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# VERBUM – VIRTUAL ENHANCED REALITY FOR BUILDING MODELLING (VIRTUAL TECHNICAL TOUR IN DIGITAL TWINS FOR BUILDING CONSERVATION)

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***SUMMARY:*** *The digital transformation of the construction sector is also involving cultural and architectural heritage conservation management to solve criticalities of information exchange in refurbishment/restoration, from the preliminary steps until the execution and monitoring of interventions. Nevertheless, time and resources required to complete digital models (point clouds, 3D meshes and HBIM model) are extensive and this can cause interruption of knowledge communication among professionals. The VERBuM project (Virtual Enhanced Reality For Building Modelling) aims at investigating how a central Virtual Technical Tour (VTT), would guarantee a continuous stream of information when other disruptive technologies are integrated in the process and their related products are linked to the VTT. The use of a VTT, based on 360° photos, may fill time and resources gaps as it is a rapid up-to-date and high-fidelityto-reality tool. The fostering of the paradigmatic change in refurbishment/restoration process requires the development of all-in-one digital environments for digital twinning of cultural and architectural heritage and its assessment, aware of potentialities and criticalities to be overcame. The research moves from stakeholders' information requirements to implement the VERBuM process supported by the central VTT, editable via cloud-based platform (VERBuM product) to exchange digital contents, uploaded in different file format, but consulted in VR by all the involved actors via web services, without any software product installation. The tool has been evaluated via SWOT analysis supported by Task-Technology Fit (TTF) model and users' perceptions. The results provide mitigation measures of threats related to distrust in use of VTT within working groups and fruition of point clouds, meshes and BIM models, possible via WebGL-based libraries.*

***KEYWORDS:*** *Cultural Heritage, Non-destructive evaluation, Material characterization, Virtual Reality, Digital Twin, BIM.*

***REFERENCE:*** *Silvana Bruno, Albina Scioti, Alessandra Pierucci, Rocco Rubino, Tommaso Di Noia, Fabio Fatiguso (2022). VERBUM – virtual enhanced reality for building modelling (virtual technical tour in digital twins for building conservation). Journal of Information Technology in Construction (ITcon), Vol. 27, pg. 20-47, DOI: 10.36680/j.itcon.2022.002*

## 1. INTRODUCTION

Complexity is a factor that affects the development of refurbishment and restoration process of architectural heritage, because of the multi-disciplinary coexistence of specialized skills, techniques and tools, sources and data, and the heterogeneity of inherent characteristics of historical-monumental buildings. This involves the formulation of validated and shared methodological approaches which correspond to compatible and versatile solutions in operational practice. During knowledge and diagnosis phases, these approaches are required to evaluate morpho-typological features, material-constructive characteristics and state of conservation, before planning interventions and verifying their coherence with the fabric.

Although techniques and methodologies for diagnostics and control of the historical-architectural heritage have currently a good level of maturity (De Fino et al., 2016), there are still open fields of research and experimentation about effective methods and tools to support professionals in knowledge sharing.

In this regard, the potentiality of digital technologies and innovative approaches, borrowed from other sectors, have been investigated to overcome the risk of fragmentation and no governability of the refurbishment/restoration process. The aim is trying to build, retrace and maintain logic relationship among the knowledge domains. In particular, research is heading towards the definition of digital twin's technologies of the built environment (Jouan et al., 2019; Boje et al., 2020; Sacks, 2020a), including the historical-architectural Heritage (Dezen-kempter et al., 2020). The digital twin is a three-dimensional virtual representation of a physical artefact, obtained through advanced digital survey techniques, including laser scanners and photogrammetry of the as-built/as-damaged building (Dezen-kempter et al., 2020), then reconstructed in a BIM model to encapsulate all the information, also measured and monitored, using cloud services (Sacks et al., 2020). Even if the potentiality of Historic Building Information Modelling (HBIM) is recognized, as it is a system consisting of representation, information management and collaboration methodologies, there will be a need to overcome a weakness of HBIM implementation. This weakness is related to the temporal gap between the beginning of survey and the end of the BIM modelling, in order to manage the simultaneous operational activities of visual inspection, in situ and remotely, such as programming and execution of diagnostic investigations, and knowledge sharing since the preliminary stages of the project.

Furthermore, the HBIM approach appears lacking in the ability to render surfaces in full-scale and accurate mode (De Fino et al., 2019). Therefore, the introduction of the Virtual Technical Tours (VTT), as photorealistic environments, has been proposed into the process. The VTT consists of 360° photos acquired from reality (Maiellaro et al., 2019), and usable in either non-immersive (via mobile device or computer) or immersive view (through the use of headset or within Cave Automatic Virtual Environment – CAVE; Bourdot et al., 2019), which have demonstrated their effectiveness in reconstructing a strong perceptual experience in the tourism/educational field and sharing knowledge through interactive tools, located in the environment to view texts, videos, audio and other digital contents (Cantatore et al., 2020).

Therefore, the research aims to the definition of a methodological framework in which reality-based 3D models (point clouds and textured meshes), HBIM and Virtual Tours are integrated. The latter with the aim of supporting the actors in the activities in which HBIM still fails to be supportive due to its peculiarities. BIM-based Virtual Reality employs any other three-dimensional modelling approach, while Virtual Tours are Virtual Environments made up of 360° real photos or videos. In the first case, the BIM model is the digital prototype of a product, which does not exist yet, viewable in Virtual Reality (Bordegoni and Rizzi, 2011; Paes et al., 2017; Mastrolembo Ventura et al., 2020). BIM-based VR differs from the 3D CAD-based VR because the first type maintains the links between geometric, topological and semantic properties of BIM objects in immersive mode and they can be interrogated.

Otherwise, the Virtual Tour generated with reality-based 360° photos/videos can be employed to understand the "as-is" conditions and make preliminary decisions about interventions, as it shows the site in full-scale and with vivid details and it is easily updatable. Therefore, VTT could be an indisputable visual record, in the knowledge, planning and execution phases of the construction site (Cantatore et al., 2020). In both digital environments (BIM-based and VT-based) for Virtual Reality, the representation of the object is full-scale and the use is intuitive, engaging and allows a sense of presence (Paes et al., 2017).

This contribution presents the results of the VERBuM project, supported by INNONETWORK 2018 - Apulian Region, in order to design and develop a digital environment for Virtual Reality and Augmented Reality to allow the immediate consultation and effective use of information, even in immersive mode, after structuring and managing it. VERBuM is devoted for managing refurbishment/restoration process in a "vertical" sense, with respect to the different methodological phases, and "horizontal" sense, with respect to the different information sources exchanged between each phase. This objective is achieved giving relevance to knowledge stratification through the introduction of further interactive tools superimposed on the spherical images.

The research project investigates the VR features and acceptance in the Italian context, where the concept of digitization is recently spreading in public procurement (Ministry of infrastructure and transport, 2017), taking its cue from developments in other sectors and in extra-national territories.

The paper starts with an Introduction to the research question, literature review and research scope definition (Section 1). In Section 2 Materials and methods are provided for VERBuM process structuration, VERBuM Virtual Environment (VE) architecture and its evaluation with Task-Technology Fit method, interviews and SWOT analysis. The application of the VERBuM process and product in two pilot case studies in Southern Italy supported the development, updating and use of the digital environment during the project progress and the definition of strengths and weakness (Section 3). In Section 4, results of the evaluation process are provided, with the aim of providing mitigation strategies of threats against VERBuM process and product.

## 1.1 Research background

In the digital era transformation of the construction sector, academics and technology companies have been investigating possible development and use of Virtual Reality to share knowledge and intents, and control the entire project process as experimented in maintenance manufacturing (Tao et al., 2018). This is gradually shaping the technical and objective-based functionalities of digital twins of buildings and infrastructures (Sacks, 2020b). The digital twin consists of the digital replica of a living or non-living physical entity, and can be reached if convergence of Information Technologies is able to fulfil any piece in representing built environment and updating it in real time (Saddik, 2018; Sacks et al., 2020). The scope of the current research falls into the management of historic architectural buildings, an existing physical entity, where technicians progressively acquire knowledge to be consolidated about as-is/as-damaged artefact, before the selection of adequate conservation strategies. Among disruptive technologies, there are Building Information Modelling (BIM) and Heritage/Historic Building Information Modelling (HBIM), this last devoted to assist restoration and refurbishment (Murphy et al., 2009; Banfi et al., 2017; Arayici et al., 2017; Francisco et al., 2020). Nevertheless, the convergence of further multimedia source and their analyses are required, for example Virtual Reality.

In literature, Virtual Reality has been employed for several objectives within design and construction phases, as investigated by (Delgado Davila et al., 2020), that provide a research agenda reflecting the actual needs of practitioners and guides the academics' future research to improve adoption. Among specific requirements, (Delgado Davila et al., 2020) consider relevant, in research and application, the integration with other built environment systems, such as sensors network. The Virtual Environment can be created with different methods: i) generating a 3D model, with CAD or BIM software products, ii) elaborating 3D point clouds; iii) elaborating 3D texturized meshes, iv) acquiring real panoramic photos or videos; v) editing 360° photos or video.

The research topic in this contribution addresses challenges in refurbishment and restoration phases, above all for reality-based representation and knowledge acquisition and study, thus literature review is limited to investigations where Virtual Tours have been employed and compared with other technologies with this specific objective. In some research works, the use of Virtual Tour focused on the conservation process where other digital documentation tools (for i.e. Historic Building Information Modelling) evidence weakness (Bruno et al., 2018; Poux et al., 2020).

