Built Environments Prone to Sudden and Slow Onset Disasters: From Taxonomy Towards Approaches for Pervasive Training of Users

Fabio Fatiguso[1(✉)], Silvana Bruno[1], Elena Cantatore[1], Letizia Bernabei[2], Juan Diego Blanco[3], Giovanni Mochi[2], Graziano Salvalai[3], Edoardo Currà[4], and Enrico Quagliarini[5]

[1] Polytechnic University of Bari, Bari, Italy
{fabio.fatiguso,silvana.bruno,elena.cantatore}@poliba.it
[2] University of Perugia, Perugia, Italy
{letizia.bernabei,giovanni.mochi}@unipg.it
[3] Politecnico di Milano, Milan, Italy
{juandiego.blanco,graziano.salvalai}@polimi.it
[4] "La Sapienza" University of Rome, Rome, Italy
edoardo.curra@uniroma1.it
[5] Polytechnic University of Marche, Ancona, Italy
e.quagliarini@staff.univpm.it

Abstract. The assessment of resilience for the Built Environment (BE) and humans exposed to SUdden Onset and SLow Onset Disasters (SUOD and SLOD) is possible when simulations are performed to predict and analyze what can succeed, and awareness and preparedness are consolidated among human users. These two steps require the representation of the Built Environment (BE), in its spatial, geometric and informative features, in order to be perceived by users. Nevertheless, different objectives and available economic, hardware/software and human resources will determine the selection of the methodological workflow and the software products chain. Thus, the research examines disruptive technologies for the creation of Digital Built Environments to highlight the potentialities of Virtual Reality in improving expert knowledge acquisition and awareness gathering. Particularly, the use of Digital Models, BIM and Virtual Tour based, supports analytical and parametric simulations and pervasive training, respectively. This last objective can be perceived through smart and inclusive Digital solutions, mostly shared via web applications, to reach a wider audience.

Keywords: Built Environment · Digital models · Human awareness · Pervasive training

1 Introduction

Resilience of the Built Environment (BE), comprehending human users, can be pursued both simulating human behavior in multi-hazard scenarios where Slow and Sudden Onset

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Disasters (SLOD and SUOD) can occur and providing risk maps within the real world after computing level of risks with quantitative or qualitative methods. These risk assessment and behavioral models are substantial for understanding which knowledge should be shared through training sessions to enhance urban resilience and human preparedness to catastrophic events against multiple risks [1]. Effective training is achievable with structured tools able to widespread and consolidate this knowledge reaching a wider audience. In this regards, disruptive technologies have been investigating for these goals in training, such as Virtual Reality (VR) and Augmented Reality (AR), which demonstrated high retention, self-efficacy and involvement, rather than traditional training material, such as slides, paper and video [2].

Describing VR or Virtual Environment (VE), it reproduces reality with specific devices after its acquisition or reconstruction in digital contents and allows an immersive experience within a digitalized environment that could not be necessarily close to the users [3]. Thus, in VR the interaction between user and environment is guaranteed by the use of traditional interfaces (monitors, keyboards and mouse) or by sophisticated devices (helmets, visors and motion sensors), able to transform the created environment from the virtual to the immersive level, enhancing perception and participation. VR applications address several purposes as they allow the visualization of reality data capture and/or the reproduction of building environment typologies, from territorial to building/element scale. As the built environment concerns, the VR aims to communicate, disseminate and enhance as well as manage and share data, information and knowledge about single buildings, system or parts to support interdisciplinary studies.

Whereas, AR uses mobile devices to superimpose elaborated digital contents to the reality when users activate specific applications, leaving user not isolated in the context [4]. AR implementations mostly address touristic application to augment monuments with supplementary information [5] or help users in finding touristic places with GPS, providing specific information. The AR technology is also being used for urban planning to overlay of new masterplan on the existing landscape, in project and construction to consult drawings and administrative and technical documents, during maintenance to retrieve instructions [6].

