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Factors for the Automation of the Creation of Virtual Reality Experiences to Raise Awareness of Occupational Hazards on Construction Sites

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Abstract: Two of the differential characteristics of the AECO sector (architecture, engineering, construction and operation) are barriers for the mass creation of training materials for its workers. On the one hand, the workplace is unique and changing over time; on the other, the aging trend of its workers and the unattractive nature of the industry for new generations of professionals. These two problems can be tackled by virtual reality technologies, which allow the agile creation of all kinds of scenarios, while their current technology may be attractive to young people and intuitive for everyone. This work shows the results of an investigation that seeks to provide automated tools based on virtual reality experiences to support learning in occupational risk prevention. This objective is part of the development of a culture for prevention, which allows the treatment of the human factor, with all its complexity and casuistry. The proposal includes the development of a process and tools that allow replicating the specific scenario where the work will be carried out, incorporating risks and probable incidents, systematically establishing cause-effect relationships, incorporating a narrative (storytelling) that provides emotional meaning to users and Lastly, the creation of a workflow that facilitates the agile development of these virtual reality experiences for each specific work.

Keywords: prevention culture; virtual reality (VR); storytelling; AECO industry; BIM; emerging technologies in construction

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1. Introduction

The construction industry (AECO—architecture, engineering, construction and operation) suffers of many difficulties and obstacles to mitigate its accident rate, one the highest among the different sectors and now growing again after some decades of certain stability [1]. This seems to be due to its very nature, with specific risk factors in the routine tasks of its workers and close interaction with heavy machinery [2]. Two of these differential factors are, compared to other manufacturing industries: (a) the workplace is also the final product of the job, so the workplace is an unique location (and most of the times, an unique final product), and also a changing location as the work develops, being precisely this the purpose of the job (in unlike, for example, the automotive industry, wherein a factory with an assembly line, the same products are produced in large quantities) [3,4]; (b) construction is experiencing a growing aging population, after firing most of its younger workers during the economic crisis of the past decade (due to the financial crisis of 2008, because of excessive risk-taking by banks, combined with the bursting of the United States housing bubble), therefore, the challenge for the construction industry in this regard is how to attract young people and how to reskill senior workers [5,6].

The first of the factors implies difficulties for the incorporation, maintenance, and verification of standard and massive security measures, which must be supervised at all times, in contrast to those other workspaces that remain stable over time, such as offices or assembly lines in factories where machinery is well controlled due to the restricted and allocated space where they operate, for example [7]. The second factor has two significant consequences: first, the aging of people extends to the own activities and tools of the construction sector, thus making it difficult to adopt innovations that usually would come hand in hand with generational change; second, once the crisis has been over and the economic recovery has begun, this same aging is now making construction less attractive for young people, which complicates the hiring of new labor, something even worser if it is required qualified and prepared people according to the most recent construction skills, such as BIM, for example [8,9].

A culture of prevention (CoP) is the set of attitudes and beliefs shared by all members of a company about safety, health, risks, accidents, and prevention measures, with a proactive look, with commitment and responsibility in safety and health issues [10]. CoP is built by changing unsafe attitudes and behaviours for safer routines and a permanent attitude of avoiding dangerous situations for oneself and others, that is, by promoting a much clearer awareness and education towards risk reduction [11]. To achieve this purpose, virtual reality tools should facilitate the automate creation, modification and adaptation of the changing scenarios of the building sites. The modular and multilayer features of the technology fits very well with these requirements, but are also key to adapt the heterogeneity of workers in the construction sector, which, according to several authors [12–14] are associated with their roles, sensitivities and profiles, depending on their level of responsibility, emotional situation (aspects associated with personal problems; moods, psychological states, fatigue, family issues, stress, among others, that could distract you from your work) and time when they should perform each assigned task. The solution should also facilitate the continuous awareness and learning of workers, contributing to a smooth transition towards the digitization of the sector and promoting the transfer of knowledge between generations, thus helping to reverse the aging trend of the industry (because technologies and digitalization could make the sector more attractive to young workers) [15,16].

Although VR and gaming for simulation and training in construction and other industries are becoming common, work is focused on the development of specific experiences (in terms of objectives and scenarios developed). Various levels of realism or levels of difficulty in virtual experiences have been implemented [17–20]. In this context, the challenges of virtual and augmented reality for the construction sector focus on real-time integration with sensorization elements, automation in the generation of virtual environments, modification of virtual models in real-time and during execution, multimodal human-computer interaction, multi-user and multi-device capabilities, developing a roadmap for improving competencies with VR/AR, developing data exchange standards, among other aspects [12,21].

Based on these points, this work shows the preliminary results of an investigation with the aim of developing virtual reality tools and procedures to support the creation of learning and awareness contents in occupational safety and health (OSH). This objective contributes to the development of a culture of prevention (CoP), by providing customised resources for each worker and building site, that is, it implies a medium and long-term measure, which contrasts with the protective equipment that must respond in real time (personal and collective protective equipment, PPE&CPE, alarm systems, in-situ supervision of prevention technicians [22]). Therefore, it is specially related to the human factor, with all its complexity and casuistry depending of each task, the different environmental conditions, the group relationship, collaborative work and profile of the individuals [23].

This work reviews the intersection between the current OHS (occupational health and safety) training methodology with the possibilities of virtual reality, through a series of elements identified as key to advance towards a personalized solution that actively involves workers in their learning, promoting automation in the creation of these VR experiences, and the use of narratives (focused on emotional content). The developments shown are focused on building projects but can be applied to other types of construction projects. Figure 1 shows the stages of research: (1) background; (2) conceptual proposal; and (3) results.

1. In the first stage, the background, a literature review was carried out, where the current OHS training, traditional methods, strengths and weaknesses are studied; and evolution and characteristics of virtual reality, with a focus on tools and fit for the needs of the construction sector. The search was carried out in the Web of Science and Scopus libraries, together with the incorporation of technical reports and web-site from recognized entities in the area. The following search topics were considered: OHS in construction; construction safety; OHS training; virtual reality for training; and virtual reality in construction sector.
2. In the second stage, conceptual proposal, key aspects were addressed to channel virtual reality towards the awareness and learning of workers; and
3. In the third stage, results, the application examples of different functionalities of virtual reality and their contributions to creating a culture for prevention.

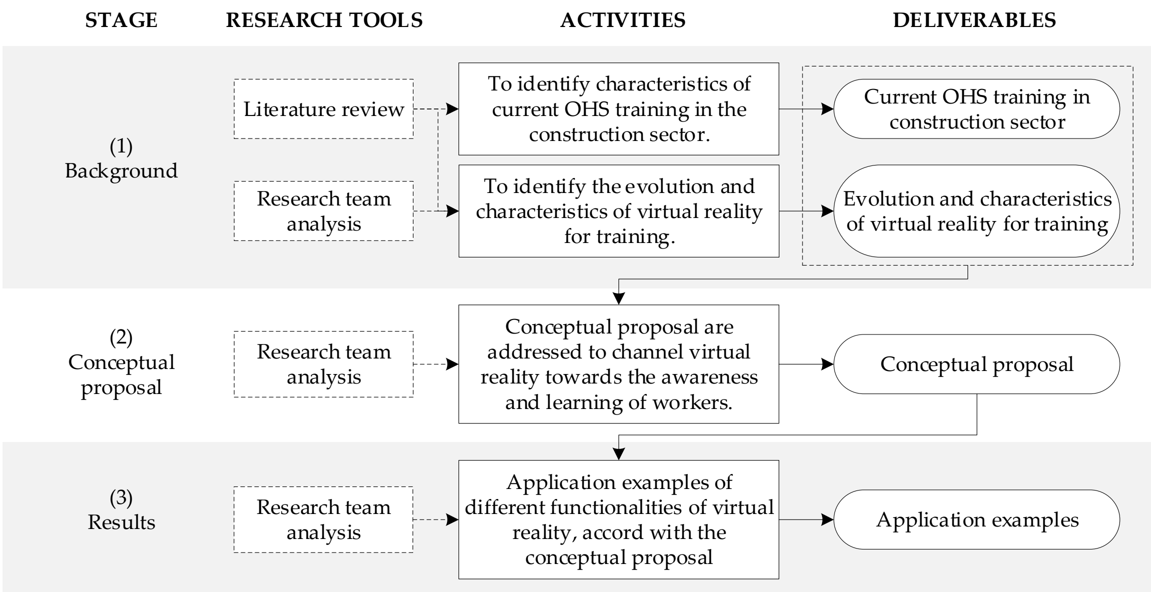


Figure 1. Research methodology.