(Napolitano et al., 2018) formalized a workflow for Virtual Tour environments (VT) and informational modelling (IM), as an intermediate solution for conservation projects where three-dimensional representation of spaces is required, but the budget or time are insufficient for a 3D model. Thus, their VT/IM environment shares building plans, previous conservation reports, image galleries, databases about past interventions and short descriptions of the conservation issues. (Rysanek et al., 2017) pointed out on weakness of Building Information Modelling (BIM) for conservation activities on existing buildings, caused by BIM parameterization, to propose Virtual Reality platforms for navigating physical environments, created with equirectangular images, labelled with data or text widgets. In the same direction, (Castagnetti et al., 2017; De Fino et al., 2019 and Cantatore et al., 2020) proposed workflows for employing Virtual Reality with the aim of streamlining the management of technical knowledge in cultural heritage. (Ferrari and Medici, 2017), within the scope of the INCEPTION project, tested the Virtual experience mock-up for captured technical data accessibility (digital documentation and 3D survey). (Feriozzi et al., 2019) investigated VT for planning and management of Smart Cities.

Serious technical VT (VTT) have been investigated in construction site with progress monitoring and safety (Jaselskis et al., 2009; Sacks et al., 2015). Apropos, software companies are continuously developing tools for construction site monitoring and safety instructions via Virtual Reality based on reality-data capture, such as Holobuilder ("Holobuilder," n.d.) and Matterport ("Matterport," n.d.).

The Virtual Tour can enter the process because it can be rapidly updated, represent temporal evolution of evident conservation state, within an integrated digital environment based on web technologies, filling the gap of other time-consuming reality capture and 3D representation methodologies, such as more geometrical accurate 3D digital surveys (laser scanning and photogrammetry), and parametric modelling (Building Information Modelling and parametric design methods).

VR has been framed within several ISO standards about Information Systems, depicting vocabulary and definitions, architecture and base components, sensor representation. The development of VR and AR applications requires a standards-based approach to design, taking into account common uses and information exchanges, in order to limit development efforts and, therefore, a waste of resources. In particular, the JTC1 technical commission has published the guidelines for the development of VR and AR applications for educational and training purposes (ISO/IEC JTC 1, 2019).

About the technical components of a VTT, they can be a set of panoramas, stereoscopic photos or videos. The panoramic pictures are in equirectangular format when opened with standard photo-viewer, but they can be enjoyed as spherical images with pano viewers. The panoramic pictures can be acquired by traditional cameras/lens with acquisition motion around a point – user rounding or with a spherical head tripods -, vertically $\pm 90°$ and horizontally $\pm 180°$, automatically stitched by embedded application or using ad hoc photo stitching software products (such as Adobe Photoshop®, PTGUI, etc.). Nevertheless, innovative 360° (or spherical) cameras exist with double or multiples fisheye lens, which provide ready-to-use panoramic images or videos. Stereo panoramas are created with a pair of 360° images (Peleg et al., 2001), taken simultaneously with two lenses placed like our eyes, about 65 mm apart and looking in the same direction, in order to create 3D space experience. The panoramic video can be 180-degree video (stereoscopic video) which captures only a 180-degree field of view, without equirectangular projection, and 6DOF video (stereoscopic 360-degree video), which also captures depth. The acquisition modes of panoramic video could be in Live panorama (updated several times per hour) and HDR (High dynamic range) panorama for detailed pictures (Ferrari and Medici, 2017).

The Virtual Tour software products are employed to create digital environments with reality-data captured photos/ videos or panoramas/videos exported by CAD or BIM models. The images/videos are scenes interconnected via sensors for locomotion (also denominated hotspots, switch), that can be provided with alternative methods such as walk-in-place, steering, joystick or teleportation (Bozgeyikli and Raij, 2016; Zhang Y., Ladevèze N., Fleury C., 2019). These interlinked scenes are augmented with digital contents that can be opened via interactive sensors (hotspots) with rules to activate visualization modes of specific additional media, mostly documents, video, pictures, audio, 3D models. Being a web-based Information Technology, it could manage webGL graphical library, increasingly used for Cultural Heritage representation and fruition with point clouds (*.las, *.pts or other formats), meshes or 3D models (*.obj, *.mtl, *.glTF, JSON) published in HTML (Santos et al., 2014; Chen et al., 2016; Nishanbaev, 2020; Ioannidis et al., 2020).

## 1.2 Research scope

The scope of this research is outlining an integrated process for knowledge acquisition, archiving, analysis and reproduction for the conservation of architectural heritage buildings, and provides an easy-to-use Virtual Environment that aims at supporting the entire process, and adding another piece of research in digital twins for architectural heritage. This digital system for the actors of the conservation process will be configured as an operational tool for project, execution and control of interventions on architectural heritage thanks to the data/information exchange with already available applications, such as Computer Aided Design (CAD), Building Information Modelling (BIM) and 3D Point Cloud Processing. In particular, the process and product will support the qualification and evaluation of morpho-typological characteristics and conservation status as continuous reference for conservation intervention design and control during execution. The results obtained via SWOT analysis have been evaluated to identify technical limitations of the commonly used technologies and provide mitigation strategies to widespread adoption of VERBuM.

## 2. METHODS AND EQUIPMENT

As declared in the Introduction, the contribution proposes the VERBuM process (a methodological framework) structured to develop the VERBuM Virtual Environment, configured as an innovative information management system that provides immersive experience in Virtual Reality for the restoration/refurbishment of architectural heritage. The structuration of the information system reflects the comprehensive methodological framework, because it can vertically manage different methodological phases recurrent in best practices, such as basic knowledge, preliminary analysis and pre-diagnosis, deepening of knowledge, diagnosis, project, intervention, and horizontally the relative different sources in input and output, such as bibliographic, archival, normative, technical, analytical and experimental documentation.

In particular, this Virtual Environment is designed to integrate a structured set of data, referenced in "space" and "time", coming from documentary research, analytical processing and on-site diagnostic investigations in a digital model of the building, created with spherical photos, augmented with photorealistic models from laser scanning and/or photographic acquisitions, also captured with Unmanned Aerial Vehicle (UAV), and integrated with HBIM models and digital documentation. The incremental knowledge is getting usable in an interrelated dynamic mode by operators of the entire process of refurbishment/restoration. The next sections provide workflows about the VERBuM process and architecture structuration of the VERBuM VE.

### 2.1 VERBuM process: methodological framework

The proposed framework starts from the concept of VR-centric workflows where the Virtual Technical Tour (VTT), based on reality-captured 360° photos/videos, is the core for programming next data acquisition activities and consolidating knowledge about the artefact, then structuring the VERBuM VE (Section 2.2). Further digital representation and documentation, derived from CAD and BIM approaches are anchored on the central VT. This choice derives from the fact that photographic recording is always a preliminary step in site inspection. 360° photos have the additional advantages to provide a comprehensive and global perception of indoor and outdoor physical environments, nearly to 3D representation, rather than traditional 2D photos. In addition, the acquisition of panoramic images is really rapid, above all when taken with specific spherical cameras, with a cost and high-resolution comparable with digital cameras. So, the creation of a VT does not require high-level of technical competences, expensive software products, high performance hardware and time/labor resources. In refurbishment/restoration, the assessment of morpho-typological, material-constructive characteristics, and conservation state are paramount for conservation project and post-execution coherence verification (Binda et al., 2007; Moropoulou et al., 2013; Fatiguso et al., 2017; Cestari and Marzi, 2018). For this reason, the baseline VT constituted by interconnected spherical photos to teleport users in physical environments can be augmented with representation and qualification of building technologies beyond surfaces and, thus, the third dimension. This is possible through additional digital space-referenced widgets (hotspots or access points) that are programmed to be interactive with human selection and dynamically respond with defined requests. These widgets are used to visualize digital media (pictures, pdf, videos, audio, resources in a host server providing their Uniform Resource Locator - URL), and sometimes to download documents. Consequently, the methodological framework of team-work can be supported by easy fruition and sharing of further contents during the project, such as available drawings and reports, digital surveys products (point clouds and texturized meshes), evolution of HBIM modelling process, diagnostic reports, intervention evaluations, administrative and economic documentation, exchanged and rapidly updated in the VE.

The technical performance requirements of the VE are designed to sustain the proposed VERBuM process (*FIG. 1*), illustrated with a Business Process Modelling Notation (BPMN) representation (Messner et al., 2011; Sacks et al., 2018; Kifokeris and Koch, 2020). The BPMN is a flowchart method that models the steps of a planned business process from start to finish, information exchanges and, also, involved actors (Object Management Group, 2011). The preliminary activity concerns the 1_Coordination of the available resources, through the formalization of the working group, the definition of phases and specific activities; in this moment, data and information requirements, their coding are defined together with the identification of reciprocal relationships.

