WP 6: Tools and guidelines for improving/designing a resilient BE assessed through case studies and virtual training

T6.1 - Virtual training development: identification of performance-based features; implementation protocols of innovative solutions within VR/AR environments, accessed on site or remotely (smartphone, tablet…) and targeted on different users' profiles (i.e. technicians, rescuers, users).

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Abstract

A key role in making cities resilient has been acknowledged to raising risk preparedness and awareness of the urban communities, by appropriate education and communication strategies, which should rely on innovative and pervasive tools. In this regard, an outstanding paradigm shift is driven by the advancement of Virtual Reality (VR), which can take advantage of Serious Games (SGs), for helping individuals develop responsive behaviors in case of both slow and sudden disasters and, thus, boosting an effective human-urban-building interaction within a wider process of safety and sustainability. To this end, the deliverable describes a VR-SGs training prototype for multi-hazard scenarios in urban open spaces. The prototype integrates results from phenomenological and behavioral analyses and is applied to representative typologies of built environment. The prototype is demonstrated for heat wave protection and earthquake response through the design and implementation of its functional features – virtual environment, interaction mode, learning outcomes and storyline – and its informative contents, including simulation-based data on surface temperatures, falling debris extent and crowd motion.

Keywords

Multi-risk scenario, urban squares and buildings, universal thermal climate index, earthquake debris, crowd evacuation motion, game environments, user experience

Approvals

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Revision versions

Revision	Date	Short summary of modifications	Name	Partner
0.1	03.01.2023	Improvements in demonstration and discussion sections	Enrico Quagliarini Gabriele Bernardini Fabio Fatiguso Mariella De Fino	UNIVPM POLIBA
0.2		Minor comments in demonstration and discussion sections	Enrico Quagliarini Gabriele Bernardini Fabio Fatiguso Mariella De Fino	UNIVPM POLIBA
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Summary

1. Introduction

The concept of urban resilience for climate change adaptation and disaster risk reduction has become a major concern for the scientific community, which has strongly focused on assessment methods and mitigation strategies for urban spaces, buildings and infrastructures (Cariolet et al. 2019; Ferreira and Lourenco 2019; Ni'mah et al. 2021; Heinzlef et al. 2022).

Nonetheless, a complementary key role in making cities resilient has been acknowledged to raising risk preparedness, awareness and perception of the involved communities (Mahajan et al. 2022), by appropriate education and communication strategies, with the double purpose to help individuals develop the behaviours, skills and knowledge they need in facing the hazards and to enhance the collective responsibility to participate in a wider process toward urban safety and sustainability (United Nations International Strategy for Disaster Reduction (UNISDR) 2015; Sakurai and Sato 2016). To this end, training tools are recommended that should deliver simple contents, real life examples, step-by-step actions, imagination and rehearsal challenges, by raising questions and providing a set of fairly straight-forward answers and solutions (Petal 2009). Consistently, the employment of a wide range of informative products is envisaged, including videos, games, social media and digital records, that can guarantee, among others, participatory learning approaches, users' engagement and flexibility in involving different target groups (Societies 2011). In this regard, an outstanding paradigm shift in communication strategies for urban community resilience might be driven by the advancement of Virtual Reality (VR), whose role for education purposes is widely accredited in all fields, including the Architecture, Engineering and Construction sector, where several applications include design teaching to students, safety preparation of workers for the construction site, operational instruction throughout inspection and maintenance (Li et al. 2018a; Wang et al. 2018; Chen et al. 2022; Tender et al. 2022), as well as emergency training for hazard simulation, evacuation wayfinding and proper use of protection devices in buildings and built environments (Lovreglio 2020a; Stone et al. 2021).

Based on the above-mentioned issues, the deliverable is going to present and discuss a prototype for VR training of users in urban open spaces as a driver for boosting community resilience and safety. According to the BeS2ecure workplan, the VR tool will follow a multi-hazard approach, including both SUdden-Onset Disasters (SUODs) and SLow-Onset Disasters (SLODs), it will integrate results from phenomenological and behavioural analyses, and it will refer to representative typologies of Italian urban open spaces in order to boost wide applicability. Particularly, among the SLODs (heat wave and pollution) and SUODs (earthquake and terroristic attack) investigated by the project, the combination of heat wave and earthquake is herein considered as the most relevant, based on the cross-assessment of available databases on critical events in Italian cities, as reported in D3.2.2.

2. State-of-the-art

2.1 Virtual Reality risk training

Focusing on the literature on VR-based risk training in buildings and built environments, as the most relevant for the present research, it should be observed that all the applications are referred to a single hazard emergency for a variety of purposes/users, as follows:

- Fire, from demonstrating the evacuation plan (route and exit identification, hazard source recognition, procedures for managing dangerous items) in favour of the building occupants and visitors (Smith and Ericson

2009; Sacfung et al. 2014; Cao et al. 2019; Oliva et al. 2019; Rahouti et al. 2021b; Shiradkar et al. 2021; Yang et al. 2021) to developing simulations on extinguishers and rescue procedures for fire fighters and operators (Cha et al. 2012; Moreno et al. 2014; Diez et al. 2016; Therón et al. 2020; Lovreglio et al. 2021)

- Earthquake (Gong et al. 2015; Li et al. 2017; Lovreglio et al. 2018; Sukirman et al. 2019; Feng et al. 2020a, b, 2022) where the users are instructed to follow the "drop, hide, cover" guidelines during the event, by making suitable choices and while experiencing the damage effects of the seismic shakes, and, then, exit an indoor environment to reach safely an outdoor gathering area;

- Flood for wayfinding and interaction with obstacles and people (Irshad et al. 2021; D'Amico et al. 2022), as well as for intuitive 3D visualization of hazard maps (Macchione et al. 2019) and mitigating public interventions (Fujimi and Fujimura 2020) in open spaces;

- Terrorist attack for training "run-hide-fight" reactions depending on the closeness to a gun-armed aggressor in an educational institution (Lovreglio et al. 2022) and showing the main sources of danger while escaping a train station after a bomb explosion (Chittaro and Sioni 2015).

The comprehensive analysis of all the above-mentioned papers highlights some recurring aspects despite the type of hazard emergency (Table 1).

Firstly, as far as the VR solution is concerned, only a limited number of works are based on the non-interactive visualisation of 3D models, displaying the effects of the hazard, such as fire smoke spread and flood water rising levels (Moreno et al. 2014; Macchione et al. 2019; Fujimi and Fujimura 2020).

Differently, the great majority exploits the potential of interactive Serious Games (SGs), where virtual gaming is used as an innovative approach for training and educating people, rather than just entertaining them. VR-SGs are based on engaging and interactive 3D environments, where cognitive learning and physiological arousal are enhanced, so that the participants can gain and retain knowledge more effectively than by using traditional learning methods, such as slides, leaflets and seminars (Feng et al. 2018).

