CONVR 2020

Teesside University

20th

Enabling The Development And Implementation of Digital Twins

Proceedings of the 20th International Conference on Construction Applications of Virtual Reality

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Preface

Welcome to the 20th International Conference on Construction Applications of Virtual Reality (CONVR 2020). This year we are meeting on-line due to the current Coronavirus pandemic. The overarching theme for CONVR2020 is "Enabling the development and implementation of Digital Twins".

CONVR is one of the world-leading conferences in the areas of virtual reality, augmented reality and building information modelling. Each year, more than 100 participants from all around the globe meet to discuss and exchange the latest developments and applications of virtual technologies in the architectural, engineering, construction and operation industry (AECO). The conference is also known for having a unique blend of participants from both academia and industry.

This year, with all the difficulties of replicating a real face to face meetings, we are carefully planning the conference to ensure that all participants have a perfect experience. We have a group of leading keynote speakers from industry and academia who are covering up to date hot topics and are enthusiastic and keen to share their knowledge with you. CONVR participants are very loyal to the conference and have attended most of the editions over the last eighteen editions. This year we are welcoming numerous first timers and we aim to help them make the most of the conference by introducing them to other participants.

Middlesbrough, UK
September 2019

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A PROPOSAL OF A SITE OBJECT LIBRARY FOR CONSTRUCTION WORKERS' SAFETY TRAINING USING BIM-BASED IMMERSIVE VIRTUAL REALITY

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ABSTRACT: *Workforce Health and Safety (HS) training in the construction sector has recently witnessed the growing adoption of immersive Virtual Reality technologies (VR) reaping the benefits of the enhanced workers' involvement and safety contents' transfer of on-site training while cancelling the related risks and costs.*

However, despite the diffusion of Building Information Modeling (BIM) and of BIM tools for construction simulation and planning, most VR training experiences are still based on generic construction site environments and are not included in a comprehensive training program that takes into account and leverages project-specific information and contents comprised in BIM Site models.

For this reason, in previous work (Getuli, Capone and Bruttini, 2020) *the authors proposed a prototype implementation protocol of BIM and VR for the planning, management and administration of three typologies of VR safety training (Layout, Activity and Emergency) via a game technology-based workflow encountering in the production of the VR training experiences a limitation in the lack of a standard categorization and informative requirements definition for construction site objects.*

In order to address this issue, the present work proposes a BIM-based Site Object Library oriented to the production of VR safety training experiences as a result of a three-step process with the definition of: 1) Object list and categories from the analysis of construction sector's regulations, case studies and site scenarios' imagery; 2) Object requirements from the analysis of their real features (e.g. visual aspects, sounds, motion patterns); 3) Object Information Sheet for the inclusion of any site objects in the library.

The implementation and validation of the proposed Site Object Library is currently in progress for the production of BIM-Based VR safety training experiences on a case study project and will be discussed in future works.

KEYWORDS: *Site Object Library, BIM, Health & Safety training, Construction workers, Virtual Reality, Game technology.*

1. INTRODUCTION

In recent years the adoption of advanced visualization technologies, such as Virtual and Augmented Reality (VR/AR), in the AECO industry has increased for several purposes (e.g. design review, stakeholder's engagement, training, etc) during the whole project lifecycle, from early design iterations to construction and operation, but, despite promising outcomes, still struggles to gain momentum due to existing development gaps (Davila Delgado et al., 2020).

In this context, the adoption of immersive VR for workforce Health and Safety (HS) training represents one of the most interesting use-cases both for the academy and the industry because of the reported benefits in terms of safety contents' transfer related to an enhanced workers' involvement and of the reduction of risks and costs related to on-site training (Sacks, Perlman and Barak, 2013; Li et al., 2018).

The introduction of users in immersive virtual environments comprising the vivid and interactive reproductions of real building and site configuration for construction education and training produced interesting results enabled by a real-scale first-person space perception (Bashabsheh, Alzoubi and Ali, 2019; Castronovo et al. 2019)

The adoption VR-enabled systems for the visualization of the project information demonstrated to provide significant improvements in term of collaboration and information sharing among different stakeholders (Pour Rahimian, 2019). Interactive VR reproductions of site layout configurations in the different planned phases (Boton,

2018) and, moreover, of relevant construction activities placed in their expected site environments proved to be an effective tool for the evaluation of safety procedures and for the inclusion of the elicitated workers' field knowledge in the H&S management process (Getuli et al., 2020).

Furthermore, concerning workers' safety training, document-based traditional training methods are overcome by VR-based methods and experiences due to the higher level of involvement and presence provided to the trainees (Perlman, Sacks and Barak, 2014). In this regard, the immersion in multi-user interactive VR environments have been proven highly effective in the training for complex tasks and construction site activities such as tower crane operation and oil and gas facilities' maintenance simulation (Guo et al., 2012; Hou et al., 2017).