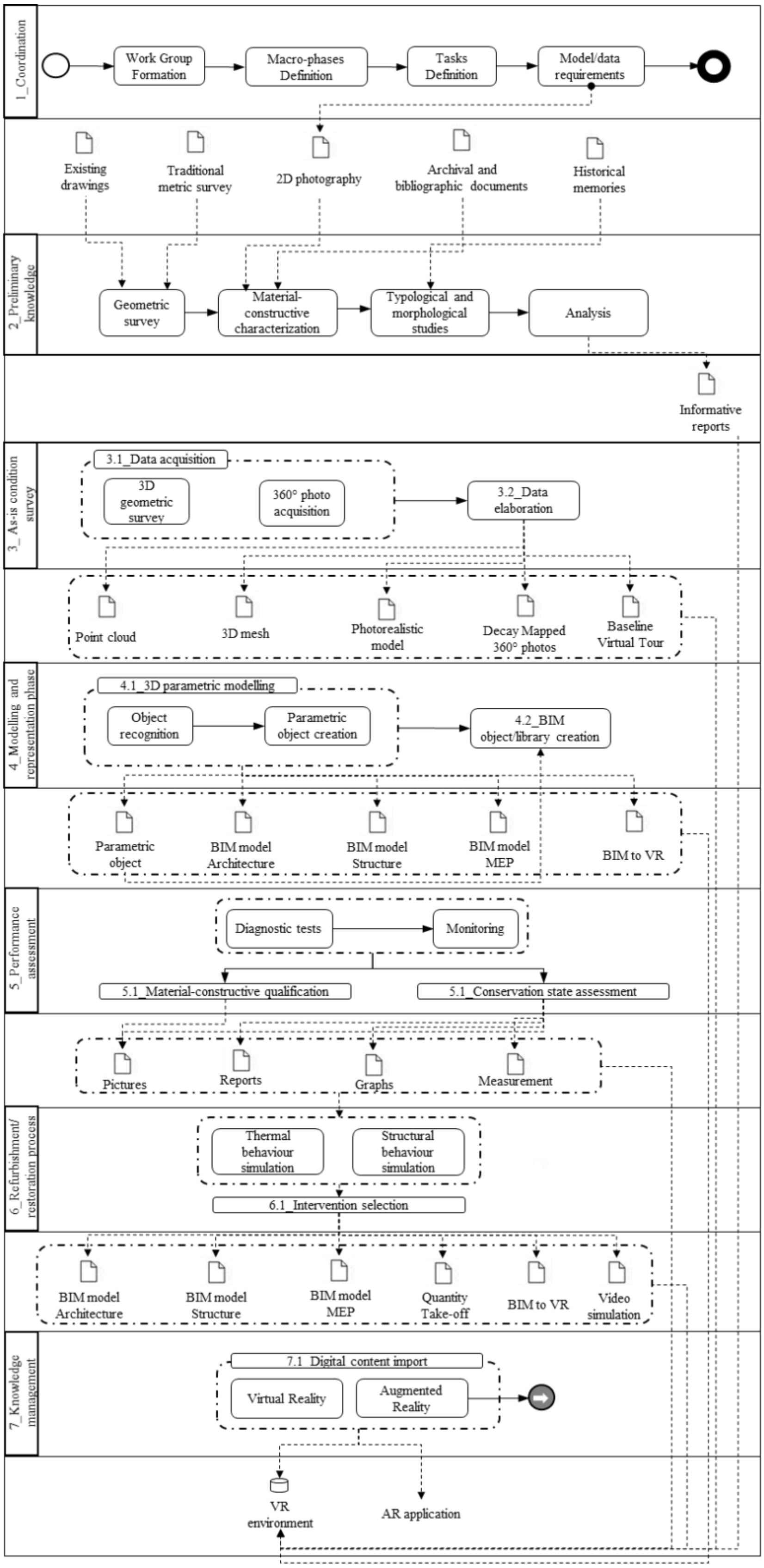


*FIG. 1: VERBuM framework: VR-centric approach*

A survey is carried out about available archival and bibliographic documents, existing CAD graphics, historical memories, photographic shots, in order to obtain preliminary information about the building typology, construction techniques, materials, previous transformations, room layout and use (2_Preliminary knowledge).

In phase 3_ As-is condition survey, metric data and information about geometry, morphology and decay patterns are acquired through traditional and digital 3D survey methods (laser scanner and photogrammetry) and panoramic pictures. Then, the setting of a complete VT is preparatory for next steps, as it is the most rapid deliverable to be obtained to support knowledge acquisition about the artefact. The digital captured data by laser scanning and photogrammetry are processed in point clouds, realistic photo-reconstructions, three-dimensional polygonal meshes in 1:1 scale, and published as webGL objects.

After, the 4_Modelling and representation phase and the 5_Performance assessment begin.

Phase 4 consists of the building reproduction from geometric surveys via Reverse Engineering in the form of 3D models, 2D drawings (plans, elevations, sections) and other digital documentation such as textual documents, video animations and so forth, helped by accurate appearance provided by immersive Virtual Tour.

The 5_Performance assessment consists of the pre-diagnosis and diagnosis phases. In the proposed process, the decay mapping can be directly drafted in the VE, working as survey inspection digital shit, with the possibility of being reproduced as superimposed map to the VT, replacing or supporting the more time-consuming traditional methods based on CAD drawing or HBIM model, shared as *.pdf files, which miss relation with real surface's appearance. In this way, decay mapping is an over imposed layer to reality-captured panoramic photos, whose visibility can be activated or deactivated. The procedural modalities for drawing thematic maps on real panoramic photos involve the use of CAD and/or photo editing, in order to produce equirectangular pictures with transparent background to be exported as *.png file. The use of sophisticated photo editing tools, such as the most recent Adobe Photoshop® versions, permits to edit panoramic photos in spherical modality through the 3D workspace, thus continuously on the picture (Cantatore et al., 2020), and to export them as rectified panorama in *.png, ready to be imported into the virtual reality environment.

In order to provide accurate knowledge about material and constructive techniques and conservation state, a planned set of instrumental surveys may be conducted, namely diagnostic (in situ and laboratory) tests.

Furthermore, data and information provided via 2_Preliminary knowledge and 5_Performance assessment, this last one consisting of 5.1_Material-constructive qualification and 5.2_State of conservation, are formatted in information sheets, diagnostic reports and technical-illustrative reports.

In the project phase (6_Refurbishment/restoration project), engineers/architects carry out the selection of adequate and sustainable interventions, conducted by the performance evaluation and analytical simulations of building behavior (for i.e. thermal and structural analysis). In addition, architectural projects rendered in BIM platform, exported as panorama or stereo-panorama, or published BIM models can be introduced in the unceasingly updated Virtual Environment (Verdoscia et al., 2020).

The entire knowledge and data/information analysis takes on a transversal role with respect to the design, the execution and the control of conservation actions once systematized, uploaded and shared within the VE, configured to be a Common Data Environment (CDE; PAS 1192-3, 2014; "Edilizia e opere di ingegneria civile - Gestione digitale dei processi informativi delle costruzioni - Parte 1: Modelli, elaborati e oggetti informativi per prodotti e processi," 2017) for 7_Knowledge management.

The leading role of this framework in this study is the structuration of the workflows of all the professionals involved supported by VERBuM Virtual Environment during in each stage (framework components) of the conservation projects. The structuration of the framework starts from the study of best practices requirements and protocol, with the aim of acting a change of team working from a paper-based and fragmented communication to a digital and all-in-one archive. This Virtual Environment has been structured to be coherent with each digital content that can be useful for knowledge consolidation.

VERBuM framework and VE have been tested though the application about two South Italian historic buildings, different for structural typology and constructive age: the masonry building Masseria Don Cataldo and the reinforced concrete structure of the Concattedrale Gran Madre di Dio, Taranto, this designed by the architect Giò Ponti.

The delineation of the entire process and its application to the two pilot case studies supported the identification of file and data formats handed over among stakeholders, in order to clarify technical features of the VERBuM VE to develop.

### 2.1.1 As-is condition survey, modelling and representation, performance assessment: methods and tools

During the as-is condition survey of Masseria Don Cataldo, spherical photos and standard photos for photogrammetric 3D reconstruction have been captured. The spherical photo acquisition campaign was carried out using a 24,2 MP Canon EOS M3 camera, mounted on a Manfrotto SKU 303SPH panoramic head. In the main room, images were acquired by rotating the camera 360° around the vertical axis with twelve 30° intervals and a 180° rotation around the horizontal axis with three 60° intervals. In this case, PTGui Pro software was used by merging the images and creating 360° panoramic images. The digital terrestrial and aerial survey campaigns with UAV were carried out to acquire the wall textures of the elevations and interior environments, including the decorative elements and the frescoed surfaces of the central hall. The indirect geometric survey of the central hall was performed with a digital photogrammetric technique (dense images matching), a non-invasive optical acquisition system based on passive sensors and widely used for the accuracy and reliability of the results. Two survey procedures were conducted, using UAV systems and cameras installed on telescopic supports on the floor. The photographic survey based on the use of UAVs was conducted with DJI Inspire T600 drone, equipped with X3 FC350 with 12,76 MP resolution camera. The survey campaign in the main room was carried out by moving the camera along the perimeter. Six flight sessions were completed, corresponding to two heights (2 and 4 m) and three inclinations in the horizontal plane (−90°, −45 °, 0°). The images were integrated with some images from the GoPro camera with 8 MP resolution, mounted on a telescopic pole, placed 4 m from the floor and oriented at +90° on the horizontal plane. The selected images have been loaded into the post-processing software Agisoft® Photoscan - now Metashape - in order to obtain a georeferenced and scaled three-dimensional model complete with textures, which can be exported as a polygonal or photorealistic mesh (*.obj, *.mtl, *.stl and textures *.jpeg or *.tiff) and point cloud (*.pts, *.las, *.ply, *.e57, etc.). The next phase 4_Modelling and representation has been performed in Autodesk® Revit 2019, using elaborated point clouds in the case study Masseria Don Cataldo and existing drawings in Concattedrale di Taranto. In the first procedure, the point cloud is imported into the Autodesk® Revit 2019 software (in *.pts or proprietary Autodesk Recap formats, such as *.rcp and *.rcs) and mainly used as a metric reference for the reconstruction of geometric profiles, to generate BIM object of the architectural elements of the central hall. The semi-automatic parametric modelling was also tested using FARO's "As-built for Revit", which allows to perform the deviation analysis between the point cloud and the BIM model, in the same BIM environment as Revit, to evaluate the Level of Accuracy (LOA) defined by US guidelines Institute of Building Documentation (USIBD, 2016).

