Game technology and Building Information Modelling for the adoption of Virtual Reality in construction safety training: a prototype protocol

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Abstract

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 these reasons, the presented contribution is based on the assumption that a more nuanced approach for construction worker's safety training is warranted and the authors propose a safety training protocol based on BIM-enabled virtual reality activity simulations. The protocol addresses three methodological issues: (1) *Planning* in terms of training typologies and related Health and Safety contents to be implemented in the VR construction site scenarios; (2) *Management* regarding the solution to integrate BIM and game technologies to deliver VR training experiences; (3) *Administration* in terms of definition of standardized rules to define a safety training schedule in a given construction project. The research gives a contribution to reduce the currently existing knowledge gap regarding how BIM and VR can be simultaneously integrated in real projects for construction safety training by using standardized rules to be extensively reproduced in different construction projects.

Keywords: Immersive Virtual Reality, BIM, Safety Training, Game Technology

1. Introduction

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 site productivity. Nonetheless, construction industry remains one of the major high-risk industries world-wide (Behm, 2005; Niza et al., 2008). The accidents are mainly caused by falling from height, workspace collision, wrong space usage, collapse and electric shock, among which falling from height and collisions are the most prevalent (Sokas et al., 2009). Other causes come from non-compliance in the application of the Health and Safety Regulation (HS) (Activity Report CPT, 2017) in terms of: (1) extensive lack of warning signals for the identification risk zones, (2) lack of site personnel 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.

Given these circumstances, there are still considerable safety problems in the construction industry in need of attention. In this respect, enhancing safety training has been identified as an important factor able to reduce the accident rates in the construction industry (Abdelhamid and Everett, 2000; Tam and Fung, 2011). This means that an efficient construction safety training programme which include standardized rules for planning, management and administration could improve safety performance through preventing accident occurrence.

Nowadays, the most flourishing technology in the construction sector is represented by Building Information Modeling (BIM) and BIM-enabled applications. This technology provides a new approach to design, construction, and facilities management, wherein a digital representation of the building process is used to facilitate the exchange and interoperability of information (Eastman et al., 2011)(Vito Getuli, Mastrolembo, Capone, & Ciribini, 2016). Currently, as reflected in the literature, there are many proposals that use BIM technology to assist with different construction management tasks as safety management. These studies demonstrate that the use of a 4D (3D + Schedule) Building Information Model can be used as an important information source for the implementation of safety protocols.

The study which is proposed in this contribution is based on the assumption that a more nuanced approach for construction worker's safety training is warranted. Our hypothesis is that the sheer complexity of a construction project and its safety-related information and knowledge make difficult their full communication to workers. Consequently, the major challenge that needs to be met is what, when and how safety training could be administered using BIM-based construction project together with an emerging communication medium such as Virtual Reality (VR).

2. Background

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. (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 (Getuli et. al 2017) (Schwabe, Teizer, & König, 2019).
3. 4D BIM: Construction schedule information integrated into a 3D BIM to increase dynamic visualization of safety procedure. (Getuli & Capone, 2018)(Boton, 2018; Choe & Leite, 2017)
4. Clash detection: for a safety design purpose, clash detection is mostly used for construction workspaces planning and management

All the aforementioned models have 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(Guo, Yu, & Skitmore, 2017). These models, somehow integrated with BIM environments, are able to collect real-time data from the sites for further analysis and give immediate warning or feedback to the site personals.
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 simulation of the real works.(Li, Yi, Chi, Wang, & Chan, 2018; Sacks, Perlman, & Barak, 2013)

All the aforementioned technologies have been used for safety training to improve construction site operation safety but 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 addition, another knowledge gap is that there are nearly no studies investigating how BIM and VR can be simultaneously integrated in real projects for construction safety training by using a coherent and standardized protocol.

For these reasons, in this research, the authors propose a **safety training protocol** based on BIM-enabled virtual reality activity simulations.