2. Background

2.1. Occupational Health and Safety (OHS) Learning Processes

Currently, training for different areas of the construction industry is mostly based on traditional content, primarily designed to ensure compliance with legal regulations, with a format of notes or textbooks, according to traditional methodologies, face-to-face classes where safety topics are described, for example, what are and how to use the protective equipment, and an evaluation questionnaire is passed. These forms of teaching have been criticized, mainly because they fail to ensure that workers acquire the content in a meaningful way, and neither do they succeed in generating culture and awareness of safety and responsibility [24]. In some other cases, there is multimedia and online complementary material, which makes classes more flexible and opens the door to many other possibilities. This multimedia material is usually videos of the construction site, cartoons of accidents, or games (e.g., identifying accidents and/or safety problems in a photograph or cartoon). This material, although it seems to be better than theoretical classes and traditional methods, does not represent a significant improvement in teaching; the cartoons are far removed from reality, and the worker sees them from a very distant role [25].

The most powerful format for an effective training of workers continues to be the practices carried out in specific physical places, representing building sites almost indistinguishable from the real ones, where they can see and practice the way to carry out certain tasks and procedures through operations practically equivalent from professional practice [26]. For OHS training, these practices provide particularly meaningful learning, as there is naturally a great difference between knowledge about personal protective equipment (PPE) when is worn, mounted, used and dismounted, compared to whether you only read or listen to its description [27]. However, these practices require an infrastructure that is costly in time and money, meaning that not always fit all types of works and needs and, additionally, they are not flexible enough to update themselves quickly to the requirements in the acquisition of upgraded OHS skills for new tasks. Therefore, it is difficult to massively build these scenarios. Multiple scenarios would have to be built to address the different typologies of construction projects, a solution that is not economically viable. In addition, although in these real scenarios the worker performs the tasks and has the real potential (in a controlled manner) to suffer an accident, multiple variables that also affect the generation of an accident, such as the behavior of other workers, factors inherent to the dynamics of the construction site, among others, are complex to replicate there [28].

It is important to emphasize that the learning process will be more meaningful and effective as the person internalizes knowledge beyond logical reasoning, that is, as it evolves from theoretical and declarative learning to procedural learning, given by the practice. Figure 2 shows how practice is essential to reduce task completion time but, more importantly in terms of prevention, to avoid loss of skills in the development of work, which is more severe depending on the learning phase in which the worker is. The X-Axis shows the number of practice trials, whereas the *Y*-axis shows the time needed to complete each task. As you invest more time practicing, you can significatively reduce the time to complete the task (for example, when learning languages or riding a bike). However, if you interrupt this practice, then you increase again the time to complete the task, especially if you are still in the first stage of learning, more theoretically and not yet incorporated into all our senses. This process is repeated in the different stages of learning a task (and thus acquiring the skills). This implies that the solution to be developed for the safety training of construction workers should encourage the repetition of prevention practices to stimulate the strengthening of good habits, such as the continuous use and proper care of PPE [29].

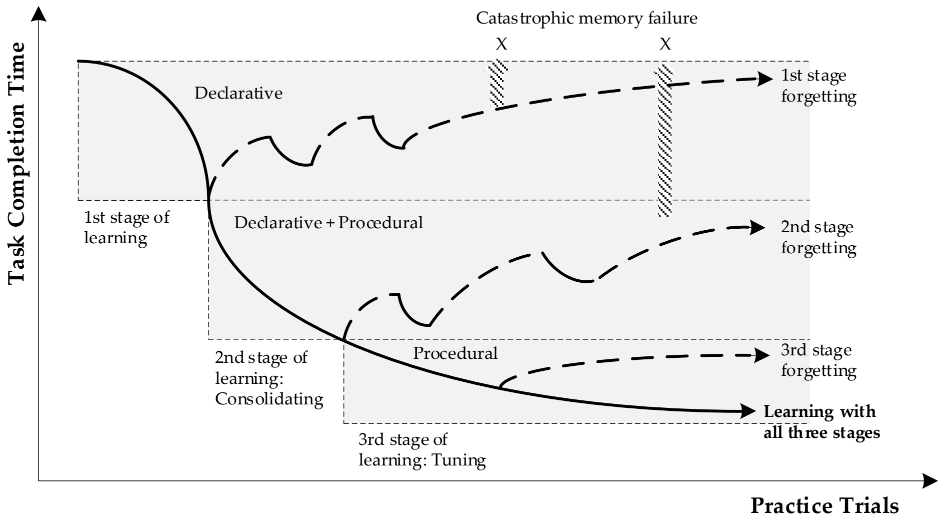


Figure 2. Loss of skills according to three stages of learning and lack of practice. Adapted from [8].

As a last element to consider for the design of a learning resource, it should be pointed out that two obstacles for training are both the frustration of the workers when they face a knowledge that they perceive as far from acquiring, as well as its opposite, the boredom, when the activity to carry out is so easy that it does not arouse their interest [30]. This difficulty was addressed by Csikszentmihalyi, with what he called the "flow channel", as described and illustrated in Figure 3.

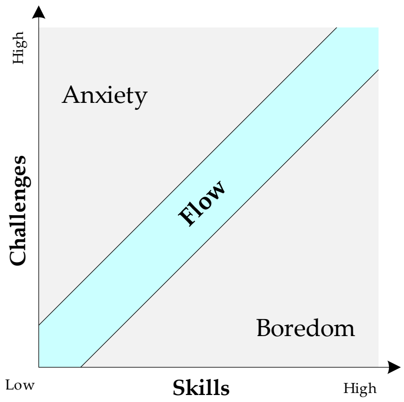


Figure 3. Flow channel according to Csikszentmihalyi. Adapted from [30].

People can be motivated if they move in that "flow", a balance between a challenge not unattainable, given the participant's abilities, but without being so basic that it is not stimulating. Therefore, the level of learning activities should be carefully designed to capture the attention and interest of the worker, and avoid feeling expelled from the subject. As it is immediate to deduce, this process must be gradual to increase the difficulty of the tasks as new capabilities are acquired and consolidated.

In view of all these criteria, current resources and training methodologies for OHS are insufficient to meet the increasing complexity of construction operations and the desirable expansion of the industry. There is a need to modernize current training systems to adapt them to the ongoing demands of the profession, taking advantage of the potential of the emerging technologies that are available [31].

2.2. Virtual Reality in Construction, the Next Level in the Building Site User Experiences

Virtual and augmented reality (VR/AR) technologies have experienced a renaissance at a commercial level, going from being minority laboratory and showroom technologies to mass and portable consumption devices, strongly linked as immersive visualization systems for the entire digital ecosystem already deployed in the architecture and engineering offices [32].

Although the history of these technologies goes back a long time (1950s for some, twenties of the last century for others), it is in the last five years that it has managed to reach the industry and the general public on a routine and massive scale. As can be seen in Figure 4, some of the key catalyzers seem to be the miniaturization (therefore, portability) of the devices (Oculus Rift glasses first, HTC Vive later), the higher memory, calculation and data transfer capacity of both graphics cards (GPU) and processors (CPU). Similarly, at the software level, it has also been essential the ability to handle three-dimensional scenarios and their interaction in real time, at highly realistic levels, achieved thanks to the evolution in rendering and human-computer interaction technologies (HCI). This has a lot to do with CAD and animation technologies developed for engineering and architecture, as well as multimedia companies in a broad sense, including tech providers for film and television, but is much more tightly related to the video game industry, as the main driver [33].

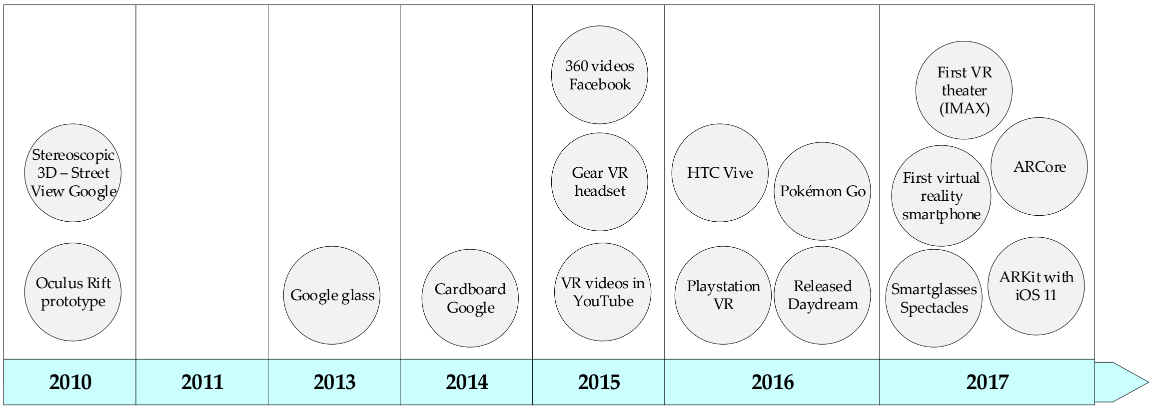


Figure 4. Evolution of virtual and augmented reality during the last decade. Adapted from [33].