Among all the available techniques for the creation of VEs, Virtual Tours (VT) are identified as a smart and fast technique because of the use of panoramic images. The continuous representation and visualization of the BE are ensured by rotations of each scene linked with others [7]. Here, the sharing knowledge, as a technical discussion of the BE, is ensured by means of external data, properly organized and referenced in the visualized VE [8]. Also Building Information Modelling (BIM) could be employed for VR applications as extensive models [9]. BIM is an approach for generating, storing, managing, exchanging and sharing information about the BE during the life cycle [10, 11] with the capability of computing inserted parameters and collaboration among process figures. This thanks to ontological representation and data structure of geometry and information of elements, permitting some operations of query, filtering, extraction and computing of parameters.

The baseline for training objectives is the reconstruction of the BE that can be obtained with the previously described technologies, with the aim to recognize, represent and characterize it according to the granular decomposition of the BE for risk assessment scopes, as defined in the BE S^2ECURE project [12]. Indeed, this research started with the definition of typologies, elements and parameters at urban and architectural scale, focusing on the disaster events occurring in open spaces OS (such as squares and streets) and affecting humans, including the BE immediately surrounding the OS, defined as frontiers (Sect. 2). The hierarchy decomposition of the BE can be reconstructed with reality-capture techniques, BIM and GIS approach and navigated with AR/VR. In this research, where urban tissue is the baseline for multi-risk assessment, GIS may be useful to implement in the process. Recently, GIS transits from 2D GIS to 3D GIS and is combined with reality-capture, 3D City and BIM models for three-dimensional and semantic models of terrestrial surface and buildings in order to obtain a different level of detail, according to a specific use and thanks to exchange standards (i.e. cityGML and ifc) [13].

Moreover, these digital models of the BE can be navigated with fast VR/AR-oriented representations. In this perspective, the research will examine the above-mentioned disruptive technologies for pervasive training of users, to be distinguished by specific training for experts, aiming at increase resilience and preparedness against SLODs and SUODs, enhancing an aware knowledge of the BE and suggesting safe human behaviours. In particular, available methods and tools for analytical and parametric simulations and virtual training will be compared in terms of required economic, hardware/software and human resources in order to determine the selection of the methodological workflow for pervasive training, illustrated in Sect. 3. This last objective can be perceived through smart and inclusive Digital solutions (Sect. 4), mostly shared via web applications, to reach a wider audience anywhere at any time and that can be easily managed by local authorities.

2 BE and Parameters Involved in SLODs and SUODs

The BE characterisation represents the first step toward the definition of the risk level of an urban settlement prone to SUODs and SLODs and the development of effective mitigation strategies [14]. Particularly, how risk factors interfere with BE elements, modifying their setting and usability during disasters, and which BE characteristics lead to higher impacts [1]. In this regard, meso-scale risk assessments allow addressing all the aspects related to the elements of the BE, which belonging to the OS frontiers, the elements content in the OS itself and the OS users in a holistic perspective [1]. According to previous analysis, OSs can be categorized into different main type of AS and LS according to morphological approaches [15, 16]. Such configurations influence the evacuation aspects during SUODs, since LSs act as rescue roads and ASs as temporary outdoor gathering areas for the stricken population [17], while, determine the exposure risk factor for SLODs depending on factors related to the solar radiation, natural ventilation and pollutant concentration [18]. For example, shapes of AS tending to quadrangular or circular guarantee the same proximity to escape routes and, the central point may be the safest place in case of fronts overturning due to earthquakes; contrary, when such configurations favour large areas exposed to intense and direct solar radiation, heat entrapment, wind block and air pollutants concentration [18]. LS types are distinguished according to the level of vehicular and pedestrian traffic [15]. In fact, the simultaneous presence of vehicles and pedestrian determines risk factors: in the case of SLODs, influences air quality due to pollutant concentration; during SUODs, it can be dangerous for the evacuation during an earthquake, or even, it may represent a terrorist threat to people. Moreover, the dimension regarding the maximum height of the OS frontiers (H_{max} built front) is also relevant for estimating the possibility of path blockage from debris due to buildings collapse, and, the canyon effect thus reducing pollutants dispersion through ventilation and the risk of solar radiant exposure [18].