The spherical photographic campaign at Concattedrale di Taranto was conducted using Samsung Gear 360 spherical camera, 24 MP resolution, on a tripod.

The non-destructive diagnostic tests were conducted with the following equipment and procedures (Table 1):

*Table 1: Non-destructive tests equipment and procedures*

| | | |
|---|---|---|
| Infrared thermography | FLIR T430sc<br>-20°C / 120°C<br>NETD <30 mK<br>FPA microbolometric sensor,<br>not cooled 320(H) x 240(V) pixel | Before the acquisition, the camera focus was adjusted in relation to the distance of the object. Following an estimation of the reference emissivity value, this value was entered as the calibration parameter. Then, a first thermal tuning of the image was performed by evaluating the range of apparent temperatures of the object. For each shot, chosen in order to minimize the presence of disturbances, both the photographic and thermal images were acquired. |

| | | |
|---|---|---|
| Sclerometric survey | Schmidt mechanical hammer type N, model GEI Concrete, n. B00756 | The sclerometric survey was performed, after a magnetometric survey, for the location of the steel reinforcements and the identification of the measurement points. The measurement of the surface rebound indices, carried out on a grid of 12 measurements and averaged over 9 values with the exception of the highest and the lowest, allowed to determine an estimated average of on-site cubic concrete resistance value by a correlation graph. |
| Magnetometric survey | Elcometer Protovale P-331 Mod. S<br>“standard” research probe<br>(Range: bar diameters 40 mm from 15 mm to 95 mm<br>bar diameters 8 mm from 8 mm to 70 mm)<br>“Deep Cover” research probe<br>(Range: bar diameters 40 mm from 35 mm to 180 mm<br>bar diameters 8 mm from 25 mm to 160 mm)<br>Probe-central unit connection cable | The magnetometric survey was conducted in order to locate the reinforcement bars inside the structural element and estimate the bar diameter and concrete cover, by scanning with a mobile probe connected to the central unit. |

## 2.2 VERBuM Virtual Environment: architecture structuration

Given the huge and heterogeneous amount of information needed to handle the overall restoration process, the VERBuM systems has been implemented in *a Software as a Service* paradigm thus fostering future updates to be plugged-in the system.

The overall architecture has been designed and developed around a customized Contend Management System (CMS) able to store and deliver all the elements which are part of a VR experience. The VERBuM CMS allows the user to put together and orchestrate all the digital elements needed to develop the restoration project, such as 360° photos, videos, multi-layered images, videos, 3D models, up to a virtual avatar able to speak to the user when wearing the VR headset. In fact, the CMS works as the back-end of the overall systems and provides information to render the User Interface both on the VR headset (when enjoying the project) and on a Web Browser (when creating the project). FIG. 2 illustrates a graphical representation of the main building blocks of the architecture. From a technological point of view: the back-end makes a massive use of cloud-based technologies and solutions exploiting the Firebase platform offered by the Google Cloud platform; the Web-based front-end has been developed using Angular.js in order to guarantee a multiplatform and multidevice experience; the VR part runs on the Facebook Oculus environment and devices.

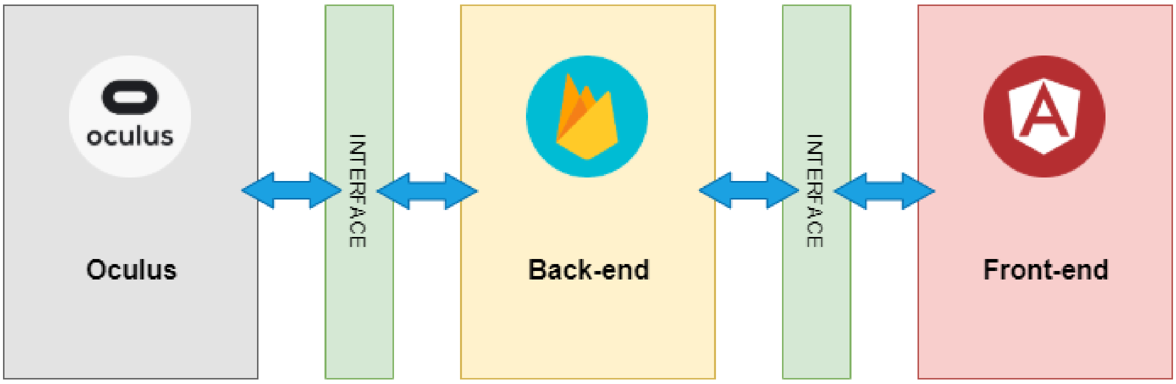


*FIG. 2: Front-end, back-end and Oculus communication interfaces*

The communication among the different modules goes through standard Web technologies and all the information is sent via POST messages over HTTP. In this respect, the back-end exposes a rich set of API that makes every operation atomic and easy to manage and debug.

### 2.2.1 VR client for Facebook Oculus

The VR client has been developed for the Facebook Oculus platform and it has been designed following the user-centric paradigm. The application must allow the user interacts with the 3D environment in a natural, smooth and strengths way as well as to manipulate objects available within the virtual scene.

The application bases on the Unity Game Engine and, specifically, on its XR (for eXtended Reality) support. Unity provides a full set of tools to create AR/VR applications by considering all the aspects related to real-time rendering of a 3D scene in a digital setting.

A Unity project consists of scenes that contain the various elements user can interact with. To build a scene, it is necessary to make use of a "hierarchy." The elements can be simple or prefabricated (Prefab), i.e., elements combined with properties already defined in advance, saved on the disk as an asset. The project window shows the directories and files on the disk that make up the project, which is called Assets. The editor allows to view the scene being edited in real-time through the Scene window. With special transformation tools in three-dimensional space such as displacement, rotation, and scaling, you can set the transform component's appropriate parameters associated with each object. The inspector window allows you to manage the various components for each object in the scene. There are different windows types: those that manage XR, audio, effects, 2D and 3D physics, rendering, UI, video, lights, custom codes, and many others. Finally, the console window allows to report errors, warnings, and messages to facilitate debugging operations.

In the case of VERBuM, standard components were used for collision management and rendering of the various parts of the scene. Simultaneously, custom code has been written in C # language for the integration with the back-end in Firebase and the Oculus API.

The main elements composing the VR application are summarized in the following Table 2:

*Table 2: VR application components*

| | |
|---|---|
| **Room**  | It physically constitutes the virtual room and consists of several sub-elements: 360Sphere is a sphere on which the 360 photos uploaded by the operator through the web interface will be shown, 360Layer_1 and 360Layer_2 are the 360 layers overlaid on the background that can be enabled or disabled by the operator when using the Oculus. The 360SphereCollider is a component; a Collider has been assigned to that allows the application to detect collisions between the beam fired by the Oculus controller and the 360 background to enable or disable the background layers. ItemsContainer is the container object for all items created within the specific room. |
| **Interaction Box**  | Developed for the management of the single object in VR within the scene. This allows the user to freely move content such as images, videos, templates, PDFs, and avatars inserted within the scene. |
| **Device Controller** | It checks the device on which the Unity compiled module is running. In fact, if it is working on the web platform, it must enable the components for editing the elements in the scene. If it is inside Oculus, it enables the components that manage virtual reality and the mapping of the controller commands. It has no graphical rendering components connected but only C # scripts that manage its logic. |
| **Audio Manager** | It manages the sound part by playing and pausing the background audio. Like the Device Component, it has no visual components. |

When the user wears the Oculus headset, they are shown a panel on the screen to insert a token to access the system and the room previously set up by the administrator operator. Immediately after logging in, the system downloads all the elements composing the room. Specifically, the elements that are downloaded following the call to the getRoomData API are:

- 360 background image;
- 360 background layers;
- Images with layers;
- Video with preview image;
- Avatar with MP3 audio;
- Switches;
- 3D models;
- PDF documents.

Each of these elements also contains the appropriate spatial coordinates to place the objects with their x, y, z coordinates, and a specific rotation. Each element is enclosed in a prefab. Starting from the ItemImage element, this is used to represent an image in the scene. It consists of three main parts: an icon shown when the item has not yet been downloaded from the network; an object that shows the actual image; the sub-elements that make up the layers. These latter show additional information superimposed on the main image. They can also be deactivated or activated in the Oculus as needed.

The other elements have almost the same structure. A substantial difference can be found in the ItemVideo and ItemPDF elements as they provide, respectively, a video viewer and a PDF. As for the former, a surface has also been implemented to show the preview of the video when it is not playing, and a spinner that shows when it is buffering. As for the PDF viewer, the corresponding buttons have been set up to navigate between pages directly together with the viewer's controller.

The input management system has been made compatible with Oculus GO to use the device controller as an input event source. According to this scheme, it is possible to use the Oculus GO controller input to send a beam with a certain direction and intersect a surface in the scene. The intersection point is where the interaction occurs, and the intersected object is the element on which the interaction is performed (virtual and raw mappings of the Oculus GO controller).