Thus, it is important for this study to emphasize the following characteristics of VR [34–36]:

- At the information level, it allows the creation of (hyper) realistic, and therefore, three-dimensional scenarios with textures, lighting and human perspectives, in line with the most complete CAD features;
- At the visualization level (sensory experience), it facilitates the immersion of the user (360°) in such a scenario (extensible to the auditory and even haptic experience);
- At the interaction level, it provides a response in real time, equivalent to video games and, more broadly, to field practices and experimental tests;
- In addition, and finally, at the content level, it allows the incorporation of different layers of data and physical engines, with different modes of representation: from the aforementioned 3D scenarios to hypertextual messages enriching the objects observed, also in accordance with available features in the video games.

When combined with the building information modeling (BIM) [37], virtual reality shows new ways of operating with immersive displays to visualize, review, and modify virtual projects for all phases of the construction cycle [38]. This kind of potential had already been anticipated before the year 2010, in some articles prior to the maturity of the technology, including the review of aspects related to risk prevention [39,40].

The advantages of virtual reality for construction safety training have been explored by several authors. For learning the use of construction machinery, virtual reality makes it possible to realistically simulate different types of machinery, and to train workers in their use and good safety practices [41–44]. In addition, it has made it possible to study the posture of workers when performing different tasks, evaluating their behavior, and obtaining conclusions for improvement [45–48]. Different authors have carried out virtual reality experiences to training workers. In general, the experiences aim to make the worker identify risks and/or have accidents in first-person, in pseudo-realistic environments of the construction site. Gamification elements are incorporated to capture the user's attention and challenge them to complete objectives [49–54]. Other studies have explored the study of emotional factors in user in a virtual reality environment, measuring the impact on the sensations experienced by the worker [55–58]. In this general context of virtual reality developments, patterns are identified: studies focus on specific scenarios, with different levels of realism (from basic to more advanced levels), with limited sets of simulated accidents. Although the methods for the development of virtual reality experiences are detailed, their replication is complex due to the absence of systematic implementation methods and rapid developments. In addition, aspects of emotionality and the incorporation of multiple variables that affect safety are not considered (VR simulations generally focus on the accident itself, not on the aspects surrounding its occurrence). Because of this, aspects associated with the rapid development of these experiences, the consideration of multiple variables, automation in the generation of virtual reality experiences, data standardization, among other aspects, are challenges that need to be improved for the massification of the use of these methodologies and technologies [12,21].

3. Conceptual Proposal

The proposed solution to provide learning and awareness contents for the prevention of occupational hazards can be broken down in different virtual reality components that are already being used for other purposes.

The first key benefit of virtual reality is the ability to create realistic environments, in order to:

1. Replicate the specific scenario where the work is carried out, to familiarize all workers prior to joining the building site, and in as much detail as necessary, at the level of:
    - tasks to be carried out, their location and schedule;
    - required displacements, both to undertake the task itself, and to stock up on tools, machinery and materials, and for the consultations or reports that must be made;
    - realistic incorporation of the collective protection equipment (CPE): fences, nets, signals, etc., and its evolution as the work progresses;
    - realistic incorporation of personal protective equipment (PPE): helmet, vest, boots, goggles, gloves, harness, and verification that it is being used properly;
2. Incorporate risks and probable incidents, such as:
    - falling objects, movement of heavy machinery, electric shock;
    - sliding from heights, stumbling over uneven terrain;
    - landslide, geological unforeseen;
    - weather conditions, rain, sun, wind, even earthquakes;
    - unexpected behaviors of other workers;

Therefore, this type of experience allows the training of workers according to their different responsibilities and tasks, considering the global environment of interaction in which they move, without exposing them to any risk to health and safety, and being able to incorporate all kinds of events, real or fictitious, such as a flood, in a programmed and artificial way. Note that these types of phenomena are significantly more complex to deploy, if not impractical, in real installations.

The first point is directly linked to the progressive evolution of the BIM ecosystem. On the one hand, the 3D dimension becomes increasingly sophisticated to recreate the realistic scenes of the work, which can be directly translated as a virtual reality experience [59]. On the other hand, the BIM 4D dimension allows the evolution of the work and its resources to be monitored over time, which is also to be expected to have a direct connection to its interactive and immersive visualization. With this foundation, a virtual training center equivalent to the physical one can be designed by incorporating the prevention elements, which are elements of the same nature and characteristics to the BIM objects. Figure 5 shows how in a BIM environment it is possible to classify the level of risk associated with the construction of the different elements of a building.

The second point requires programming, a code not much different from that used for video games and specialized platforms, with functionalities that allow the incorporation of risks through development at a high-level programming level, through environment parameters and menus, or through low-level languages, writing lines of code. The choice of one or the other will depend on the type of demanded casuistry [60]. Figure 6 shows an example, where the player falls when interacting in an area without collective protection elements (safety fences).

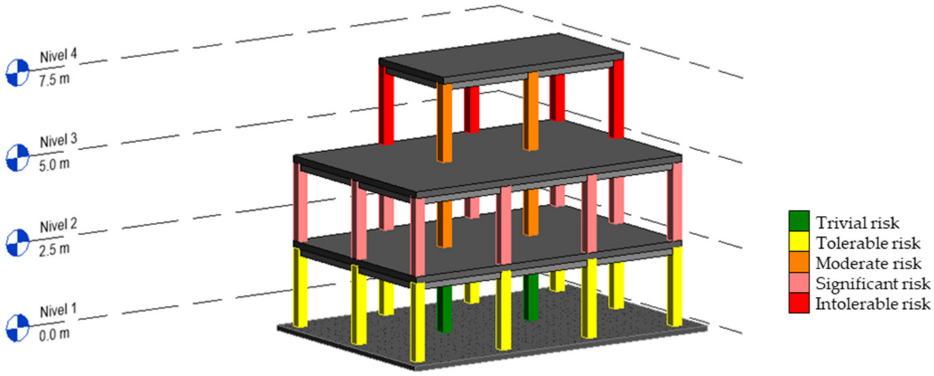
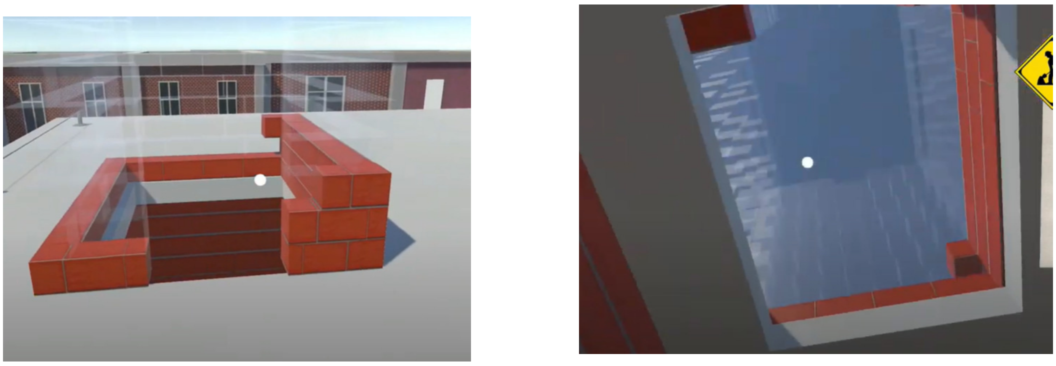


Figure 5. Classification of the level of risk associated with the construction of building columns in Autodesk Revit.



(**a**) (**b**)

Figure 6. Programming of interaction in unsafe area (**a**) unsafe area without protection; (**b**) player's fall.

These developments naturally lead to the gamification elements of the experience, such as rewards (completing the required tasks in the required manner and time) and penalties (loss of health or agility when the accident occurs), which can extend to those of video games (score, time, achievements, medals, etc.) [61].

