# WP 3 – Representative models of Built Environment Typologies (BETs) prone to SUOD/SLOD. Case studies selection and data collection

**T3.1 Definition of representative BETs models prone to both SUOD and SLOD. BE characterization as function of the building-open space-infrastructures interfaces (e.g. Façades on Square, Street, Pedestrian route) in terms of morphology and construction technologies. Development of tools/methods for BETs representation in extensive models (BIM based) and fast models (VR/AR oriented)**

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## Abstract

Starting from previous experiences in literature, the deliverable focuses on the Virtual Reality and Augmented Reality as a comprehensive State of Art of meaning, tools and methodology. In detail, the work identifies two types of approaches focused on the VR/AR tools: the BIM-centric workflow to derive VR/AR contents from a 3D BIM-Based modelling and the VR-centric workflow where the Virtualize environment derives from the real one by means of 360° photos and it is augmented with external information contents (CAD, BIM, digitalized paper documents, video, and so forth).
Moreover, the multiscale potentialities have been determined extending the workflows towards a 3D-GIS-based workflow aimed at the representation of BE according to their well-fitted scale of details.
Due to that, the representation of BETs in VR and AR environments has been determined as a systematization of their main properties and relative opportunities derived by the described workflows.



## Keywords

Virtual Environment; Augmented Environment; Built Environment representation; VR-centric and BIM-centric workflows; BET representation in 3D-GIS.

## Approvals

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## Summary

## 1. Introduction

The representation of the surrounding environment moved always man towards a simple and effective conversion of geometric and material properties into lines and colours, until the actual necessity to improve them towards parameters, properties, performances.
Because of these goals, the technology supports all the design fields and processes providing innovative tools to represent the built environment, as well as to manage all the information and properties related.
Virtual Reality (VR), Augmented Reality (AR) and 3D modelling represent the modern keywords in the design field of Built environment, as well as the actual "toolkit" in discretizing Built environment for its modelling, testing and managing also in a multiscale approach.
The following section describes and discusses methodologies and tools of VR and AR already applied in the field of urban environment as a comprehensive State of Art.
**Virtual Reality** (VR) technology or **Virtual Environment** (VE) reproduces real environments with specific devices after reality acquisition or reconstruction in digital contents and allows an immersive experience within a digitalized environment (quite similar to the real one) that could not be necessarily close to the users. In fact, VR allows the visualization - in high-resolution and three-dimensional mode – and the interaction - in a real-time - with virtual environments and objects, providing full fruition to users (Milgram and Kishino 1994; De Paolis 2012).

While, **Augmented Reality** (AR) derives from the VR concept, but it superimposes elaborated digital contents to the reality when users activate specific applications. **AR** completes (enriches/augments) the reality through computer generated virtual objects and digital information, and user is not isolated, but can interact in real time with both real and virtual objects (differently from VR that replaces real world and isolates users) (Azuma 1997)(Billinghurst et al. 2015).

VR applications require technical devices, such as smartphone, tablet and specific peripherals, while AR only uses mobile devices to add digital contents to the reality.
The virtualization of the Built Environment can be conceptualized within the Reality-Virtual Continuum taxonomy (Milgram and Kishino 1994) where Virtual Reality (VR) and Augmented Reality (AR) are linked. In particular, the Real Environment (RE) (or Built Environment (BE)) consists of the opposite pole of Virtual Environment (VE) in this taxonomy, and AR is closer to RE as in AR the real world presence is predominant rather than virtual data (Figure 1).

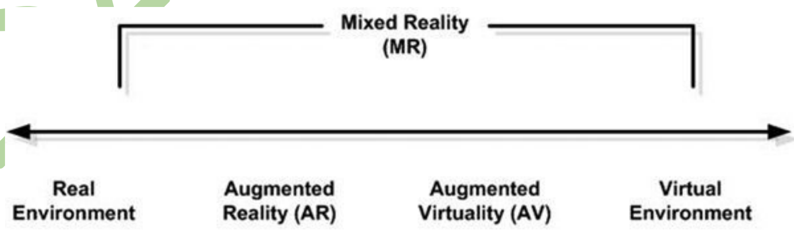


*Figure 1. Reality-Virtual Continuum. Source:* (Milgram and Kishino 1994)

The set of systems interposed between real and virtual environment is defined as **Mixed Reality (MR)** which comprehends **Augmented Reality** (AR), near to Real Environment, and **Augmented Virtuality** (AV) near Virtual Environment.

## 2. AR and VR. Levels, application fields and features of digital environments.

### 2.1 Levels of virtual reality and application fields of VR and AR

In **Virtual Reality**, 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 a virtual to the immersive level, enhancing perception and participation. Thus, different levels of VR are configured according to VR device features:

1. **Non-immersive:** the user visualizes the virtual environment through a monitor and interacts with it with a simple mouse without having a high perception.
2. **Immersive:** the VR system is able to determine a deep absorption in the virtual environment. The user achieves this level of perception through specific VR display technologies and sensors:
   - Head Mounted Display, such as headsets and stereoscopic helmets, allows user to view the virtual environment, isolating him/her from the physical environment around;
   - data gloves with motion sensors to interact with the simulated space;
   - trackers sensors to track users' position and movements to adapt the virtual environment to his/her perspective.
3. **Completely immersive**: large semi-immersive or fully projection-based systems are used to project the virtual environment creating virtual rooms consisting of three, four or 6 large screens, i.e. computer-assisted virtual environments (CAVEs) and domes.

The above-mentioned technologies are employed to combine multidisciplinary tools applied in several fields, such as the medicine (Fuchs et al. 1998; Pietrzak et al. 2006), the aeronautics (Julier et al. 1999), the pedagogical and educational sectors; the main objective of VR tools in these sections consists of dissemination of textual knowledge contents in an innovative and interactive way (Ben-Joseph et al. 2001; Cobb et al. 2002; Kaufmann and Schmalstieg 2002; Gillet et al. 2004).

In Architecture, Engineering, Construction and Operation (AECO) domain, 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 a) **communicate, disseminate and enhance** as well as b) **manage and sharing data, information and knowledge** about single buildings, system or part of them to support interdisciplinary studies in new building/infrastructure construction and building rehabilitation/urban regeneration projects.

A classification of VR applications can be provided, according to the main objectives, underlining potentialities and goals:

a. **VR for the use, communication, dissemination and enhance** of potential tourist urban area (e.g. Cultural sites), also borrowing applications, such as the WebGis-3D platforms, to share knowledge; the use of these platforms allows to pass the geographic boundaries and ensures a first level of knowledge for sites, overlooking the physical presence on site of users (Cardaci and Versaci 2013). In the case of touristic or historical sites, digital models constitute the basic accessible data within the platforms allowing to a wider public the remote fruition of cultural heritage part of sites usually inaccessible or unknown (Gabellone 2014). The created virtual environments are conceived as a platform where representations (maps, satellite images, 3D models and links to documents) and associated information are structured at different scales, creating spaces for sharing knowledge as well multidisciplinary and interoperability dataset (Meschini 2011). Because of the high potentialities, some applications were applied in cultural heritage promotion as in the ARCHEOGUIDE (Vlahakis et al. 2001) (Augmented Reality-based Cultural Heritage On-site GUIDE), funded by the European community. It had the aim to provide a personal assistant to tourists in specific cultural sites; the resulting system used the AR technology to rebuild ancient ruins and to render environments in real time taking into account both position and orientation of tourist within the site. Here, Virtual Reality technologies allowed the enhancement of historic environments, describing their evolution and showing their features. So, the navigation within the virtual environment allows the visualization of details positioned in poorly accessible areas, obtaining detailed information compared to the traditional way to enjoy them. Virtual Reality systems are also able to guide users in the un-real spaces consenting their exploring through specific paths, answering to different interests of various users.

b. **VR for the data management and cataloguing** by the creation of databases; thus, built environment can be implemented in a Virtual environment adding other data (photographs, measurements, diagnostic surveys), which are organized and categorized in the most appropriate way. This operative approach was borrowed from business applications and it is essential in supporting the protection and conservation of Cultural Heritage. The INSITER project (Roders et al. 2016) (Intuitive Self-Inspection Techniques using Augmented Reality for construction, refurbishment and maintenance of energy-efficient buildings made of prefabricated components) experimented AR and VR techniques for data management and processes of heritage over the time, even if closely related to the management of energy efficiency processes. In addition, VR can explain artefacts at building/element scale with the creation of a virtual-historic environment, functional to represent the historical and scientific values, as well as to evaluate the historical-temporal transformations of the environments themselves, focusing on previous activities and future evaluation for processes currently underway, in order to support core activities in history, architecture and archaeology (De Paolis 2012).

As far the levels of interaction between users and virtual environments, **Augmented Reality is featured by its own immersive level with no main differences/classification**

In BE application, AR mostly address touristic application to augment monuments with supplementary information via tablet/smartphone (Layer, Geotravel) (Tian et al. 2013) or help users in finding touristic places with GPS, providing specific information.

The AR technology can be employed for project and design purpose, for i.e.:

- **Urban planning:** overlay of new masterplan on existing landscape, visualizing 3D models (1:1) about future buildings/infrastructure, in the exact position where they will be realized;
- **Project and construction:** project manager can consult drawings and administrative and technical documents about the project on the field.
- **Maintenance**: it allows to have information during maintenance activity by technician, taking advantage of the overlapping maintenance instructions to visible environment (Palmarini et al. 2018).

### 2.2 Features of a Virtual Environment

From the IT point of view, the management of data, the creation of virtual environments and the interaction with the VR by users can be associate to a Virtual Environment of Things (Wu et al. 2014). In detail, the Virtual

Reality consists in three main components (Gutierrez et al. 2005): the **Virtual Environment (VE)**, as the container of data, interrelated between them, featured by a coordinated system of geometric or proportional information; the **Software Component (SC)** useful for the creation of VE and for the real-time reading of actions derived by external actions (as input of Hardware Interface); the **Hardware Interface (HI)** constituted by the hardware components useful for the interaction between external users and Virtual Environment.

As the Virtual Environment concerns, VE can be associated to the real one and so main related to three main elements (Ellis 1994, 1995):

1. the Content, that represents and describes all data in the VE. All the *objects* in the content are "characterized" with their properties and actions;
2. the Geometry is the descriptor of the VE field of action. It allows to associate properties as dimensionality, metrics and extent of VE as well as its constraints and orientation;
3. the Dynamics are the rules of interactions among its contents describing their behaviour as they exchange energy or information.

Innovative VE development frameworks are based on reusable and pluggable components, made of dynamically loadable modules, organised into a hierarchy of module containers. These containers are objects were imported elements (contents) are stored within a specific room.

The Software Component is made of a back-end, script development dashboard, and a front-end the visible part of the software program as User Interface, deputed to acquire imported data, then transferred to the back-end.

As far as the Architecture and Built Environment concern, the VE can be characterized by different nature of contents, geometry concerning the goals discussed in §2.1 while dynamics are related to the hardware/software components. Such as examples in explaining the nature of data:

- **Contents** can be supported by the use of three-dimensional models (CAD, point clouds or polygonal mesh), media files (images, video and audio) or text files (archive documents, reports).
- **Geometry** can be included by geometric descriptors included in three-dimensional CAD models or point clouds and polygonal meshes derived from the laser scanning or digital photogrammetry techniques.

## 3. Tools for Virtual environment design

Built Environment representation can be carried out through:

- Virtual Tours, structured on digital and proportional environments (non-measurable) and navigable (e.g. spherical images) and added information contents;
- Three-dimensional modelling with B-rep or Boolean representation or parametric modelling (BIM).

### 3.1 Virtual Tour: a smart tool for the VR design

Among all the available techniques for the creation of virtual environments, Virtual Tours are identified as a smart technique because of the use of panoramic images. Specifically, the use of spherical images allows a continuous representation and visualization of any digital sub-environment - as the elementary unit of the whole object to represent in the virtual environment. Moreover, the complete fruition of environments is ensured by rotations of the scene (Cardaci et al. 2013) both horizontally (±180°) and vertically (±90°).

Spherical images – in a planar visualization, equirectangular images - can be simply obtained by means of specific devices (spherical head cameras, additional cameras with double/multiples fisheye lens) or by traditional cameras/lens collecting simple images to edit in a panoramic way (e.g. Photoshop merging).

The panoramic images can be visualized in two ways:

- as an equirectangular photo (distorted photo-plane) by traditional visualization tools;
- in a full-screen mode, well-calibrated to the camera lens and in an immersive way by common viewers, such as Quicktime or Flash and Java (Zonno et al. 2012).

All the Virtual Tour software products that use panoramic images allow the creation of VE as an ordered system (georeferenced) of spherical images linked together by specific relations.

In detail, three classes of elementary unities compound the Virtual Tour (Cantatore et al. 2020):

- the *scenes* (or spherical images) constitute the basic data of contents describing visual properties of the VE (colours, elements of the real environment, etc.); moreover, the scenes constitute the properties of **geometry** for VE where orientation, extension and dimensionality can be recognized.
- the *external media* are the additional **contents** of scenes having various nature (.jpeg, .pdf, .tiff, .doc, .mp4,.mp3, etc.) that support the characterization of visualized elements in VE;
- the *hotspots* define the relations between each entity as **dynamics** of VE. Each Hotspot can support a rule of interactions according to which for:
  - each scene is linked to *n* other scenes in the Virtual Tour;
  - each scene is connected to *n* external data,
  - each hotspot links a media.

  Moreover, specific and complex hotspots can be found in the **SC** structures having major rules of interactions in the Virtual Tour content management. In detail:

  - an over ordered and geo-localized system of hotspots to support the users positioning inside the Virtual Tour (e.g. orientation maps) display the plans of the virtualized environment;
  - an over ordered system of hotspots linked to single data aimed at the creation of data-list of all the contents (e.g. menu).

Nowadays, the available Virtual Tour software creator (**SC**) are evolutions of the Krpano program, the first application conceived by the Austrian Programmer K. Reinfield. It had not a graphical interface and it was implementable exclusively in .xml language. Among the commercial ones, Tourweaver©, 3D Vista Virtual Tour©, Panotour©, My 360©, Real Estate Virtual Tours Creator© and VirtualTourEasy© are the most used for the described purpose (Cardaci et al. 2013).