Nonetheless, the diffusion of immersive VR for safety training is still limited to few early adopters mainly due to the existing implementation barriers related to the required specialistic know-how and to the poor integration with other established technologies and methodologies in the field.

For this reason, acknowledging Building Information Modeling (BIM) as the leading methodology and the common ground for the development of innovative applications, the authors already identified in previous works the opportunity to integrate BIM and game technology to foster VR safety training (Getuli et al., 2018; Getuli Capone and Bruttini, 2019). Moreover, in order to demonstrate a larger-scale feasibility of immersive VR for workers' safety training, an implementation protocol for planning, management and administration of HS contents with BIM and VR has been proposed and tested on a real case study project (Getuli, Capone and Bruttini, 2020). From the development and the results obtained in the aforementioned research work, it emerged among other issues the urgent need for an asset of resources that supported this implementation.

Therefore, this work aims to address this issue with a proposal of a BIM-based Site Object Library oriented to the production of VR safety training experiences. Since the study is currently ongoing, the results related to the problem analysis and to the library framework definition are here discussed, along with the proposition of a dedicated implementation support tool, leaving the discussion of the library implementation and validation to future works.

2. RESEARCH CONTEXT

The present work is to be considered as a branch of a broader authors' research effort regarding the development and implementation of a prototypical protocol for the integration of BIM and immersive VR technologies for construction workers' safety training as can be found in (Getuli, Capone and Bruttini, 2020). For this reason, in this paragraph a brief overview of the cited protocol is reported with reference to the issues that motivated this work (see Figure 1).

The proposed protocol aims to define a workflow for the implementation of workers' safety training sessions via immersive VR centred on the exploitation of the site model resulting from a BIM-based construction planning process for the representation of the workers' training scenario. It consists in a five-stepped cross-platform workflow which starts in a BIM authoring environment (1) with the acquisition of a multidisciplinary BIM model which is then enriched (2) with construction planning and H&S data oriented to the definition of site-specific workers' training scenarios (3). For this purpose, three training typologies, with the related aims and contents, have been defined (see Table 1) along with a decision support tool based on the identification of specific training milestones upon the construction schedule. Once modelled the training scenarios accordingly to the target training typology, the site's layout geometries and information are exported to a game-engine environment for their integration with additional multimedia contents and for the scripting of the necessary users' interactions (4). As final step of the process, the proper VR training experiences are eventually delivered according with the training schedule and administered to the workers via a supported immersive VR device (5).

The protocol was tested in a real case study project that comprised the production and administration of three VR training experiences and pointed out several implementation issues. Among these, it emerged the need for an organised asset of digital safety contents dedicated to the identified training typologies and optimized both for the BIM-based site modeling and the VR experience production (steps 2-4).

In particular, to facilitate the protocol's implementation the authors focused in the development of a Site Object Library with the following characteristics:

- Progressive objects classification system oriented to the scope of the different typologies of safety training and suitable for various site configurations, construction activities and emergency events occurrences.

- BIM-ready version for each site object whose representation in the BIM model of the site has relevance for a safety training purpose, including object's geometry and the related H&S data and workspaces. This version is intended for a BIM-authoring environment and is mostly replaced later in the game-engine environment whit more suitable versions for their VR representation.
- VR-ready version for each site object intended to the production of realistic and interactive experiences able to foster the trainee involvement and therefore the training effectiveness and the safety contents' transfer. In this regard all the multimedia aspects contributing to the immersivity of the VR experience must be considered: graphic fidelity, audio contents and interactivity features.

All site objects included in the site layout modelled in the BIM authoring environment are usually present also in the delivered VR training scenario, whether they are directly transferred or replaced with more suitable VR versions. Nonetheless, depending on the objects or on the training typologies, site objects can present just a VR implementation due to their subsidiary function for immersivity and interactivity purposes related to the VR training experience (e.g. materials in storage areas, risks placeholders, PPE, manual tools, emergency equipment, etc).