When dealing with these challenges at a functional level, it quickly becomes necessary to have new elements related motivation and progressive acquisition of skills by workers, as the main interest of the authors of this work [34]. These elements can be synthesized in the following three: the programming of cause-effect relationships, as the core of prevention mechanisms; the use of storytelling to keep the user's attention; and, finally, the automation of the entire process, to simplify the creation of many and progressively much more complex virtual reality learning experiences [62]. The combination of all these elements completes the proposed solution for a virtual training of workers in OHS:

1. The systematic establishment of cause-effect relationships, linked to the technique of the cause tree to investigate accidents [63], extensible to the consequences to be highlighted during the training experience, such as, for example:
    - injuries from a fall that can lead to a limp;
    - loss of visibility if smoke is produced due to fire;
    - worse precision in the user's movements if the worker is fatigued or affected by a high temperature;
2. The incorporation of a narrative (storytelling) that provides emotional meaning to the users, that motivates them to develop and run the experience in the best possible way. This element not only results in the improvement of their skills, but also opens up a wide range of possibilities depending on the type of training required, the profile of the worker and the experience of their colleagues. Narratives are an essential part of

informal learning methods at work [64], and can help more effectively channel all of the group's accumulated knowledge;

3. The creation of a workflow that facilitates the agile development of these virtual reality experiences for each specific work, as a precursor to the automation of these experiences. On the one hand, this flow facilitates the organization of tasks for designers and programmers who must create each specific experience, while, on the other hand, it defines the requirements for the design and implementation of platforms that automate the entire process, which would speed up the creation and the deployment of this training material to all kinds of prevention technicians without the need for programming knowledge.

The following section shows some results obtained considering each of these design points. The development platform used has been Unity3d® [65], although alternative tests have also been carried out on Unreal Engine®, with not significant differences with regard to the research goals. The first generation HTC Vive™ [66] glasses have been used for virtual reality visualization.

4. Implementation Results

4.1. Replica of the Specific Site Where the Work Takes Place. Import Processes and Photorealistic Recreation

Traditional CAD packages such as Autocad [67], 3D Studio Max [68], Blender [69] among others have photorealistic representation through their layers of materials, textures, lighting and visualization in conical perspectives simulating the behavior of real cameras. Many of them facilitates the edition of the camera movements and paths to simulate visits (walkthrough animations) that, for the construction sector, represent virtual walks inside buildings or infrastructures. All these functionalities are also found in the BIM ecosystem packages (Revit [70], Archicad [71], Allplan [72], Lumion [73], Bimsync and many others), which are usually complemented by stereoscopic representation for visualization using virtual reality glasses and CAVEs.

A first use of Unity3D® responds to these basic features: importing of a CAD or BIM geometric model of the building site and its enrichment through several properties. That is, the assignment of materials (as shown in Figure 7) and inclusion of complementary objects (neighboring buildings, vegetation, work tools, etc.). In the implementation results shown below, data from a real building were obtained. This is an office and laboratory building of the Universitat Politècnica de Catalunya (Spain). It consists of four floors and one subway floor, designed in reinforced concrete. The BIM models contain geometrical information, materiality data, and construction process data. Once in the context of virtual reality experiences, these materials acquire two uses: (a) visual, for aesthetic purposes; and (b) physical, for motion simulation and object interaction purposes. In VR and unlike CAD/BIM packages, the user is able to interact with the environment and to respond according to a programmed physical engine. As an example, users cannot pass through walls but could move a fence or net depending on its consistency and anchorages.

On the other hand, the use of additional objects to those traditionally used in BIM/CAD packages also has a dual purpose: (a) aesthetics, such as vegetation and people in the renderings of buildings; (b) functional, for the learning objective, in this case the interaction of the user with the work elements attending to an adequate OHS, which directly refers to the use of CPE and PPE. For example, Figure 8 shows a light alert, which indicates a danger zone in the worker's path through the virtual environment.

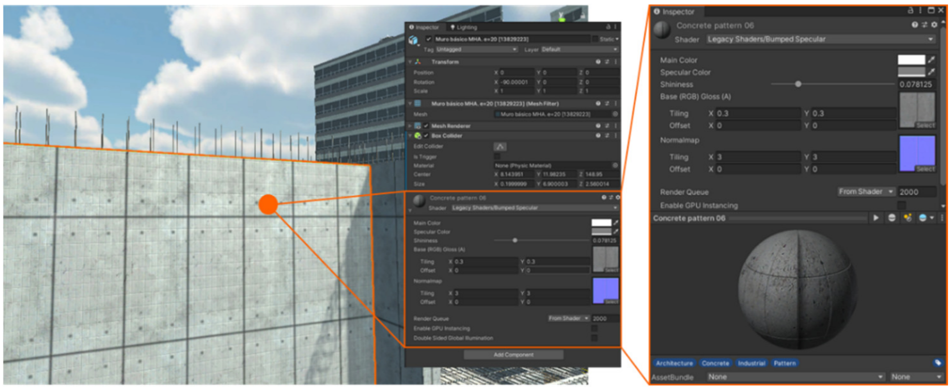


Figure 7. Selection of materials in Unity3D® (Unity Technologies, San Francisco, CA, USA) with their corresponding textures.

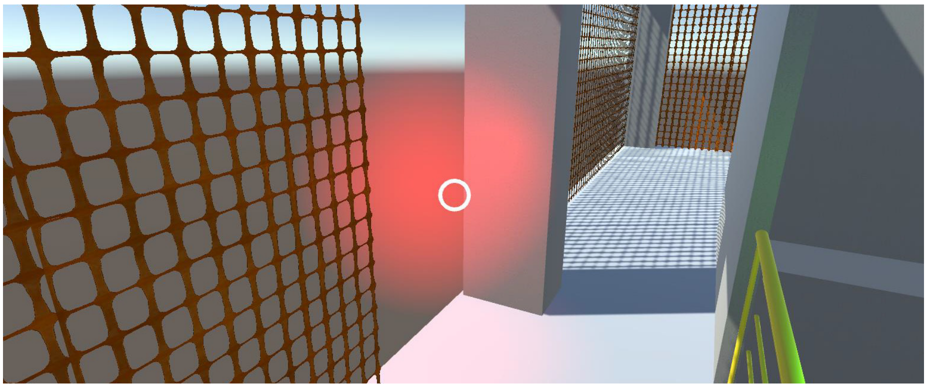


Figure 8. Recreation of a risk due to a defect in the maintenance and supervision of safety nets (CPE).

The incorporation of cameras and lighting, equivalent to design software, is an important element for virtual reality experiences, highlighting two relevant aspects: (a) it is common to select the camera in the "first-person shooter" (FPS) format, according to video game terminology), which has a direct impact on user experimentation through the eyes of the protagonist, which is key to enhancing the immersion and worker involvement in the experience; (b) although lighting appears to be an additional photorealistic supplement of no particular importance, note that it is related to a set of risks that deserve separate attention, such as glare from the sun or, in opposition, falls and accidents due to poor visibility, as shown in Figure 9.

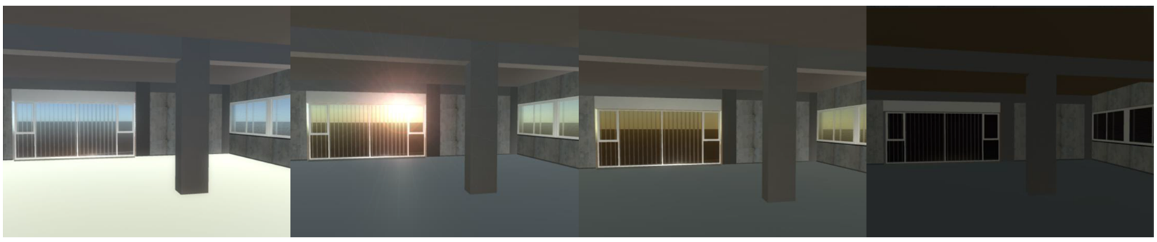


Figure 9. Lighting, which can carry associated risks such as changes in light, from glare to darkness, hindering adequate visibility.

4.2. Initial Workflow

To formalise the above steps, an initial workflow can be defined by combining the BIM/CAD (building information modeling/computer-aided design) models and objects with gamification elements, according to the following sequence (described schematically in Figure 10). These steps are to:

1. Import the building model from 3D Studio/Revit or similar CAD/BIM packages;

2. Add the camera (FPS) for the character carrying out the experience, in this case a worker to whom it must be taught the tasks to be performed and their related dangers;
3. Add materials, textures and lighting, as well as construction site objects (pallets with materials, machinery, stairs, etc.), and even ambient sounds (especially machinery noise);
4. Add CPE: fences, nets, signs, etc;
5. Define and program the hazards to train the worker (falling objects, tripping, etc);
6. Encodes the interaction of the workers with the building site, objects and hazards;
7. Add gamification elements such as worker health that decreases if an accident occurs (penalty), and a score based on their achievements (reward);
8. Compile for virtual reality devices (HTC Vive, Oculus, Cardboards, smartphones/tablets).