The definition of the OS geometry is provided by the types of elements of the OS frontiers and the OS itself. The permeability of the OS in terms of number, width and position of the accesses affect both SUODs and SLODs: multiple accesses enhance the evacuation process avoiding overcrowding; good permeability increases the ventilation. The greenery and water bodies presence and position within the OS influence the physical vulnerability for exclusively SLODs risks: they can mitigate the increasing temperatures and air pollution. On the other hand, the presence of special buildings, town walls, porches mainly interact with the SUODs risks: such constructions have more structural weaknesses (i.e. typical failure mechanisms) in response to earthquake [16]; buildings belonging to cultural heritage are more prone to overcrowding since being tourist attractions [19]. In addition, other elements content in the OS that involve a 3D spatial modification, such as fountains, monuments and quote differences, can be considered as obstacles for users during the post-earthquake emergency phase. Regarding terrorism, fixed or mobile elements in contents [20] represent the main elements that should enhance the vulnerability to a terrorist attack. Most of these parameters can be obtained directly from 2D or 3D models. In addition, either GIS or BIM tools can help enrich the quality and quantity of data collected to be used for studying the BE.

The constructive features of OS frontiers and the materiality of the OS itself influence the response to both SUODs [16] and SLODs [21]. In case of earthquakes, constructive features define the vulnerability in terms of structural performance and damage suffered by buildings that could determine the path blockages by debris, thus affecting the safety of OS users and preventing access to rescue [16, 22, 23]. The materiality and finishing of façades and OS pavement influence the heat balance, determining the façades and pavement surface capacity for capturing, releasing or emitting heat; thus, making its surroundings warmer or cooler.

Characteristics of use of the OS itself and the functions of the facing buildings provide the exposure risk factor of both earthquakes and terrorism by determining the number of OS users and the potential crowding conditions over the time which may increase disasters' casualties. Moreover, overcrowding may hinder the evacuation process and influence the behaviour and the motion of evacuees, especially of those that have no familiarity with the urban layout (i.e. tourists). Specifically, buildings of political, religious or cultural value (e.g. parliament, churches, monuments, museums, theaters) and specific uses of the outdoor space (e.g. nocturnal attraction for young people, special events) suggest the evaluation of the "exposed value" since they represent sensitive targets for terrorist acts [19]. Regarding SLODs, the space use and functions determine only crowding levels and type of users; however, these exposures shall be constant or recurrent, for the BE users, to generate significant health deterioration. The definition of the spatio-temporal users' pattern and the availability of database integrated with

Table 1. Summary of the main BE parameters described, specifying if they affect the whole OS or buildings (Bs) and the relation with Seismic (S) or Terrorism (T) SUOD, as well as Heat wave (H) or air pollution (P) SLOD

Macro-area for BE classification	Criteria	OS	Bs	Risk/s related			
				S	T	H	P
MAIN TYPE							
	Prevalent shape	x		■	■		
	Dimension	x		■	■	■	■
	H_{max} built front		x	■		■	■
	H_{min} built front		x	■		■	■
CHARACTERISTICS OF GEOMETRY AND SPACE							
Frontier	Structural Type (SA/SU)		x	■			
	Accesses	x	x	■	■	■	■
	Special buildings		x	■	■		
	Town walls	x		■	■		
	Porches	x	x	■	■	■	■
	Water	x				■	
	Quote differences	x		■	■		
	Green area	x	x		■	■	■
Content	Special buildings		x	■	■		
	Canopy	x				■	■
	Fountain	x			■	■	
	Monuments	x			■		
	Dehors	x			■		
	Quote difference	x		■	■		
	Archaeological sites	x			■		
	Green area	x				■	■
	Underground park	x		■			
	Underground cavities	x		■			
CONSTRUCTIVE CHARACTERISTICS							
Frontier	Homogeneity of built environment age		x	■			
	Homogeneity of constructive techniques		x	■		■	■
	Urban furniture/obstacles	x		■	■		
Content	Pavement/Surface materials	x				■	■
	Pavement lying	x			■		
	Pavement/Surface finishing	x				■	■
	Urban furniture/obstacles	x		■	■		
CHARACTERISTICS OF USE							
	Daily crowding	x	x	■	■	■	■
	Sensitive target to terroristic attack	x	x		■		