2.2 Serious Games

Among the VR-SGs, many are immersive, where the trainees feel surrounded by the virtual environment by means of headsets or multiple projected screens, while fewer are non-immersive (Smith and Ericson 2009; Moreno et al. 2014; Cao et al. 2019; Macchione et al. 2019; Rahouti et al. 2021b; Shiradkar et al. 2021; Yang et al. 2021; D'Amico et al. 2022), where the virtual environment is displayed using a desktop monitor or a smartphone. In general, non-immersive games are preferred when the application should meet cost/benefit optimization requirements, when the training is stationary, without any actual physical displacement of the participants, so that a limited field of view would not affect significantly the perceived experience and when the simulation-sickness, as a side effect during and after exposure to VR environments, is a prominent concern. Conversely, immersive VR-SGs are widely recognized as more effective, in terms of engagement, satisfaction, and presence (Buttussi and Chittaro 2021).

Risk	Users	VR solution	Immersivity	Perspective	Motion	Setting	Hazard/ Damage	Ref
Fire	University students	SG	-	TP	-	Floor plan of university building type	-	(Shiradkar et al. 2021)
	General public	SG	NM	FP	FL	Indoor rooms of building type	Quantitative fire smoke spread by CFD simulations and crowd movement by agent-based fire evacuation model	(Yang et al. 2021)
	Hospital staff	SG	NM	TP	-	Floor plan of the Vincent Van Gogh Hospital, Belgium	Qualitative fire and smoke effects by particle systems of the game engine	(Rahouti et al. 2021b)
	University students	SG	-	TP	FL	Interiors and exteriors of building at Bangkok University, Thailand	-	(Sacfung et al. 2014)
	General	SG	IM	FP	TP	Interiors of office building type	Fire smoke simulated by FDS	(Oliva et al. 2019)
	Museum visitors	SG	NM	-	FL	Interiors of museum type	-	(Cao et al. 2019)
	Children	SG	IM	FP	FL	Interiors of house type	Qualitative fire smoke based on case history by the City Fire Department	(Smith and Ericson 2009)
	General public	SG	IM	FP	FL	Interiors of airplane cabin, hotel room, control room, kitchen, warehouse and factory types	-	(Therón et al. 2020)
	Generic public	SG	IM	FP	-	Warehouse, electrical, office and worksite types	-	(Lovreglio et al. 2021)
	Firefighters	SG	IM	FP	FL	Interiors of two-storey building type	Quantitative fire dynamic simulation data from literature	(Diez et al. 2016)
	Firefighters	EM	NM	-	-	Urban/forest environment type	Quantitative fire spread based on customized algorithms	(Moreno et al. 2014)
	Firefighters	SG	IM	TP	FL	Interiors of Jukryeong road tunnel, South Korea	Quantitative fire dynamics data on fluid flows simulated by CFD	(Cha et al. 2012)
Earthquake	University staff	SG	IM	FP	TP	Floor plan of an office building at the University of Auckland, New Zealand	Qualitative scenario based on New Zealand Mercalli Intensity scale	(Feng et al. 2022)
	Hospital staff	SG	IM	FP	TP	Floor plan at the Auckland City Hospital, New Zealand	Qualitative scenario based on New Zealand Mercalli Intensity scale	(Feng et al. 2020a)
	School staff	SG	IM	FP	TP	Interiors of school and office types	Qualitative scenarios based on New Zealand Mercalli Intensity scale	(Feng et al. 2020b)
	General public	SG	IM	FP	FL	Interiors of house and office types	Qualitative scenario based on historical database	(Li et al. 2017)
	Hospital staff	SG	IM	FP	TP	Floor plan at the Auckland City Hospital, New Zealand	Qualitative scenario from New Zealand Mercalli Intensity scale	(Lovreglio et al. 2018)
	University students	SG	IM	TP	FL	Interiors of dormitories at Nankai University, China	Quantitative scenario directly generated by a simulator platform	(Gong et al. 2015)
	Building occupants	SG	IM	-	FL	Interiors/exteriors of house type	-	(Sukirman et al. 2019)
Flood	General public	SG	IM	FP	TP FL	Interiors of parking lot and exteriors of town types	Quantitative water levels by hydraulic modelling	(Irshad et al. 2021)
	General public	SG	NM	FP	FL	Interiors of building and exteriors of a town types	Quantitative water level values from simulation modelling	(D'Amico et al. 2022)
	General public	EM	NM	-	-	Exteriors of the old town of Cosenza, Italy	Quantitative water level maps from numerical hydraulic simulation	(Macchione et al. 2019)
	General public	EM	IM	TP	FL	Exteriors of town and river types	Qualitative water rising and evacuees' running	(Fujimi and Fujimura 2020)
Terrorism	University students	SG	IM	FP	TP	Floor plan of university building type	Qualitative characterisation of terrorist attacker and gun based on reported statistics and previous studies	(Lovreglio et al. 2022)
	General public	SG	IM	FP	TP	Interiors/exteriors of train station type	Qualitative scenarios derived by traditional, publicly available civil defence materials	(Chittaro and Sioni 2015)

Regardless the level of immersivity, VR-SGs frequently show the following game choices:

- The training contents are delivered as learning objectives by subsequent and self-contained scenarios within a storyline, where the player is asked to solve a problem, make a choice or take an action in relation with virtual items and characters and, afterwards, he/she is instructed on the right answer by immediate feedback. This approach is acknowledged as beneficial to improving the understanding and recall, as well as to promoting the immersion and motivation of learners (Padilla-Zea et al. 2014).

- The player interacts with the virtual world by first-person perspective, thus seeing the scenes through the virtual character eyes, instead of third-person perspective, when the user plays as the avatar with a camera view behind the virtual body. This is proved to be outperforming, because it might induce a sense of embodiment toward the virtual body trough self-location and ownership (Gorisse et al. 2017).

- The navigation might rely on teleporting, which allows at moving from one pre-set wait point to another, in order to prevent disorientation and motion sickness, especially in wide and complex environments. However, free locomotion is chosen, particularly when the tasks are quite simple and limited in space and/or the application involves some post-training behavioural assessment.