The creation of a Virtual Tour by spherical images consists of three main phases:

1. importing the acquired images and processing them in the virtual tour creation software;
2. connecting the scenes by hotspots;
3. implementing information and documentary contents by hotspots.

Inherent characters and geometric features of each sub-environment require to be evaluated before the acquisition due to the nature of photographic shots. The spherical scene - the result of the single-shot – is fully representative of a room or environment featured by comparable geometric characters in the three dimensions. So, when sub-environments are featured by predominant geometric characters (for example the heights in the cloisters or the length in the corridors) several acquisitions are required to ensure a good representation of the environment to virtualize.

When the object of the virtualization is an open area (as LS and OS defined in D1.1.2), the acquisition campaign for the environment representation should consider all the geometric parameters that feature it. In fact, starting from the geometrical nature of spherical images, the campaign should consider a single cubic unit of reference, as the cube in which the spherical image is circumscribed (Figure 2).

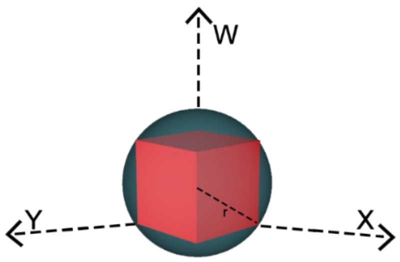


*Figure 2. Relation between the spherical image field and minimum cube for the discretization of spaces.*

Minimum dimension of radium for sphere should be related to the minimum element in the BE to represent, in order to have a complete visualization (e.g. the accesses along the boundary of BE or the urban furniture in the content).

As far the maximum number of spherical shots concerns, shots have to take into account 3 main geometrical characters of Open Environment (OS/LS) (Figure 3):

- X maximum width in plan
- Y maximum length in plan
- W maximum high along the frontier.

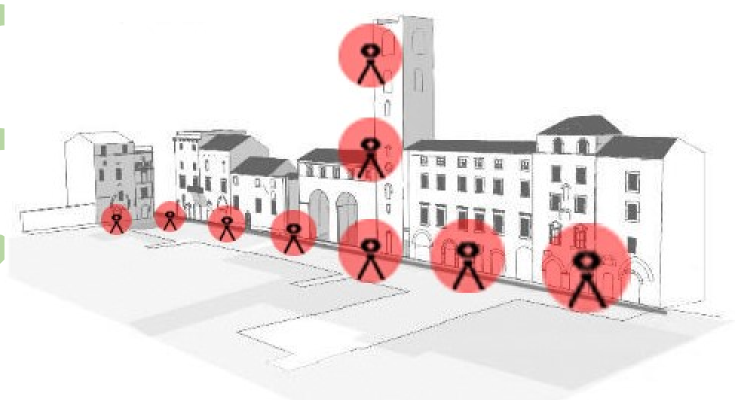

*Figure 3. Scheme of prevalent dimension of BETs according to geometrical characters X, Y and W*

Finally, the geometric relation between elementary cube (or sphere radium r) and geometric distribution of shots should be related to the lens technologies. In detail, r should be related to the focal length *F* according to:

$$f/ = \frac{F}{d}$$

Where f/ is the focal ratio related to the speed and clarity of the optical system and d the aperture diameter d.

### 3.2 VR/AR and BIM: Potential integration for virtualizing and analyzing Built Environment

The VR can be based on 3D modelling technologies (maintaining topologic, semantic and geometric relations) or equirectangular photos, basically 2D captions (with a 180° or 360° field of view), but usable as a 3D perception due to cubic or spherical mapping (De Fino et al. 2019a). In particular, 3D modelling and 2D captions can consist of reality-based (A) or virtually reconstructed sources (B):

A.1) Point cloud or texturized meshes acquired via laser scanning or photogrammetry techniques;
A.2) 180°/360° photos shot via spherical camera or smartphone;
B.1) 3D geometric and information model;
B.2) 180°/360° images extracted from the virtually reconstructed model.

Among these, the B.1 input can be obtained via Building Information Modelling (BIM). Building Information Modelling (BIM) is a process, an approach, for generating, storing, managing, exchanging and sharing information about the Built Environment, during the life cycle (Azhar et al. 2008), and it is enhanced by several disruptive technologies that serves as tools and methods for addressing specific objective/uses. BIM, as a methodology for digital representing reality with different levels of geometric and information detail within a collaborative and interoperable workflow, it conceptualizes the virtualization of the real world. A comprehensive analysis of BIM methodology is developed in D3.1.2.

The relation between Virtual Reality (VR), Augmented Reality (AR) and Mixed Reality (MR) and BIM stands on the evidence that VR, AR and MR can be considered as complementary methods within a BIM process, with different accessibility and fruition modes of the digital reality. The virtualization of real environment allows both analysing the as-built/as-damaged spaces and comparing alternative simulations for understanding possible consequences, before intervening with factual actions. As so, the BIM data-rich model supports the application of the rich-data in various fields. As BIM are data-rich object-based models, they can be employed for multiple purposes within a holistic process during the building/infrastructure/open spaces life cycle. This thanks to ontological representation and data structure of geometry and information of elements, permitting some operations of query, filtering and extraction of parameters according to simulation purposes (Pauwels et al. 2008a) (Eastman et al. 2011). Nevertheless, data-based modelling organized in objects (semantically labelled) should deal with interoperability issues, with interruptions of communication among specific tools, open question also when surveying VR/BIM full integration. Both VR/AR and BIM tools are employed for generating and storing information and data for decision making and delivering new construction projects and existing building/infrastructure interventions (Volk et al. 2014). In particular, the information requirements for "as-built" modelling of a historical building concern both technical information on building components and historical/analytical information (Bruno et al. 2018). Picking VR and AR as they are widely thought, they are tools that enhance BIM processes in retrieving and presenting information with efficient communication in an interactive and collaborative project. Definitely, VR and AR add easy and instant interaction with real world, after its digitalization and simulation. In literature, some critical analysis of the state-of-the-art about the integration of VR and AR with BIM have been developed and published (Kim et al. 2013) (Jiménez Fernández-Palacios et al. 2016)(Sampaio 2018)(Sidani et al. 2019). The current target, concerning integrating VR and BIM, is the study of how to use or adapt those VR devices and how to establish links for the presentation of information contained in a BIM model. Before analysing methods for integration, a clarification should be provided: an essential VR aspect is the visualization and human interaction of virtual worlds, while BIM creates and manipulates building data and information. VR from BIM models gets easy understanding of virtualized world using software products more or less sophisticated, which require specific skills. The complete implementation between BIM and VR/AR should be addressed via direct acquisition and visualization (model-data retrieving of parameters) and linked file structured in a 3D model, which consists of interoperability between software products.

In particular, some VR/BIM uses are:

- Quality defect management
- 4D model supporting construction activity (time/costs) (Sampaio 2018)(Kim et al. 2013),
- Safety in construction site
- 7D model concerning maintenance
- Egress analysis (fire pathfinder, earthquake simulation, etc.) (Lovreglio et al. 2018)
- Education
- Cultural Heritage fruition (touristic)
- Restoration/refurbishment for knowledge sharing – diagnostics (Bruno and Fatiguso 2018)(Bruno et al. 2017)(De Fino et al. 2018)

In the commercial and academic sectors, some tools are developed to integrate VR systems with BIM tools and platforms with different methods, listed below:

- Use of plug-ins in BIM software products for VR applications, enhancing direct link (Figure 4);
- Exchange of file formats from BIM tools to be imported into VR software products;
- Development of customized APIs/plug-in (Figure 5);
- Development of cloud-based platform for digital twins (virtual models) with embedded VR applications.


*Figure 4. Enscape© plug-ins in BIM software products for VR applications via direct link*


*Figure 5. Exchange format from BIM software and VR web application Sketchfab*

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. The language models are exchange formats among applications, categorised in proprietary and open-source ones. The attributes inserted in 3D models might be also mapped in XML and IFC format (BuildingSMARTInternational 2020), or gbXML (Green Building XML), an industry supported standard for storing and sharing building properties between 3D Architectural and Engineering Analysis Software) (Green Building XML 2020). The BIM model can operate as a single archive for consultation and query of such data, or provide documentation and representation for VR applications. In semantic web applications, the communication between BIM software and VR has been improving via ifcOWL specifications for Built Environment ontology representation and JSON for web publishing. While, cityGML is an open standard data model and exchange format to store digital 3D models of large scale (cities and landscapes), allowing interoperability between BIM and Geographic Information System (GIS) (Dore and Murphy 2012).

## 4. BIM-centric and VR-centric approach

Two typologies of workflows can be defined when analysing software/tools and case studies to link and read information and data in VR-based and BIM-based software products (Figure 6):

1. **BIM-centric workflow:** BIM modelling software are used to represent BE, both “as-built” and project alternatives as 3D models navigated in VR.
2. **VR-centric workflow:** tools for virtual tours collect 360° photos (acquired by camera or provided from 3D models, improved with photo editing software) and external information contents from CAD, BIM, digitalized paper documents, video, and so forth.

In **BIM-centric workflow**, the central virtual model of a building/infrastructure/open space comprehends linked single models per each discipline, managed and controlled by multiple companies. The benefit of VR applications stands on the possibility of consulting BIM data via immersive (glasses) or display-based devices (tablet, PC, smartphone, TV). The data consulting from BIM models with display-based devices can be performed with plugins, BIM viewers or customized applications and web-based platforms, in remote mode or on site (Figure 7). In **VR-centric workflow**, the VR environment is the core for sharing data and information, retrieved from different sources in the most common data formats (for i.e. deliverables from BIM, CAD, recordings, digital documents, etc.) and imported in the platform (De Fino et al. 2019b) (Figure 8)(Figure 9).

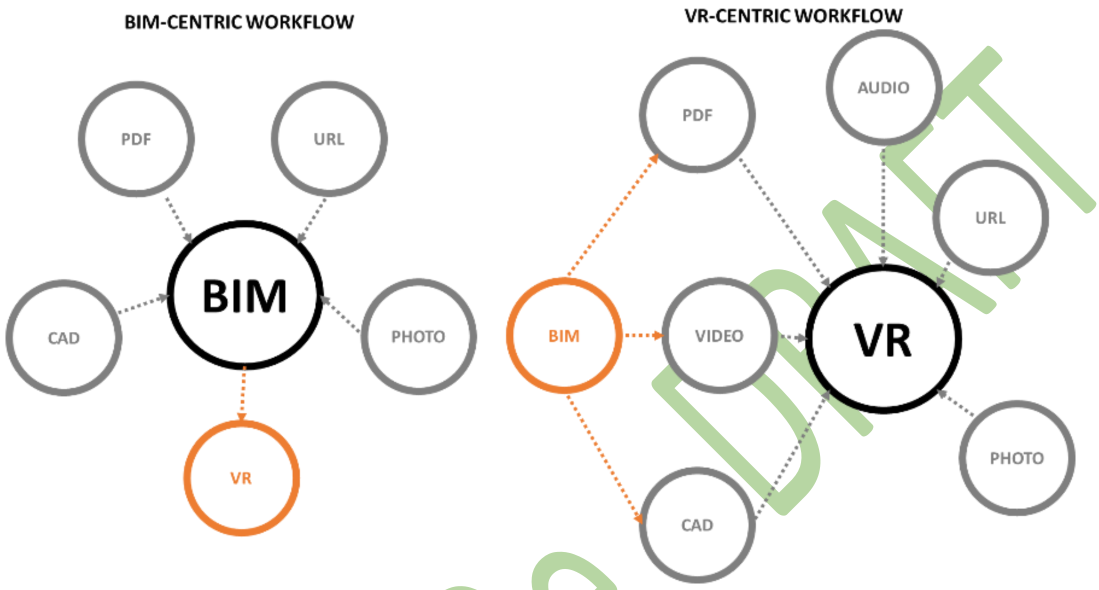


*Figure 6. BIM-centric and VR-centric data and information schema (authors)*

*Figure 7. Revit Live VR for decay mapping, description and intervention indication (Master thesis: Metodologia BIM e rilievo a servizio di architetture tradizionali. Student: G. Sorino, Supervisor: Prof. G.R. Dell'Osso, Co-supervisor: Ing. S. Bruno, Prof. A.J. Delgado)*