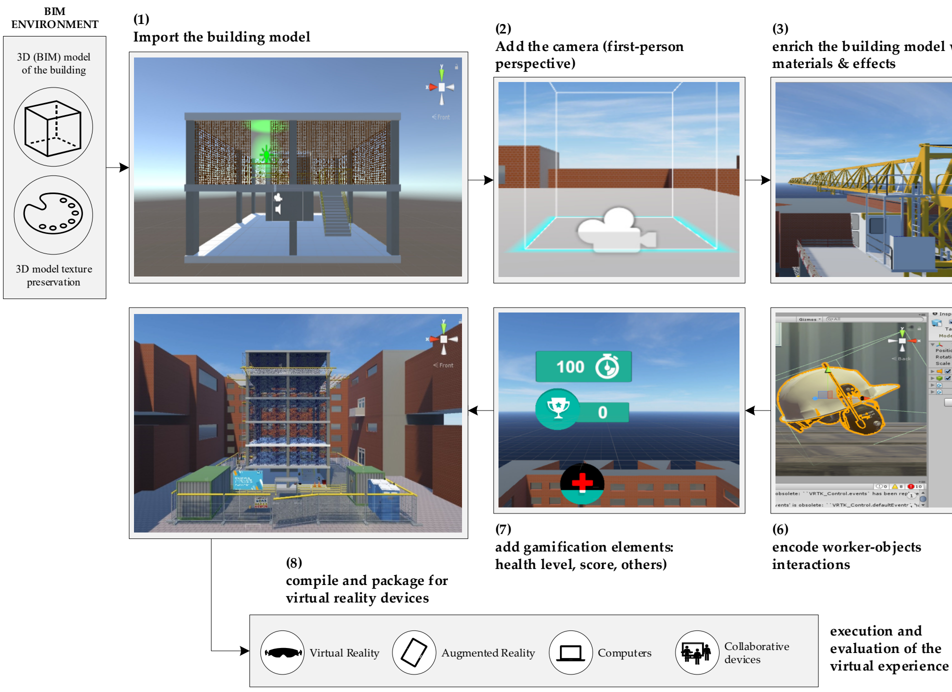


Figure 10. Basic workflow for creating virtual reality OHS experiences.

The technological tools for the implementation of the workflow and the development of virtual reality experiences are shown in Figure 11. Tools from BIM environments (Autodesk Revit), general 3D modeling tools (Autodesk 3DS max and Sketchup), scenario generation and interaction in virtual environments (Unity 3D and Microsoft Visual Studio), and the subsequent user interaction, through various devices (HTC Vive, Oculus, Cardboards, smartphones/tablets) are linked). In addition, Table 1 shows the details of the tools used (hardware and software).

This whole process can be extended to several types of construction workers, using the same workflow and technological tools. A significant profile is that of the prevention technicians, who require a slight variant in approach. Their mission is not to avoid risks for themselves, but for other workers. They must identify the risks, label the spaces and machinery, verify the installation and correct use of all the CPE and PPE required by the area and each worker. A virtual reality walkthrough can be built replicating what a site visit would be for inspection of the OHS measurements. This VR experience can be adapted as tasks progress and the site changes, as prevention measures also evolve with work schedule. Figure 12 shows the workflow associated with this process.

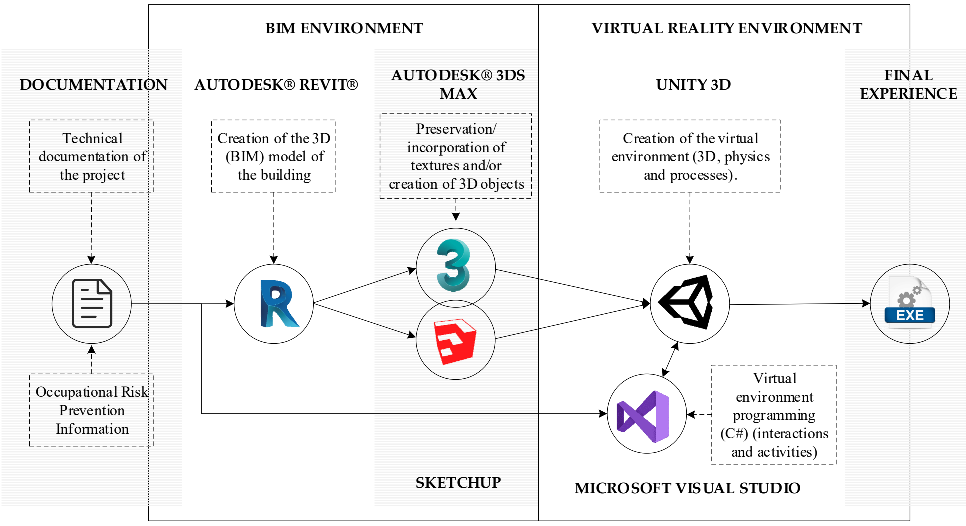


Figure 11. Tools for the development of virtual reality experiences.

Table 1. Technical details of the tools used.

Tool	Technical Specification
Laptop PC	- Model: Dell Latitude E5450 (Dell, Rondrick, TX, USA) - CPU: Intel Core i7-5xxx (2′6 GHz, 4 MB) (Intel, Santa Clara, CA, USA) - Display: 1366 × 768 Pixels (14”, 16:9) - Memory: DDR3L-SDRAM, 8 GB (max 16 GB) - Operating system: Windows 10 Enterprise (Microsoft, Redmond, Washington, DC, USA) - Graphics: Intel® HD Graphics 5500 (Intel, Santa Clara, CA, USA), NVIDIA GeForce 840M (6060 MB) (Nvidia, Santa Clara, CA, USA)
VR glasses	- Model: HTC Vive - Display and resolution: OLED 2.160 × 1.200 pixels
Autodesk Revit	- Type: BIM modeling software - Version: Autodesk Revit 2019, educational version - Developer: Autodesk - Country: USA
Autodesk 3Ds Max	- Type: 3D animation and graphics creation software - Version: 2018, educational version - Developer: Autodesk - Country: USA
Sketchup	- Type: three-dimensional (3D) face-based graphic design and modeling software. - Version: Sketchup 2019, v19.1, WINDOWS - Developer: Trimble Navigation - Country: USA
Unity 3D	- Type: game creation system - Version: Unity 2019.4 - Developer: Unity Technologies - Country: USA
Microsoft Visual Studio	- Type: integrated development environment - Version: 2019 version 16 - Developer: Microsoft - Country: USA

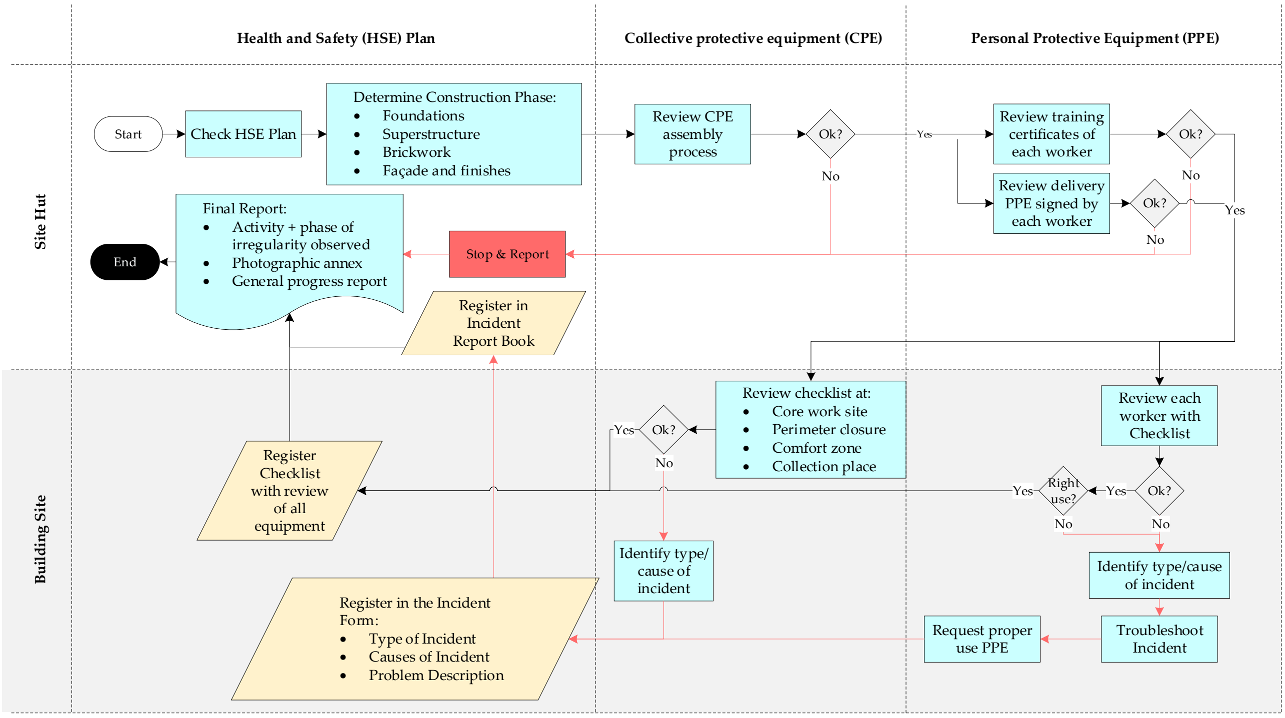


Figure 12. Simplified scheme of supervision activities for the prevention technician at the building site.