3. Research objectives and method

As mentioned before, the aim of this work is to draw up a prototype protocol for the design and administration of safety training to construction workers based on an innovative and interactive learner-centric approach developed to be extensively suitable for different construction projects and moreover of easy implementation. In order to achieve this, the research focused on the following objectives:

- <u>Construction site simulation using Immersive Virtual Reality</u>: the training protocol is centred on the trainee's direct real-scale experience of an interactive virtual environment representing the real site with the related construction activities;

- Integration with a BIM-based construction site project: all the information required for the design, management and administration of the safety training are acquired and consistently integrated in a BIM-based health and safety plan;
- Ease of implementation: the training methodological and operational framework shall be oriented to its users, namely OHS trainers and trainees, avoiding possible implementation barriers: (a) no need for ICT specialized knowledge for the practitioners; (b) adoption of ergonomic and user-friendly immersive VR technology; (c) low costs for the implementation and (d) high portability of the hardware setup.

The methodology adopted in this research is discussed in the following paragraphs.

1) VR safety training

When dealing with a well-established matter as it is safety training by using new tools as it is Virtual Realty, the risk of focusing just on the technological aspects of the implementation could threat the robustness of the approach. To prevent this, prior authors' concern was to address comprehensively the training process, identifying three methodological issues: planning, management and administration of such a training. On the basis of the aforementioned aspects, this research work is driven by the following key questions:

- Planning: Which are the VR training typologies and the related training aims? When do the VR training sessions have to be administered? Which types of VR training have to be related to each session? Who are the appointed trainees for each VR training session?
- Management: How do the training contents are developed for the planned VR training session?
- Administration: Where the VR training sessions take place? How many trainees are involved in each VR training session and for how long? Which modes of VR training experience sharing and trainees' involvement are provided? Who are the OHS practitioners involved and which are their roles during the VR training session?

The integrated solution to these questions is reported in the wider context of the whole VR training development and administration workflow discussed in the paragraph 4.

2) Operational framework

Besides the methodological issues outlined above, the technical implementation and administration of the proposed VR training protocol is centered on the following three requirements:

- BIM-compliancy: The assumption is that a BIM construction plan is the initial data source -site's 3D geometries and information- for the generation of the scenarios of the VR safety training sessions.

- Game technology: The authors adopted a game technology solution based on the game engine "Unity". This platform allows the customization of the user experience during the immersive VR training session and his interaction in the virtual site scenario.
- Mobile VR: In order to mitigate the implementation costs and enhance the hardware setup portability in a construction site, thus facilitating the implementation of the proposed protocol, immersive VR for mobile devices based on the Google Cardboard platform was selected as target technology for the development and administration of the VR training experiences.

3) Use of a case study

The VR training protocol was applied to a construction project based in Italy that served as case study for the development of the training sessions' contents and their implementation. The case study consists of a construction of a new complex of three one-storey buildings with cross-laminated timber (CLT) structure atop an existing office facility in the city of Pisa, in central Italy.

4. Virtual Reality Training Protocol

This research aims to define an operative protocol for the planning, management and administration of safety training for construction workers centred on a BIM-based construction plan and administered by mean of immersive VR simulations of the site's layouts and construction activities. In this paragraph, the training protocol and the related dataflow is presented in Figure 1 and discussed in terms of its methodological aspects and tools. With reference to Figure 1, the five identified steps are numbered and individually discussed in the following paragraph.

4.1 Step 1 - Federated BIM Model acquisition

The VR training sessions are set in a BIM-based virtual reproduction of the construction site that must be consistent in term of layout, facilities and equipment in the same configuration the worker will find in site after the training. For this reason, it is necessary to acquire the BIM model of the construction comprehensive of the all building elements eventually arranged in multiple mono-disciplinary models provided from different firms – e.g. architectural, structural and MEP. Then, once assessed the model's integrity, the process can move to the BIM implementation of the site plan, construction schedule and safety procedures.

4.2 Step 2 - BIM construction schedule and site plan implementation

In this phase the acquired federated BIM model is integrated with a construction schedule and site layouts' plans. Furthermore, for the building elements considered relevant for the training purposes according to the H&S manager's experience, the required workspaces and H&S data related to their construction activities are introduced in the BIM Model for the later training planning phase.