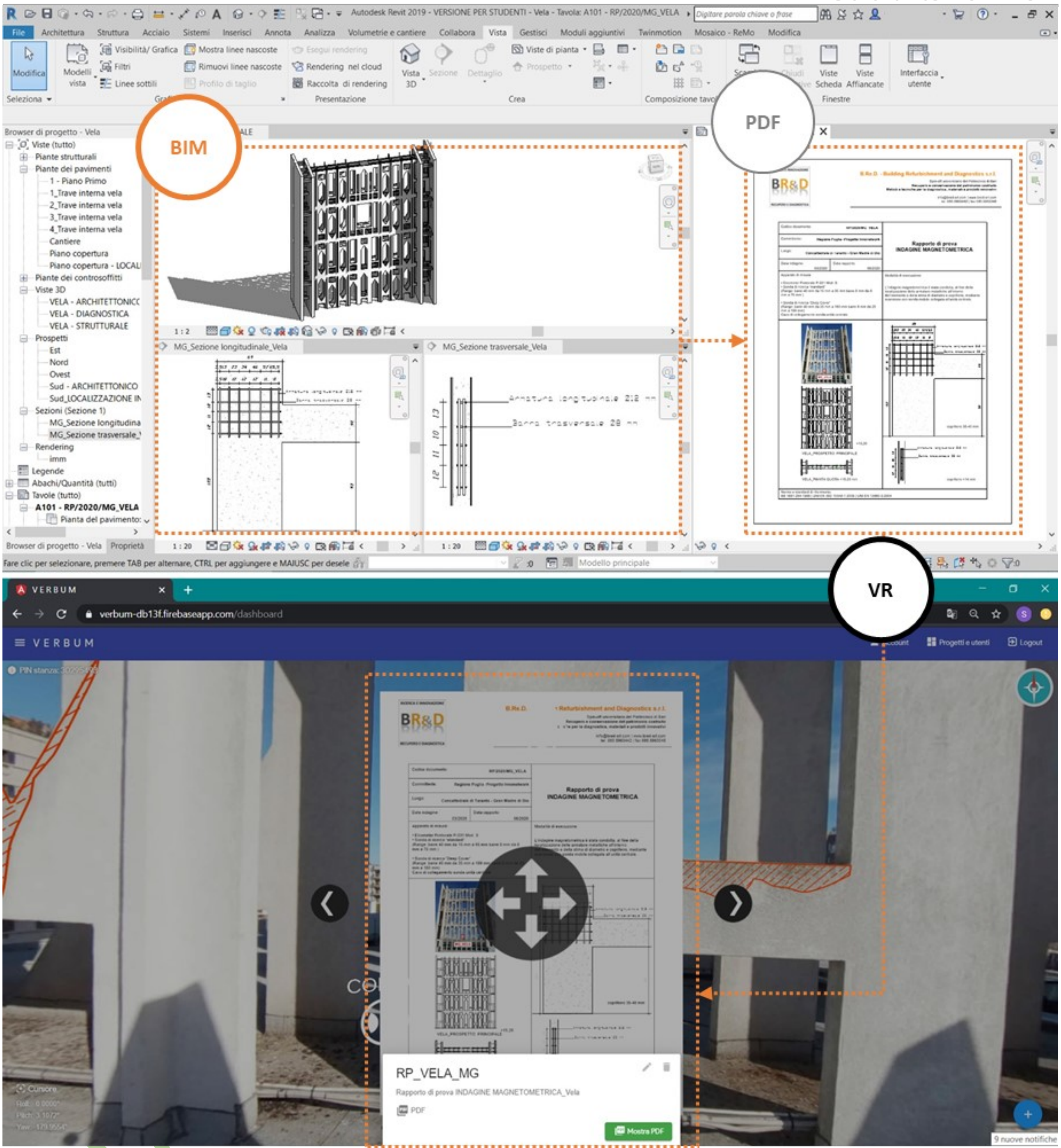


*Figure 8. VR-centric workflow for sharing data and information in the VERBuM virtual environment after import from different sources. In particular, representation of rebars identified via magnetometric test performed on the "Vela" of Concattedrale Gran Madre di Dio, Taranto, Italy* (BReD srl et al. 2020).


*Figure 9. VR-centric workflow for sharing data and information created from different sources in the most common data formats (for i.e. deliverables from BIM, CAD, recordings, digital documents, etc.) and imported in the platform* (De Fino et al. 2019a).

## 4.1 Analysis of BIM and VR/AR applications

In this section, BIM and VR/AR applications are examined. In detail, Table 1 summarizes the potentialities of VR-centric workflow, highlighting input and output data as well as the potential interoperability between data to enrich the virtual environment.

The BIM-centric workflow can be performed via the following plug-ins, stand-alone tools and cloud-based platforms, listed in Table 2 below. When VR environment is implemented via plug-in of BIM software products, there is no export of exchange format, as the 3D model is directly used for VR.

Differently, the use of software for game engine, i.e. Unity and Unreal or web-based platform (i.e. Sketchfab and Poly by Google) request inputs formats. Generally, these file formats are .fbx, .obj, .mtl, .glTF, .zip with texture files (.jpeg, .tiff). Another feature of BIM-centric tools regards the capability of automatically eliciting properties once an object is selected as relationships are maintained between objects and properties.

*Table 1. Data details for the VR-centric workflow and details of specific software.*

| VR-centric workflow | | | |
|---|---|---|---|
| **Software** | **VR environment** | **Type of data that can be implemented** | **Export** |
| **TourViewer (Easypano)** | Standard panorama (.jpg, bmp, .gif, .png) | images (.jpg, bmp, .gif, .png) | Flash VR |
| | | Video (.mp4, .mov, .mpg, .flv) | Flash VR (exe) |
| | | PDF | Flash VR (swf) |
| | | Link URL | html |
| **3D Vista** | Standard panorama (.jpg, .bmp, .tiff) | Images (.jpg, bmp, .gif, .png) | VR Ready, compatible with Oculus, Samsung Gear VR, Google Cardboard, VR BOX and VIVE) |
| | Live panorama | Video (.mp4, .mov, .mpg, .flv) | .exe, compatible with android and iphone, or windows and IOS |
| | HDR panorama | Video 360° (.mp4, .ogg, .mkv, .wmv, .m4v, .webm) | html |
| | Stereoscopic panorama, created in a CAD program (sketchup, 3D Max, Revit, V-Ray, etc.) or taken with a 360° stereoscopic camera. | Link URL | |

*Table 2. BIM-centric workflow details for most used tools/plugin, highlighting information about possible products/processes and relative viewability of properties.*

| BIM-centric workflow | | | |
|---|---|---|---|
| | | ***VR/BIM product/process*** | |
| **Tool** | **Plug-in** | **Info** | **Properties** |
| Revit + SENTIO VR | | | |
| Revit + IrisVR | x | Object parameters and files | x |
| Revit/SketchUp+ Enscape | x | real-time visualization and rendering walkthrough, perspectives, geometric details, and eventual modifications without exit from Revit | x |
| Revit+Twinmotion | x | Real-time visualization and rendering walkthrough | |
| Revit Live | | Real-time visualization and rendering walkthrough | x |
| Visidraft | | Models form elevations and plans in real world | |
| PrioVR | | Natural body movement for interactive actions via sensors | |
| | | ***Display-based VR*** | |
| A360 - Autodesk | | Collaborative platform | x |
| Trimble Connect - Trimble | | Collaborative platform | |
| Recap PRO/360 | | Point cloud (3D) and immersive VR | |
| | | ***AR/VR/BIM products*** | |
| Smart Reality app | | Compatible with Revit (only models) – mobile app | |
| Augment | | Use of BIM models | |
| Covise | | Use of BIM models | |
| Unity | | Programming interfaces for serious games | x |
| Unreal | | Programming interfaces for serious games | x |
| | | **Cloud-based BIM-AR** | |
| 3Dweb (Jiao et al. 2013) | | | |
| EON Icube | | | x |

## 5. Changing scale: from micro to macro. Potential integration of AR/VR tools with GIS for fast models

The SoA-based definition and characterization of BE (D.1.1.1) identify typologies both at architectural (building) and urban (city/neighborhood) scale, thus their extensive/accurate representation requires tools to virtualize hierarchy of urban settlements and frontiers, where buildings, open spaces and linear spaces constitute the principal elements to organize and structure the Built Environment organism. This insight leads to study potential integration of AR/VR tools with GIS for fast models.

Among the other experiences about, the 3D-Imp-Act is a project which employs photorealistic 3D documentation of pilot-cases, Virtual /Augmented reality models and 3D artefacts/environments of historic sites geo-locate in a Web-GIS based mapping in order to represent the complexity of Built Environment of historic sites and territorial networks (De Fino et al. 2019c) (Figure 10).

In particular, D3.1.3 focuses on the transition from 2D GIS to 3D GIS, as 3D City models. 3D City models can be suitable for fast representations VR/AR-oriented and interoperable with reality capture and BIM approaches with open standards (i.e. ifc and cityGML) or exchange formats (fbx, obj, stl, etc.).

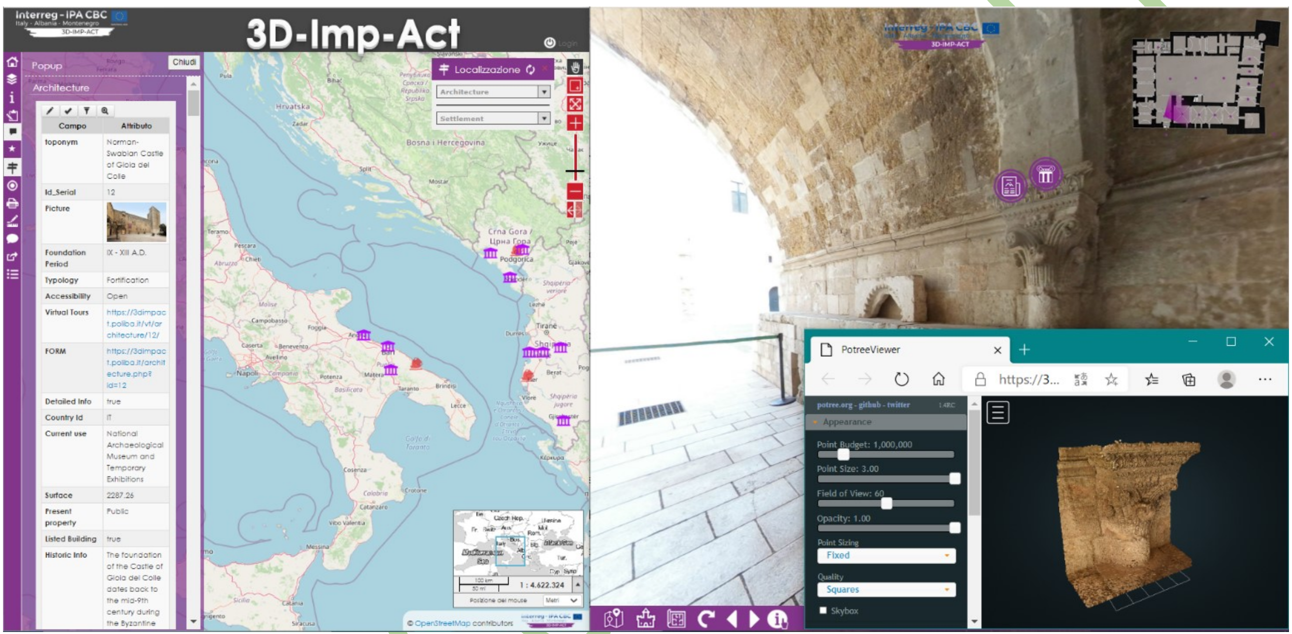


*Figure 10 3D-Imp-Act project web-GIS platform for navigating historic sites and territorial networks and related documentation about historical papers, video reconstructions of historic photos, decay mapping, URL links to highlights structured in the platform* (Polytechnic University of Bari et al. 2020).

### 5.1 3D City Model (3D GIS)

A 3DCity Model can be defined as the digital representation of the terrestrial surface and the built environment of a city. Urban three-dimensional and semantic models have different representation scale and level of detail related with a specific research field (Stadler and Kolbe 2007).

This urban three-dimensional model can be employed for several purposes and application fields, such as: urban planning, telecommunication, architecture, public infrastructure and buildings, marketing and economic development, real estate, tourism and entertainment, e-commerce, education and citizen training. The fruition of city models requires a representation with a very high level of detail to reproduce built environment as real as possible. Thus, a 3D textured-model is sufficient for this specific use, with geometric and aesthetic information about buildings. While, models for acoustic and environmental pollution analysis or emergency management must include detailed semantic properties (Benner et al. 2005). In literature, 3D City models have been applied for several analysis about the built environment such as: visibility analysis, estimation of energy demand (Figure 11), shadow areas estimation, service network management, solar evaluation, indoor space use, noise emission evaluation, infrastructure design (Biljecki et al. 2015). This typology of Built Environment representation allows the reproduction of territorial/urban elements with geometric and non-geometric information, employing reality capture, BIM/3D models and GIS data, with exchange formats and open standard such as cityGML. In addition, digital contents can be added (images, Virtual Tours, audio, video, textual information, etc).

**The city model comprehends built structure, elevations, vegetation, hydraulic devices, urban furniture.**

In 10. Appendix, applications of 3D City model are described in order to identify functionalities, specifications and uses in Built Environment management.

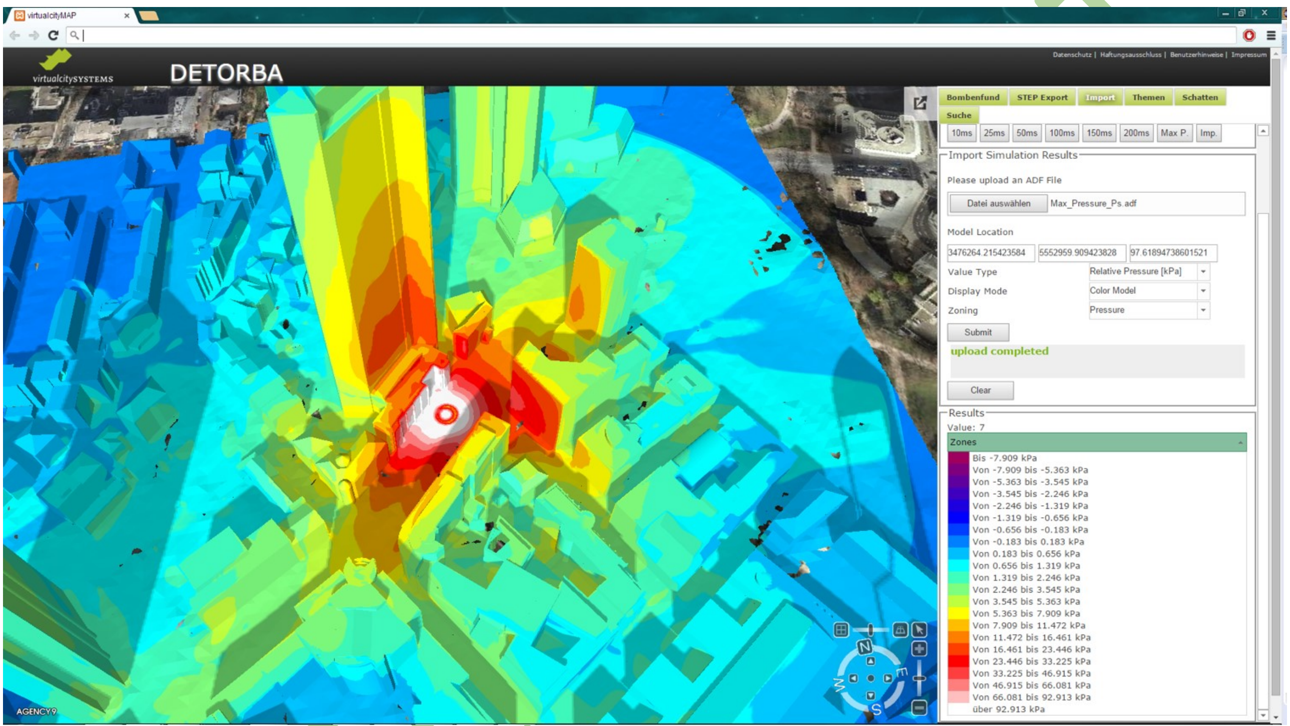


*Figure 11. 3D city models may be used for simulation and analysis of the effects of explosions in urban areas. This example shows the blast pressure wave propagation in urban environments. Possible applications are the prediction of effects of structural integrity and soundness of the urban infrastructure, and aiding safety preparations for evacuation in the case of bomb discovery and defuse. Source:* (Biljecki et al. 2015)

### 5.2 CityGML

The CityGML (City Geographical Geography Markup Language) is an open international standard developed by the Open Geospatial Consortium to consent data interoperability among several platforms. Its use consists of the three-dimensional representation of construction and urban areas for 3D data exchange about 3D objects (Ulm 2010). Specifically, it is a semantic information model suitable for exchange 3D urban objects, based on an open model data developed on XML (eXtensible Markup Language). In addition, CityGML is implemented as a Geography Markup Language 3 (GML3) schema, the international extensible standard to exchange and code geospatial data, written by Open Geospatial Consortium (OGC) e ISO TC211. CityGML is based on standard series ISO 191xx, Open Geospatial Consortium, W3C Consortium, Web 3D Consortium and OASIS. CityGML is applicable for large areas and small regions and can simultaneously represent terrain and 3D objects with different levels of detail.