2.3 Built environment and hazard modelling

Furthermore, as far as the modelling of the environment is concerned, except from some cases related to fire (Moreno et al. 2014) and flood hazards (Macchione et al. 2019; Fujimi and Fujimura 2020), VR-based risk training applications are generally developed within indoor scenes (e.g. offices, universities, hospitals). The environments might be either the virtual replicas of real places that the trainees are usual occupants of (e.g. workers, students, staff) or some representative typological models, whenever the training should be usable for a wider set of users/situations. In both cases, great care is given to displaying realistic settings, in terms of colours, textures, lightening and furniture, and to animating realistic Non-Playable Characters (NPC), namely avatars not controlled by the SG user. Only in a few cases the NPCs are designed, in terms of actual position and movement, according to preliminary agent based simulations (Yang et al. 2021; D'Amico et al. 2022). Differently, the outdoor spaces, as the main training environments or as the safe areas that players reach at the end of the indoor training, are generally more simplified and schematic, due to their complexity and extent. Only in one case, such a schematization results from the taxonomic assessment of real cases (D'Amico et al. 2022).

Similarly, the VR hazard/damage representation is a key issue in most applications. Two main approaches might be undertaken: quantitative and qualitative. The quantitative approach implies the preliminary customized simulation of the event for a specific context, based on the availability of detailed data on both the hazard (e.g. origin, magnitude, duration) and site (e.g. material, constructional, morphological, functional) characteristics. It is quite common for flood (Macchione et al. 2019; Irshad et al. 2021; D'Amico et al. 2022) in order to estimate the water levels from hydraulic modelling, as well as for fire (Cha et al. 2012; Moreno et al. 2014; Diez et al. 2016; Oliva et al. 2019; Yang et al. 2021), when flame and smoke spreads are calculated by computational fluid dynamics (CFD) simulations. The qualitative approach, widely recurring especially for earthquake and terroristic attack training, relies on existing datasets from previous events in similar contexts or from institutional documents and it is recognized as a good balance between realistic representation and effective training, because it displays a plausible scenario and keeps the SG's developer free to locate the damage in strategic positions for specific learning purposes. In any case, most works pay particular attention to audio/visual effects to reproduce the emergency, although they avoid disturbing images, involving injury and death, that can violate ethical principles and induce distress in the engaging experience.

2.4 Proposed VR-SG approach

In view of the above, the proposed VR-based risk training prototype for users in urban open spaces is developed as SG, recognized as the most effective and appealing solution. Moreover, in order to ensure wide and flexible application for different users/purposes, both the immersive and non-immersive versions are implemented and the overall structure is conceived as addition of self-contained training modules. However, from the methodological point of view, the prototype shows several original and novel aspects: it proposes a multi-risk approach, by considering couple events of heat wave and earthquake, that are not covered even as single risks by previous studies on VR training in outdoor settings; it involves the innovative representation of quantitative hazard/damage data for heat wave and earthquake VR training, from analyses on surface temperature distribution and falling debris, as well as from agent-based simulation of the crowd position; it displays VR environments resulting from taxonomic typologies of urban open spaces by balancing the realism of the scenes, the adaptability to several contexts and the computational feasibility.

3. Methodology

The development of the VR-SG training prototype in urban open spaces follows two main stages: (i) the identification of the methodological framework, as reported in the present section, where the correlation with the general research project outcome is also highlighted; and, (ii) the tool design and implementation, as reported in the section 4.

In detail, the methodological framework is outlined in Figure 1, with reference to the most common design requirements, namely *VR Environment*, *Perspective and Motion*, *Training Objectives* and *Items*, *Hazard/Damage* representation, *Non-Playable Characters* and *Storyline*.

Above all, it should be noted that the training is developed into three main subsequent phases: it is initially focused on the *Heat Wave* (*HW* - Phase 1) as an ordinary “slow” condition, which is overwhelmed by the extraordinary “sudden” effects of the *Earthquake* (*E* - Phase 2), which, in turn, leads to the *Post-Earthquake* scenario (*PE* - Phase 3) once the seismic shakes stop. This sequence is consistent with the multi-hazard SLOD-to-SUOD approach (Curt 2021), where the SLOD is used to populate the scenario, since it affects the distribution of the users “in” the public open space, whereas the SUOD appears in the SLOD-affected scenario and implies the evacuation “toward” the public open space.

Moreover, the sequence seizes the opportunity to build independent heat wave protection and earthquake response learning sessions, in order to address further inter-locking multi-hazard prototypes (e.g. heat wave + terroristic attack, pollution + earthquake).

Therefore, concerning the design aspects, the *VR Environment* is based on the representation of Built Environment Typologies (BETs), as identified in D3.2.1 and reported in (D’amico et al. 2021a). All the BETs were originally modelled as squares bordered by streets and buildings, through composition of schematic solid volumes. For the training purposes, the models need to be enriched with architectural details of the facades (frames, cornices, balconies) and urban furniture (outdoor bar/restaurant areas, street bollards). However, repetitive patterns, simple decorations and plain surfaces are chosen to keep the idea of a typological, although recognizable, context and to restrain the computational load. The First Person is considered as the most appropriate *Perspective* to enhance the embodiment, particularly in view of the non-immersive application, and the Teleporting is chosen as *Motion* solution, taking into account that the navigable area is wide and unfamiliar to the user, so that free locomotion could cause the trainees to get disoriented and the game to slow down.