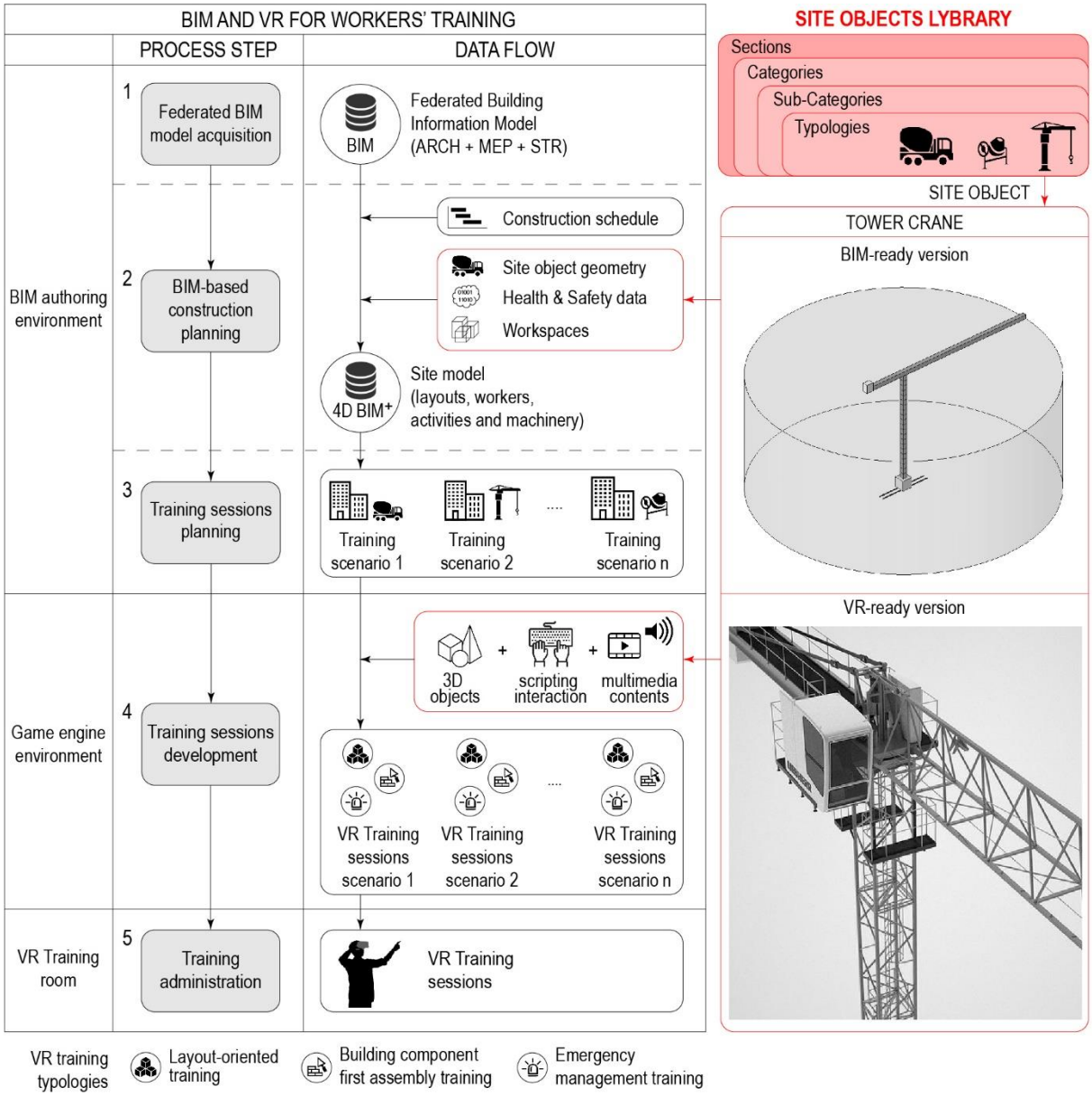


Fig. 1: Integration of the Site Objects Library in the proposed BIM-based implementation protocol for workers' safety training with Virtual Reality

Table 1: Typologies of safety training.

Training typology	Aims and contents
Layout-oriented training	The workers can experience the virtual reproduction of a forthcoming specific site layout configuration acknowledging the position, safety procedures and access and usage authorization for: site areas, equipment, facilities, plants, circulation paths, activity workspaces and specific risk zones.
Building component first assembly training	The workers can experience the virtual reproduction of a relevant construction activity (e.g. Building component first assembly occurrence) in the specific site layout in which it will take place, visualizing and interacting with the planned workspaces and learning about both the site and activities-related risks and the safety procedures to implement.
Emergency management training	The workers can experience the virtual reproduction of an emergency situation that could occur during a specific construction phase (and site layout/activities configuration), learning and implementing the planned emergency procedures, emergency equipment position and functioning, escapes route and rescue vehicles' paths. For the training purposes two typologies of emergency are distinguished: 1) Workers' illness or accident; 2) Fire.