The data structure of CityGML consists of classes and relationships for most relevant topographic objects in cities and regional models with geometric, topologic, semantic and aesthetic properties with modularization capabilities (Kolbe et al. 2005). Indeed, the schema presents generalization hierarchies between thematic classes, aggregations, relations between objects, and spatial properties (Gröger et al. 2006). The data model is made up of a core module and **thematic extension modules** (vegetation, aggregates, buildings, terrain, infrastructure, city furniture, etc.) (Figure 12).

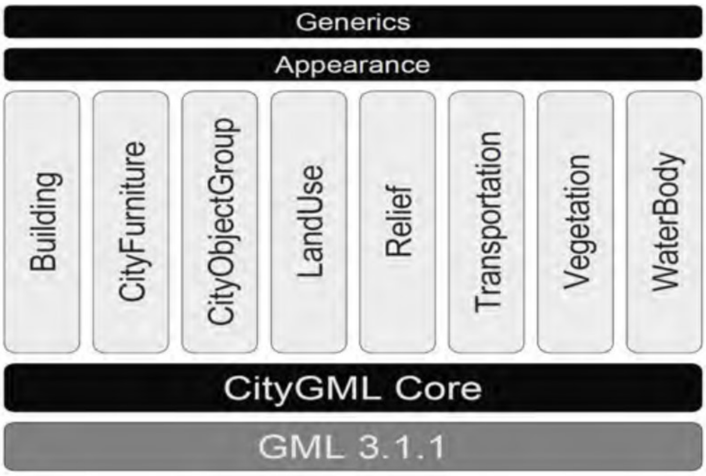


*Figure 12. Modularization of CityGML 1.0.0. Vertical modules contain the semantic modelling for different thematic areas. Source:* (Kolbe 2009)

Last version of CityGML 2.0 (3.0 in progress) introduces 13 **thematic extension modules**: Appearance, Bridge, Building, CityFurniture, CityObjectGroup, Generics, LandUse, Relief, Transportation, Tunnel, Vegetation, WaterBody e TexturedSurface. The base class is *_CityObject,* sub-class of *GML _Feature* and all the objects inherit properties from *_CityObject*. *_CityObject* subclasses comprehend different thematic area of a city model separated by modules.

The three-dimensional representation via City GML distinguishes five Levels Of Details (LOD) from urban/territorial to building scale, as conceptualized in BIM approach from building to element scale. LODs can represent 3D geometry, 3D topology, semantics and appearance in 5 discrete scales (Gröger et al. 2006)(Kolbe 2009)(Figure 13):

- LOD 0 – Regional model, a 2.5 Digital Terrain Model with an aerial image or a map. The buildings are identified as polygons;
- LOD 1 – City/Site model, a "block model" w/o roof structures, where BE is reproduced with 3D blocks;
- LOD 2 – City/ Site model, a textured, differentiated roof structures with a real representation;
- LOD 3 – City/Site model, with detail architecture models representing mouldings, doors and windows; vegetation and transportation are present;
- LOD 4 – Interior model, or "walkable" architecture models, completes LOD3 adding indoor walls in buildings.

An object can be contemporarily represented in several LODs to consent its visualization and analysis according to geometric and thematic information; in addition, two sets of CityGML about the same object in different LODs can be combined and integrated (Gröger et al. 2006).

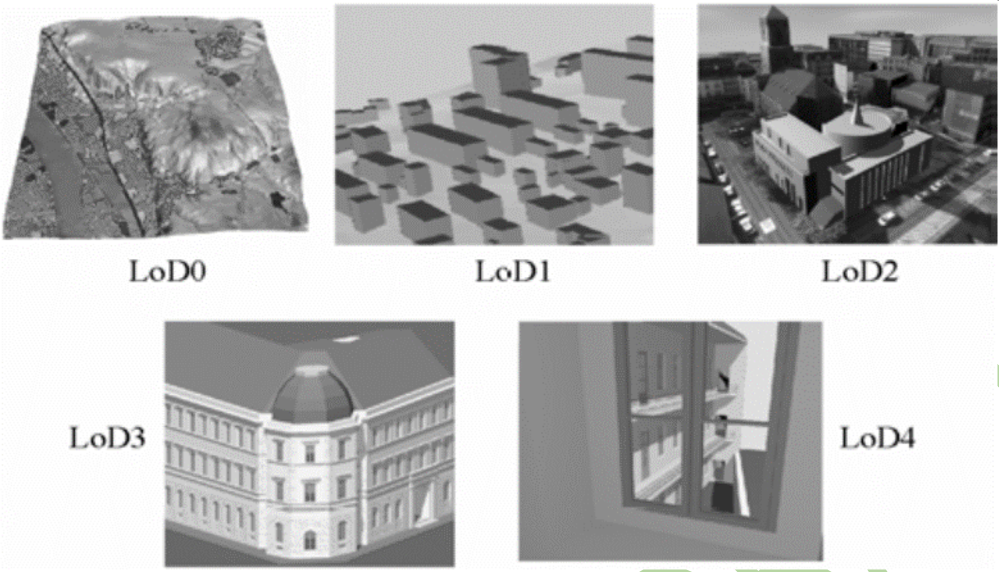


*Figure 13. Livello di dettaglio (LOD) previsto dallo standard City GML. Source:* (Kolbe 2009)

The extension of CityGML occurs through the ADE (Application Domain Extensions) to ass new properties in CityGML classes, as ifcDOC tool for IFC standard in BIM approach. These properties can be number of dwellings in a building or other domain-specific feature classes. Each application field corresponds to a standardized ADE, that can be merged in the same dataset.

ADEs can be defined and standardized by combining relevant information with specific application fields. More than one ADE can be used in the same dataset (Figure 14).

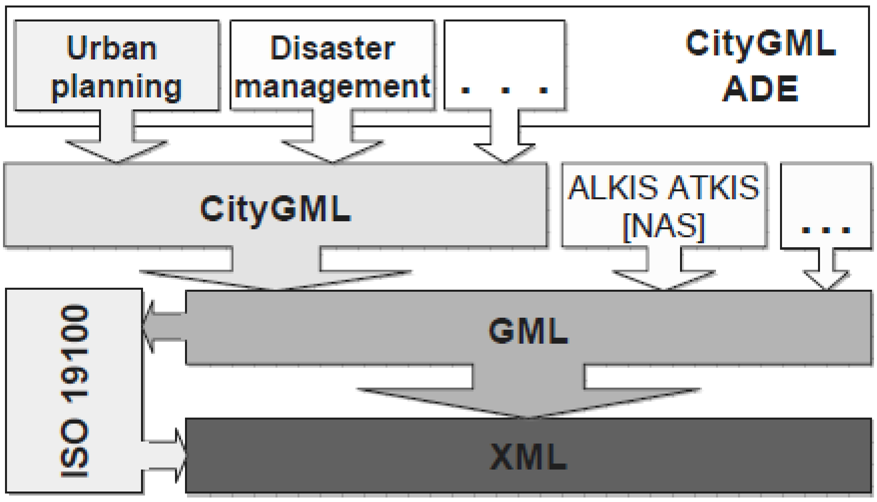


*Figure 14. CityGML Application Domain Extensions are XML schema definitions based on the CityGML schema. They extend CityGML by new feature classes and additional attributes for existing classes. CityGML is an application schema of GML (like others, e.g. the German national cadastre standard ALKIS). Source* (Kolbe 2009)

Applications exist to convert IFC data (from BIM) to CityGML in order to use existing BIM models, for i.e. the proprietary Feature Manipulation Engine (FME) by Safe Software (Jusuf et al. 2017) or the open source BIMserver (de Laat and van Berlon 2011). Moreover, Reality capture outputs can be added (meshes or point clouds) via exchange data format (fbx, obj, stl, etc.) (Figure 15).

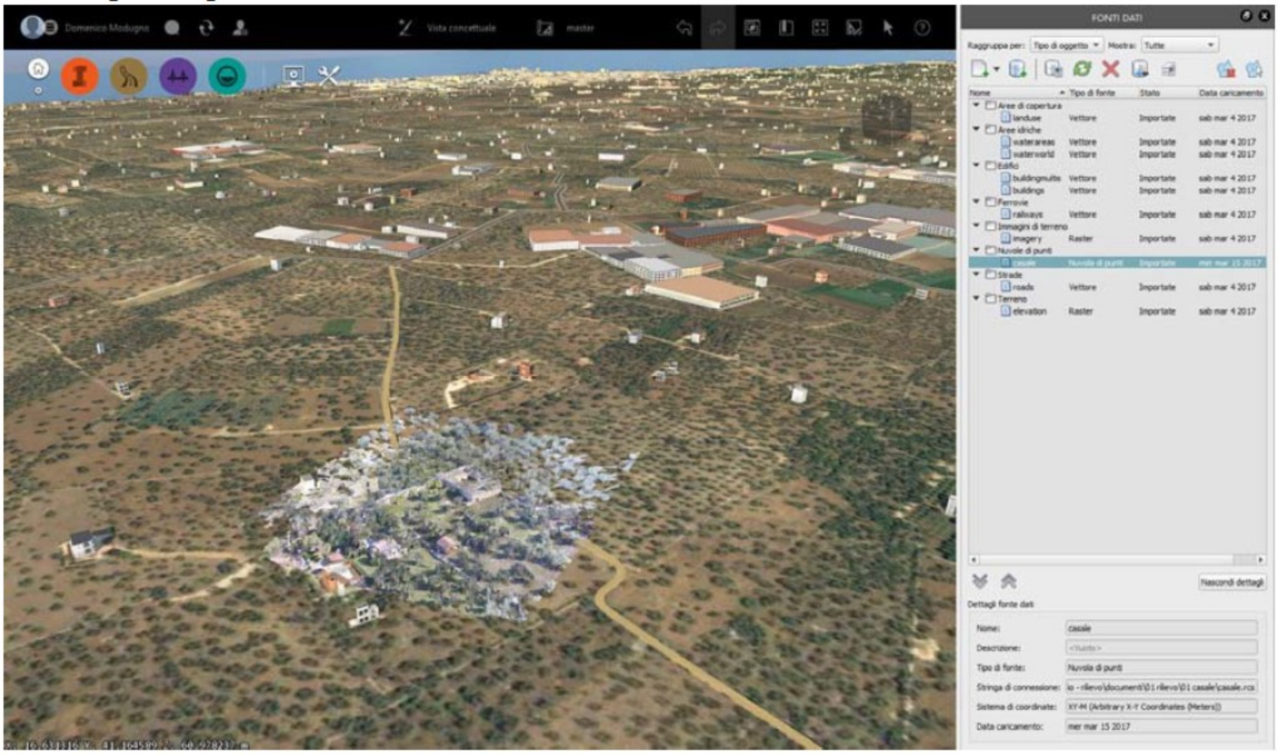

*Figure 15. Insertion of point cloud data acquired via drone in a 3D City plan to record Apulian rural churches and architecture (Autodesk© Infraworks) – Source: The survey of the built environment within BIM approach - Il rilievo del costruito nel BIM – Master thesis: Domenico Modugno, supervisors Prof. Guido Raffaele Dell'Osso, Eng. Silvana Bruno* (Modugno et al. 2016)

### 5.3 Analysis of software products for 2D and 3D GIS

The 3D City Models can be created integrating specific tools thanks to data exchange and cloud services, and can manage urban tissues both in 2D and 3D; the content of 3D City Models can be exported in KML, COLLADA, and glTF formats for Google Earth, ArcGIS, the WebGL-based Cesium Virtual Globe, and so forth.

3D city data can be imported into **Google Maps** and **Google Earth** as textured 3D building models in any of the following file formats: .kmz (with collada), .skp, .dae. Non-textured 3D building models in any of the following file formats: .shp, .kmz (with collada), .skp, .dae and other specific formats.

**ArcGIS CityEngine** (ESRI) is based on real-world GIS data or virtually reconstructed city (past, present, or future configurations). It is able to create a complete city all at once instead of modelling each building individually. Then, CityEngine permits rapid adjustments to the architectural style or other features and multiple scenarios. The tool outcomes can be exported in high-end visualization software or game engines and permits automation of creation pipeline via procedural scripting and Python. According to the possibility of combining it with VR and BIM, the engine imports 2D and 3D data – both solid and BIM models, with a specific LOD, representing building components, furniture, vegetation, and other 3D assets about the BE. CityEngine supports **OBJ**, **Collada** (DAE), **DXF**, as well as **VOB**, it stores textures in a single folder for easy reuse and sharing. Autodesk **FBX** is used for exchange to game engines and visual effects (VFX) tools. The scenes can be published to the web for sharing 3D models, analysis results, or project proposals. The city representation can be visualized in immerse virtual 3D city with the ArcGIS 360 VR app. The challenge in integrating BIM and GIS tools regards the loss of information and metadata when converting an information rich asset from BIM or GIS into a 3D model format to be used for game engines and graphics tools. Thus, it will be accepted that the 3D graphics conversion workflows are one directional. For these asset formats that typically do not have support for coordinate systems or geospatial coordinates, georeferencing information is stored externally from the model and may be lost during format conversion processes (ESRI 2020).