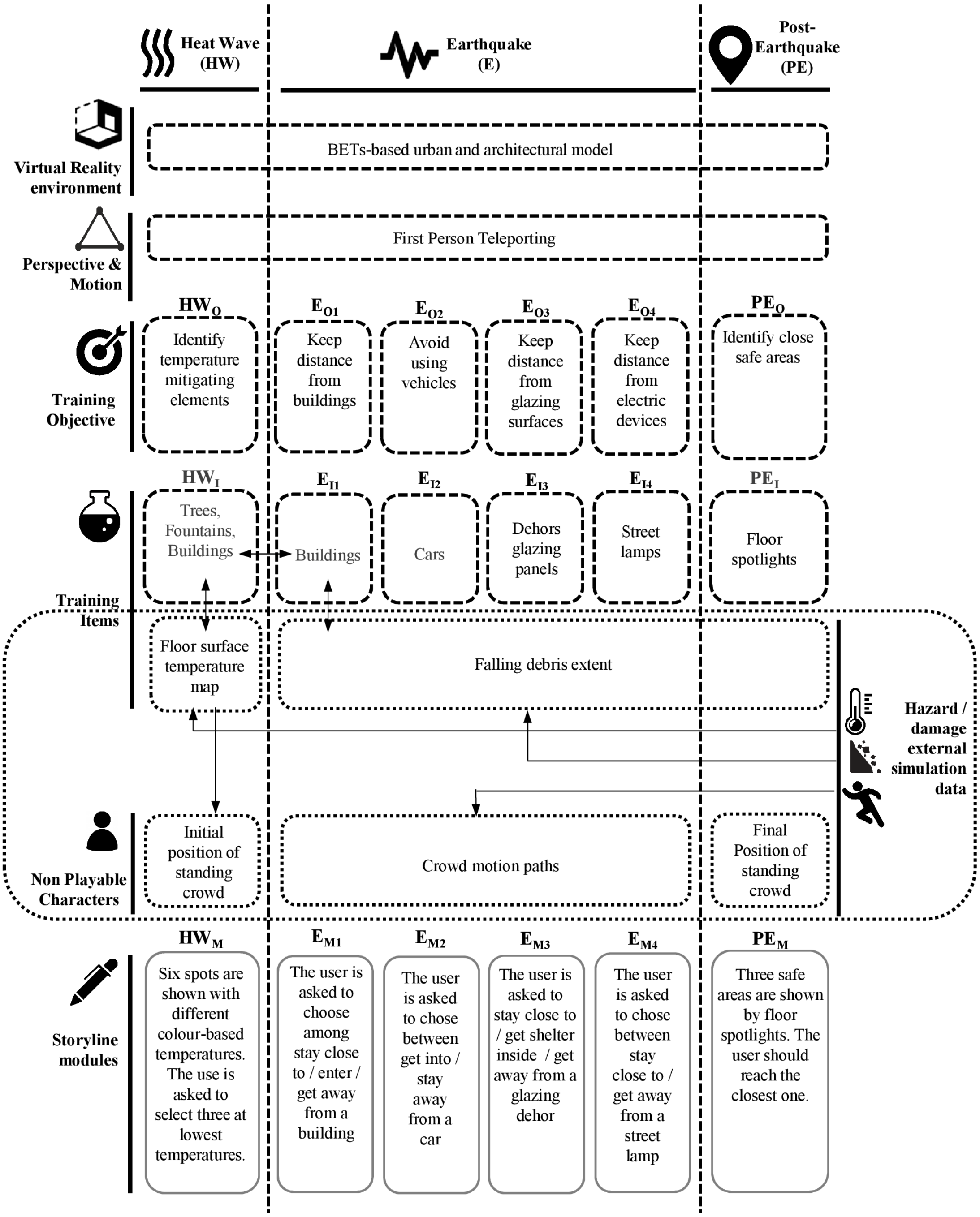

Figure 1. Methodological framework

The *Training Objectives* are based on national government documents (2023a, b), consistently with most state-of-the-art works. Particularly, for the heat wave protection, the recommendations by the Italian Ministry of Health are related to the identification of outdoor mitigating elements, where the temperature peaks are supposed to be lower compared to the surroundings (HW_O), whereas, for the earthquake response in open spaces, the rules by the Italian Department of Civil Protection are adopted on avoiding closeness to buildings that could collapse (E_{O1}), glazing surfaces/objects that could break (E_{O2}), vehicles that could hinder rescue operations (E_{O3}) and electric devices that could catch fire or emit sparks, (E_{O4}), as well as on reaching a designated safe area after the seismic shake (P_{EO}). Consistently, the scenes are populated by *Training Items* (e.g. trees, fountains, buildings, cars, glazing panels, street lamps) that could support the description of the learning tasks. Moreover, further *Training Items* are related to the hazard/damage representation, resulting from external simulation data on floor UTCI (Universal Thermal Climate Index) maps for the *HW* session and falling debris extent for the *E* and *PE* session.

In detail, according to D4.2.3, the floor UTCI map is generated for a specific location as a colour-graded, 5m x 5m spaced grid, which results from the elaboration of selected data of the hottest week from statistic open repositories by a tool-kit of three-dimensional microclimate simulation software tools (J. D. Blanco Cadena, M. Caramia, G. Salvalai; Blanco Cadena, Juan Diego; Caramia, Martha; Salvalai, Graziano; Quagliarini 2022). Moreover, according to D4.1., the falling debris extent is estimated, based on a damage matrix, which relates the damage grade of the buildings facing a square and the related presence of debris falling on the ground with the hazard and vulnerability of the open space (Bernabei et al. 2021). Simulation data are herein exploited also for the prediction of the crowd position and movement throughout the training, in order to model the *Non Playable Characters (NPCs).* In particular, the initial "standing" position in the *HW* session is associated to the probability of UTCI-based acceptability (Cheung and Jim 2019), while the motion paths during the *E* session and the final position in the *PE* session is estimated by an agent-based simulation, as described in D4.1 and D4.11_SW manual and reported in (Bernardini et al. 2023; Quagliarini et al. 2023). Finally, the *Storyline* is developed following a slightly different narrative for the three phases, in order to diversify the player-game interaction. In any case, it is articulated in independent modules, each one related to a specific *Training Objective* and correspondent *Training Item* (HW_I+ E_{I1}+ E_{I2}+ E_{I3}+ E_{I4}+ PE_I), in view of flexible expansion and adaptation. In the *HW* session, as a memory game, the user is asked to select some floor spots that are featured by lower temperatures, corresponding to mitigating elements (HW_I), after exploring the UTCI map, which fades out before the game starts (HW_M). In the *E* session, as a puzzle game, the user is asked to take a decision among several alternatives (E_{M1}, E_{M2}, E_{M3}, E_{M4},), related to the proximity of danger sources (E_{I1}, E_{I2}, E_{I3}+ E_{I4}). In the *PE* session, as a speed game, the user is asked to reach the closest safe area in the shortest time (PE_M), among the ones designated by projected spotlights (PE_I). Although independent, the modules are herein proposed in order to have a common *Training Item* at the end of the *HW* session and at the beginning of the *E* session, in order to highlight some correspondences within the multi-hazard vision. For instance, the item could be risk decreasing for one hazard (e.g. buildings casting shadow that mitigates the temperature) and risk increasing for the other one (e.g. buildings collapsing due to seismic shakes).

4. Demonstration

For the purpose of illustrating the operational choices and achievable results from the application of the proposed general framework, a demonstration is herein presented and accessible as a Video (see attachment). It is worth pointing out that the models and data displayed have been selected, among the available project outcome (e.g. BETs, UTCI maps, debris falling, crowd paths), in order to test representative and comprehensive conditions.