3. RESEARCH OBJECTIVES AND METHOD

In order to provide a coherent framework for a library of virtual objects dedicated to the production of BIM-based immersive VR experiences for construction workers' safety training according to the aforementioned implementation protocol, the research focused on the following objectives:

1) *Site Objects' classification*: Identify and classify the objects required for the modeling and simulation of virtual reproductions of construction sites to be used for workers' safety training via immersive VR.
2) *Site Objects' requirements definition*: Define the objects' requirements in terms of geometry, information, graphics and interactivity features with reference to their uses; namely: worker's Health and Safety training, construction site BIM-based modeling and planning (4D) and construction site and activities simulation via immersive VR technologies.
3) *Site Objects' Information Sheet*: Design an information sheet common to all the objects' categories and serving as a library implementation support tool. In fact, all the relevant information identified for every object in the library are reported in the sheet allowing for a consistent object's choice and implementation in the construction site model dedicated for workers' training.
4) *Site Object Library's implementation and validation*: Implement the library with objects related to every identified category and according to the defined requirements. Validate the implemented objects with their adoption for the production of immersive VR safety training simulations based on the BIM model of the construction site.

The library implementation and validation are currently object of an on-going research and concerns the production of several immersive VR training experiences to be tested directly with the workers involved in the construction of the children's hospital "Stella Maris" in the city of Pisa (Italy). Therefore, leaving the detailed discussion of the related approach and results to future works, in the following steps is presented the method adopted for the library development (see Figure 2):

1) *Characterization of a generic construction site for workers' safety training purpose*: The first step in the development of the proposed site object library consisted in answering the following questions:

   - Which tangible objects, different from the building components, can be found in a construction site and are relevant for workers' safety training purposes? (equipment, scaffolding, fences, machinery, workers, etc.)
   - Which non-tangible objects could be relevant for workers' safety training purposes? (workspaces, site areas definitions, risks identification, etc.)
   - How could these objects be classified for their consistent implementation of BIM and VR site models for a generic construction project?

   In order to address these questions, it has been conducted the analysis of different knowledge sources, namely: literature (case studies); construction site imagery and national (Italian) Health and Safety regulation about construction site and workers' training.