(*continued*)

Table 1. (*continued*)

	Vehicular accessibility	x					
	Pedestrian accessibility	x					
	Type of users	x	x				
ENVIRONMENTAL CHARACTERISTICS							
	Climatic zone	x					
	Type of infrastructures	x					
	Permanent elements (natural and man-made)	x					
	Hazard assessment	x					

GIS/BIM tools would enable a more precise and constantly updated definition of the real impacts [24, 25].

Finally, the characteristics of the environment where the OS is located contribute to the definition of the hazard level of SLODs according to the climate zone (e.g. maximum seasonal temperatures). Moreover, specific hazard that may affect the area (e.g. tsunami, landslide, wildfire, storm/tornado, etc.) and, the presence of strategic infrastructural network that may be susceptible to damage, are also considered as additional risk elements of both SLODs and SUODs.

All the described BE elements are then summarized in Table 1, relating to single SLOD and SUOD and highlighting the relevance with the scale of detail.

3 Approaches for the Pervasive Training in Virtual BE

Approaches and materials to enhance recognition and knowledge of BE elements that influence multi-risk scenarios, as screened above, will be investigated in this section to provide innovative and interactive VR tools for knowledge dissemination and pervasive training. The virtual training via VR can be implemented in several modalities, but the first objective to structure an effective tool is the reconstruction of the BE with different accessibility and fruition modes of the digital reality. The training material should be prone to web publication in order to reach the goal of widespread (pervasive) training materials for expert and non-expert users.

In the VTs, the VE is based on indoor and outdoor spherical images or videos, maintaining real colours and elements, linked together to re-create the building morphology [8] through locomotion switches. After the preparation of the baseline VT, this can be augmented with external media, in several common use formats, attached to interactive popups, called hotspots or widgets.

Nevertheless, VT can comprehend panoramas exported by 3D models, such as CAD and BIM. Moreover, BIM models themselves can be navigated in VR (both display-based and immersive), sometimes with the opportunity to query parameters added to each element, in remote mode or on-site using QRcodes and tags. The continuous digital flow from BIM and VR/AR applications requires the acceptance of shared languages (standards and exchange formats) for unique understanding among the software products, and interoperability when possible both on-desk and on-line applications. The transition from architectural to urban scale is supported by GIS models for which interoperability with BIM is created developing the open standard cityGML, after the conversion of IFC data from BIM models [26–28]. Moreover, the use of Reality capture outputs (meshes or point clouds) in 3D city models increases the recognition of each BE element affecting risk scenarios due to a higher level of detail and accuracy.

