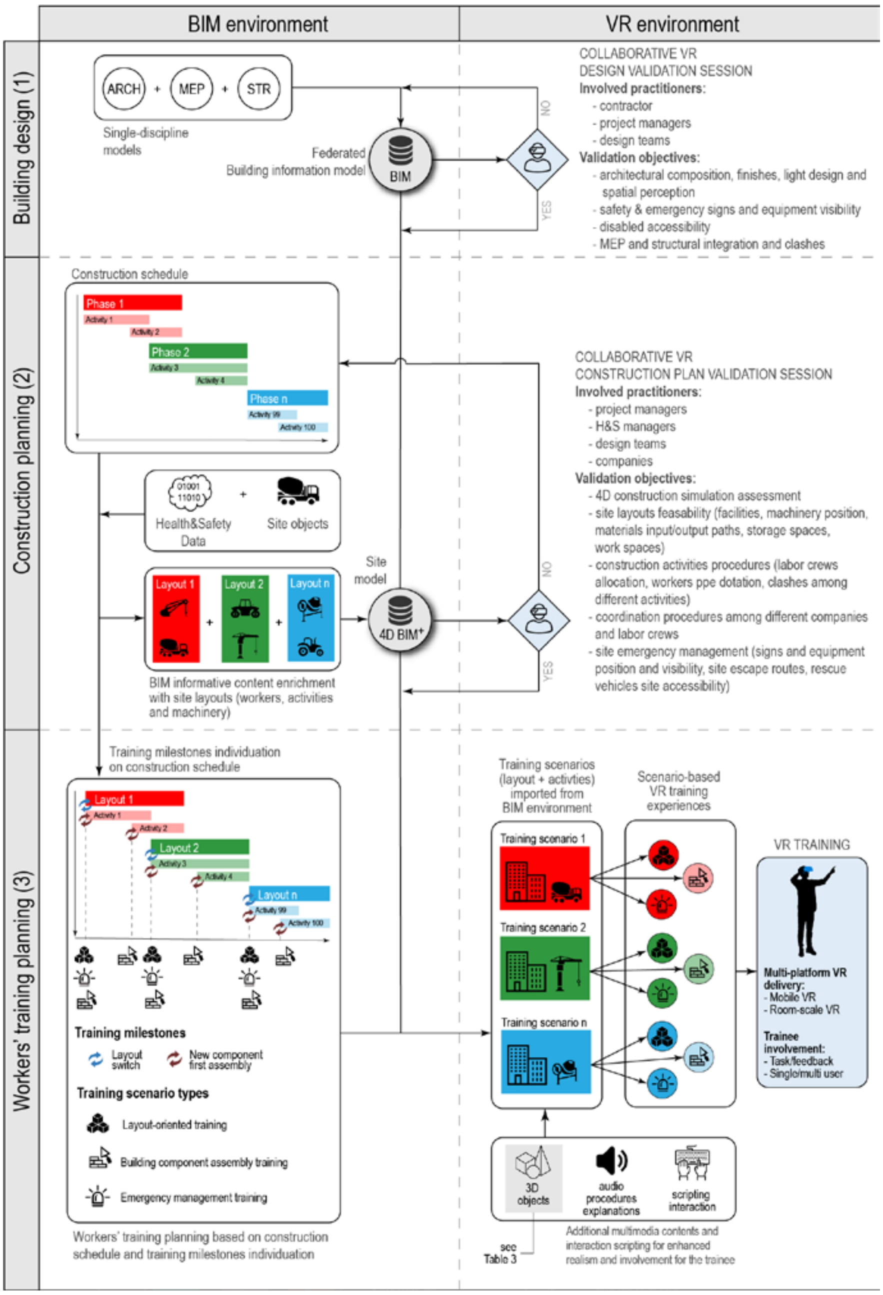


Figure 1: Conceptual project framework for introduction of Virtual Reality in Construction Health & Safety schema

In addition, construction activities -related to specific building objects- should be represented in terms of required workspaces to be constructed in order to be later able to validate safe procedures, personal protective equipments (PPEs) and accidental clashes in a VR site model up to date (see Table 4). An extensive explanation of this approach has been proposed by the authors in (Getuli and Capone 2018). By using this BIM, it is also possible to instantly set and share coordination procedures among different companies and validate site emergency management measures.
Once again, to preserve interoperability, it's crucial to deliver the site information model optimized for VR collaborative validation session in an IFC format.