As far as the *VR Environment* is concerned, the BET was chosen as the most representative from the project cluster analysis, in terms of number of associated real cases on the Italian territory (about 35% of more than 1000 open spaces) and related occurrence of heat wave and seismic events (D'amico et al. 2021b). The selected BET2a (Figure 2), modelled within MAXON Cinema4D® from the available Autodesk Revit® BIM design (Figure 3), corresponds to a trapezoidal-shaped urban square of about 2000 m^2, bounded on all sides by the fronts of buildings with an average height of 20 m and accessible by pedestrian streets at the four corners. The main characteristics of the BET are the presence of: building façades with probability of overturning in case of earthquake and obstructing the open space; two dehors and a church hosting users in crowd conditions due their use, a central sculptural moment and a series of street bollards which can be obstacles for the users' movement and slow down the evacuation process. Compared to the basic project configuration, in order to fulfil the *Training Objectives* and related *Training Items*, the monument corresponds to a fountain and two of the southeast street bollards to trees (*HW_I*), while a south bollard is replaced by a streetlamp, a car is added near the church, and transparent envelope surfaces are provided for the dehors (*E_I - PE_I*).

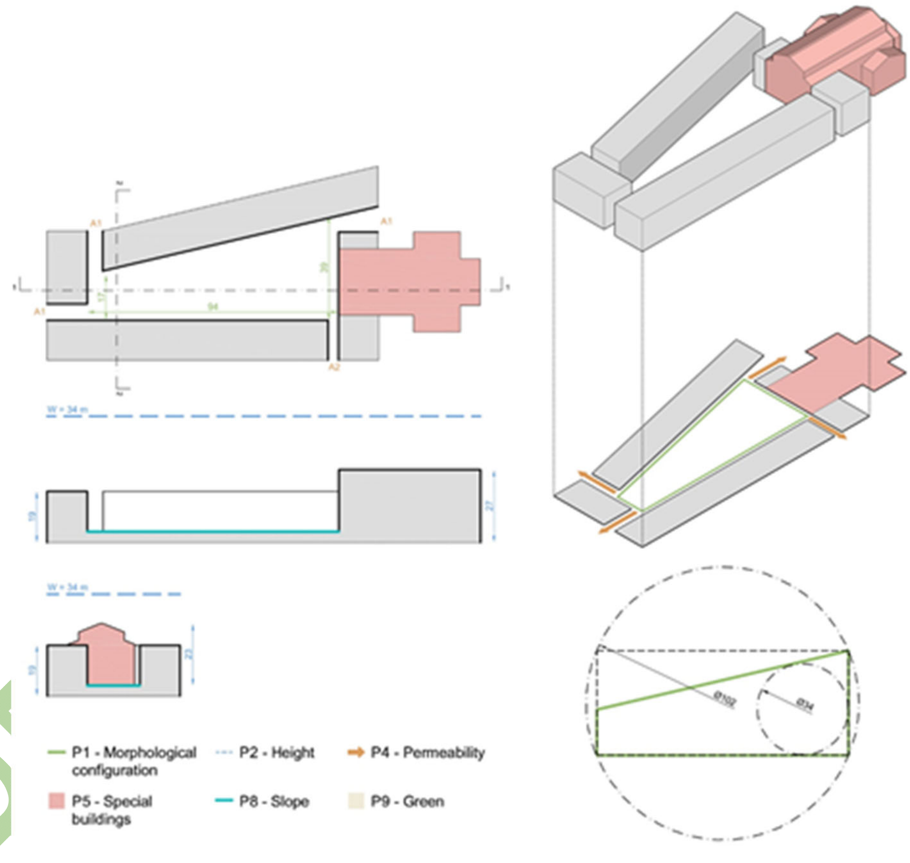

Figure 2. Bes2escure BET2a

All the assets were imported within the Epic Unreal Engine 4.6® simulative programming environment (Christopoulou and Xinogalos 2017) for the preliminary surface texturing and light mapping of the scene and the following development of the game, by programming of the user interface, implementation of visual, sound and special effects, as well as animation of characters, depending on the narrative sessions and modules, as detailed below.

In general, it should be outlined that, within the simulative environment, the interactive contents and player experience are available in First Person *Perpsective* and Teleporting *Motion,* adopting a dual, non-immersive and immersive, game mode. In the non-immersive mode, the mouse and the keyboard are used for controlling the 360° game view and behavioural choices, respectively. In the immersive mode, tested on the VR headset Meta Quest 2, visual orientation relies on gyroscopic sensors and laser tracking, while gesture control is enabled by hand-based oculus touch controllers.

Figure 3. VR environment corresponding to the selected BET

Therefore, following the *Storyline*, after registering and being instructed on the general purposes of the simulation, in the first *Training Module (HW_M)* the player is placed at the northeast corner of the square, on whose floor a UTCI map in false colours from yellow to red is projected (Figure 4). In the specific case, the map refers of the city of Aosta (Italy) due to the wide range of thermal values (from 30°C to 38°C) compared to the available project datasets. The player can explore the map by moving through six spots, including three spots close to shading/mitigating elements, namely a building, the fountain, and a tree, at relatively lower thermal values ($UTCI_{1,\ building}$ = 30°C, $UTC_{I2,\ fountain}$ = 34°C, $UTC_{I3,\ tree}$=31°C, $UTC_{I4\text{-}5\text{-}6,\ generic\ square}$=38°C). For each spot reached by the player, the whole scene changes to the corresponding colour in the UTCI map and it is enriched by several effects (Figure 5), whose intensity is proportional to the thermal values, including visual animations - heat blurring - and sounds - shortness of breath and accelerated heartbeat. Furthermore, consistently with the communication strategy, the *NPCs*, at this stage in a “standing” position, are more concentrated in the most shadowed/mitigated spots, depending on the UTCI-based acceptability. Consequently, they are meant to facilitate the player in taking cues from the behaviour of other people while making decisions.

In line with the idea of a typological, although recognizable, context, for the *NPCs* it was chosen to use schematic and neutral figures that would contain the computational load and still allow for an overall effect of presence and movement. To this end, symbolic characters were designed with humanoid rigging, through the configuration of bones and weighted joints (Arshad et al. 2019) within Cinema4D (Figure 6). Nonetheless, they were programmed in Unreal Engine to display randomly up to thirteen different kinematic states of slow movements in order to make the crowd more realistic (Figure 7). With this configuration, about 300 characters were simulated without any video-game lag.