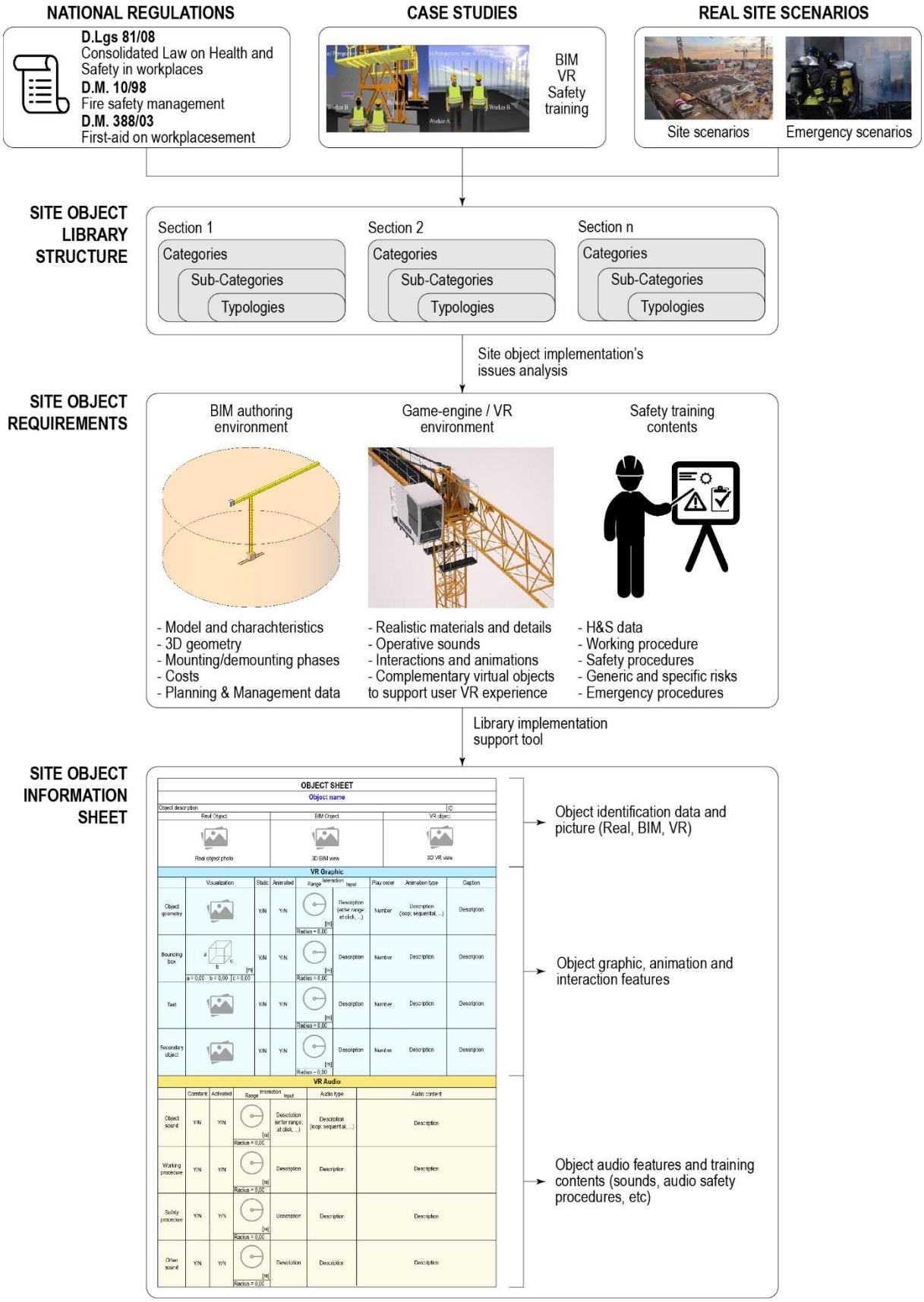


Fig. 2: Site Object Library development workflow

2) *BIM and VR site objects' requirements:* In order to define the objects' requirements in terms of geometry, information, graphics and interactivity features, the authors focused on their implementation processes in the BIM authoring environment (site planning) and in the game-engine environment (VR training experience production), keeping in mind the objects' purpose in term of transfer of H&S contents.
3) *Site objects' Information Sheet design:* After the identification of the objects' requirements, a further research effort regarded the design of a single-page sheet comprising all the relevant information of each object. Thereby the H&S managers using the library are provided with an effective implementation support tool, so that they could search and choose the most suitable object just going through their information sheets, before importing them in BIM or VR authoring environment.

4. SITE OBJECT LIBRARY FOR BIM-BASED WORKERS' SAFETY TRAINING WITH VIRTUAL REALITY

4.1 Structure of the Site Object Library

The results of the analysis conducted for the characterization of the general construction site (literature, case studies, national regulation) with the purpose of the production of workers' safety training-oriented contents, determined the division of the proposed Site Object Library into the following three main sections (see Fig. 3):

1) *Construction site layout and activities*: This section comprises all the tangible and non-tangible objects which can be identified in a construction site and are relevant for the description of its layout configuration and on-going activities. The objects classified under this section are used to represent in a virtual site model not only the physical components and equipment but also the workspaces and the risks related to the environment and construction activities. They allow the production of BIM site models and VR scenarios dedicated to "Layout-oriented" and "Building component first assembly" training typologies.
2) *Emergency management – Fire*: This section comprises all the objects which can be identified in case of fire on a construction site and are relevant for the emergency management training.
3) *Emergency management – Illness*: This section comprises all the objects which can be identified in case of workers' illness or accident on a construction site and are relevant for the emergency management training.

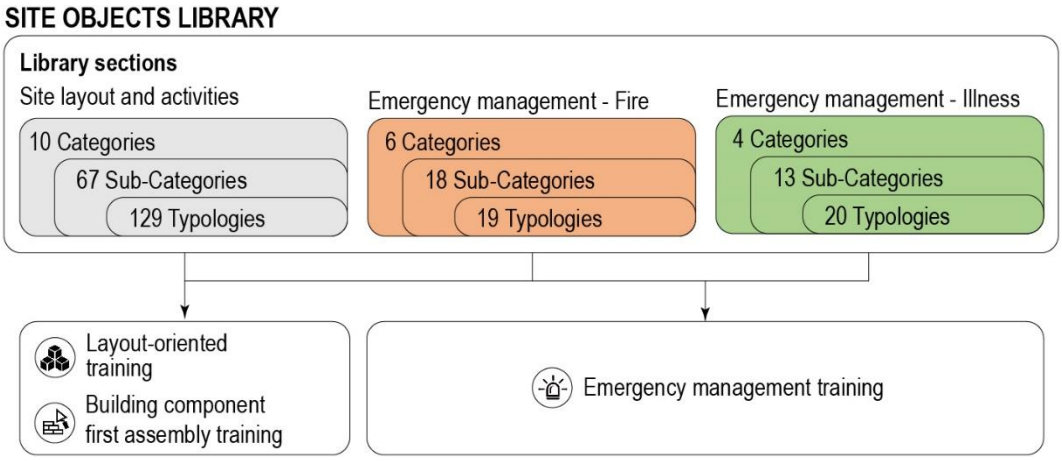


Fig. 3: Structure of the Site Object Library

Each section presents a three-level progressive classification for the objects based on categories, sub-categories and typologies. The "Emergency management" sections of the library dedicated to both Fire and Illness emergency training are currently in progress and will be discussed in future works. The object classification of the "Site layout and activities" section is reported in the following Table 2-3.

Table 2: Site Object Library: Construction site layout and activities modeling (continues).