Aside the adopted BIM authoring platform, this is achieved through three methodological steps comprising: (1) the construction schedule implementation, (2) the site modelling and, finally, (3) the 4D construction simulation. In particular, according to the proposed protocol's aims, the BIM site layout modelling is oriented to the definition of an effective data source for the implementation of the site scenarios where the immersive VR training sessions will be set. For this reason, with reference to previous authors' works, two modelling scales are here distinguished: *layout scale* and *activity scale*.

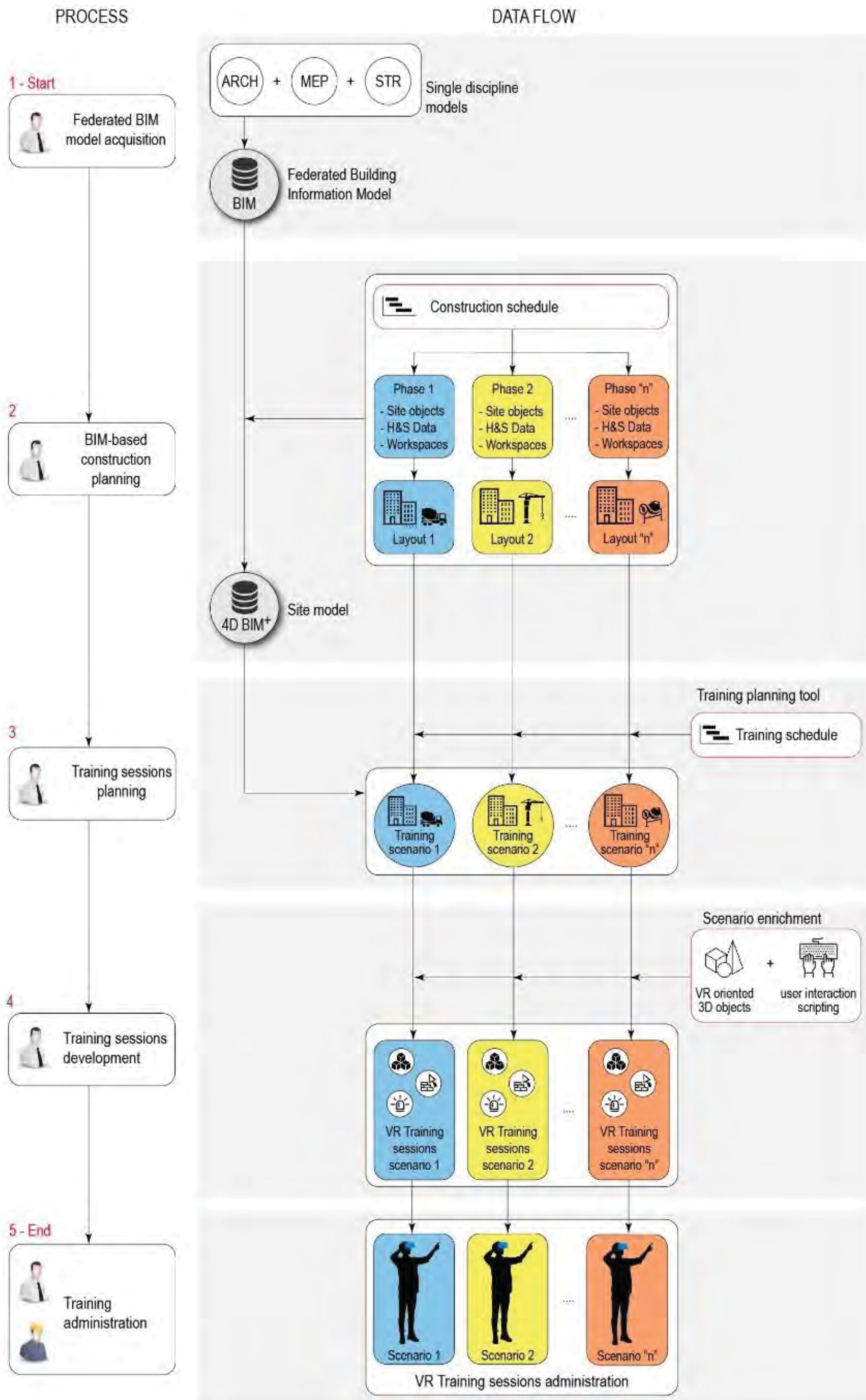


Figure 1: Virtual Reality training protocol application process and data flow

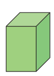
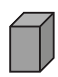
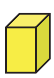
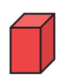
Activity modelling

The modelling of a construction activity in a BIM environment represent an open issue despite being addressed with different solutions based on the representation of the site space usage - usually called workspaces- via parametric objects with attached non-geometrical information (e.g. time needed for completion, risks, etc).