## 2.3 VERBuM evaluation

The validation and evaluation of an Information System (IS) only take place in subsequent stages of implementation and use. In scientific literature and at industrial level, the analysis of the potential success of an IS is conducted through different evaluation models, according to the specific aim of obtaining information about interactive relation between outcomes, in terms of process effectiveness, before the IS use, and the context areas. In this research, the IS to be evaluated concerns Virtual Reality (VR) technologies, products of digital geometric survey campaigns (aerial and terrestrial laser scanning and photogrammetry) and Building Information Modelling (BIM), with the aim to identify integrated use processes, evaluating the most effective and strategic uses of each technology investigated for the management of the refurbishment and restoration, according to the objectives to be pursued.

In the technical and academic fields, the use of innovative technologies is widely recognized as an enabler of competitive advantage at an organizational level (Smithson and Hirschheim, 1998). However, the effectiveness of these systems depends on the organizational structures (represented by defined roles and responsibilities of the actors) and on the overall size of the operating system in which it is inserted. Therefore, the evaluation of potential and criticality cannot fail to consider the performance factors of an organization. In particular, a distinction must be made between the integrated use of methodologies in the field of scientific research with respect to the technical-applicative field, in order to consider the differences about human and physical resources (hardware and software) and time resources in the two organizational models. Indeed, in research contexts physical resources (hardware and software) frequently (although not widespread) have more performance features and the timetable are more distributed over time spans ranging from annuity; while, in professional contexts, mid-range laptops are used and time is more limited and linked to contingencies and deadlines. For this reason, the research projects involved academics, professionals and construction companies.

There are different models and theories for evaluating IS and use processes, the selection of which depends on the area and context of use (Lu et al., 2012).

These models are used in the screening phase to identify the factors that can cause criticalities or amplify the potential of technologies and processes. Therefore, the results of evaluation and validation were useful in identifying criticalities and potentials through the SWOT analysis of the VERBuM platform and the use processes, and they consequently supported planning strategic and improvement solutions.

Given the solid correlation between use of the IS and organization, individual intentions and collective intentions (working group) must be investigated, in order to assess the effectiveness of the IS in an organic and comprehensive way. Therefore, a first phase of validation took place through the testing of the first and subsequent versions of the platform by the members of the research group in charge of consultation activities for the IT development of the VE. The consulting was provided by the internal collaborators of the diagnostic teams, as well as research coordinator, (B.Re.D. – Building Refurbishment and Diagnostics srl). Furthermore, the meetings with the other members of the research group provided suggestions for improving the IS by expressing their usual needs during the design and execution phase (viewing and consultation of pdf documentation, exchange of pdf documentation, compilation of inspection forms, degradation mapping, interventions, audio recording during inspections or revisions to documents, visualization and use of 3D meshes and point clouds without the use of technical software, consultation of diagnostic results, video about execution procedures of interventions). In addition, the construction company counterpart expressed interest in understanding the possible ways of interfacing BIM technologies with the VE under development.

In particular, feedbacks were sent via email to the developer team, in the form of direct observations and shared notes about use tests of the VE prototype version, and concerned the request for optimal procedures for creating the VTT: i) loading scenes and hotspots for moving from one scene to another, pointing out the need to define the north for each scene as an initial point of view in the switch from one scene to another, ii) uploading of digital content in the different formats identified as recursive within the exchange processes in design and construction site management phases. In addition, suggestions were provided about the graphic interface, for example relating to hotspot icons to easily suggest the type of digital content, visibility and size; preview of spherical photos in the general menu, the possibility of editing or deleting digital contents, dimensions of the contents and dimensions in terms of digital memory (in particular, for equirectangular photos, pdf and 3D models) and addition of descriptive texts regarding the digital contents. Further requested improvements concerned the introduction of the manual drawing tool directly in the VTT, so that it can be used as an inspection notebook in the phases of survey of degradation; the addition of the "Layer" tool to superimpose contents to the 360° photo, in the same equirectangular format, such as the decay and intervention mapping. Furthermore, the pdf document download function has been introduced, which is relevant in knowledge sharing processes.

The success of the application is influenced by the union of three constructs: technological characteristics, operational requirements and individual skills. Individual satisfaction focuses on individual interests, while the overall degree of satisfaction of the IS depends on operational requirements and technical-performance specifications (Goodhu, 1988). Therefore, the use of the Task-Technology Fit (TTF) model is agreed as a tool for evaluating/validating VERBuM product and process, focusing the analysis on identifying the correspondence between the technology functionalities and the operational requirements (tasks)(Goodhue et al., 1995).

The development of the VE follows the principle of usability, centred on functionality, trying to offer an easy-to-use interface when creating the VT and, on the other hand, satisfying users with immersive experiences.

Quantitative analysis, trough questionnaires, was performed to understand the level of knowledge of VR/AR technology in the selected sample, its potential uses in refurbishment and restoration decision-making processes and to identify the effectiveness of the VERBuM digital environment in use through the proposed methodological framework. In particular, it helped to further identify the strengths and weaknesses of the process and product through SWOT analysis. The questionnaire was first tested by three specialists, including an academic researcher, expert in structuring and processing the results of the interviews, external to the research team, and two researchers belonging to the group, to ensure the clarity, the structure and the logics of the questionnaire. The platform was tested during the workshop sessions held in a week, organized on the Teams platform for the eight remote sessions with the experts, in order to proceed safely during the COVID-19 period, and three sessions in physical presence at the Polytechnic University of Bari, which involved three PhD students. At the end of the test, the testers answered to a mixed type survey questionnaire (open, closed and scaled), consisting of 24 questions: two with open answers, thirteen with closed single answers and nine with scaled answers, Likert scale from 1 (not at all) to 5 (a lot). The sample of 11 interviewees was selected from experts in the refurbishment and restoration sector as a convenience sampling, whose socio demographic profiles are resumed in Table 3.

*Table 3: Interviewees characterization*

| | | |
|---|---|---|
| **SOCIO-DEMOGRAPHIC PROFILES** | | |
| 1 | GENDER | |
| | Man | 3 |
| | Woman | 8 |
| 2 | AGE RANGE | |
| | 26-35 | 8 |
| | 36-50 | 2 |
| | 51:65 | 1 |
| 3 | EDUCATIONAL QUALIFICATION | |
| | Master degree in Architecture | 3 |
| | Master degree in Building Systems Engineering | 3 |
| | Master degree in Building Engineering and Architecture | 2 |
| | Post-lauream (PhD, specialization school) | 4 |
| 4 | PROFESSION | |
| | Employee | 3 |
| | Entrepreneur (Architect/Engineer) | 1 |
| | PhD students | 3 |
| | Student | 4 |

In particular, the sample of interviewees is composed by two employees of the public administration, an architect, two employees of a construction company, three PhD students in Refurbishment of historic buildings and three undergraduates, whose thesis topic concerns VR and HBIM to support the knowledge phase. The majority of interviewees are women (73%), young adults with age from 26 to 35 (73%), almost the 36% with post-graduate instruction (PhD), and mostly equally subdivided against their profession (architect/engineer employee, architect/engineer entrepreneur, PhD students and students). Consequently, the response to the qualitative questionnaire is not influenced by the experience, but from the tested capability of the VERBuM VE as compared to both theoretical (education), Research&Development (academics) and operative requirements (professional experience).

## 3. VERBUM VALIDATION

The proposed methodological framework was tested for the knowledge acquisition, diagnosis and identification of restoration interventions of the (A) fortified Masseria Don Cataldo, and maintenance interventions of the (B) Concattedrale Gran Madre di Dio, Taranto, designed by Architect Giò Ponti, both located in southern Italy.

The Concattedrale Gran Madre di Dio, Taranto, is an ecclesiastical building belonging to the modern architecture, built in the more recent past (1966 - 1970) and, as such, a vast and in-depth project documentation is available, until the ones about the maintenance interventions: the restauration of “La Vela” (2001-2013) and the external facades (2017-2019).

Masseria Don Cataldo is a historic building, whose first building nucleus dates back to the seventeenth century, two floor levels and built with hewn stone ashlars joined with mortar, intended for the management of surrounding farmlands. Since 1724, it has been affected by multiple interventions of expansion and transformation. Nevertheless, differently from the first case study, material-constructive characteristics and residual performances of Masseria Don Cataldo are hidden or not ascertained. During the 2_Preliminary knowledge phase, archival and bibliographic documentation (jpeg and pdf) have been collected, catalogued and shared within the actors through the following-up of the project, in order to use them in planning next on-site visual inspections and surveys and reconstructing the historical-design and construction processes. These initial activities allowed the acquisition plan of spherical photos in number and position, as well as the study of environmental conditions (low light, absence of horizontal surfaces for acquisitions, and so forth); in such a way as to guarantee total coverage of the asset and an effective overlap between contiguous scans. Nevertheless, the acquisition plan of spherical photos about the roof floor, drawn up prior to the inspection, underwent changes during the on-site activities. The planning of the knowledge consolidation through surveys and experimental diagnostics (3_As-is condition surveys and 5_Performance assessment) requires a rational selection between a multiplicity of techniques and methods for instrumental investigations, in order to identify the most suited protocol. The metric and photogrammetric survey phase was integrated with a spherical photo campaign (phase 3) for the creation of the baseline Virtual Tour. The geometric survey and the collection of available material were useful for the HBIM modelling in authoring software platforms (phase 4). During diagnostics tests execution, annotations have been drawn on the scenes about decay mapping and notes about diagnostic tests (FIG. 3).