	Real site			BIM	VR
Workspaces	Construction site			X	X
	Main entrance	Main gate guard house		X	X
		Access barrier		X	X
	Materials staging areas	Mechanical materials area		X	X
		Instrumentation materials area		X	X
		Garbage area		X	X
		Excavation ground area		X	X
	Machine areas	Fabrication area	Iron	X	X
			Wood	X	X
			Concrete	X	X
	Working area	Dig			
	Parking	Worker		X	X
		Site construction machines		X	X
Warehouses	Office			X	X
	Sanitary facilities			X	X
	Portable toilet			X	X
	Changing facilities			X	X
	Storage of personal protective equipment			X	X
	Perishable materials			X	X
	Refectory			X	X
	Dormitory			X	X
	Medical room			X	X
	Waste container			X	X
Worker	Workman				X
	Engineer				X
Service lines	Electricity			X	X
	Grounding set				
	Water supply	Service water			
		Sewage			
	Gas line			X	X
Preparations	Fences for construction site	Polyethylene orange net		X	X
		Stand alone panel		X	X
		Hiding fence		X	X
		Road barriers			X
		Concrete road barriers		X	X
	Parapet			X	X
	Scaffolding			X	X
	Wheeled tower			X	X
	Forklift			X	X
	Construction site elevator			X	X
Viability	Driveway entrance			X	X
	Driveway exit			X	X
	Pedestrian entrance			X	X
	Pedestrian exit			X	X
	Driveway	Internal		X	X
		External		X	X
	Walkway	Internal			
		External			
Risk identity	High-altitude fall				X
	Slipping				X
	Opening in the floor				X
	Material falling from above				X
	Interaction with other works				X
	Risk of burning				X
	Risk of electrocution				X
Site construction machines	Heavy earth moving	Digging and loading	Excavator	X	X
			Dredge		
			Loader	X	X
		Transport	Dumper		
			Lorry	X	X
		Digging and transport	Bulldozer		
			Trailblazer		
			Leveler		
			Telehandler		

Table 3: Site Object Library: Construction site layout and activities modeling.

		Real site		BIM	VR
Site construction machines	Lifting and material handling machinery	Crane	Jib crane for scaffolding		
			Column slewing jib		
			Bridge crane		
			Gantry crane		
			Tower crane	X	X
	Concrete machine	Batching plant		X	X
		Concrete mixer truck		X	X
		Concrete mixer		X	X
		Truck concrete pump		X	X
	Forklift				
	Truck			X	X
	Truck crane				
	Bobcat				
Various	Red speaker				X
	Private cars				X
	Van			X	X
	Bag of cement				X
	Block of cement				X
	Cable reel				X
	Pallet				X
	Worktable				X
	Ground aggregation				X
	Text - Score				X
	Text - Input				X
Poster advertising	Construction site poster				
	Prohibition	No access for unauthorised person			X
		Smoking and naked flames forbidden			X
		Work in progress			
		Do not extinguish with water			
		Not drinkable			
		Do not remove the emercency devices and protections			X
	Warning	Corrosive material			
		Toxic material			
		Explosive material			
		High temperature			
		Drop			
		Opening on the ground			
		Oxidant material			
		Overhead load			X
		Danger:electricity			
		Danger: digging			X
		Work in progress			
		High-altitude fall material			
		Obstacles			
		Industrial vehicles			
		Scaffolding under construction			
		Vehicles exit			X
	Mandatory	Wear respiratory			X
		Wear ear protection			X
		Wear safety helmet			X
		Wear safety shoes			X
		Wear safety gloves			X
		Wear safety overall			X
		Wear safety harness			X
		Wear eye protection			X
		Wear face protection			X
		Pedestrians on right			
		Check ropes and chains			
		Vehicle at walking pace			
	Safety	See related Library section			
	Fire fighting	See related Library section			
	Signs	Sign for marking obstacles			
		Sign for marking dangerous locations			
		Sign for marking traffic routes			

4.2 Requirements of the Site Objects (BIM vs VR)

From the implementation of the cited BIM-based protocol for the development and administration of VR experiences for workers' safety training and from the analysis of similar applications in case studies, real site scenarios and national health and safety regulation, emerged that the virtual representation of a site object has the following different requirements depending of the purpose and the environment for which they are intended to be used.

4.2.1 BIM Site object

BIM site objects commonly used for the construction site planning process have different graphical and informative development levels (LOD-LOI) set depending on the project phase and requirements. In order to leverage the site layouts resulting from this process for the development of site-specific VR safety training scenarios, the graphical detail of the site objects should be limited in order not to affect the file performance in the selected BIM authoring platform, considering moreover that they are mostly replaced with more detailed objects in the VR development environment for immersivity purposes. Nonetheless, is crucial that the information regarding the following safety training aspects is added to the site model via dedicated objects or customized parameters: workspace and paths, risks evaluation results and placeholders, workers' positions, working and safety procedures. This information serves then for the development and customization of the VR objects' features: multimedia contents (audio/video), animation, interaction.