For this study, aiming to the immersive VR visualization of the construction activities for safety training purposes, an approach developed from the activity workspaces modelling of (Getuli et al. 2018) with the integration of specific H&S data, is proposed as follow which consist of four data packages:

- Activity workspaces: The working-cloud that spatially represents the construction execution of a building component is modelled via 3Dimenstional objects consisting in parametric bounding boxes conveniently arranged around the component itself. These static volumes, virtually limiting the spaces that are dynamically occupied in site during the construction activity for different needs and times, are classified via the proposed colour scheme (Table 1) in order to communicate both in the BIM environment, to the H&S manager, and in the immersive VR simulation, to the trainee, their future usage.

Table 1: Workspaces definition

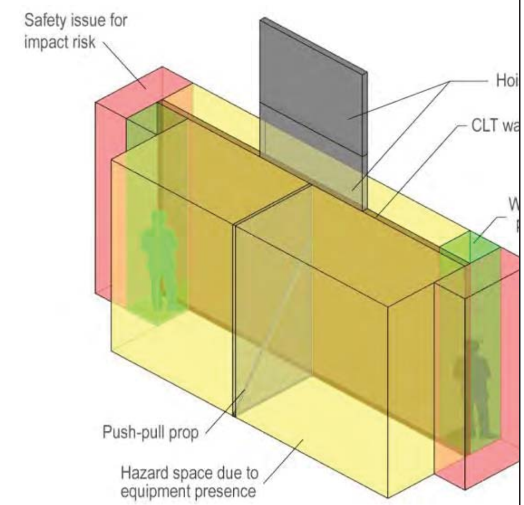
	*Labor crew space*: represents the space required by the labor crew installing the construction product		*Equipment space:* represents the space required by the equipment supporting either the construction product or the labor crews
	*Hazard space:* represents a hazard space generated by a Labor crew space or Equipment space		*Safety space:* represents a tolerance (safety distance) between two workspaces to prevent safety hazards such as collision between two spaces or a tolerance space from objects falling from height

- Labor crew members: They are represented via parametric objects that, besides carrying all the relevant information for the identification of the worker involved in the activity (e.g. name and surname, company, qualifications, etc), are inserted in dependence of a "labor crew space" and serves for the understanding of their position and role during the modelled construction activity for the later development of the VR training contents.
- Work sequence and safety procedures: The construction activity is decomposed in phases/tasks for which the operational procedures and the related safety directions are defined (see Table 4). This information is then integrated as additional text data into the BIM object of the construction activity and serve for the later implementation in the VR training contents development.

- Construction and risk data: Information related the required equipment, their costs and the prescribed Personal Protective Equipment (PPE) are integrated in the construction activity model along with the risk evaluation outcomes for a pre-defined set of risks.

With reference to one of the construction activities object of the VR training experiences developed in the case study (i.e., CLT wall panel installation), the example of the parametric BIM object which is based on the method proposed above is reported in Table 2.

Table 2: BIM model of a CLT wall panel installation activity with safety training informative contents (geometries and data)