- Phase 3: Workers' training planning during the Construction execution

At this stage site plans are validated and the project is going to enter in the construction phase. In the proposed framework, the HS manager will use the validated Site Information Model to plan immersive VR training sessions for education and coordination of workers in site.
In the proposed workflow the training scenarios are related to the specific construction site and its time evolution. In fact the input driver of those scenarios is the 4D BIM model and the related site layouts coming from the previous planning phase.
The authors propose three different workers' training typologies with different safety training perspectives (see Figure 2).
According to the proposed training typologies a workers' training schedule can be obtained (see Figure 1). Infact, the HS manager is supported with a simple decision criterion consisting in the individuation of two training milestones upon the construction schedule:

1. Layout switch: when the layout change a VR workers' training session is required;
2. New component first assembly: before the assembly of a building component is performed for the first time in site a VR training session is required.

Once the training schedule is available is necessary to pass to the VR environment to develop the training experiences. In fact, unlike the previous VR workflows in which the VR validation session are usually limited to the first-person exploration of the virtual building, the informative content of the Site Information Model is not sufficient to develop an interactive and realistic immersive experience for workers' training and education. The VR training experience to be effective needs to immerge worker in a vivid, realistic and interactive virtual environment in which he can not only move around but also have interactions with realistic objects, perform tasks and generally be involved in a learning path that drives him to achieving the training objectives. This realism gap in the BIM site model is the reason why the VR model for workers' training should be enriched with extra contents. This is due to the different development purposes between a BIM for site planning and a VR model for safety workers' training .
Infact, while in the BIM approach a low Level of Development (LOD) is sufficient to represent site objects (see Table 1), in

VR Training typologies		
Layout-oriented training	When [milestone schedule]	Before each site layout transformation [layout switch]
	What	-Activities coordination and workspaces management -Workers', materials' and vehicles' site circulation -Facilities and site zones access and usage authorization
Building component first assembly training	When [milestone schedule]	Before every first assembly of a new component [new component first assembly]
	What	-Site-specific and activity-related risks they are exposed to and safey measures to adopt -Workspaces visualization -Labor crew , safety, equipment, hazard and safety spaces
Emergency management training	When [milestone schedule]	Before each site layout transformation [layout switch]
	What	• Type 1: Workers' illness or accident • Type 2: Fire Management • Emergency procedures and equipment position (estinguisher • Escape routes and emergency assempbly area • Rescue vehicles access and circulation paths

Figure 2: VR Training typologies

the VR Model the realism of the virtual site environment and the ways in which the users can interact with its objects is the core issue for the effectiveness of the workers' experience itself.
To better show this difference in Table 2 is reported a comparison of the same views of a site layout in BIM coming from the Design stage and VR environments for workers' training. The images are referred to the installation of a jib crane.
In the authors proposal, there is no reason to force the BIM platforms to reach an hight Level of Development of the site model. It has to be sufficient for a straight VR implementation. The given BIM is infact used as a base reference in terms of machineries position, risk zones identification, storage areas allocation and so forth.

In the following Tables 3-4 a proposal of informative and graphical contents that make up the VR traing scenarios are explanined. Table 3 is referred to the BIM content which is the imput of the VR scenario implementation and Table 4 the addictional contents included in a VR application.

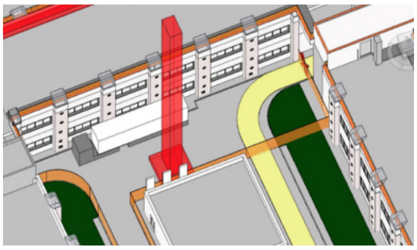
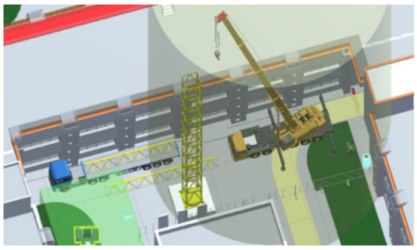
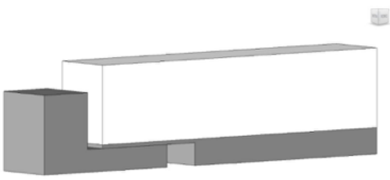
Site layout representation and visualization	
BIM Model	VR Model
	
The 3D geometrical representation and relevant data of the building and its environment. For each phase or site layout, it serves as 3D base static environment with all the information related for the VR scenario.	Site facilities, machineries, workers and any other site objects is replaces in the VR environment to reach a suffiecient realism for a VR immersive experience.
Site objects representation and visualization (e.g. vehicles)	
BIM Model	VR Model
	