In the same way, this set of virtual reality experiences can also contribute to making an adequate design considering preventive measures at work, both considering the risks during the execution stage, and later during the operations and maintenance phase.

By integrating the considerations of different roles at work with the basic workflow, the scope of the virtual reality experience is greatly extended. The programming of the elements with the ability to interact in the scene can be classified as follows:

1. The machinery, which are dynamic objects, heavy cranes or vehicles in movement, with the risks of running over workers, one of the most common accidents on construction sites;
2. The CPE themselves that can change consistency or place if they are hit, cut or manipulated;
3. Interactive clipboard for data acquisition from the immersive environment, to review aspects of CPE or PPE, for example, as shown in Figure 13.

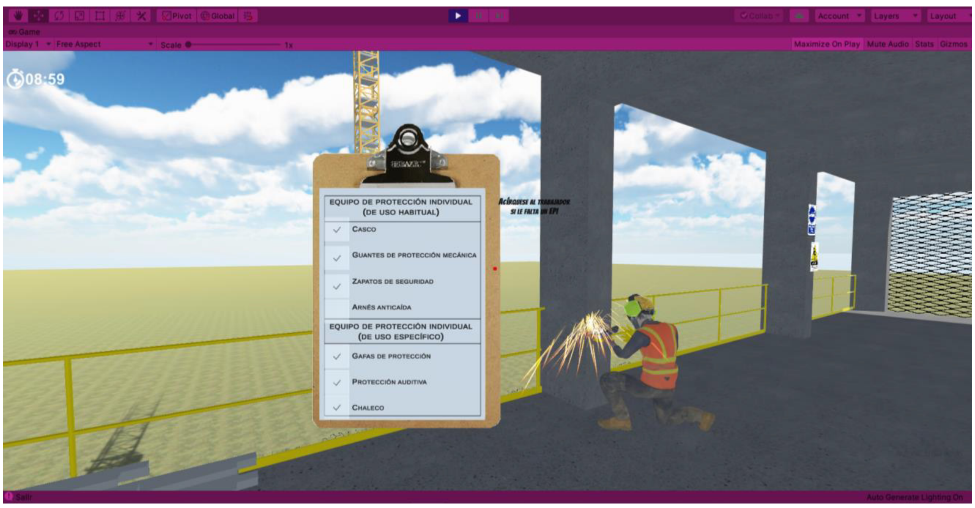


Figure 13. Replication of one of the activities to monitor security elements using virtual reality.

4.3. The Human Factor beyond the First Person in Virtual Reality Experiences

Until now, the interaction of the user (worker or prevention technician) with the environment has been described, but without mentioning the possible encounter with other agents or reactions of other workers with a presence on the site. This presence is very important in terms of OHS, since each worker could suffer damage due to the actions of the user/worker and every worker is also an active preventive element that must guarantee not only their safety, but also that of their colleagues. From a technological perspective, people can be represented on the scene in basically two ways:

The first, as characters with automated behavior (programmed as bots), so that the user's attention for risks and protection elements is extended to other people in their environment, so as not to harm them if they are carrying out any dangerous activity (welding, cutting, handling of machinery or heavy material, etc.), or being damaged by them (as shown in Figure 14, e.g., interaction with a welding worker).

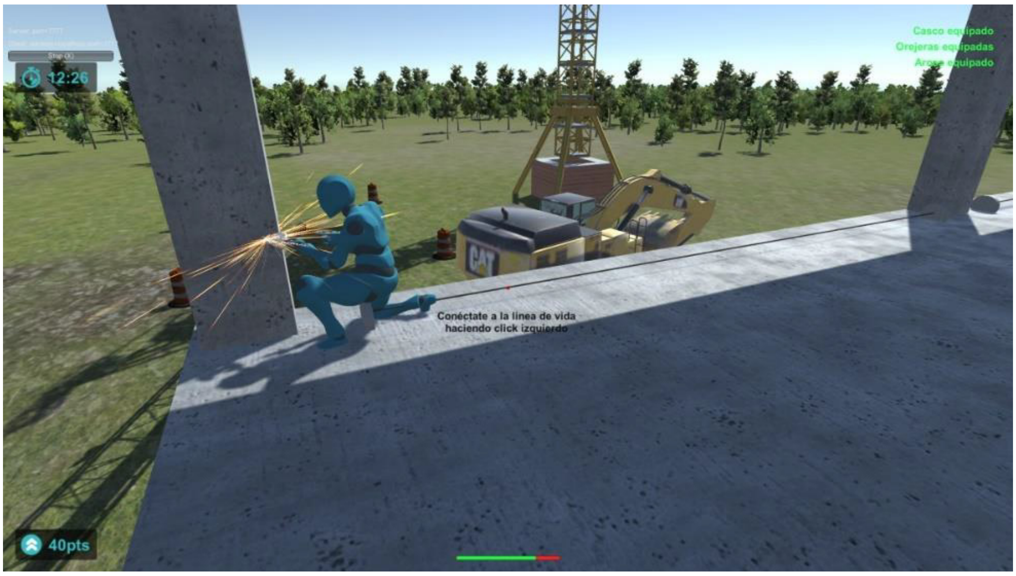


Figure 14. Worker and machinery as interactive and animated parts of the stage to consider.

The second way to incorporate other people is that they are also users of the same virtual reality site, which in video games is known as multiplayer experiences. This modality significantly multiplies the possibilities of awareness and learning formats, allowing, for example: (a) simultaneous users, prevention technician and the worker/workers, in the same virtual site; (b) explore, from a formative point of view, the contrast between collaborative versus competitive strategies, etc.

This feature is a very powerful tool for developing various narratives too. Figures 15 and 16 show the basic client-server schematic and the appearance of simultaneous screens for two participants.

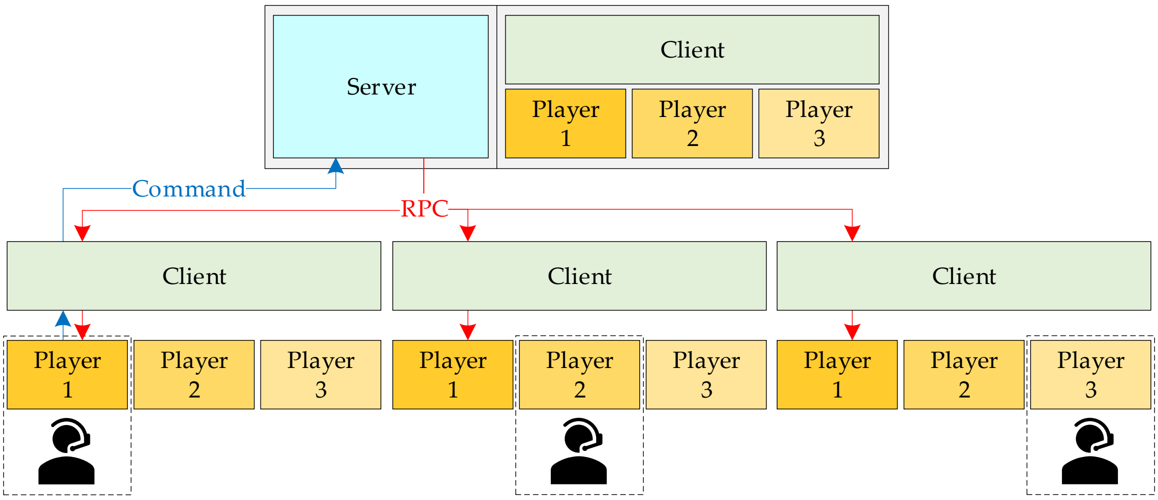


Figure 15. Basic diagram of the communication (remote procedure call, RPC) between the server and the clients (participants of the experience).