 Lowering and alignment of the CLT wall panel	 Activity workspaces - BIM model
Labor crew	
	*Crane operator:* Worker assigned to the crane operation in order to lift the CLT wall panels from the truck and to move and to lower them to their designed location. He must operate from a convenient position to visually check the load during its moving and to communicate by voice with the other labor crew members.
	*Workers*: Carpenters assigned to the alignment and fastening of the CLT wall panels. They must manually drive the panels to their final position and then brace and fasten them once they are correctly aligned. They must communicate with the crane operator during panels' moving.
Work sequence	**Safety procedures**
1) *Loading/unloading* A worker on the ground ensure the correct fastening of the hoist belts to the CLT panel that has to be lifted. Once the load is attached, the crane operator proceeds lifting the CLT panel and moving it to its final location or to a dedicated temporary storage area.	- Check the consistency with the installation sequence of the CLT wall panels during their positioning phase. - Check the correct fastening of the hoist belts and the conformity of the lifting accessories before each lift.
2) *Fastening to concrete footing* The crane operator moves the CLT panel towards its assigned location where it is received from two workers that manually handle it during the last phase of its lowering. Once correctly aligned, the workers fix the required push-pull props to the CLT panel and fasten it to the concrete footing.	- Pay attention during the moving of the CLT wall panels in order to prevent their collision with building parts, pieces of equipment and workers. - Keep the CLT wall panels attached to the crane until the completion of its fastening to the concrete footing and its bracing with push-pull props, in order to prevent roll-over.

3) *Fastening to the adjacent panel* Once the workers have braced the CLT wall panel and fastened it to the concrete footing, they fasten it to the adjacent wall panels making use of a rolling scaffold to work at level higher than 2,00 m above the floor. Finally, the workers release the hoist belts from the panel and make signal to the crane operator to load the next panel.		- Make use of a rolling scaffold positioned on the inner side of the CLT wall panels to carry out their lateral fastening to the adjacent wall panels and the following releasing of the hoist belts.	
Construction data		**Risk data (0-5 scale)**	
Equipment 1:	Push-pull prop	*Fall from high:*	2
Equipment 2:	Rolling scaffold	*Crush:*	3
Equipment 3:		*Hit or struck by:*	1
PPE 1:	Safety helmet	*Loads manual handling:*	0
PPE 2:	Safety shoes	*Noise:*	0
PPE 3:	Protective gloves	*Cut/pierce:*	2

4.3 Training sessions' programming

In this stage the H&S manager programs the training sessions on the basis of the construction schedule and of the contents of the 4D BIM model consisting, for each construction phase, in all the geometries and data related to the site layout, objects, facilities and the building elements with the associated construction activities. Therefore, the required information is available to address the following key-questions related to the programming activity of the safety training:

- What? - Definition of training typologies, aims and contents
- Why? When? – Definition of the criterion for the decision of training schedule (date-typology-trainees)

Once defined the training schedule, for each planned training scenario (site layout + activities) the 4D BIM site model is filtered so that the needed contents are available to be transferred in the game-engine environment for the development of the immersive VR training experiences.

4.4 Training typologies

The authors investigated which safety training sectors and contents' transfer methods were better enhanced by the adoption of immersive virtual reality technologies to provide the trainee's first-person real-scale experience of the site and the related construction activities in a safe virtual environment (V; Getuli, Giusti, Capone, Sorbi, & Bruttini, 2018)

As a result, for the proposed protocol, three training typologies are defined in terms of comprehensive aims and contents (Table 3). Furthermore, the decision criterion is provided for each training typology based on two construction schedule milestones, namely "**Layout switch**" and "**New component first assembly**". Detailed specification for the training decision method is given in the following paragraph.

Table 3: VR safety training typologies and characteristics

Layout-oriented training	**Aims**	- Activities coordination and workspaces management - Understanding of workers', materials' and vehicles' site circulation - Illustration of site's facilities and zones access and usage authorization
	When [training milestone]	Before each site layout transformation [called "**layout switch**" in Figure 4 -training schedule-]
	Contents	- *Site areas; Equipment, facilities, plants; Activity workspaces; Paths; Specific risk zone*
Building component first assembly training	**Aims**	- Illustration of site-specific and activity-related risks trainees are exposed to and safety measure to adopt consequently - Visualization of construction activity workspaces configuration
	When Training [milestone]	Before every first assembly of a new component [called "**new component first assembly**" in Figure 4 -training schedule-]
	Contents	- *Workers; Equipment, facilities, plants; Activity workspaces; Paths; Safety procedures; Specific risk zones*

Emergency management training	**Aims**	- <u>Type 1</u>: Worker's illness or accident
		    - Illustration of illness or accident related safety procedures
		- <u>Type 2</u>: Fire management
		    - Illustration of emergency procedures, equipment position and emergency circulation
		    - Understanding emergency circulation in terms of escape routes, assembly areas and rescue vehicles' access and paths