Also, **Infraworks Autodesk** represents within a real-world context of the built and natural environment for visualization and analysis. It can create models from GIS, Raster, DGN, and SketchUp, even importing BIM files and point cloud e mesh in .rcs, .ply, .obj, .fbx, .stl. In addition, it can provide tools for web publication and VR fruition of 3D models (Baik et al. 2015).

QGIS, an open source GIS software, can be employed for 3D city model and support exchange data about 3D city modelling such as (Biljecki and Ledoux 2016):

- Input vector data (read natively by QGIS) - GPKG, SHP, GeoJSON
- Input point cloud data - LAS, LAZ (compressed format), PLY
- Output data - OBJ, DXF, CityJSON, CityGML

## 6. VR tools for BETs representation

The critical analysis of BIM, VR, AR and GIS tools is propaedeutic to define potentialities in the representation of BETs, as they are specifically defined in D.1.1.1 and D.1.2.1 and afterwards investigated in D3.1.1 as *"Definition of representative BETs models prone to both SUOD and SLOD. BE characterization as function of the building-open space-infrastructures interfaces (e.g. Façades on Square, Street, Pedestrian route) in terms of morphology and construction technologies. Development of tools/methods for BETs representation in extensive models (BIM based) and fast models (VR/AR oriented)".*

All the described tools can represent Built Environment Typologies with a defined level of detail, in terms of geometric features and properties, using a **central 3D model** (urban/building) and/or a **central virtual tour based on reality-capture spherical photos**.

In particular, the identification of VR/BIM tools for representing BETs, conducted in this deliverable and in D3.1.2., supports the disaggregate specification and potentialities per each tool to be combined into a holistic framework.

In a **BIM-centric workflow**, BIM and GIS represent reality (**all the 9 BETs parameters**) with **a) graphical expression** of BETs parameters via **2D drawings**, **3D objects** within the model itself and **b) properties** (parameters) derived by models, these last ones used to calculate further inserted parameters, via analytic or conditional formulas within the same BIM platform. In particular, parameters in BIM and GIS can be classified in **a)** directly provided by parametric representation tools or **b)** derived by analytical and conditional formulas. The parameters w=width and L=length are used for representing ***Morphological configuration* (P1)**. ***Morphological configuration* (P1)** is characterized by geometrical parameters in BIM models; while the ratio R=w/L is calculated as further parameter recalling w and L in the analytical formula. Similarly, w and L are identified in 2D and 3D GIS as parameters, with possibility of entering R as a calculus. The same specification can be given for parameter ***Dimensions*** **(P2)**, expressed in terms of maximum height ($H_{max}$) of the frontiers and width (w) of the OS. The quantitative evaluation of ***Permeability*** **(P4)**, as access quality, is possible as it is a geometric feature based on lengths, angles and conditions with possibility of measuring and calculated them in BIM and GIS software products. The presence and quantification of ***Porches*** **(P7)** is related to the percentage against the length of frontiers, thus the parameter can be analytically obtained in BIM, 2D GIS and 3D GIS. The ***Slope*** **(P8)** is another geometric information, sometimes associated to a represented object, thus identified in GIS and BIM by a number/dimension about the quote difference or by the presence of stairs. The graphical expressions and parameters can be formatted into deliverable (drawings, reports, objects) in different file formats (pdf, pictures, video, spherical photos) to be shared within a BIM-centric workflow or in a VR-centric workflow.

In a **VR-centric workflow**, BETs representation can be conducted in three levels of representation (LoR):

A. *n* spherical photos (scenes) interlinked by shift hotspots (Figure 16);
B. *n* hotspot plans (Figure 17);
C. *n* hotspots (Figure 18).

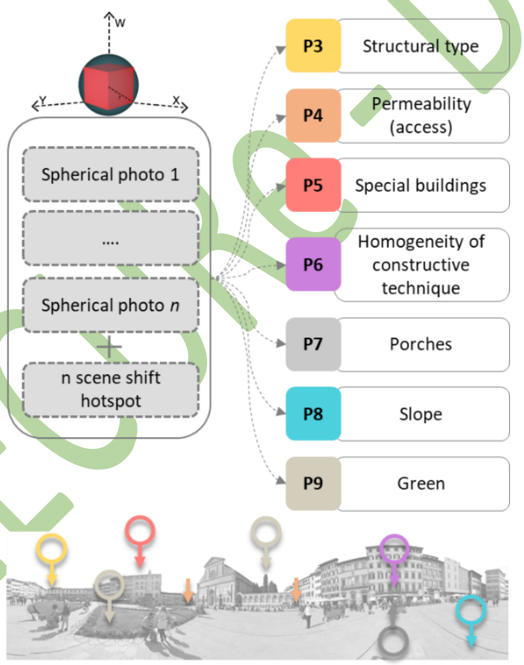


*Figure 16 Level of representation A in VR based on spherical photos (scenes)*

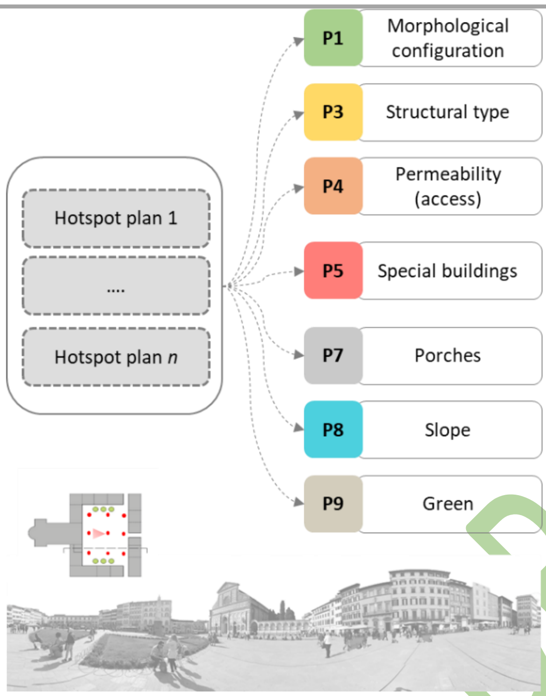


*Figure 17 Level of representation B in VR based on hotspot plans*

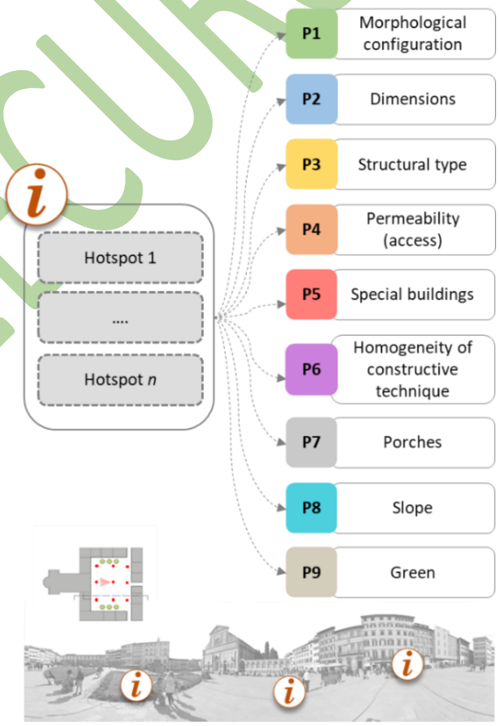


*Figure 18 Level of representation C in VR based on hotspots*

The Virtual Tour created with *n* spherical photos, reality-based or model-based, (LoR A) can make directly viewable the physical appearance of **7 BETs parameters** (**P3**, **P4**, **P5**, **P6**, **P7**, **P8**, **P9**) in W direction (vertical axis), only with *n* scenes interlinked by shift hotspots, thus after the project of an acquisition plan. Major details of BETs can be obtained with minor distance between each 360° photos (in X, Y and W directions) and between camera and object (Figure 19).

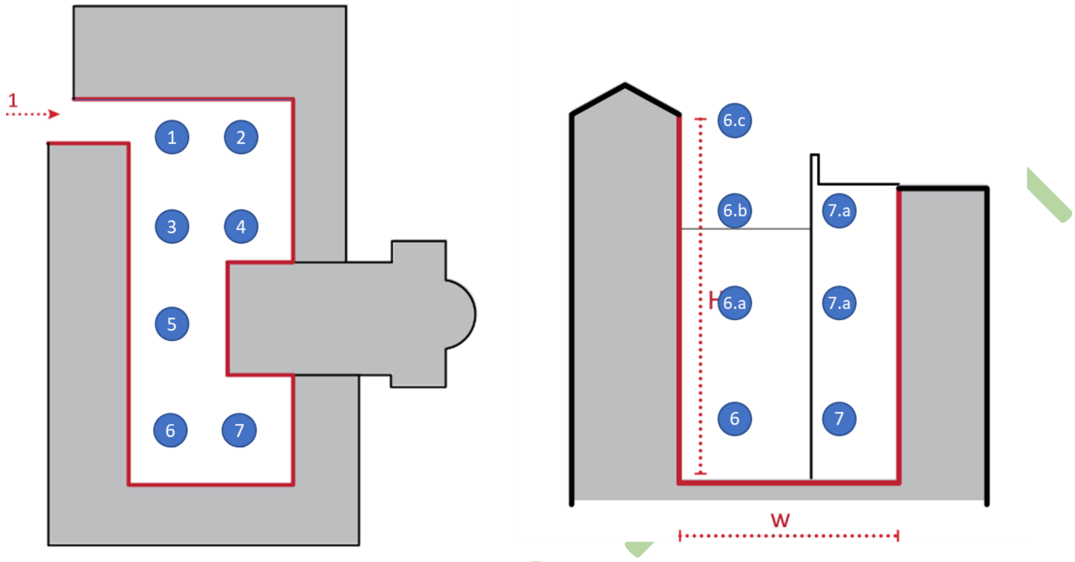


*Figure 19 Acquisition plan of spherical photos (scenes) in X, Y and W directions*

The perception of the ***Morphological configuration*** **(P1)** 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. The *n* hotspot plans also add visual perception (in X and Y directions) to **P3, P4, P5, P7, P8 and P9**. The higher level of detail is strictly related to the representation scale and representation accuracy of each hotspot plans.

The third level of representation C, in VR-centric workflows, consists of inserting hotspots to dynamically show additional and detailed information about the BETs. After the insertion and augmentation of hotspots with external data (Figure 20), **the BETs can be fully reconstructed**. Indeed, external information sources can complete the representation of **all the entire set of 9 BETs parameters**, in qualitative and quantitative modes. As investigated in the literature review, these hotspots allow the interaction with the user converting a request in action. The external data to be shared and communicated can derived by different sources and exchanged in different file formats (pdf, URL, videos, pictures, audio media, etc). These medias are able to describe: historical evolution, constructive-material characterization, analysis of morphological configuration, dimensions, structural type, permeability, special buildings, porches, slope and green (Figure 20).

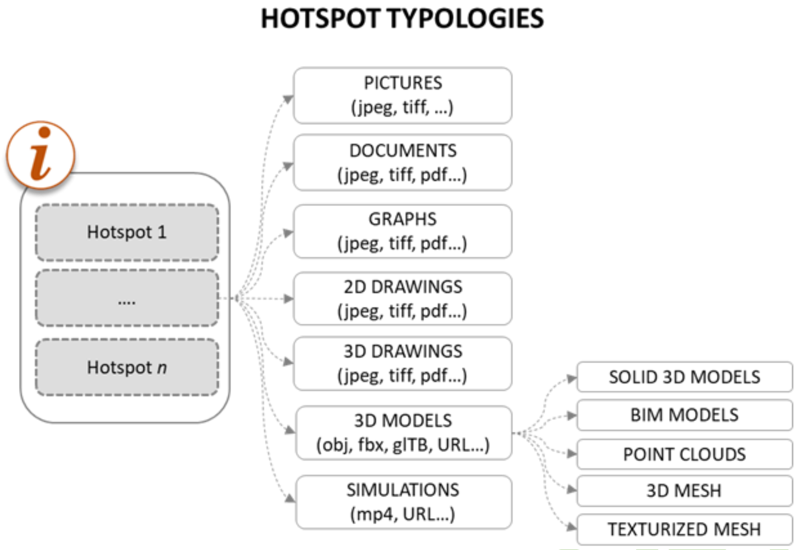


*Figure 20 Hotspots typologies and external data*

The integration of BIM approach in VR-centric workflow can occur in each level of representation (A, B and C). Specifically, external data produced within a BIM-based approach are specified in Table 3:

*Table 3 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. BIM models can represent single BETs elements or complete BETs. |
| | Simulations generated with BIM models exported as video |

As parameters of BETs (P1, P2, P3, P4, P5, P6, P7, P8 and P9) have been selected, among the ones identified via survey (D3.1.1. Table 1 and Table 2), the definition of the three LoR in VR-centric workflow is extendable also for those parameters belonging to the survey form of D1.1.2 describing OS in the BE (Table 4). The coloured cells represent the BETs parameters (P1, …, P*n*) referenced with parameters from D1.1.2.