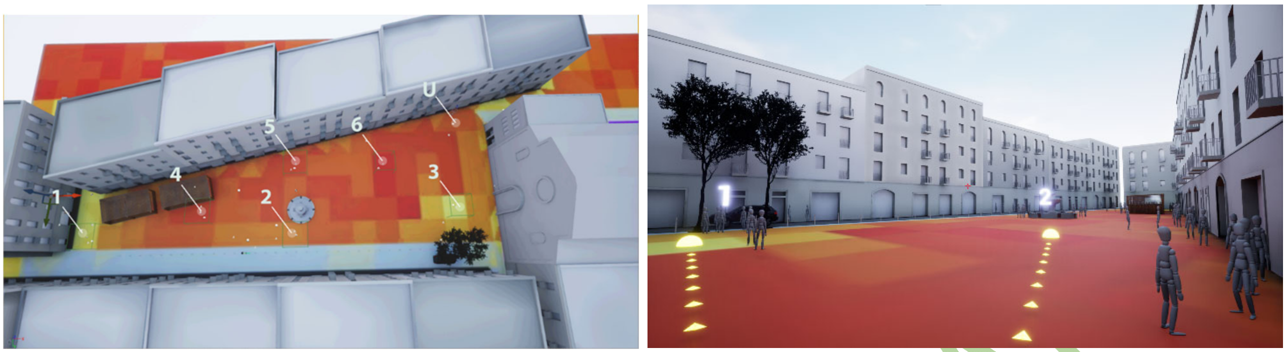

Figure 4. UTCI map from the initial user position (U) within the VR environment. Top (left) view, including the number of spot position in plan, and ground (right) view

Figure 5. Visual effects and NPCs during the HW session – spot 6 (left) and 3 (right)

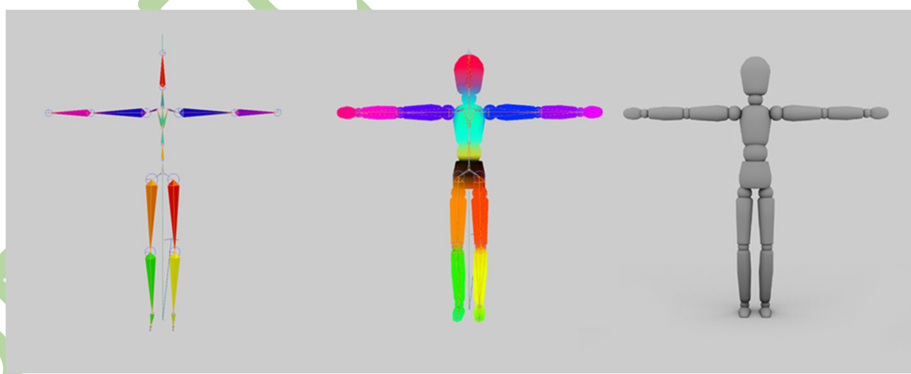

Figure 6. NPCs configuration diagram. From left: rigging phase, weighing phase, skin-rendering phase

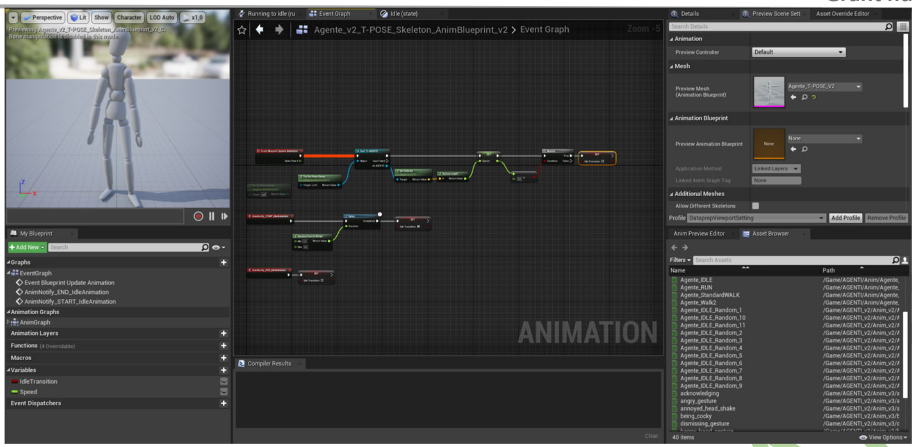

Figure 7. NPCs simulative kinematic configuration

At the end of the exploration, the player returns to the initial location and, having disappeared the thermal map and the related effects, is asked to select three locations with relatively lower temperatures, always being able to choose, from the initial and intermediate locations, between one right and one wrong option. After the selections are made, a feedback screen appears with the explanation of which the correct choices are and why, as well as the summary of the gained "lives"- maximum three - for the following sessions. The *HW* session ends close to the building on the west side of the square, corresponding to a shaded spot, which is thermal risk decreasing.

Here, the *E* session begins, where the same building is seismic risk increasing, due to potential debris falling. Particularly, in the first (E_{M1}) out of four *Training Modules*, the player is asked to take a decision (stay close to – enter - get away from the building) after visualizing the available choices, both as a list on a pop-up screen and as highlighted hot spots in the virtual spaces (Figure 8), where he/she can be teleported. The choice should be provided in the maximum time frame of 12sec, during which the most impacting debris falling occurs. This falling is purposefully concentrated in the very area and time frame in which this module takes place, having chosen, from the available project datasets, a scenario with higher vulnerability of the buildings on the west side, with an estimated debris width of 10.72m for a 475-year return period. In detail, for the game animation, a simulation was carried out within Cinema4D using MoGraph-Voronoi operators with attribution of physical properties of gravity, acting on mass, turbulence and force parameters, in order to achieve the expected visual configuration (Figure 9 and Figure 10). At the end of the module, a feedback screen appears with an explanation of what the correct choice is and why (Figure 11).

For the purpose of strengthening the training content, in case of wrong answer and subsequent loss of a "life" gained in the *HW* session, the player repeats the module. The aforementioned pattern – multiple choices, selection, teleporting, feedback - is repeated in the next three modules *($E_{M2\text{-}3\text{-}4}$)*, that are related respectively to the opportunity to avoid vehicles (get into - stay away from a car), proximity to glazed elements/surfaces (stay close to - get shelter inside - get away from glazing dehors), and contact with electrical devices (stay close to - get away from a street lamp), for which specific animations are also provided, such as glass shattering and sparkles.

However, more generally, in all the *E* modules, there are both visual - fire smoke and image shaking for seismic tremors - and sound effects - seismic tremors, crowd screams, car and property alarm systems, ambulance sirens - the latter ones appropriately diversified in frequency and intensity throughout the session to enhance the simulation realism. In the immersive mode, seismic vibrations are also simulated by the controller's haptics feedback.