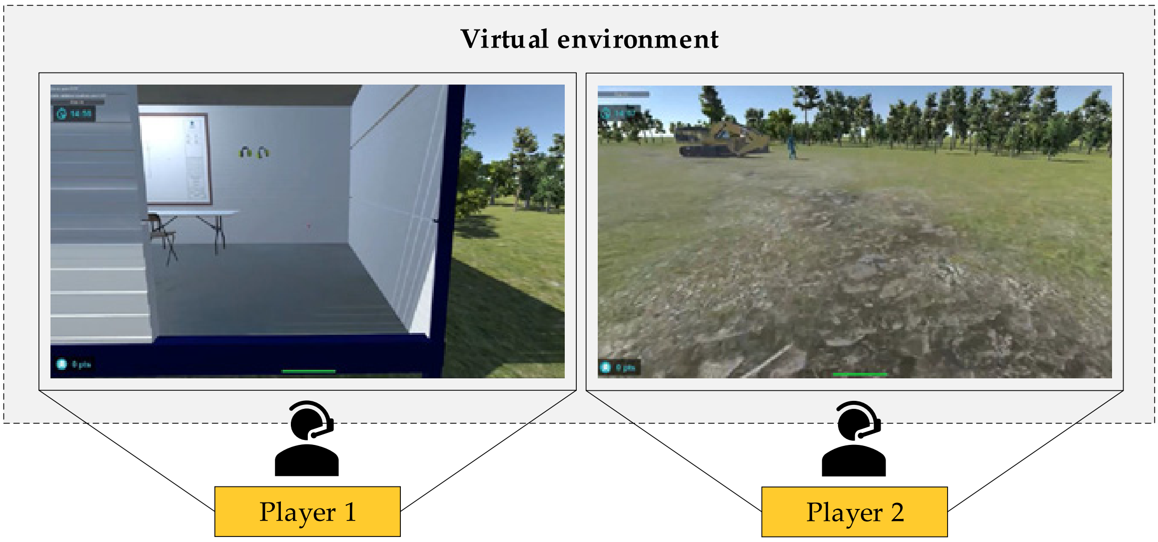


Figure 16. Two characters and two points of view (roles, and actions) for the same VR experience.

4.4. Narratives (Storytelling) in Virtual Reality Tools for OHS

All the elements described above constitute the scaffolding of virtual reality experiences to recreate construction tasks and OHS measures at the building site. However, they are "just" components, isolated and without connection to each other or emotional meaning, which is essential to develop a culture of prevention. Designing meaningful learning requires a conscious design of the complete sequence of actions and stories, the "script", which in other scopes is referred to as the narrative (storytelling).

According to the proposed solution described in the previous section, three levels of development are required:

1. A cause–effect relationship tree, which establishes a connection between the tasks to be performed by the worker, the associated risks and the consequences of bad (or good) practices in carrying out the activities;
2. A gamification layer, in the form of loss of health, modification of skills or punctuation, depending on the prevention measures and ways in which the tasks are carried out; and
3. A translation of this cause-effect relationship tree into state machines to be programmed in the virtual reality experience creation platform.

Then, the prevention technician parameterizes the process based on their training objectives, as illustrated in the Figures 17 and 18. Figure 17 shows the conceptual design of the gamification aspects of a virtual experience. Different routes and options that the user could follow, together with the consequences of these actions, are detailed. Thus, according to the user's decision, points can be earned or discounted, or the experience can be terminated if the user has an accident (end of the game). Figure 18 shows part of the implementation of the animation routes in Unity 3D.

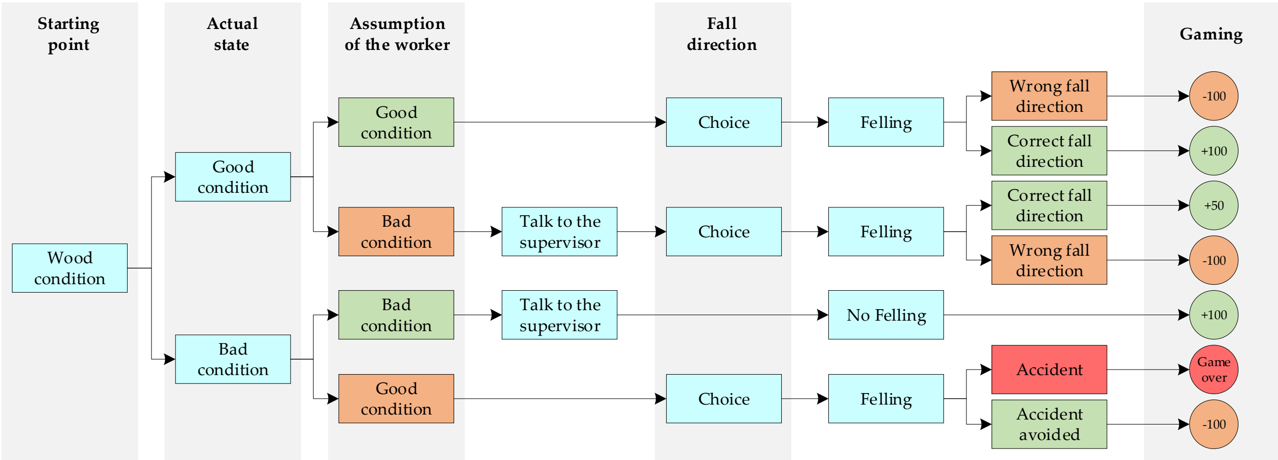


Figure 17. Situation tree representing a simplified case of a feller with the score associated with the gamification layer.

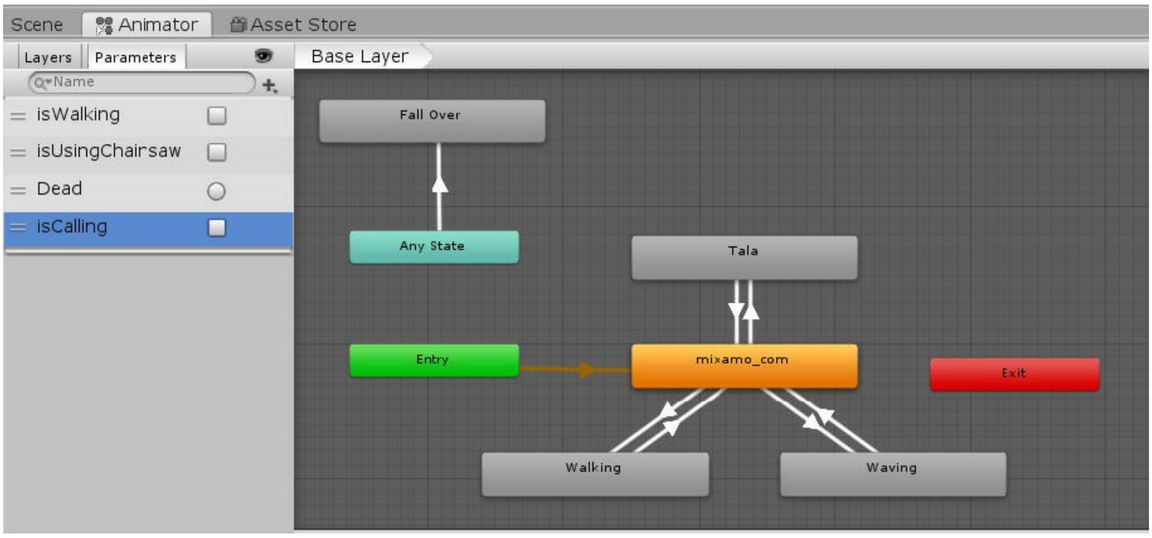


Figure 18. Situation tree correspondence with the VR platform state machine.

These relationships are the foundations for creating the virtual reality training experience. They would be the equivalent of sequences or scenes for multimedia creations such as cinema or video games. The extension of these relationships to an upper level (narrative/storytelling) can be carried out following the structure proposed by traditional techniques (trigger, conflict, turning points, climax and resolution sequence). This scheme is lineal, but other sophisticated tools for creating nonlinear interactive stories are also available.

Figure 19 shows a map with the elements and workflows for the systematic development of narratives in the creation of virtual reality experiences. The story is articulated via its contents and the key elements of a plot diagram to map the events in a story. The story (Box A) draws on the structured compilation of stories about accidents, from the perspective of those who suffered or witnessed those experiences, which is broken down into all its components: accident context (role of the worker, emotionality, personal aspects, immediate surroundings, and general aspects), state before and after accident (cause-effect relation-ships of accidents), and singular aspects of the story (singularities due to the human factor, for example). Thus, for example, in the “accident context > worker role”, *n* categories of worker roles can be established. On the other hand, each accident history will have one of these roles (A, B, C, . . . , *n*), which must be indicated. Similarly, the data for the other accident stories are collected and classified and for the following categories. With the different accident stories, common and standardized elements it is possible to obtain and generate a database and guidelines for each type of accident.