*Table 4 LoR of the entire set of BETs parameters in VR-centric workflow*

| SECTION 1 – MAIN TYPE | | | |
|---|---|---|---|
| B, C | | S1_0 | Prevalent shape |
| | | S1_1 | Dimension |
| A, C | | S1_2 | $H_{max}$ built front |
| | | S1_3 | $h_{min}$ built front |
| SECTION 2: CHARACTERISTICS OF GEOMETRY AND SPACE | | | |
| Frontier | | | |
| A | | S2_F_1 | Structural Type (SA/SU) |
| | | S2_F_2 | Accesses |
| | | S2_F_3 | Special buildings |
| | | S2_F_4 | Town walls |
| | | S2_F_5 | Porches |
| | | S2_F_6 | Water |
| | | S2_F_7 | Quote differences |
| | | S2_F_8 | Green area |
| Content | | | |
| A, C | | S2_C_1 | Special buildings |
| | | S2_C_2 | Canopy |
| | | S2_C_3 | Fountain |
| | | S2_C_4 | Monuments |
| | | S2_C_5 | Dehors |
| | | S2_C_6 | Quote difference |
| | | S2_C_7 | Archaeological sites |
| | | S2_C_8 | Green area |
| | | S2_C_9 | Underground park |
| | | S2_C_10 | Underground cavities |
| SECTION 3: CONSTRUCTIVE CHARACTERISTICS | | | |
| Frontier | | | |
| C | | S3_F_1 | Homogeneity of built environment age |
| A, C | | S3_F_2 | Homogeneity of constructive techniques |
| A, B, C | | S3_F_3 | Urban furniture/obstacles |
| Content | | | |
| A, B, C | | S3_C_1 | Pavement materials |
| | | S3_C_2 | Pavement lying |
| | | S3_C_3 | Pavement finishing |
| | | S3_C_4 | Urban furniture/obstacles |

In order to understand the advantages of each representation tool (BIM/GIS and VR) in BETs representation a score has been assigned to BIM and VR workflows to assess the management of BETs for different purposes (representation, management - updating, modelling - simulations), considering the overall time-resources (operators, hardware, software) requirements (Table 7). The evaluation matrix about BIM-centric workflow derives from Appendix 9.1, in D3.1.2. In particular, the effectiveness marks assigned from 1 to 3 correspond to (Table 5):

*Table 5 Effectiveness marks correspondence for representation, management, modelling and time-resources of BIM and VR approaches*

| | 1<br>Limited | 2<br>Good | 3<br>High |
|---|---|---|---|
| Representation | Several digital contents for BETs representation are required. | Few digital contents for BETs representation are required. | Very few digital contents for BETs representation are required. |
| Management | Users' work for updating BETs representation via information modelling are required. | Limited users' work for updating BETs representation via information modelling are required. | No users' work for updating BETs representation via information modelling are required. |
| Modelling | Low computing capabilities | Limited computing capabilities | Flexible computing capabilities |
| Time-resources | Intensive labour hours for BETs acquisition and representation, several software products and top of the range hardware are required. | Numerous labour hours for BETs acquisition/representation, numerous software products and efficient hardware are required. | Few labour hours for BETs acquisition/representation, limited number of software and standard hardware are sufficient. |
| (-) ineffectiveness | | | |

The evaluation of VR-centric workflow against the representation factor depends on the LoR required for depicting each BET parameter, corresponding to the development stage of the Virtual Tour (A consisting in the only *n* scene connected by shift hotspots, B includes hotspots plans, and C comprehends the import of digital contents). If LoR A is sufficient for BET parameter representation, the representation effectiveness of the Virtual Tour is equal to 3; the addition of LoR B corresponds to 2; while, if the BET parameter can be represented only with LoR C (external information), the effectiveness decreases to 1. This evaluation corresponds to the representation effectiveness of individual BET parameter (Table 6).

*Table 6 Correlation between LoR of VT and mark*

| BET parameters | LoR required | Evaluation |
|---|---|---|
| P1 | B, C | 2 |
| P2 | C | 1 |
| P3 | A, B, C | 3 |
| P4 | A, B, C | 3 |
| P5 | A, B, C | 3 |
| P6 | A, C | 3 |
| P7 | A, B, C | 3 |
| P8 | A, B, C | 3 |
| P9 | A, B, C | 3 |

*Table 7 Evaluation matrix – BIM/VR for BETs parameters*

| BETs PARAMETERS | Representation | Management | Modelling | Time-resources |
|---|---|---|---|---|
| | | **BIM-centric** | | |
| P1 | 3 | 2 | - | 2 |
| P2 | 3 | 3 | 3 | 2 |
| P3 | 1 | 3 | 1 | 2 |
| P4 | 3 | 3 | 3 | 2 |
| P5 | 1 | 3 | 1 | 2 |
| P6 | 3 | 3 | 3 | 2 |
| P7 | - | - | - | - |
| P8 | 3 | 3 | 3 | 2 |
| P9 | 3 | 3 | 3 | 2 |
| **TOTAL** | 20 | 23 | 17 | 16 |
| | | | | **76/108** |
| | | **VR-centric** | | |
| P1 | 2 | 3 | 1 | 2 |
| P2 | 1 | 3 | 1 | 3 |
| P3 | 3 | 3 | - | 3 |
| P4 | 3 | 3 | - | 2 |
| P5 | 3 | 3 | - | 3 |
| P6 | 3 | 3 | - | 2 |
| P7 | 3 | 3 | - | 2 |
| P8 | 3 | 3 | - | 2 |
| P9 | 3 | 3 | - | 2 |
| **TOTAL** | 24 | 27 | 2 | 21 |
| | | | | **73/108** |

The need of integration VR and BIM/GIS for quantitative analysis lead to not consider VR-centric workflow as an effective tool against analytic modelling for simulations, for this VT is ineffective in modelling/simulating. In the reverse, building a baseline Virtual Tour (A+B) is not time consuming and really cost-effective. The addition of external contents in VR-centric workflow determines a decrease of representation effectiveness of the only VR tools and the time/resources may be calibrated with the ones required for the elaboration of the external documentation, for example employing BIM and GIS. Obviously, if the additional material from CAD/BIM/GIS approach is just available, the uploading of these in the Virtual Tour is easy, contributing to demonstrate the benefit of VR-centric approach in information management and updating of the entire set of BET parameters, depicting the VR potentiality as dissemination and training tool.

Nevertheless, a correlation with the Level of Detail of Open Space in Built Environment model and output for simulation, investigated for the uses of BIM technologies, is required for a comprehensive assessment and to outline a framework for BET communication in VR-centric workflow, employing BIM deliverables (Figure 9 in D3.1.2):

- LOD 100 and LOD 200: LoR A, LoR B and LoR C are required, established as useful for BET classification and analysis. Specifically, the only LoR A supports the qualitative evaluation of some BET. Nevertheless, the additional use of external documentation is required to complete BETs classification and express numerical values of parameters, consequently arriving to LoR C. In this sense, the level of detail of VT can increase but integrating further methods, such as BIM and GIS. Focusing on the current deliverable topic about VR/AR tools for BET representation, an operative workflow is proposed for this scope (Figure 21).
  In the phase of BETs classification and analysis, the consultation of LoR A VT aids the acquisition of information for implementing LOD in GIS and BIM, thus populating models via visual analysis, to be augmented with measurements, calculations, and constructive details.

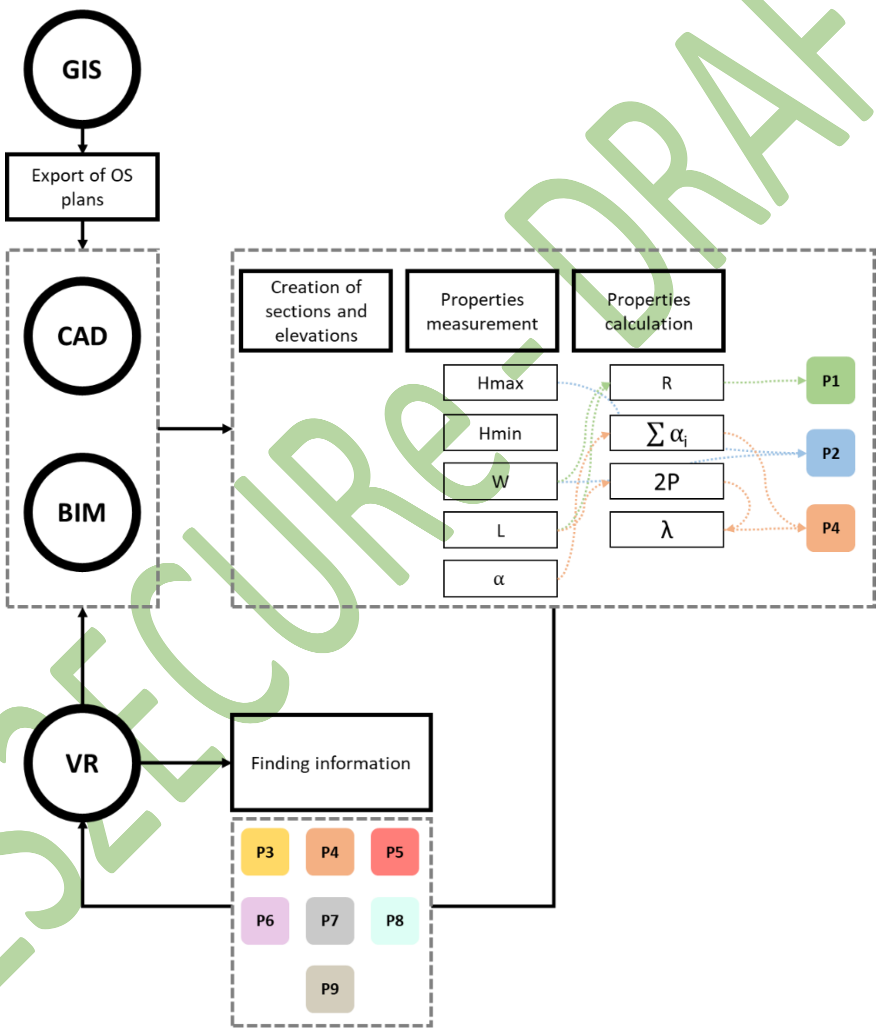


*Figure 21 Workflow for BET representation in VR/AR*

- LOD 300: LoR A, LoR B and LoR C are required. It corresponds to deepening of geometrical and informative data, a more detailed definition of the building component of the OS frontier, focusing in particular on the opening of the façade, the 360° photos will be acquired with a less distance to the frontiers and one from another shot. It comprehends the BET classification and analysis. In addition, the human-related factors are included in LoR C, as additional digital contents about the exposure and vulnerability parameters, such as crowding level, motion quantities information, and type of users (see D2.2.5 annex).

- LOD 350: LoR A, LoR B and LoR C are required. Information about façade and opening are more detailed than LOD 300, thus requiring a higher number of 360° photos to acquire details and reduce distortions, in addition to the scan-to-BIM survey. The detail about wall, topography materials and conditions, structural aggregates of buildings in the frontier, fixed and temporary obstacle in the OS are characterized by uploading further digital contents with interactive hotspots.
- LOD 400: LoR A, LoR B and LoR C are required. The role of Virtual Reality will be central in representing the most exhaustive characterization of building components with a constructive in-depth level of definition. The LoR C includes digital contents about constructive details, technical information. The VR/AR technology is informed by the results of the simulations for training purposes.

As the BETs representation should reach an extensive scale (infrastructural networks and urban tissues), BIM-centric and VR-centric workflows can be both interlinked with GIS tools, for 3D City modelling.

In particular, the 3D City modelling consists of 3D models and Virtual Tours (from BIM-centric and VR-centric approaches), augmented with several information contents. Specifically, BETs representation can be mixed, using together BIM models, solid three-dimensional models and reality-data capture, such as point clouds, 3D texturized meshes, and digital terrain models (DTMs) representing the shape of the earth's surface (topography). BIM models, solid three-dimensional and digital data from reality acquisition can represent infrastructure, road elements, and other BETs. The BETs representation in GIS environment (2D and 3D) follows specifications of BIM-centric workflows.

According to the main results of analysis about VR/BIM tools and BETs representation, it is clear that different levels of representation can be reached according to the combination of these different tools (Figure 22), according to defined objectives and uses of BETs representation. Analysing Figure 22, each tool can be used as it is, without any dependency from the others, or they are combined, within the workflow, in configurations where the tools need to be involved for BETs representation. As 3D GIS is based on geometric and parametric definition of 2D GIS, the use of the one excludes the other. The VR-centric workflows are identified by combination where VR is the first element (empty background icon), the BIM-centric workflows start from BIM and GIS utilization (grey background icon). The holistic frameworks are identified in the combinations where three or four tools are required (orange background icon).

The use of only one tool represents BETs itself, considering the possibility of inserting external data (media) obtained from traditional sources (CAD, document scans, video recording, pictures, etc.).

When VR is employed together with BIM, BETs representation can be conducted in LoR A, B and C; in this last condition, hotspots are augmented with BIM products (Table 3). While, the association of VR to 2D GIS or 3D GIS guarantees the use of Virtual Tours as digital contents. This combination can be upgraded using BIM for producing 3D models to be imported into geographical/urban representation.

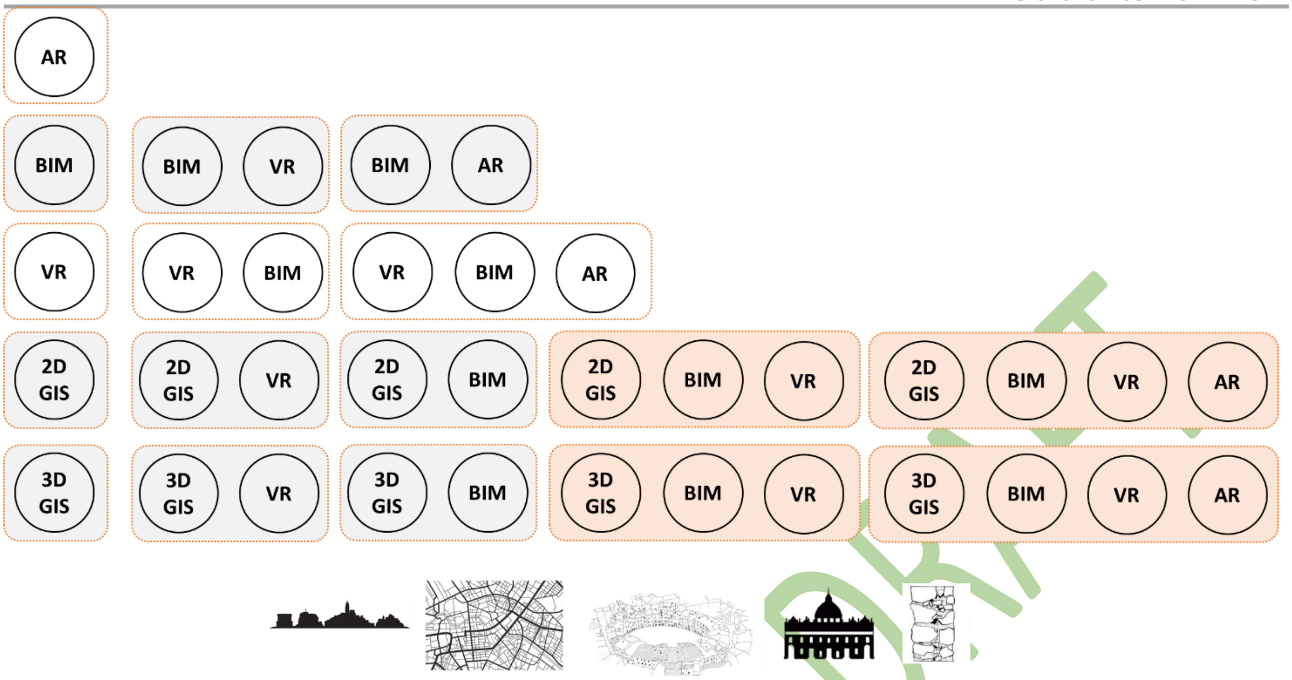


*Figure 22 Proposed alternative combination of tools for BET representation (Source: authors)*

## 7. Assessment of BIM/centric and VR/centric approaches

The assessment of the different tools for BETs representation is carried out through the SWOT analysis which identifies strengths, weaknesses, opportunities and threats of each one (**Errore. L'origine riferimento non è stata trovata.**). The aspects reported in the SWOT matrix are inferred through the analysis of the state of the art, experience, commercial reports.
All the potentialities and criticalities highlighted are directly transposed to a 3D city model scale which is configured as a georeferenced database of the information imported from the two workflows.