Figure 8. Visualization of alternatives during the E session in a pop-up window (1- stay close to the building; 2 - enter the building; 3 - get away from the building) and in the virtual scene (3 – get away from the building)

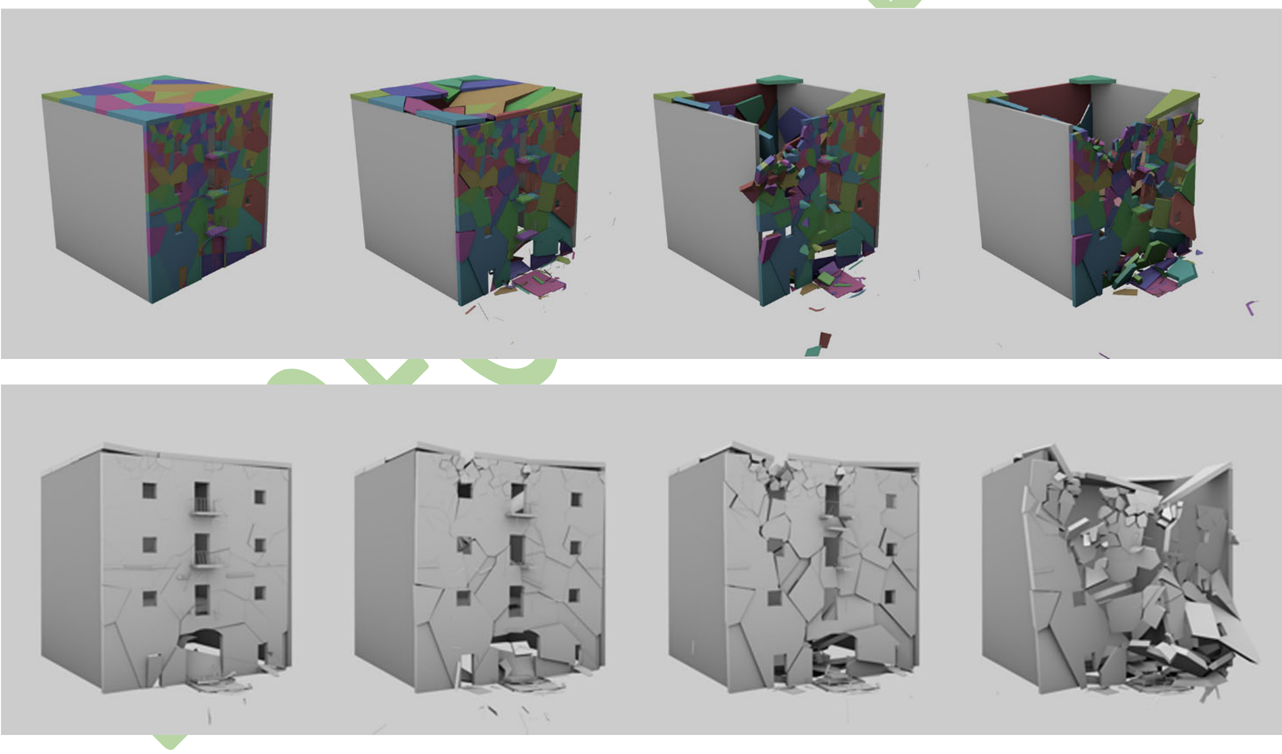

Figure 9. Collapse dynamics study: Voronoi subdivision evidence (above) and physical properties parameterisation analysis (below)

Figure 10. Study preview of the chosen collapse sequence in the 3D scene

Figure 11. Visualization of feedback screen during the E session after selecting alternative 2 (Wrong answer. It is recommended to move away from the buildings and the areas close to them, in order to avoid falling debris)

Furthermore, in all *E* modules, specific attention was paid to the crowd movement, in its double role of slowing down/distracting and leading/encouraging individual actions toward safe areas. In particular, given the initial position used in the *HW* session, the movement trajectories, the overall evacuation time and the final position refer to the outcomes of a specific project agent-based simulation. The simulation, which was based on a statistical profiling of the users by gender and age and on the discretisation of the space into 50x50cm cells, as reported in D4.1 and presented in (Bernardini, Quagliarini and Orazio, 2023), made it possible to estimate in 95 secs the time for each agent to reach the furthest position from the buildings, among the ones unoccupied by others, on the basis of movement rules linked to the speed and view factor of each agent, the admissible density of agents in a single cell and the presence of obstructive elements (Figure 12). Within Unreal Engine (Figure 13), the motion of the agents was programmed by Artificial Intelligence algorithms for path-finding that avoids contact with other agents and physical obstacles and it was designed through the implementation of 5-state mean interpolation based on the speed (Figure 14).

With this configuration, about 250 characters were simulated without any video-game lag.