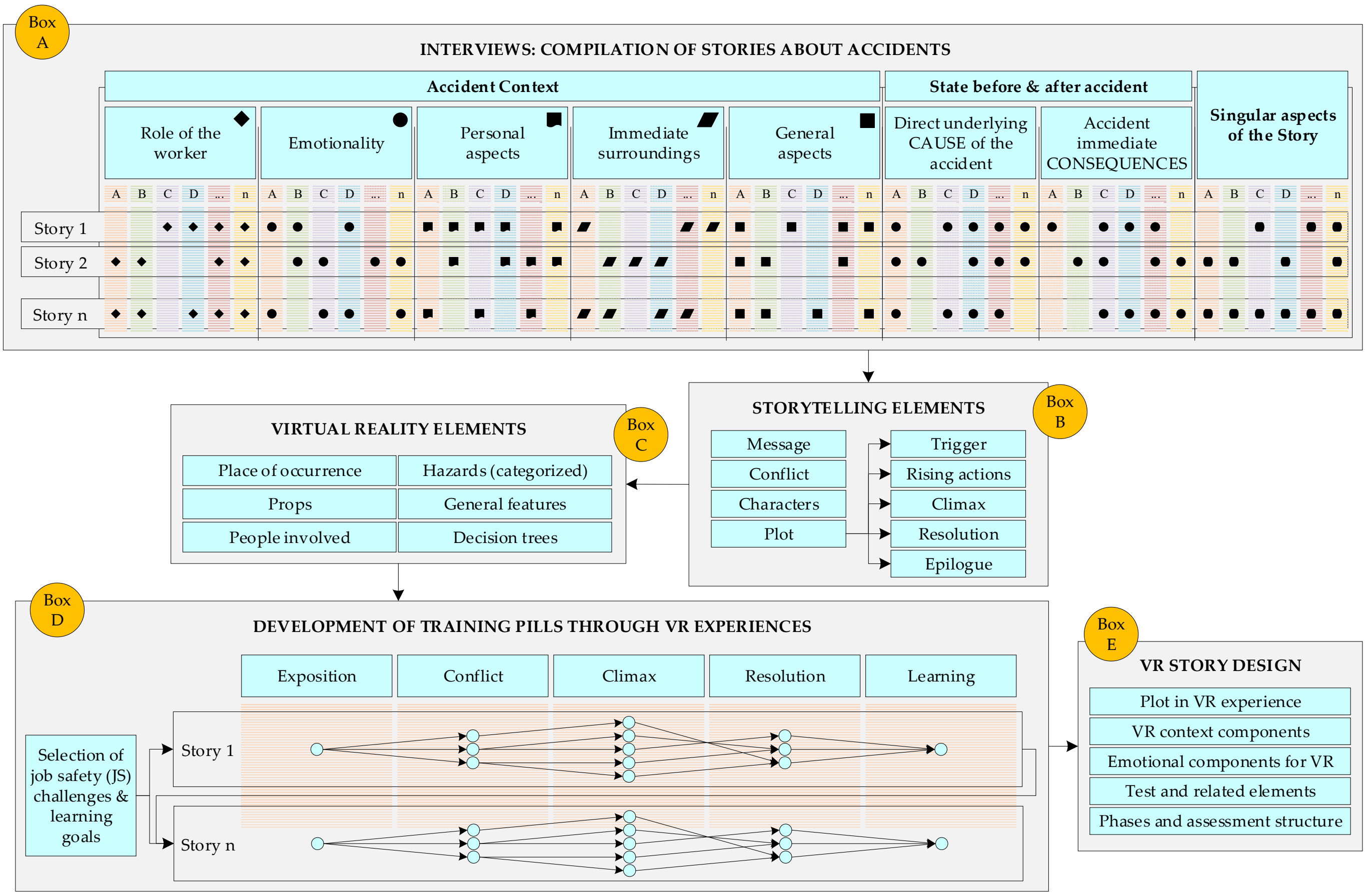


Figure 19. Map for developing narratives for VR training experiences for OHS in construction.

The storytelling elements (Box B) follows a structure similar to the plot diagrams and narrative arcs used for the creation of fiction: exposition, conflict, approach, rising actions, climax and resolution. These components are standardized, categorized and integrated into the elements of the related context (roles, characters, environments, causes, etc.) that result in a flow that determines the variables necessary to implement in virtual reality (Box C): scenarios, characters, accidents, decision trees.

Finally, prevention training needs are organized according to different sections of the storytelling (exposition, complication, climax, resolution and learning again). In the exposition stage, the situation and environment are described, the characters and their locations are described, along with the role and activities to be performed by the user. In the complication stage, variables, events, and/or barriers are incorporated, to disrupt the worker. In the climax stage, a high-impact event is developed, and action to resolve the main conflict must be performed by the worker. In the resolution stage, a reflection of the event and consolidation of knowledge is acquired. Finally, the specific story ends and the following challenges for the user continue. The standardization of the context elements allows obtaining a set of scenarios and tools in the virtual environment, which are used to bring to life the story exposed in the different sections of the plot, in iterative cycles of risk challenges.

These cause–effect relationships can be systematized to streamline the process by implementing a more generic and automated tree scheme, including parameters such as the relationship of each risk with its consequences and certain conditions, as shown in Figure 20.

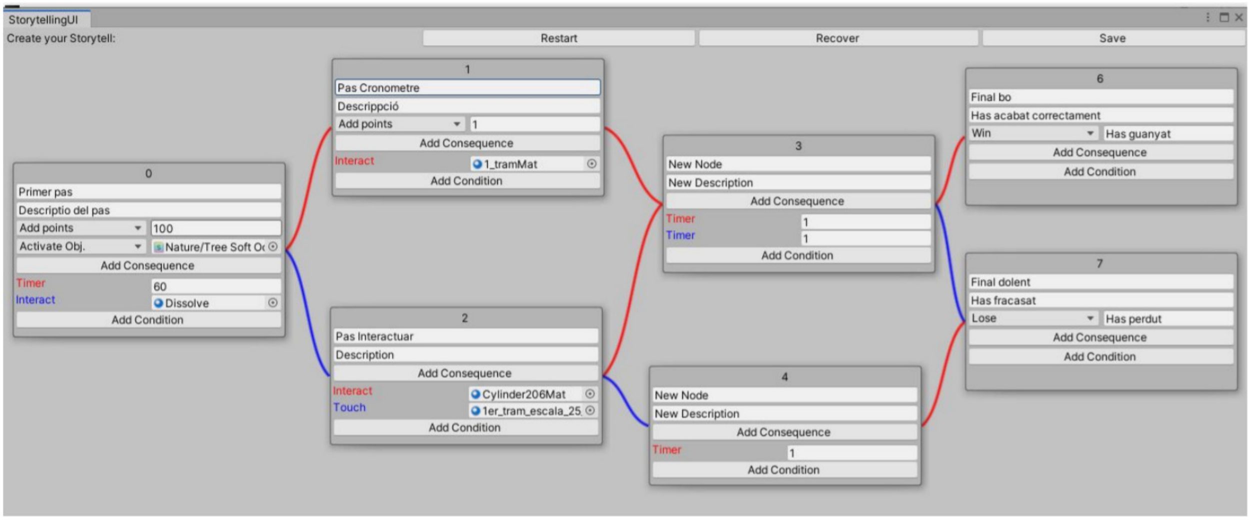


Figure 20. Conceptual diagram of the generic structure for the programming of the storytelling, based on Unity3D®.

5. Conclusions

Through the implementation of various virtual reality experiences aimed at training in occupational risk prevention, it can be concluded that:

- Virtual reality technology is mature enough to create training experiences for construction professionals with increasingly shorter development times thanks to the emerging tools available in the BIM ecosystem and its growing compatibility and interoperability;
- It is proven the technological feasibility to build prevention training systems ranging from simple virtual walkthroughs to complex narratives similar to those available for fiction, in the film or video game industry;
- For a practical implementation of these experiences, the development of new methodologies, procedures and programming tools that facilitate the automation of the entire process is required, so that it can be easily and routinely adapted to every one of the construction tasks.
- Because of the different problems of the sector, the challenges of how to attract young people to the construction sector, and how to avoid senior people being out of the new digitalization process, VR is a quite appealing way to bring young people to this sector and a very easy-to-use and intuitive (smartphone and videogame style) framework for senior people. In this research, the training with narrative has been conceptually planned and technological tools/framework provided, but not yet assessed. Further work should implement and analyze the impact of these aspects with SSH (social sciences and humanities) professionals.

Although the developments shown in the document are exemplified in building projects, the methodological approaches and technological tools developed can be applied in other types of construction projects, adapting scenarios and prioritizing risks and hazards according to the type of construction. In addition, the methodologies and technologies developed should be validated more extensively, to obtain conclusions regarding efficiency and elements for continuous improvement.

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