• schematic representation optimized for the communication of the relevant informative content during the layout design phase (vehicle dimensions, position, type, time, cost, etc.) • low LOD to keep a "light" workflow and not to affect model performance	• very high LOD of the 3D model to reach the higher grade of realism possible without affecting reproduction performances of the target VR device. (for a smooth VR experience mobile VR needs 3D models with a lower LOD than room-scale pc-based VR)

Table 1: VR Training scenario contents exported from the BIM environment

Table 2

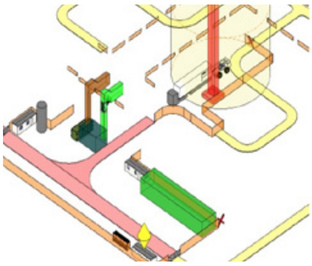
Content	Description
Building and Environment 3D model and data 	The 3D geometrical representation and relevant data of the building and its environment. For each phase or site layout, it serves as 3D base static environment with all the information related for the VR scenario.
Site layouts' 3D model and data 	The 3D geometrical representation and relevant data of site layouts and construction activities in the different phases. It serves as reference for the site implementation in VR. It includes: • Signs or symbolic virtual representation of vehicular and emergency site circulation; • Signs or symbolic virtual representation of storage, work and hazard spaces; • Machinery and equipment (depending on their LOD, they could be replaced with non-BIM 3D objects with enhanced graphical detail for VR realism purposes) • Site fences and barriers

Table 3

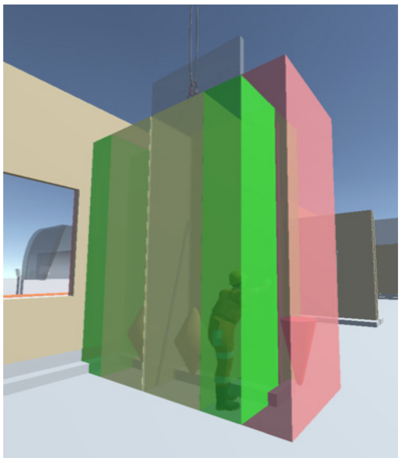
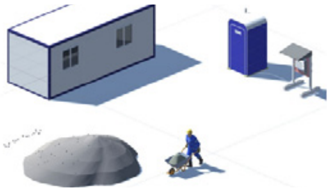
Content	Description
Work spaces 	In the VR scenarios with the simulation of the assembly of certain building component (a panel of a wood structure in the figure), additional virtual volumes and placeholders are positioned in the VR environment for the representation of the work spaces as follow: • Labor crew space (green): the space most likely occupied by workers during the construction activity; • Safety space (yellow): the space that has to remain free during the construction activity for safety reasons and that is occasionally needed to the workers involved; • Equipment space (grey): the space occupied by the equipment needed for the contruction activity; • Hazard space (red): the space with a specific risk related to the construction activity both for the workers directly involved and the possible other workers in the nearby; • Safety (yellow) and hazard (red) spaces symbolic placeholder: used to better spot the presence of a safety and hazard space.
Site workers 	In the BIM model, for each phase and site layout, workers are represented via symbolic placeholders to consider their position during the construction activities. Although this method allows to put the relevant health and safety information without affecting file performance and keeping the workflow "light" on the BIM side, the workers placeholders must be replaced in the VR developing environment with 3D objects with enhanced graphical detail for realism purposes. For this reason, every worker in the VR scenario should be represented in a static or animated way that reproduce the activities in which they are involved. Furthermore, all the VR scenario should be filled in with the actual workforce present in site and with other people outside if they are relevant for the training experience. (e.g. sites in urban contexts, activities carried out in partially operative buildings, etc.)

Table 2: VR Training scenario contents exported from the BIM environment
Table 3: VR Training scenario contents added in an VR application

Site machineries

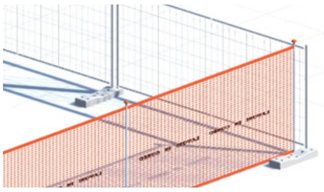
In the BIM model site machinery is represented in its operative position and with a virtual volume of its working space. Usually the BIM objects that stand for them have a rather low LOD and should be replaced in the VR developing environment with 3D objects with enhanced graphical detail for realism purposes.
The replacement must keep the relevant health and safety information from the BIM environment and never lead to a misrepresentation in the position, type, dimension, working space and operational procedures.