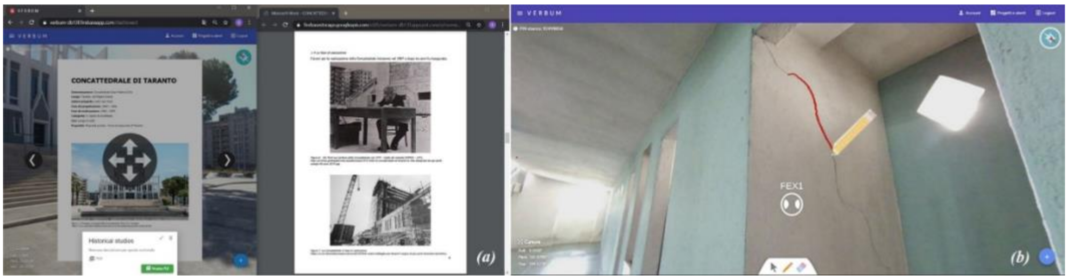


*FIG. 3: (a) VERBuM augmented with archival and bibliographic studies; (b) annotation tool for on-site decay mapping (B)*

The study of conservation state through the elaboration of thematic maps about crack and damp patterns and building pathologies according to the UNI 11182/2006, is generally represented in CAD, recently in BIM. In VERBuM process and product, the decay mapping procedures tested by (Cantatore et al., 2020; Fino et al., 2019) are performed, on the basis of on-site preliminary identification and representation through the annotation tool present in the VERBuM platform.

As an example, the FIG. 4 shows the raster mapping performed on the surfaces of “La Vela”, Concattedrale Gran Madre di Dio, Taranto with Photoshop CC® software. While, the vector mapping with CAD applications was carried out in the central hall, Masseria Don Cataldo. The innovative method consists of the implementation of the spherical decay mapping within the VE using the "Layers" tool, which allows to superimpose the decay mapping on the spherical image, to be activated or deactivated with on/off tool. However, the degradation mapping drawings, created in CAD or BIM applications, can be exported as pdf or pictures and shared in the VE platform as well.

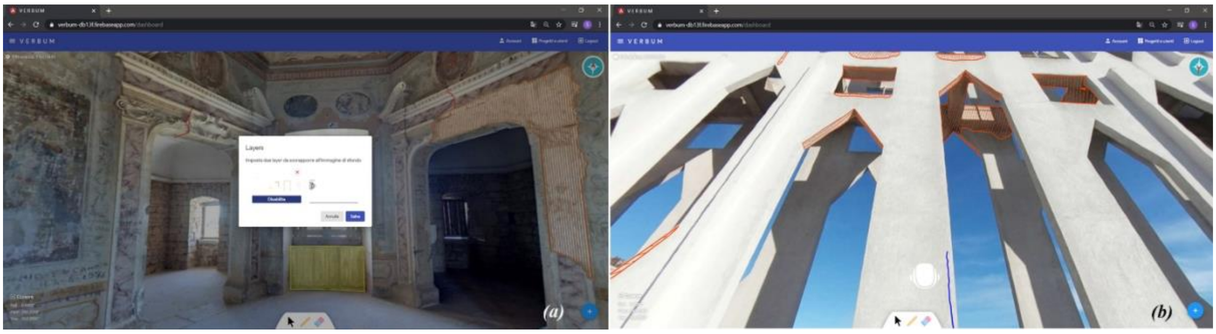


*FIG. 4: VERBuM application. (a) Vectorial decay mapping on equirectangular photo and use of "Layers" tool. (b) Raster decay mapping on spherical photos added as layer.*

The selected diagnostic investigations aim to identify the material-constructive characteristics and causes of deterioration. Thermographic recordings of the external facades and interior rooms were carried out at Concattedrale Grand Madre di Dio, which revealed the direction warping of the plane brick-concrete floors, the reinforced concrete frame, visible from the shots on the walls that delimit the chapels. In addition, there are large areas with low surface temperatures, compatible with the presence of water seeping and condensation phenomena, especially in correspondence with the external walls, roofing floors and window openings. The material-constructive characterization of the structural elements of “La Vela” was carried out via magnetometric survey, detecting the thickness of concrete cover, the diameters of reinforcement bars and brackets and their relative steps. Likewise, magnetometric investigations (identification of the concrete cover and reinforcement bars) and sclerometric investigations (mechanical characterization of the concrete) were carried out on one of the two obelisks on the altar of the upper church. The test reports have been processed with traditional and BIM software applications, printed in pdf files and shared in the VERBuM platform. The **Error! Reference source not found.**FIG. 5 illustrates the uploaded of the thermographic survey of the indoor.

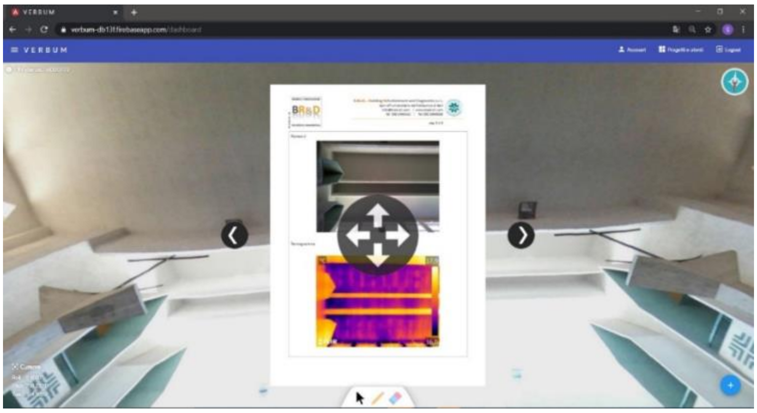

*FIG. 5: VERBuM application: report test about thermographic photos shared within VERBuM VE (B)*

The Infrared thermography shows the structure of the clay-concrete slabs and humidity spots on the surface.

The magnetometric test supported the identification of the rebar position and diameter of "La Vela", drawn as parametric objects in the BIM model, employed to export the pdf report (FIG. 6).

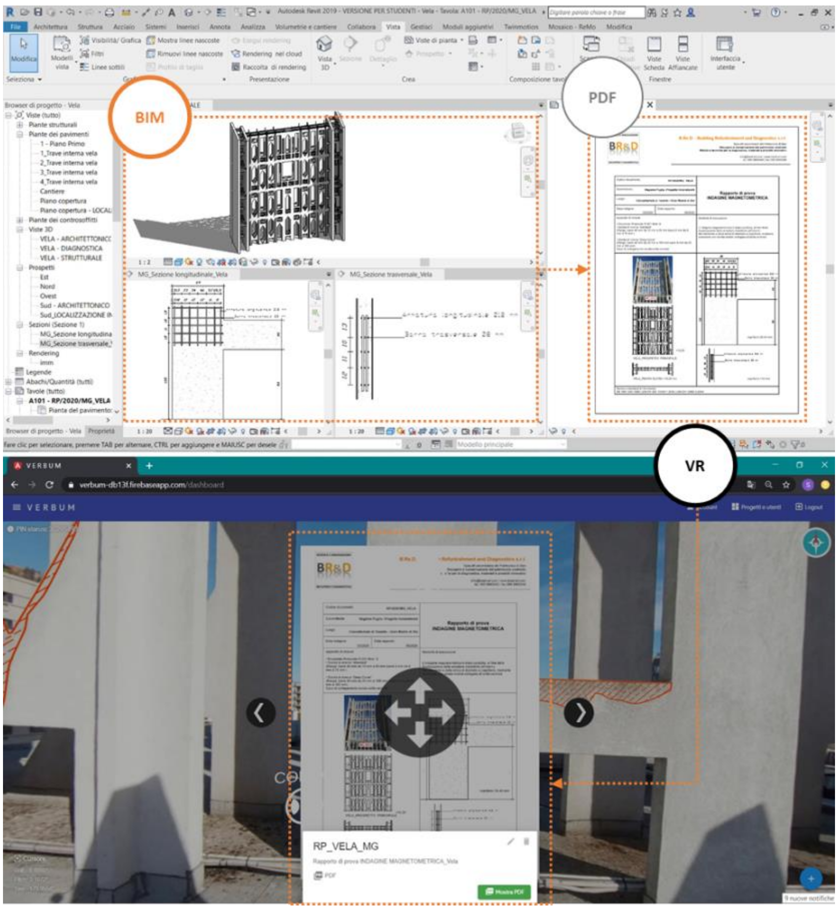


*FIG. 6: VERBuM application: report test about magnetometric survey on "La Vela", elaborated in BIM software and shared in the developed VE (B)*

This diagnostic test helps to identify that the concrete cover is lower than the minimum value in regulations, causing cracks of the concrete cover.

The structural typology of Masseria Don Cataldo is load-bearing masonry with stone blocks, barrel-vaulted floors in stone ashlars on the ground floor and mirrored pavilion vaults on the first floor, steel-beam and brick slabs in the loggias, wooden slabs in a room near the stairwell that connects the original tower to the more recent building body. In this case study, the knowledge acquisition methodology to characterize the architectural and construction components aimed at identifying the stratigraphic composition of the masonry walls, thicker than 60 cm, of the stone barrel vaults, the construction technique of the frescoed vault of the central octagonal hall, on which the possibility of carrying out destructive surveys is forbidden, as they would damage the continuity of the frescoes. Therefore, radar investigations were planned to qualify i) the vault between the ground floor and the first floor, in correspondence with the central hall, ii) the masonry in stone blocks, with a total thickness of 68 cm, which circumscribes this room. The infrared thermography involved the mirrored pavilion vault, with an octagonal plan. The analysis of the radargrams, both longitudinal and transversal, detects the cross section of the barrel vaults present on the ground floor. The thermographic survey returns information regarding the material-constructive characteristics of the vault and degradation phenomena. In some images, the texture of the vault in tuff blocks (≈20x40 cm) is recognizable, with staggered joints, with horizontal and regular courses. Thermography confirms that the visible spots on the vault are caused by seeping (FIG. 7).