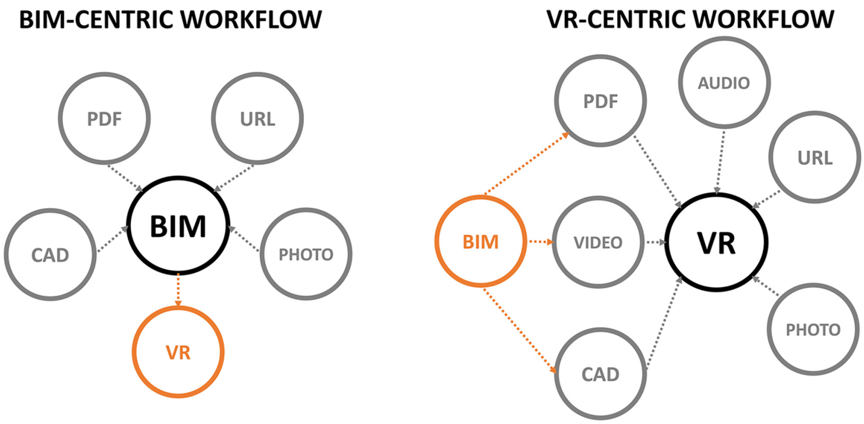

Fig. 1. BIM-centric and VR-centric data and information schema (authors)

According to the analysis of available approaches for VR, two typologies of workflows can be defined to link and read information and data (Fig. 1):

1. BIM-centric workflow: BIM modelling software products are mainly used to represent, analyse risks and then navigated in VR for training.
2. VR-centric workflow: virtual tours with 360° photos or videos acquired by cameras are the main tools for virtual training, immediately available for adding external information contents such as digitalized paper documents, video, and web pages, and progressively implemented with panoramas and 3D models from BIM or CAD and assessment outcomes, such as risk maps and evacuation simulations.

The selection of the methodological workflow for pervasive training is guided by the comparison of available tools and methods for analytical and parametric simulations and virtual training in terms of required economic, hardware/software and human resources.

The assessment of the different tools for training, BIM and VR, is carried out through the SWOT analysis which identifies strengths, weaknesses, opportunities and threats of each one beyond risk and resilience management purposes (Table 2).

Table 2. SWOT analysis between BIM (BIM-Centric) and VR (VR-Centric) workflows in representing Built Environments.

STRENGTHS (S)	BIM	VR	WEAKNESS (W)	BIM	VR
Better documentation	■	■	No universal software platform		■
Reduction of costs in overall process	■	■	High labor consumption	■	
Automation of drawing execution	■		Errors in reflecting the true form of the building	■	■
Representation with different level of details	■	■	High costs of implementation in a company	■	
OPPORTIUNITIES (O)			**THREATS (T)**		
High interest in use	■	■	Lack of legal regulations and binding standards		■
Implementation of the technologies in many countries	■	■	Lack of qualified and experienced standards	■	
Developing higher awareness among all stakeholders	■	■	Unwillingness of the contractors/clients/users to employ	■	■
Educating students	■	■			

The VR-centric workflow based on VTs demonstrates advantages in representation and usability capability via interrelated data sources built on top of a reality-based, comprehensive and rapid reconstruction of the BE through spherical panoramas or video. The most effective potentialities of VR-centric against BIM-centric workflows regard the usability features such as possible involvement of users with low expertise in software usage, lightweight outputs/file, ease of widespread, reduced cost for acquiring software, reduced cost for user software training. The use of spherical photos is an inexpensive technique because of the low costs of required tools (spherical head, tripod and remote control for remote photo shooting) and smartness in creating spherical images themselves. In fact, those are the result of a processing phase (acquisition of wide-angle images, alignment of them and photo-stitching) usually performed by the camera. In addition, the parameters related to the BEs can be modifiable over time, thus efficiency and low time consuming in updating BE representation may be investigated. According to this requirement, the most rapid updating and efficient management of VT emerge against time consuming and expensive modelling and arranging the reality in BIM and GIS applications, and this can be very useful for public authorities called to manage pervasive training tools. On the other hand, BIM-centric workflow allows a parametric modelling of objects with a structured and well-defined architecture to consult them with their properties, but the BE reconstruction can be very labor intensive because of the element-by-element modelling and expensive in terms of human resources to create it, software and hardware. This can lead organisations to select traditional approaches with CAD and documentation to disseminate knowledge about risk assessment. Nevertheless, BIM can be effective if it is selected for specific simulations and assessment, such as human behaviour modelling and risk indices and maps calculations. In this situation, the BIM deliverable identified as training material can be easily added to the VT, as an example, the videos of evacuation paths simulations.