4.2.2 VR Site object

The production of immersive VR experience for workers' safety training based on site-specific scenarios exported from BIM models involves the replacement of the most part of the implemented site objects with their dedicated VR-oriented counterparts. According to the exported safety training-related contents cited above, the VR site objects are in fact customized in terms of audio, graphic and interactivity features to enhance the experience realism and immersivity and therefore to improve the trainee involvement and the safety contents transfer. In this regard, the identified features which characterizes a VR-oriented site objects can be distinguished for Graphic and Audio contents as reported below (see also Fig. 4):

- VR Graphic: The visualization of the site object in the VR environment comprises 4 aspects that exceed the BIM object capabilities:
  - *object geometry* with an appropriate level of detail and realism depending on the selected VR technology,
  - object tridimensional *bounding box*
  - possible additional *text information* (e.g. labels with identification references, etc)
  - *secondary objects* for safety training purposes (e.g. virtual object for training supports such as direction arrows, interaction placeholders, etc).

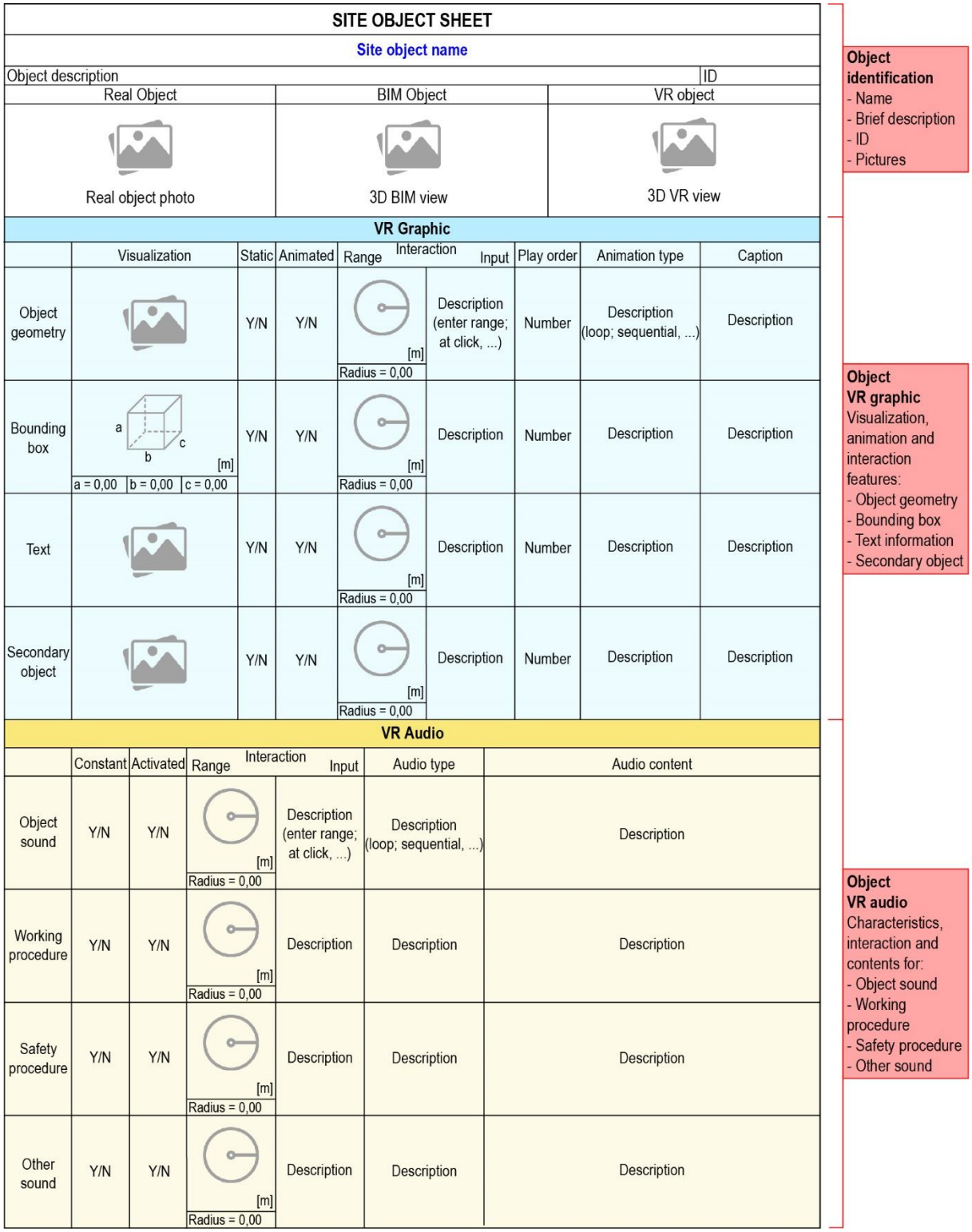
  Depending on the training purposes and object characteristics, each cited aspect can be visualized with graphic elements which are static, animated or both. In case of animations, they can be activated within a certain *range* or in response of an user *input* in the VR environment and they can be presented in various *types* (e.g loop, sequential, etc) and in *ordered* combinations with other animations.