The VR-centric workflow demonstrates advantages in representation and usability capability. In particular, it allows *n*D representations (time, costs, sustainability, Facility Management), with different Levels of Detail, both about geometric and non-geometric information, via interrelated data sources. On the other hand, BIM-centric workflow allows a parametric design of objects and structured and well-defined architecture to use them with their properties. The most effective potentialities of VR-centric against BIM-centric workflows regard the usability features such as possible involvement of users with low expertise, lightweight outputs/file, ease of widespread, reduced cost for acquiring software, reduced cost for user 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 (Cardaci et al. 2013). In addition, the parameters related to BETs can be modifiable, thus efficiency in updating BETs representation may be investigated. According to this requirement, the most rapid updating and efficient management of VT emerge against modelling and arranging the reality in BIM and GIS applications, requiring time and costs.

*Table 8. 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 | ■ | |
| **OPPORTUNITIES (O)** | | | **THREATS (T)** | | |
| High interest of the leaders of the construction market | ■ | ■ | 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 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. 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. Geovirtual Environments (GeoVE) offer an intuitive, innovative and challenging way to incorporate, explore and analyse information in a pervasive manner. Indeed, the pervasive tool usage depends, above all, on the most shared level of competence in relation to the use of the applications.

## 8. Conclusions

This study leads to outline two levels of training workflows to be conducted in the next phases of research towards a holistic framework able to reach a wider group of users Appendix 10.2 (Figure 29**Errore. L'origine riferimento non è stata trovata.**). The **specific training** is based on BIM-centric simulation and modelling, aimed at testing the behavioural design within BETs at micro/meso/macro scale thanks to different scenarios simulations for technical users and professionals. The **pervasive training** is based on web-based 3D city models (3D GIS) for navigating Virtual Tours, augmented with informative data, of BETs, 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 preparedness of users, with self-training.

In the operative workflow shown in Appendix 10.2 (Figure 30**Errore. L'origine riferimento non è stata trovata.**), the **BE representation** aims to the definition of models prone to both SUOD and SLOD. The critical analysis conducted evidences that BIM and GIS are employed to produce and edit contents that describe BETs' and real case studies' parametric modelling, while Virtual Tours works as an easy-to-use and easy-to-update platform for full-scale representation of the BE. 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 based on BIM software products 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 to be organized in **risk management plan**. For this reason, BIM-centric workflows are devoted for **specific training**.

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 is 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 to all the intrinsic and extrinsic information of the Built Environment.

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# 10. Annex

## 10.1 3D City Models: examples of AR and VR tools in 3D GIS models

### 10.1.1 Berlin

The project "Land Information Systems"[1] has been one of the first ones to test a 3D City Model in an Information Systems for urban/environmental plan and management (*Flächeninformationssysteme auf Basis virtueller 3D-Stadtmodelle*), the so called Geovirtual urban environments. The aim of the project was to create prototypes of 3D Information Systems for Potsdam and Berlin, in Germany (Ross et al. 2007). Further applications of these geovirtual environment (GeoVE) are urban/environmental plan, real estate management, business promotion, city marketing (Ross et al. 2009).
It is a very ambitious project from a dimensional point of view: the area to be three-dimensionally modelled is equal to 498 sq km and it is composed of about 247,000 buildings, as well as streets, squares, public gardens, etc.

The city has been modelled at different levels of detail:

- LOD 2 (Figure 23) provides texturized building models geometrically obtained by extrusion of the plan profiles (extracted from the cadastral plan of Berlin) and the roof morphology.
- LOD 3 (Figure 24), the most prestigious and relevant buildings have been modelled with a higher level of detail;
- LOD 4, interiors of buildings have also been modelled.

*Figure 23. Buildings in LOD 2. Source:* (Kada and McKinley 2009)

[1] This project is part of the German research program RE-FINA (Research for the Reduction of Land Consumption and Sustainable Land Management) funded by the Federal Ministry of Education and Research. The project was born in 2003 from an agreement between Hasso-Plattner-Institute Potsdam, Technical University of Berlin, and 3DGeo GmbH.


*Figure 24. 3D City Model di Berlino on line, nello specifico Il palazzo del Reichstag in LOD3. Source:* [http://vterrain.org/Locations/de/](http://vterrain.org/Locations/de/)

Berlin's prototype resulted in a 3D Information System with information derived from different sources such as cadastral, environmental, transportation network data (see example of results in Figure 25). The information can be viewed within the system by superimposing images on the three-dimensional model, or due to the action of specific hotspots (labels) that also allow connection to external databases (Figure 26).
While, the Postdam's three-dimensional model, developed according to CityGML standard, is composed of 1,304 buildings in LOD2, 50 buildings modelled in LOD3 and a Digital Terrain Model with a ground resolution of 3 meters. An aerial image with a 25 cm ground resolution was used as land plot; trees and urban lighting were uploaded in **.3ds format**.

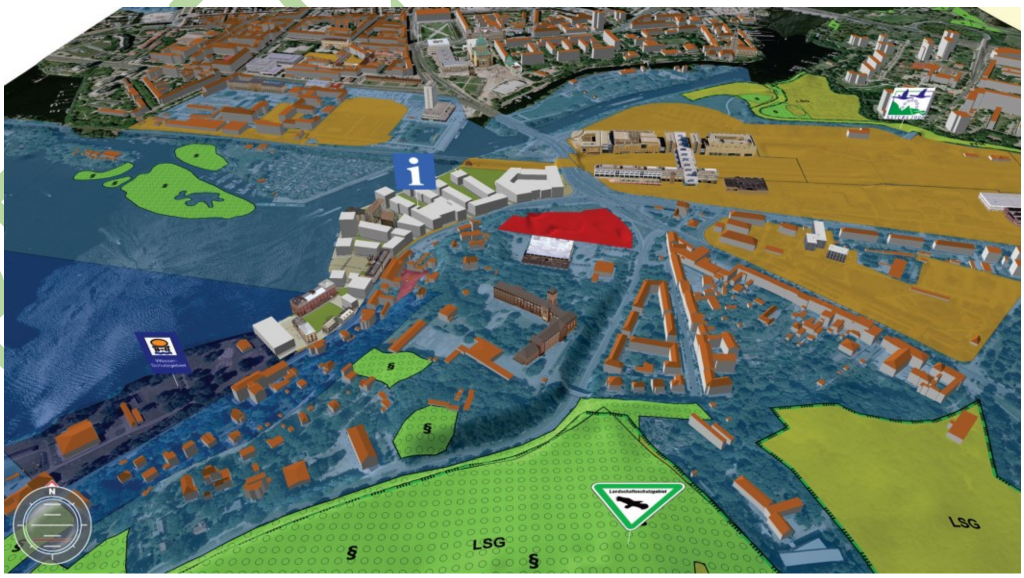


*Figure 25. Screenshot of the prototypic 3D Land Information System with integrated geodata including nature protection areas as raster-based terrain texture, water protection areas and polluted land cadastre as vector-based terrain textures. Source:* (Ross et al. 2009)

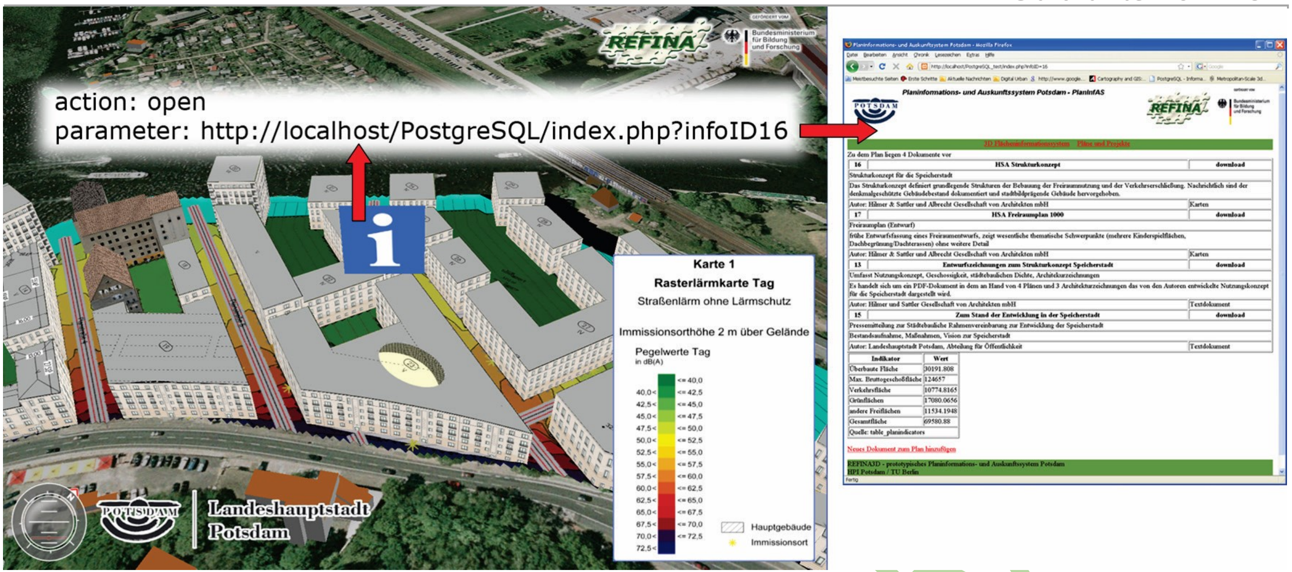


*Figure 26. Actions were used to relate 3D labels and 3D symbols to external applications such as web-based information portals and overlay images were used to integrate legend information into the 3D display. Source* (Ross et al. 2009)

### 10.1.2 New York City

The 3D city model of New York concerns a student project within the master's program Geodesy and geoinformation at TUM.

The main purpose of the project was to create the three-dimensional model of the city integrated with spatial and semantic information. The model integrates data from around 30 data sets separate from the New York Open Data Store in a single CityGML dataset. The model includes the geometric representation and semantics of all the buildings of New York, land plot, streets, parks, digital terrain model and water. Furthermore, this model was used for further studies, such as the analysis of solar aeration (see Figure 27), traffic simulations, the evaluation of solar energy production, through the systems installed on the roofs and facades.

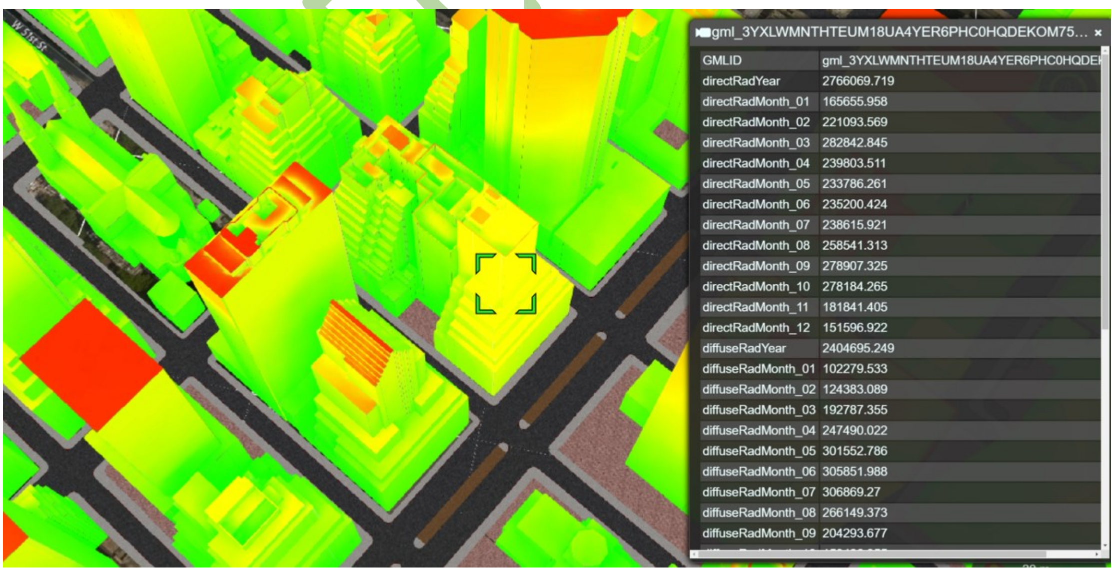


*Figure 27. 3D visualization and exploration of the results of a solar irradiation estimation for buildings in central Manhattan (New York). (Source:* (Yao et al. 2018)

### 10.1.3 Betlemme City

The project of 3D Bethlehem[2] is triggered with the aim of supporting the administrative practices that regulate the territorial government, through the creation of a city management protocol. The project aims to create a geometric and information management system recording building interventions within historic urban centre of Betlemme, from constructive to territorial scale, via a reflective analysis about the city centre. The city of Bethlehem has an irregular urban layout, typical of an Arab city, characterized by a complex system of open spaces and thickened volumes, articulated in labyrinths of streets and alleys, of both public and private relevance. The analysis on the urban tissue has allowed the municipality to understand the urban aspect, leading to the need to integrate a new protocol based on the digitization of the built heritage.