For Macro-scale representation, 3DCity Models are configured as a powerful tool for the management and integration of multidisciplinary data, that can integrate BIM, VR and AR technologies. Moreover, the WebGIS solutions offer an intuitive, innovative and challenging way to incorporate, explore and analyse information in a pervasive manner of digital models of the BE via web. As the VT is a web-based tool, it can be loaded in a webGIS platform to create a network of cities where risk assessment and virtual training products have been configured. In webGIS can converge BIM models as well, if they have been created for specialist analysis of risk assessment. Thus, the 3D city model can be featured by all the potentialities and criticalities highlighted for VR and BIM-centric approaches due to the process of its implementation.

4 VR-Centric Approach Applied to BE Prone to SLODs and SUODs

Resulting from the previous discussion, the VR-centric approach has been examined in depth for the BE representation towards the main aim of pervasive training. In detail, the main features of VE based on VR-centric approach are declined to the BE and elements introduced for the risk assessment (Sect. 2).

In a VR-centric workflow, BE reconstruction for training can be conducted in three levels of representation (LoR):

A. n spherical photos (scenes) interlinked by switch hotspots;
B. n hotspot plans;
C. n hotspots.

The Virtual Tour created with *n* spherical photos, reality-based or model-based, (LoR A) can make immediately viewable the physical appearance in W direction (vertical axis), only with n scenes interlinked by shift hotspots, thus after the project of an acquisition plan. Major details of BEs can be obtained with minor distance between each 360° photos (in X, Y and W directions) and between camera and object. Each element of the frontier and the content of the OS (accesses, special buildings, town walls, porches, water, and so on) is easily and vividly recognized and identified within the 360° photos.

The perception of the morphological configuration of the OS is guaranteed by adding the *n* hotspot plans (LoR B), as they are 2D drawings and follow the user's movements, showing his/her field of view. Moreover, the number of scenes, enclosed in the plans, directly reflects the morphological features of BE, as well as influences the acquisition plans. In fact, the *n* hotspot plans also add visual perception (in X and Y directions), while the presence of several levels of acquisition in the same point of acquisition gives back the dimension of buildings heights (W direction) or relative differences between horizontal and vertical dimensions (Fig. 2). The higher level of detail is strictly related to the representation scale and representation accuracy of each hotspot plans.

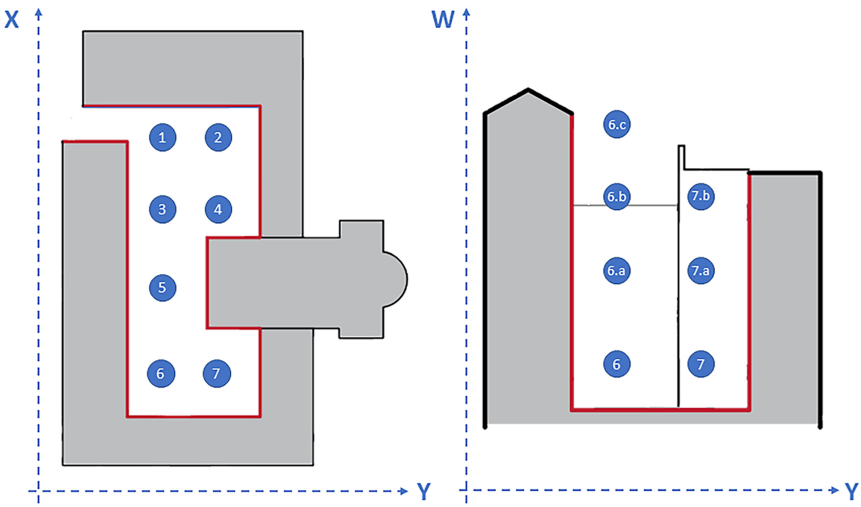

Fig. 2. Acquisition plan of spherical photos (scenes) in X, Y and W directions

The third level of representation C, in VR-centric workflows, consists of inserting hotspots to dynamically show additional and detailed information about the BE. After the insertion and augmentation of hotspots with external data, the BE can be fully reconstructed and training material can be shared. The external data to be shared and communicated can be derived from different sources and exchanged in different file formats (pdf, URL, videos, pictures, audio media, etc.) (Fig. 3). These media can describe the BE and its intrinsic and extrinsic features such as the analysis of morphological configuration, dimensions, structural type, special buildings, porches, slope and green, and so on (Table 3).