- VR Audio: The delivery of appropriate audio contents adds depth to the VR experience and strongly contribute to the training contents transfer in several ways. Considering the immersivity aspect of the VR experience, specific sound related to the site objects, construction activities and even the background sound of the construction site, can raise the realism of the experience and the involvement of the trainee if carefully controlled in order not to be too distracting for the training purposes. Nonetheless, the most important aspects regarding the audio features consists in the chance the offer to deliver training contents related to *working procedures*, *safety procedure* and interaction-related sounds (e.g. training notifications, objects activations etc). The mentioned procedures can be implemented on the scripted instructions included in the BIM version of the site object with dedicated voice recording or directly "read" from a speech synthesizer. As discussed above for the graphical animations, also the audio contents can be presented in different types (e.g. loop, sequential, etc), can be constant or activated within a certain *range* or in response of an user *input* in the VR environment.

4.3 Site Object Information Sheet

The following Site Object Information Sheet (Fig. 4) has been designed accordingly to the requirements identified above and in order to provide an operative tool which could both facilitate the implementation of the site objects

in the proposed library and drive and support the choices of the H&S manager during the production of the safety training experiences both in the BIM and VR environments. The proposed single-page sheet comprises all the relevant site object data in three sections, namely: *Object identification*, *VR Graphic* and *VR Audio*. Since the characteristics of the BIM version of the site objects is more limited and dependent on the safety contents which have to be transferred in the VR experience, the sheet focuses mainly on the VR graphical and audio aspects related to the requirements discussed in the previous paragraph and leaves the BIM information to the object representation in the top section (Object identification).



SITE OBJECT SHEET

Site object name

Object description	ID

Real Object	BIM Object	VR object
Real object photo	3D BIM view	3D VR view

VR Graphic

	Visualization	Static	Animated	Interaction: Range	Interaction: Input	Play order	Animation type	Caption
Object geometry		Y/N	Y/N	[m] Radius = 0,00	Description (enter range; at click, ...)	Number	Description (loop; sequential, ...)	Description
Bounding box	a, b, c [m] a = 0,00 b = 0,00 c = 0,00	Y/N	Y/N	[m] Radius = 0,00	Description	Number	Description	Description
Text		Y/N	Y/N	[m] Radius = 0,00	Description	Number	Description	Description
Secondary object		Y/N	Y/N	[m] Radius = 0,00	Description	Number	Description	Description

VR Audio

	Constant	Activated	Interaction: Range	Interaction: Input	Audio type	Audio content
Object sound	Y/N	Y/N	[m] Radius = 0,00	Description (enter range; at click, ...)	Description (loop; sequential, ...)	Description
Working procedure	Y/N	Y/N	[m] Radius = 0,00	Description	Description	Description
Safety procedure	Y/N	Y/N	[m] Radius = 0,00	Description	Description	Description
Other sound	Y/N	Y/N	[m] Radius = 0,00	Description	Description	Description

Object identification
- Name
- Brief description
- ID
- Pictures

Object VR graphic
Visualization, animation and interaction features:
- Object geometry
- Bounding box
- Text information
- Secondary object

Object VR audio
Characteristics, interaction and contents for:
- Object sound
- Working procedure
- Safety procedure
- Other sound

Fig. 4: Site Object Information Sheet (blank fac-simile)

5. CONCLUSIONS

At this development stage, the research achieved its first three objectives with the proposition of a Site Object Library for the BIM-based production of VR experiences for workers' safety training according to a prototypical dedicated protocol. In fact:

1) Site objects that are relevant for H&S purposes have been identified and classified within a three-level framework comprising three sections with three progressive sub-categories for a total of 168 objects' typologies;

2) The information requirements for the virtual site objects for safety training purposes have been outlined considering both the BIM and VR contents' development environments comprised in the safety training protocol, stressing the importance of the multimedia and interaction features that they should provide for they effectiveness during the training experiences.

3) A Site Object Information Sheet has been designed as an operative support tool for the library implementation and in order to support H&S managers during the VR training scenarios and contents' production.

The next steps of the research, that is currently focused on the production of VR safety training experiences for the workers involved in the construction of the new children's hospital "Stella Maris" in the city of Pisa (Italy), will concern the full library implementation, along with all the objects identified at this stage and its use and validation for the cited case study project. Therefore, the analysis and the discussion of the related results will be reported in a future comprehensive work.

ACKNOWLEDGEMENTS

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