Site facilities



In the BIM model for each layout and construction phase, site facilities are usually represented in their current position along with storage spaces and other auxiliary elements. Not always these facilities have a 3D representation, and even in that cases they have a rather low LOD. For this reason they should be replaced in the VR developing environment with 3D objects with enhanced graphical detail for realism purposes. Each element replaced or added (e.g. building materials stocked in storage spaces) must be coherent with the site layout modelled in the BIM environment.

Fences and barriers

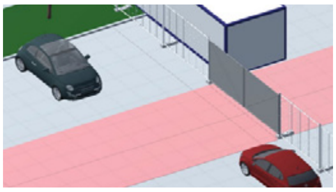


In the BIM model for each layout and construction phase, fences and barriers are usually represented in their current position with symbolic 3D objects or even just with lines in 2D views.
For realism purposes, dedicated 3D objects with enhanced graphical detail should be replaced or added in the VR developing environment in their expected position.

Context element

Elements that help users to understand the environment they are in, during the VR training experience and make the scenario more convincing. Depending on the particular project and site they can be considered as contexts element: trees and vegetation, cars, street furniture, etc.
Except for models used for presentation purposes (renders, etc) or other specific uses, these kind of contents are often not included in a BIM workflow. Nevertheless they are very important to increase the sense of immersion of the VR experience and therefore the effectiveness of the training.

Emergency vehicles

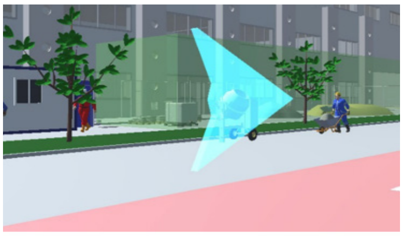


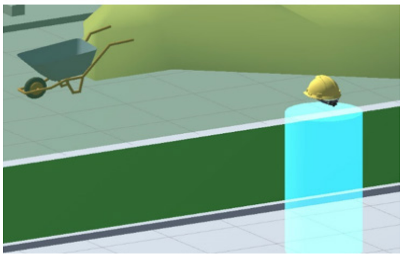
With the aim to train site workers to the emergency management in case of fire and accident is crucial to add in the VR developing environment convincing 3D static or animated 3D objects of emergency vehicles in the position expected during the rescue operations in line with the site vehicular circulation modelled in the BIM environment.

Placeholders

In the BIM model particular hazard spaces or areas for which is important to have specific safety information have been marked with 3D symbolic placeholders.
In the VR developing environment some animation and interaction features are added to these completely virtual elements to better gain the attention of the worker during the training experience.

Virtual auxiliary elements





In addition to the real virtual elements added or replaced with reference to the BIM model of the building site, there are other virtual auxiliary elements that must be added in the VR developing environment during the design of the training experience.
These elements must be designed to help the user to understand what-to-do and where-to-go during the experience and must be clearly visible and distinguished from the representation of the elements of the real environment.
As an example, with reference to the work done for this case study, among them can be included:

- Floating animated blue directional arrows (lead to the point of interest in the scenario)
- Floating bouncing red arrows (mark point of teleport from different levels of the site; used in case of the presence of a real elevator, stair, ladder or as a shortcut to rapidly visit different parts of the site)
- Gates (cylindrical volumes used as hotspot or triggers for interaction with the user; when the user enters the hotspot the construction phase changes along with the site layout)

Furthermore there are additional contentets that authors propsed to implement in the VR scenarios that serves for realism and immersiveness purposes:

- Audio contents: sounds from the site environment and related to the simulated activities; audio explanation of work procedure and other experience support instructions.
- Interaction: scripting of the interaction between the trainee and the site objects (machines, tools, materials, etc.) or with other virtual objects (see Table 4).

DISCUSSION

The proposed model will be tested by the authors in two different italian case studies in order to be validated. In terms of “VR developing technologies” -that were not the objects of such a contribution, the authors refer to cross-platform game engines dedicated to the creation of multimedia interactive digital contents deliverable for many different platforms from PC to mobile devices. Mainly designed for the game development, this engines are broadly adopted also to create interactive virtual reality environments with the combination of 3D models and other multimedia contents from every compatible source. The customization possibilities offered through code scripting have spread the adoption of this engines also far from the entertainment industry and they are more often used for research purposes and complex simulations.
Nowadays, unlike many industry and educational sectors where these engines are used to develop custom VR training experiences, in the AEC industry they are often relegated to project validation sessions. Without prejudice to the importance of the validation purposes for wich already exist commercial user-friendly VR platform, in the authors opinion the adoption of these engines is essential to develop the needed training contents in terms of realism and interactivity.

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