The experience of the city of Bethlehem highlights the need to update the practices of representation for the analysis of the historic city with the application of digital capture protocols.

During the first phase of the project, reality capture and cataloguing of the building were performed. Specifically, the survey was carried out with different methodologies, such as laser scanner, mobile mapping system and terrestrial photogrammetric procedure and UAV.

The building cataloguing began with a typological subdivision of the historical tissue into areas, tissue units, building units and open spaces, adopting alphanumeric codes. The Built Environment, as catalogued, was compared with the administration's digital maps to define urban units in accordance with the intervention provisions regulated by the Municipality.

The result consists of a database accessible through the navigation of the georeferenced city and 3D building models, which can be interrogated thanks to specific descriptors and fields (Parrinello 2019).

### 10.1.4 Hong Kong City

The 3D city model of Hong Kong was created to analyse noise pollution resulting from the intensity of vehicular traffic. Hong Kong is one of the most densely populated in the world, and it is characterized by 40/60 storey residential buildings.

The experts used a GIS map with information relating to noise pollution, in order to analyse criticalities deriving from noise exposure of residential buildings. This map, not considering the height of the buildings, did not report the attenuation of the noise, and therefore, it was not very reliable. For this reason, a three-dimensional model of the city has been created, georeferenced and integrated with information relating to the noise level that has allowed public and private authorities a better understanding of the noise pollution (Lafioune and St-Jacques 2020).

### 10.1.5 Singapore City

In 2014, the Land Survey Division of Singapore Land Authority (SLA) launched a Whole-of-Government (WOG) project called 3D National Mapping with the aim of creating a national 3D map of the entire city of Singapore, through laser scans. The three-dimensional model was developed according to the OGC CityGML standard, from LOD 0 to LOD3 (Soon and Khoo 2017).

[2] The research and cooperation project is co-financed by A.I.C.S., the Italian Association for Development Cooperation among the initiatives proposed by local authorities. The Municipality of Pavia is the leader, followed by partners from the Municipality of Bethlehem, the University of Pavia, the University of Bethlehem, the VIS, the Province of Pavia, the ANCI Lombardia, the SISTERR, the Order of Engineers of the Province of Pavia and the Order of Palestinian Engineers.

### 10.1.6 Chennai City

The 3D city model of the city of Chennai in India was created to analysis the urban vertical development in the last ten years. The planners used the three-dimensional model created in **ArcMap** and **ArcScene** as a tool to support decision-making. This model was created essentially to measure the impact of urbanization on existing infrastructure, specifically, to check the capacity of the existing sewage network (Ahmed and Sekar 2015) (Figure 28).

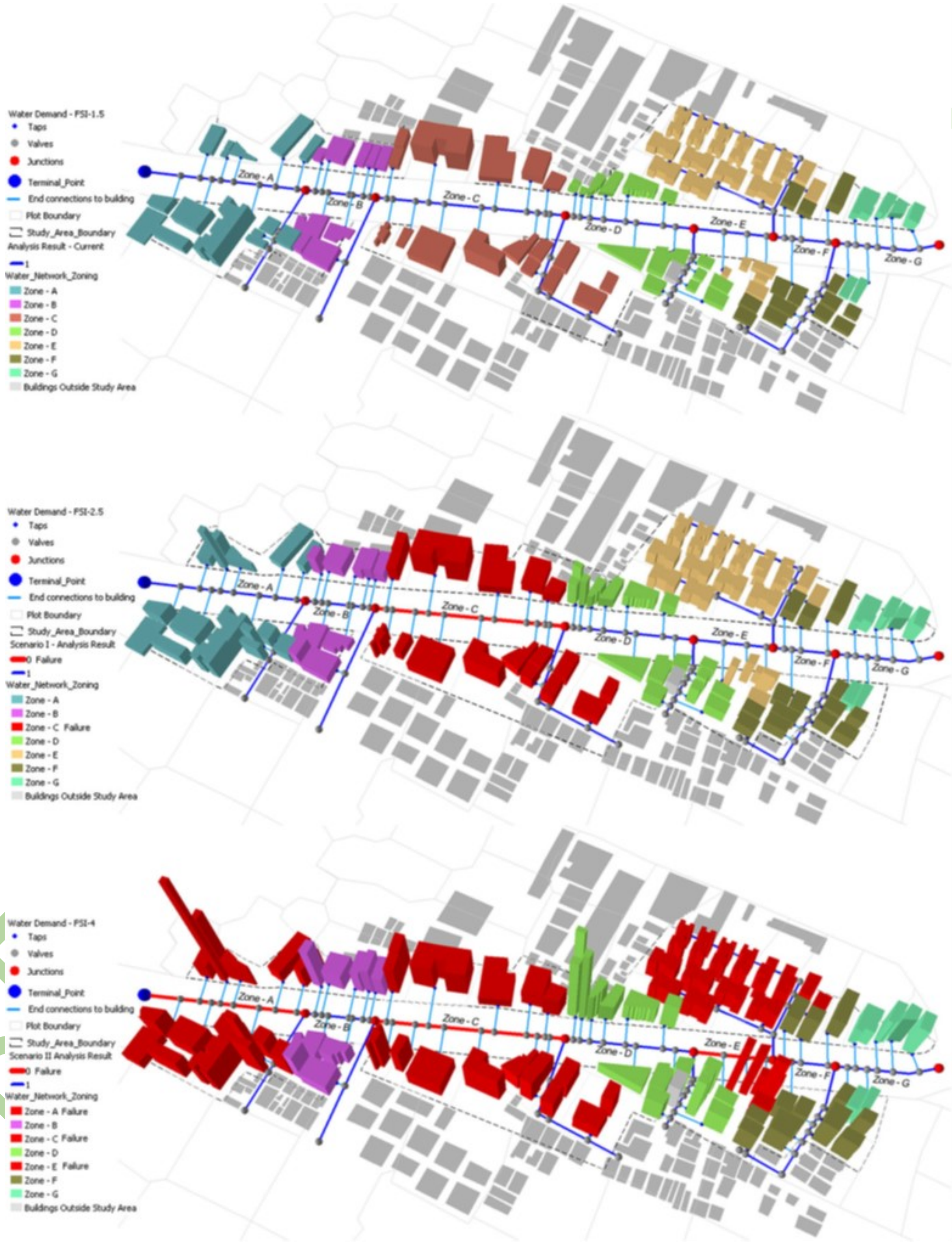


*Figure 28. 3D volumetric analysis results of the water supply network. Source:* (Ahmed and Sekar 2015)

## 10.2 Operative workflow

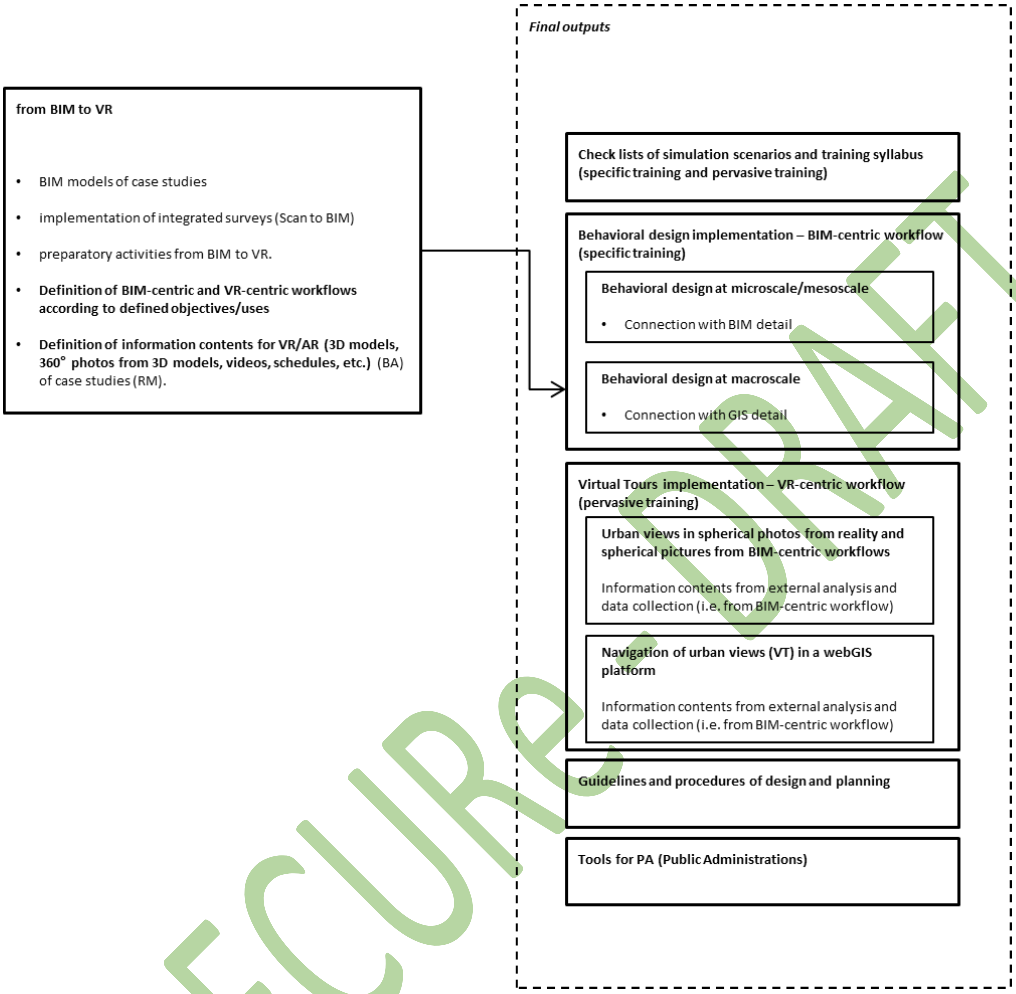


*Figure 29 Connection between WP3 and WP4/WP6*

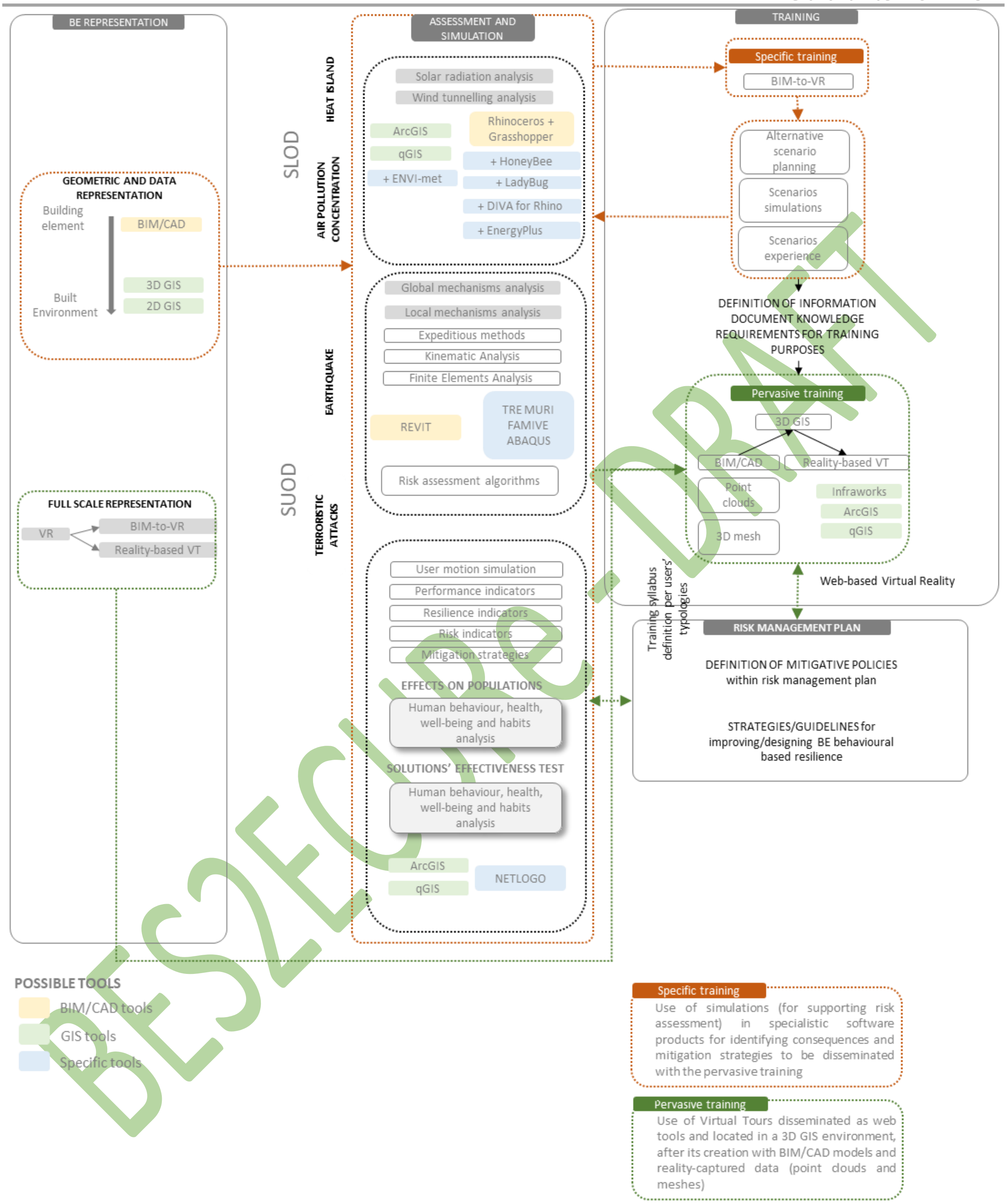


*Figure 30 Proposal of general operative workflow in BE S²ECURE project*