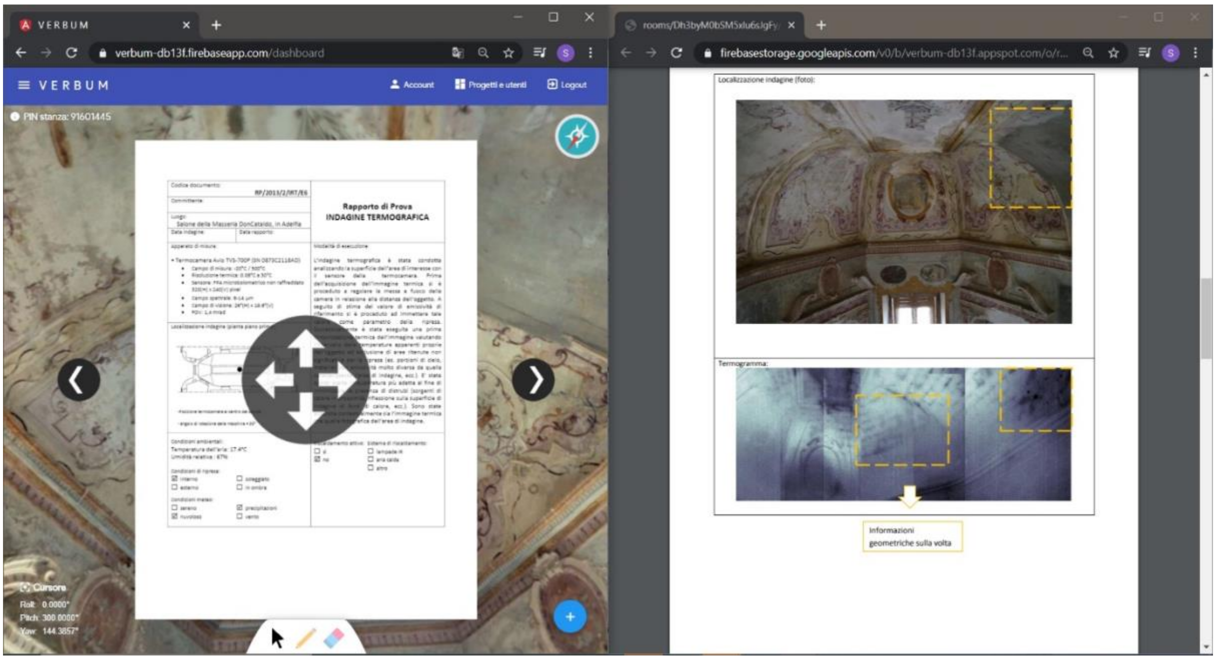


*FIG. 7: VERBuM application: report test about thermographic photos shared within VERBuM VE (A)*

Simultaneously, the modelling and representation in HBIM followed up, starting from original drawings and reality-captured 3D models (point clouds and 3D mesh). During the refurbishment/restoration process, the HBIM model can be shared, with progresses about the project, within the platform after its publication on a web viewer (FIG. 8).

Using the same application concepts, point clouds and texturized 3D mesh can be navigated and analyzed within the same VERBuM VE, after their publication as webGL object.

The HBIM model can be employed for project conservation and maintenance activities, as it can support decision making on alternative scenarios, modelled in the same BIM platform, and elaborate detailed drawings with execution phases simulations, time and cost coordination, quantity take-off schedules.

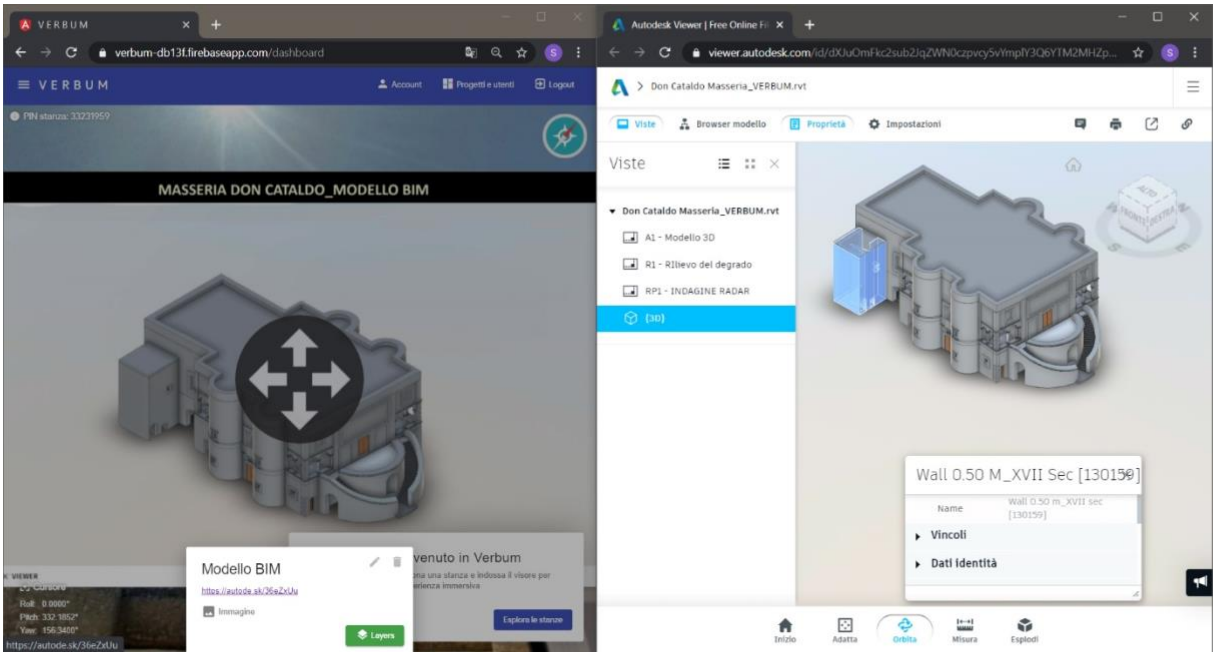


*FIG. 8: VERBuM application: navigation of HBIM model within VERBuM VE*

## 4. RESULTS AND DISCUSSION

According to the Task-Technology Fit – TTF theory, as selected IS evaluation method, the technical-performance specifications have been identified and classified as: P) project-defined, S) development-reached and A) pilot cases application-used (Table 4).

In particular, some of these technical-performance specifications answered to preliminary requirements (P) defined in the first stages of the VERBuM project by the research team member, starting from literature review, existing software products, personal experience as architect/engineer professionals (both firms and studios), academics, technicians, computing programmers. All of them have been confirmed and applied during the development of the VERBuM VE (D) and validated with the application to the pilot cases (A). The project requirements of the VE architecture (P) established mostly regard the selection of web-based VT editing tools against installed software products (such as TourViewer and 3D Vista), in order to ensure interoperability, avoid high performance hardware where the software is installed and its updating. This has the consequent advantage for remote and collaborative team-work. Nevertheless, this aspect has required the activation of user authorization commands to permit the editing mode (D, A). Even, ensuring high resolution of accurate and realistic representation of the built heritage in desktop/mobile mode and in immersive mode and, contemporarily, stable information technology platform, use of quick screen update and stabilization and reduced reaction time of commands. The other requirements are related to the use of VERBuM VE, including user's orientation options and greater flexibility in platform customization. Large attention has been given to hotspot actions to open recurrent and innovative file format and information typologies.

The evaluation of the VERBuM VE and process has been also carried out after test sessions addresses to possible stakeholders, as introduced in Section 2.3, external to the project partners.

The eleven interviews compiled in the workshop sessions provided significant results. Nine interviewees had experiences of VR: entertainment (2); project presentation (6), interior design products navigation (1); collaborative platforms (5). Only three individuals employed software products to create Virtual Tours. Some insights about the VERBuM process and product have been sintetized in Table 5 and **Error! Reference source not found.**.