	When [training milestone]	Before each site layout transformation [called "**layout switch**" in Figure 4 -training schedule-]
	Contents	- *Emergency subject; Workers; Emergency equipment and rescue vehicles; Paths and escape routes; Safety procedures; Specific risk zones*

4.5 Training schedule for VR safety training programming

For the training sessions programming activity, based on the typologies described in the previous paragraph, the H&S manager is required to determine a training schedule -specifying dates, training contents and trainees involved- in accordance with the construction schedule. In fact, the training schedule serves the dual purpose of programming the training contents development and of ensuring a correct timing in the relationship training-mission. In support of the H&S manager's decision, a training schedule criterion is proposed, based on the individuation of the two training milestones upon the construction schedule:

- *Layout switch*: Before each site layout relevant transformation (e.g. changes in the circulation, area function transformation, plant or facilities assembly/dismantle, etc.) the workers that will operate in a changed working environment have to be involved in VR training sessions that regard their safety behaviours at a layout-scale.
- *New component first assembly*: Before that a relevant building component is introduced in site or assembled for the first time from an assigned labour crew, the workers involved have to be trained for the procedures and risks related to the activity in the specific site configuration and in respect of the near ongoing activities. Relevant changes in the assembly procedures of a building component that has already been built or the occurrences of relevant specific activity-related risks that were not present before, count as first assembly for the determination of the training milestone.

The application of the decision method, in accordance of the training milestones specified above for each training typology, is shown in Figure 4. Once determined the training milestones, the H&S manager, along with the construction manager and the companies' site managers, decide convenient dates for the training sessions to be administered (e.g. one week – three days in advance respect the milestone's date).

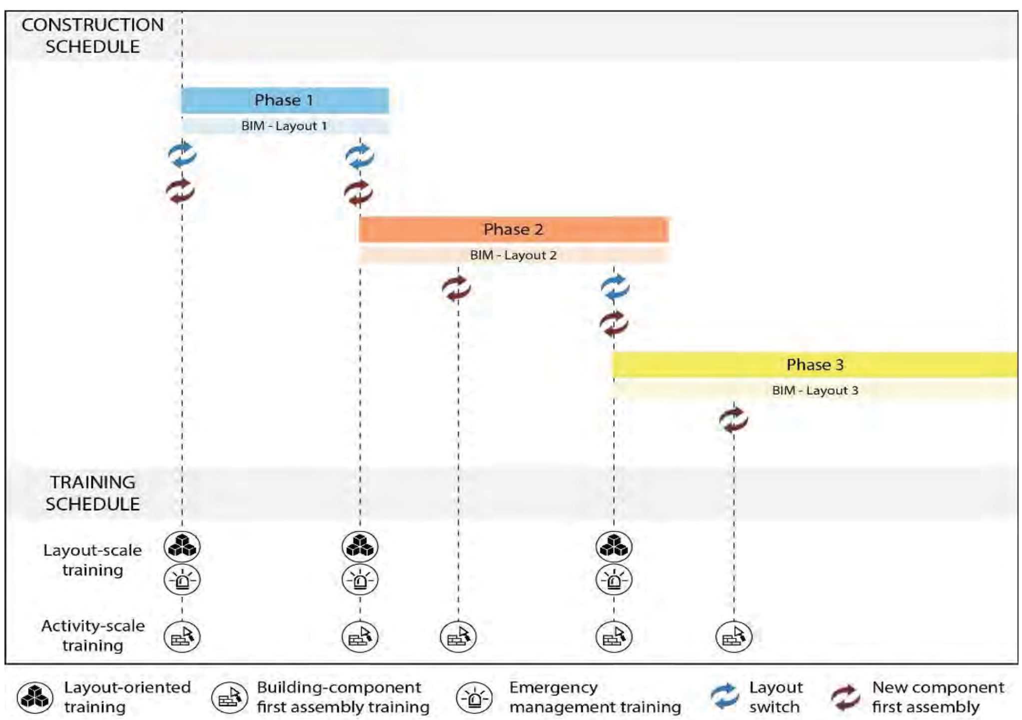


Figure 2: Proposed safety training schedule

4.6 Training sessions' development

For the development of training scenarios, the BIM-based 3Dmensional models and data referred to a certain training scenario are extracted and imported in a game-engine platform where every single training experience is developed giving attention to the trainee's relation with the virtual site reproduction in terms of: (a) What the trainee sees; (b) How the trainee interacts with what he sees.