The BIM, when employed for risk assessment, can be integrated in the VR-centric workflow in each level of representation (A, B and C). Specifically, external data produced within a BIM-based approach are specified in Table 4.

The VT created for recognizing and disseminating BE criteria will configure material for pervasive training to be shared via web, supported also by tags in the real world, and navigated on displays or headsets. The pervasive training is based on web-based 3D city models (3D GIS) for navigating Virtual Tours, augmented with informative data about the BE, guidelines and procedures, in form of digital contents derived from BIM-centric workflows, useful to support public administrations in the risk management and widely enhance the preparedness of users with self-training.

Table 3. LoR of the entire set of BEs parameters in VR-centric workflow

Macro-area for BE classification	Criteria	LoR in VR		
		A	B	C
MAIN TYPE				
	Prevalent shape		■	■
	Dimension		■	■
	H_{max} built front	■		■
	H_{min} built front	■		■
CHARACTERISTICS OF GEOMETRY AND SPACE				
Frontier	Structural Type (SA/SU)	■		
	Accesses	■		
	Special buildings	■		
	Town walls	■		
	Porches	■		
	Water	■		
	Quote differences	■		
	Green area	■		
Content	Special buildings	■		■
	Canopy	■		■
	Fountain	■		■
	Monuments	■		■
	Dehors	■		■
	Quote difference	■		■
	Archaeological sites	■		■
	Green area	■		■
	Underground park	■		■
	Underground cavities	■		■
CONSTRUCTIVE CHARACTERISTICS				
Frontier	Homogeneity of built environment age			■
	Homogeneity of constructive techniques	■		■
	Urban furniture/obstacles	■	■	■
Content	Pavement/Surface materials	■	■	■
	Pavement lying	■	■	■
	Pavement/Surface finishing	■	■	■
	Urban furniture/obstacles	■	■	■
CHARACTERISTICS OF USE				
	Daily crowding			■
	Sensitive target to terroristic attack	■		■
	Vehicular accessibility	■		■
	Pedestrian accessibility	■		■
	Type of users			■
ENVIRONMENTAL CHARACTERISTICS				
	Climatic zone			■
	Type of infrastructures	■		■
	Permanent elements (natural and man-made)	■		■
	Hazard assessment			■