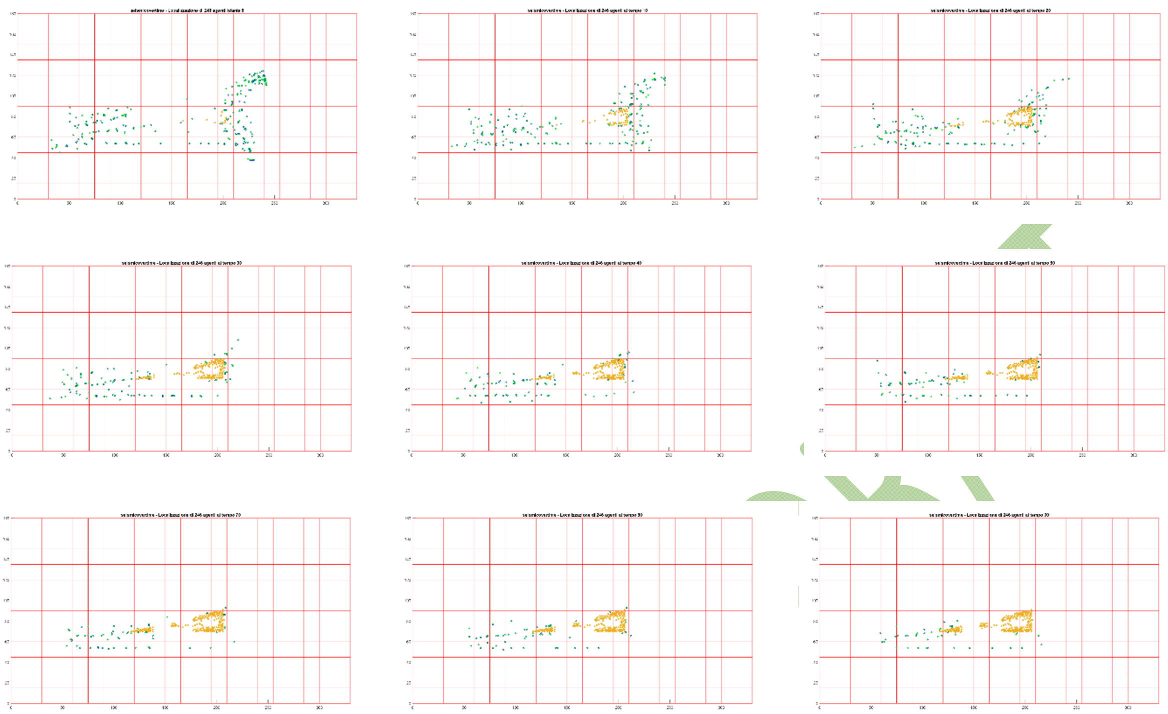

Figure 12. Crowd movement derived from the agent-based simulation every 10 secs

Figure 13. Crowd movement toward the centre during the E session

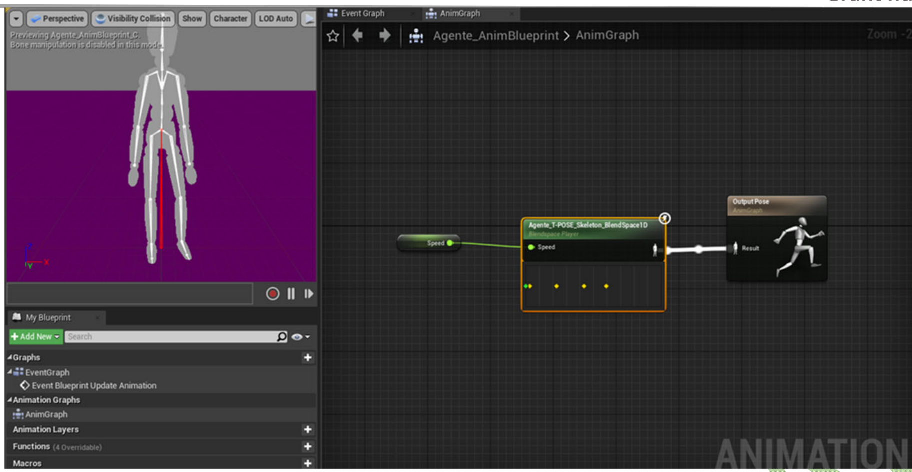

Figure 14. Kinematic motion programming via speed-based interpolation

It should be noted that the crowd movement develops independently of the time taken by the player to complete the responses in the *E* session (within the maximum limit of 12 secs per module), being able to variably extend also to the *PE* session. Furthermore, for the PE session, the final position of the *NPCs*, resulting from the project agent-based simulation, is used to identify and display areas in the centre of the square, suitably pointed out by directional street lights (Figure 15). Among these, corresponding to spots in furthest position from the buildings, among the ones unoccupied by others, the player must select the nearest one (PE_M), before ending the game and visualizing the remaining “lives” and the total time spent.

Figure 15. Highlighted safe areas in the PE session

5. Discussion

The proposed prototype was conceived to provide with an advancement in the state of the art on VR-SG training, with a view to scalability and flexibility for different conditions, in order to address wide application to real case studies.

As a matter of fact, from the methodological point of view, it relies on a novel multi-hazard approach, compared to single-risk training from related works, and it applies the modular structure of self-contained learning units to the sessions, in addition to the training objectives/items within the same session. Thus, it might enable multiple combinations, by addition of contents for specific contexts (e.g. instructions of local authorities, further urban elements that are either risk increasing or decreasing) or specific activities (e.g.

rescue operations, use of protection devices), as well as by application to single hazards or to different SLOD-to-SUOD training scenarios. In any case, the resulting digital product is versatile in terms of dissemination, since it envisages interactive non-immersive and immersive playing modes, besides the potential non-interactive recording of videogame exemplary sessions, differently from previous experiences. Accordingly, it might target users with different digital maturity, eventually depending on age, education and social/economic levels. Moreover, it might fit demonstration venues with several technological equipment, in terms of availability and number of computers and headsets. Furthermore, although supported by the innovative combination of quantitative simulation data on UTCI, falling debris extent and crowd position and motion, the proposed workflow might be equally carried out following a qualitative approach or using different hazard/damage sources, including those summarized in Table 1 (e.g. local sensors, statistical data, past events, intensity scales from national guidelines, scenarios by protection bodies, representations by game engine functionalities).

In addition, the application on representative typologies of urban spaces, while ensuring broad and adaptable enforceability, it makes the game development feasible for large-scale virtual environments, where a good balance among reliable representation, resourceful contents and computational load is paramount. In this regard, modelling reality-based three-dimensional settings for interactive exploration and action would affect the technical feasibility, compared to the applications in the literature, where only indoor environments are highly realistic and dynamic, while the motionless visualization is foreseen for outdoor scenes.

The above-mentioned balance also motivated the operational choices in developing the demonstration prototype. For instance, it was decided to display repetitive patterns, simple decorations and plain surfaces for the environment and schematic and neutral figures for the crowd, by giving more emphasis on the visual and sound effects and on the presence of numerous characters surrounding the player to make the experience engaging and authentic. Similarly, the training approach was based on the selection of alternative spots to reach by teleporting, rather than by more complex tasks, such as manipulation of objects or fulfilment of activities, whereas the purposeful interaction was mainly entrusted by the immediate feedback for each learning unit and the possibility to fail and repeat the choice as a way to strengthen the knowledge, assuming that errors are necessary steps in the learning process rather than an undesirable outcome.

All the recalled aspects open up to multi-purpose applications of the proposed methods and tools to real case studies. In particular, the prototype, due its scalable and flexible features, might be exploited for awareness rising on common rules in response to critical situations within “as-built” scenarios. To this end, great attention should be paid toward the spatial configuration (evacuation routes, gathering areas, obstructing and protective elements), the functional uses (special buildings and commercial activities with high people density) and the crowd motion (in its double role of slowing down/distracting and leading/encouraging individual actions toward safe areas). Additionally, the prototype might be used for communicating “as-designed” scenarios, by virtual simulation of specific mitigation and protection solutions, in order to test, on the one hand, their acceptability and usability as risk decreasing systems, and, on the other, their perceived compatibility as elements that visually and physically modify the open space known by the users. This kind of applications could also involve the visualization and selection of several design alternatives within the VR environment, such as street furniture layout and shaping; risk, wayfinding and emergency signs; positioning of first responders; flooring systems to point out safe areas).

The above-mentioned scenarios might involve different trained groups. The general public, including occasional visitors (e.g. tourists), could be instructed on risk management issues, eventually along with more conventional VR communication of historical and architectural contents. Differently, target groups of local stakeholders (e.g. citizens, neighbourhood associations) could contribute, through their training response, to participatory decision-making processes on risk assessment and resilience improvement.

Accordingly, the training and testing phases can be addressed to outreach resilience campaign by city management authorities. Nevertheless, they might also be suitable for behavioural analyses by scholars, in terms of wait-or-flight response depending on the training item/module, view-tracked attention toward specific events/elements, and repulsion-or-emulation of the crowd movement directions, that in turn might lead to specific insights on evacuation guidelines and practice.

6. References

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T4.1 Development of simulation model including human behavior representation and BETs modifications for selected SLOD/SUOD – SOFTWARE MANUAL