Both the aforementioned aspects are affected from the choice of the knowledge transfer method and of the target VR technology for the delivery and administration of the training experiences. In this regard is recalled that for the proposed protocol is considered a mobile VR technology.

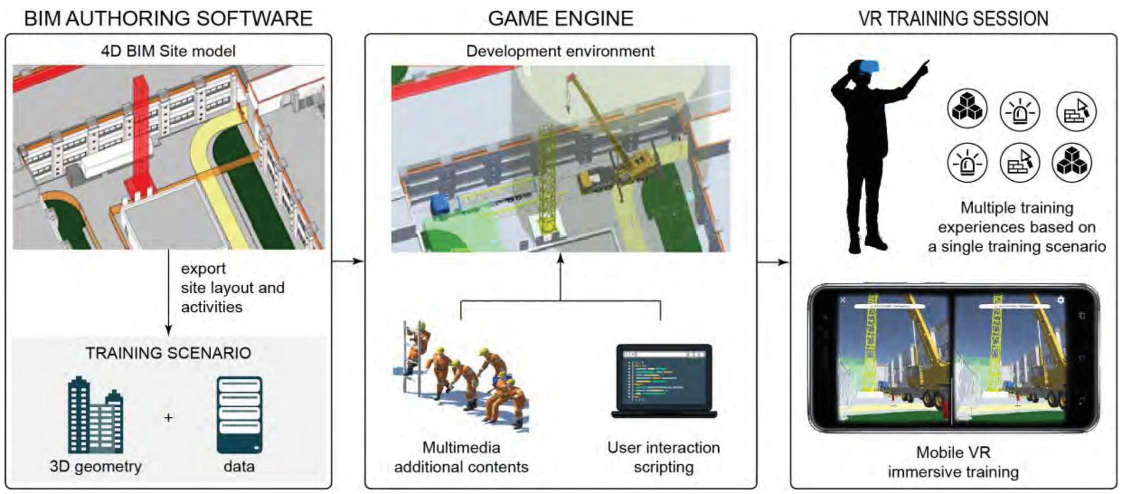


Figure 3: VR training contents development workflow

4.7 VR-oriented graphical enhancement and additional contents implementation

In the proposed protocol two different developing environments - BIM and game engine - are determined and kept separated in respect of their purposes. In fact, on one hand the processes of construction scheduling, site planning and safety training data integration are carried out on a BIM authoring platform and results in the 4D Site Information Model discussed before, while, on the other hand, these same contents are further edited and enriched in a game engine platform to deliver a suitable environment for immersive VR experiences. In order to achieve the training objectives, the trainee must proceed in a learning path through the virtual reproduction of the site where he can not only move around but also interact with a vivid and realistic environment. For this reason, since the Level of Development (LOD) of the site's objects contained in the Site Information Model is sufficient just for the scheduling and planning purposes but not fulfils the realism requirement of an immersive VR experience, their replacement with more graphically detailed objects is to be considered. Furthermore, auxiliary virtual objects that support the trainee to explore the virtual environment and to access and receive safety training-related information have to be added in the game engine environment.

5. Conclusions

This work contributes to provide a standardized protocol for a viable integration of BIM and VR technologies for construction safety training in real projects. A 5-steps process have been drawn and procedures defined to support the VR training planning, management and administration. In particular, the technological aspects have been addressed with the adoption of game technology, to provide a coherent data flow from the BIM environment to the VR training experience delivery, while, from a methodological perspective, standard training typologies, with related contents and aims, have been paired with a decision support tool based on the construction schedule, to fully determine the training sessions.

At this stage, the proposed protocol has been developed and implemented in terms of planning and scheduling of three VR training sessions regarding the case study (installation of wall, beam and roof panel of the CLT structure). Those experiences are currently being administered to the workers involved in the construction execution. The results will be published in future publications.

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