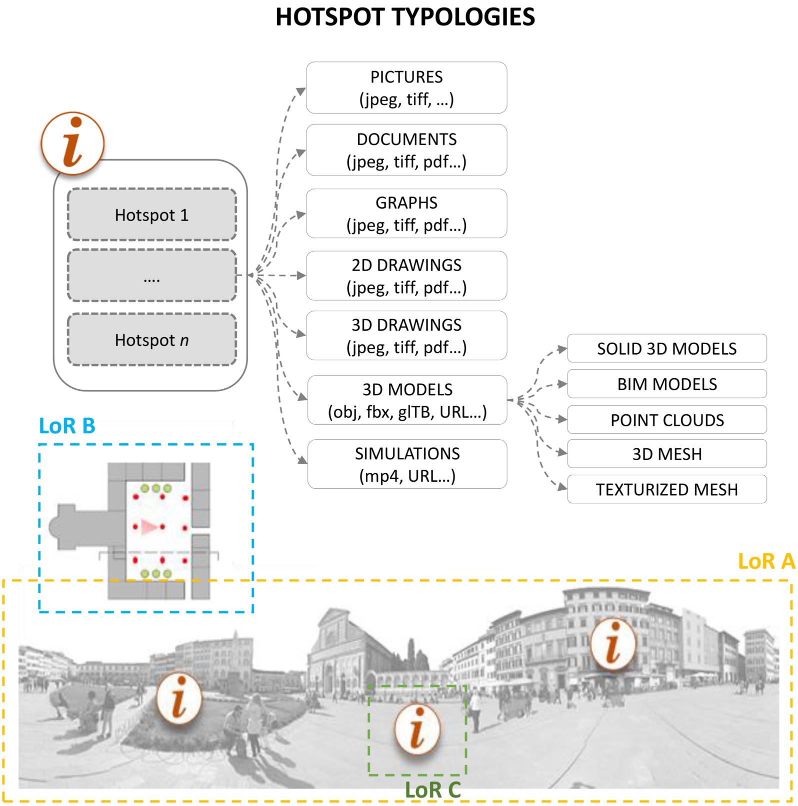

Fig. 3. Hotspots typologies and external data

Table 4. Specification of external data derived by BIM approach for VR-centric workflow

LoR	EXTERNAL DATA SPECIFICATION FROM BIM
A	Spherical photos from BIM models
B	Hotspot plan as exported BIM plan view
C	Graphical drawing exported by BIM models (plans, elevations, sections, 3D views, constructive details, …)
	Documentation exported by BIM models (reports, data sheets, graphs, …)
	BIM models as obj/fbx file or URL, after publication on a web viewer
	Simulations generated with BIM models exported as video

5 Remarks and Conclusions

The three-dimensional reconstruction of a real environment provides a higher analysis and perception. Navigating within a virtual environment, the user has the opportunity to move freely approaching the architectural elements, obtaining detailed information equal to the vision that will be obtained nearby, but staying a few kilometres away from the Built Environment.

The critical analysis conducted highlights that BIM and GIS are employed to produce and edit contents that describe BEs' and real case studies' parametric modelling, while Virtual Tours work as an easy-to-use and easy-to-update platform for full-scale representation of the BE. This study leads to distinguish two levels of training workflows for the enhancement of resilience in the BE, including humans. These training methods will fulfil a relevant objective of BE S^2ECURe project, as the outlining of a holistic framework able to involve experts in risk management and reach a wider group of users, firstly providing a taxonomy about Built Environments prone to Sudden and Slow Onset disasters within disruptive technologies. The specific training is based on BIM-centric simulation and modelling, aimed at testing the behavioural design within the BE at micro/meso/macro scale thanks to different scenarios simulations for technical users and professionals. The parametric tools such as BIM and GIS (2D and 3D GIS) are more suitable for simulation and analysis of real events. Indeed, parametric modelling can be employed for multiple analytical modelling and analysis, aimed at deriving risk matrix and indicators, creating several alternative scenarios for identifying risk mitigation measures, guidelines and strategies to SUOD and SLOD within a risk management plan.

As the VR-centric approach is a smart tool, it will be employed for pervasive training, due to capabilities of sharing, communication, education, collaboration and dissemination. Indeed, selected results/deliverable of simulation and analysis will be located on a represented built environment - as it is seen by humans – with reliable spherical photos for disseminating acquired knowledge in a friendly and accurate manner. Hotspots would be inserted for sharing deliverables provided by other processes/analysis phases on the Built Environment, as drawings, images, spreadsheets, multimedia file such as video. The creation and next maintenance of Virtual Tour are effective for editors, also if they are without expert skills, because the acquisition of spherical photos is rapid and it does not create unresolvable interferences with users and spaces. These can be managed within a basic 2D or 3D GIS web-based platform for geographical localization. The use of 3D City model will be a collecting tool for the representation, exploration and analysis of heterogeneous georeferenced spatial information to provide immediate and intuitive use of all the intrinsic and extrinsic information of the Built Environment with effects on risk scenarios.

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