*Table 4: VERBuM technical performance requirements - design phase (P), development (D) and application (A)*

| | **Technical-performance requirements** | **P** | **D** | **A** |
|---|---|---|---|---|
| P1 | Accurate and realistic representation of the built heritage, including frescoed surfaces, decorative elements and decay phenomena | x | x | x |
| P2 | Accurate understanding of three-dimensional space remotely | x | x | x |
| P3 | Creation of various, extensive and complex virtual environments | x | x | x |
| P4 | Archiving of historical information | x | x | x |
| P5 | Archiving of technical information | x | x | x |
| P6 | Mapping of degradation, directly on the spherical photo | | x | x |
| P7 | Layer mapping of degradation/interventions superimposed on the spherical photo (on/off tool) | | x | x |
| P8 | Support for diagnostic investigations plan | | x | x |
| P9 | Integration with BIM approach | x | x | x |
| P10 | Easy collaboration with actors who do not use BIM tools | x | x | x |
| P11 | Sharing of contents in different formats (pdf, gtlb, obj, jpeg, png, mp4, mp3) | x | x | x |
| P12 | Easy creation of the Virtual Tour (scenes, teleportation and upload of digital content) | x | x | x |
| P13 | Easy modification and updating | x | x | x |
| P14 | Switching from one scene to another while maintaining the path direction | | x | x |
| P15 | High resolution in desktop/mobile mode | x | x | x |
| P16 | High resolution in immersive mode | x | x | x |
| P17 | Stable information technology platform | | x | x |
| P18 | Reduced reaction time of commands | | x | x |
| P19 | Greater flexibility in platform customization | x | x | x |
| P20 | Single platform consisting of two parts - Virtual Tour Editor and Viewer in Headset | | x | x |
| P21 | Virtual web-based environment – it avoids installations on pc and not influenced to pc/notebook/ smartphone performance | x | x | x |
| P22 | Authorization to access in editing mode | | x | x |
| P23 | Use of scene PIN to automatically access a specific scene in immersive mode | | x | x |
| P24 | Use of scripts with quick update and stabilization | | x | x |
| P25 | Not influenced by software and hardware updates | x | x | x |
| P26 | Training tool | x | x | x |
| P27 | Integration with point clouds, 3D mesh and textured mesh | x | x | x |
| P28 | Possibility of on-desk use for those who have difficulties in using the headset device (motion sickness) or do not have the headset device | x | x | x |
| P29 | Unique archive of previous projects to be compared for acquired building pathologies, interventions, architectural and construction characteristics | x | x | x |

*Table 5: Evaluation of VERBuM features from questionnaires*

| | **QUESTIONS – Likert scale (1-5)** | **Average** | **Standard deviation** |
|---|---|---|---|
| Q1 | Are the functions of the digital environment adequate and sufficient for the phases of the refurbishment/restoration process? | 3,91 | 0,70 |
| Q2 | Is the graphic interface of the Information System intuitive for the creation of the virtual environment and the implementation of its contents? | 4,45 | 0,52 |
| Q3 | Does the immersive environment allow an in-depth knowledge of the building, with regard also to the next phase of conservation state identification? | 4,18 | 0,87 |

| | QUESTIONS – Likert scale (1-5) | Average | Standard deviation |
|---|---|---|---|
| Q4 | Do you consider the annotation tool useful and essential to draw a closed polyline, enclosing the area of interest with the mouse or the pen (with devices equipped with a touch display)? | 4,82 | 0,40 |
| Q5 | Is the IT system suitable for optimizing and facilitating the collection, storage, management and analysis of multidisciplinary information? | 4,64 | 0,50 |
| Q6 | With regard to the functions in the menu, is the data hierarchization and the implementation decision of attributes within the information system satisfactory? | 4,00 | 0,89 |
| Q7 | Does the VERBuM platform appear a controlled and calibrated system of integrated data? | 4,00 | 0,63 |
| Q8 | Can the employment of the platform be a useful tool for those involved in the conservation process? | 4,55 | 0,52 |
| Q9 | Based on your job activities/university experience, do you believe that the use of innovative tools that exploit Virtual and Augmented Reality techniques can help and promote the knowledge and analysis of assets? | 4,55 | 0,52 |

The average value of respondents is always higher of the neutral perception (score 3) per each feature investigated with the questions from Q1 to Q9, and the deviation standard less than 1, per each feature, explicates that the respondents' perceptions are near to the score average, high per each feature investigated, starting from almost (4).

Consequently, the functionalities of the VERBuM VE are considerate almost adequate and sufficient to support the entire process, with an intuitive graphic interface to edit the VE and the implementation of digital contents. VERBuM VE consents a good knowledge of the fabric to support the conservation state study. The presence of an annotation tool is considerate essential to take notes on the top of the spherical photos and it can ensure an efficient collaboration and communication among the professionals. As the VERBuM VE is a digital archive with a vivid 360° representation of the reality, it can assist the collection, storage, management and analysis of multidisciplinary information. In addition, the data hierarchization and type results satisfactory for the objectives. The IS seems controlled and calibrated even if hosted in the web. Generally, it is a beneficial and innovative means for all the actors involved since the surveys until the project, execution and maintenance of the architectural heritage, also compared with the traditional methods they conduct in their job activities.

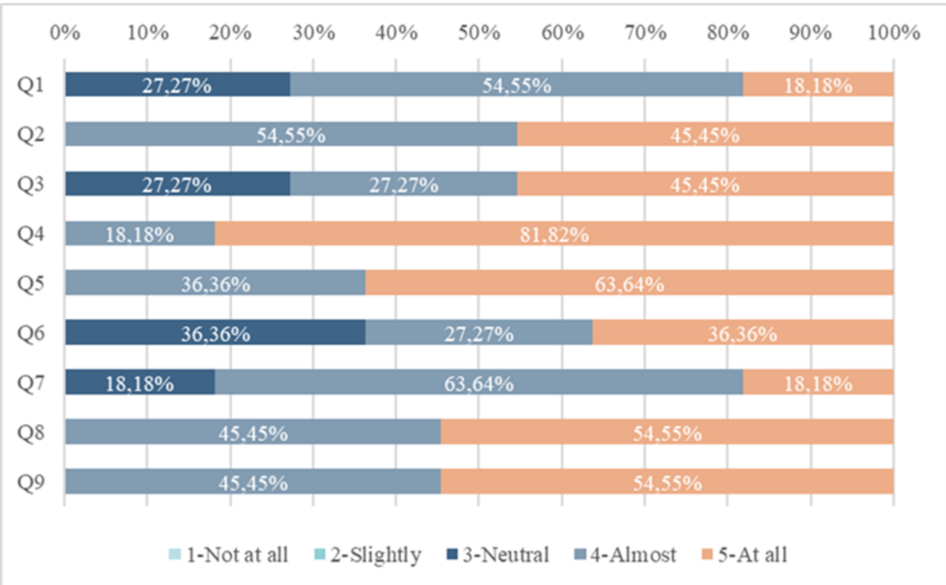


*FIG. 9: Perception of respondents in questions Q1 to Q9*

While, the percentage of respondents per score from 1 to 5 demonstrates that the majority of them positively evaluate the VERBuM VE and process. In particular, the 81,82% of respondents appreciated the insertion of the annotation tool to be directly used on the spherical photos (Q4). In addition, the IT presented can optimize and facilitate the collection, storage, management and analysis of multidisciplinary information. Indeed, the 63,63% of respondents answered that the IT is suitable at all (5) at Q5. A higher number of neutral answers have been registered for question Q6 (36,36%) with regard of the data hierarchization and the implemented attributes, and this can be read as some of them have no need for data hierarchization and confirmed the implemented attributes, or maybe they hide their indecision.

Other six questions with YES/NO answers, about the tool and the process, have been administered and reported in Table 6:

*Table 6: Technical insights about the VERBuM platform*

| | **QUESTIONS – Likert scale (1-5)** | **Percentage** |
|---|---|---|
| Q10 | Do you think that the use of the VERBuM Platform can be an operational tool for the design, development and control of interventions on architectural heritage? | 100% |
| Q11 | Do you think that the VERBuM platform allows an immersive experience in Virtual and Augmented Reality of architectural heritage? | 100% |
| Q12 | With regard to the previous one, do you believe that the digital environment allows for simple management and use of information in the refurbishment/restoration process, in a "vertical" and "horizontal" sense? | 100% |
| Q13 | Does the digital system allow the planning and management in an integrated way of multiple and different activities related to the refurbishment/restoration process? | 100% |
| Q14 | Is the connection of three-dimensional models, point clouds and BIM models an interesting function for digital cataloging and analysis of the investigated asset? | 100% |
| Q15 | Does the digital system have original, unpublished and different elements that distinguish it from those already on the market? | 100% |

All the participants believed that the VERBuM platform i) can be an operational tool for the design, development and control of interventions on architectural heritage, ii) provides its immersive experience in Virtual and Augmented Reality and iii) it is a digital environment for simple management and use of information in the refurbishment/restoration process, in a "vertical" and "horizontal" sense, iv) allows the planning and management of multiple and different activities related to the refurbishment/restoration process in an integrated way. The connection of three-dimensional photorealistic models, point clouds and BIM models is considered an interesting function for digital cataloguing and analysis of the investigated asset. Focusing more on software product characteristics, individuals agreed that the digital system has original, unpublished and different elements that distinguish it from those already on the market.

In addition, interviewees provide insights about strengths and weakness about the VERBuM product, briefed in Table 7.

The answers of the open-ended questions are coherent with the answers given in the previous questions, above all the benefits of the VERBuM VE. The capability of manual annotation on the spherical photos is specifies by most respondents and this can valuable to add later all heterogeneous information required to communicate and make decisions about interventions. The functionality of information layers is also a beneficial ability, for example for decay and intervention mapping. These kind of web based platform is appreciated for the use of web viewers with graphic supports and intuitive tools. From the operational point of view, the VERBuM VE allows contextual control of multiple digital documents for remote inspections, as it is a single archive everywhere available.

While, the weaknesses have been identified in order to improve the VE architecture. The information layers require a time stamp to be associated to the period of acquisition or creation, and be flexible according to specific knowledge project in order to avoid software abandon. Moreover, the images cannot be zoomed causing difficulties in reading. Another negative aspect is the lack of a table of digital contents and analytical modules for quantitative data analysis are required. The missed interactive map with the interlinked scenes reduces the potentiality of the VE to have an easier method to go from a room to another, limiting the user's orientation. If the feature of a web based platform is recognized as a benefit for remote collaboration, respondents identify the risk of difficulties in using it when internet connection issues occur.

*Table 7: Strengths and weakness of VERBuM product*

| |
|---|
| **What are, in your opinion, the strengths of the VERBuM platform about digital capabilities?** |
| Ability to rapidly view different information layers |
| Great amount of loaded/loadable information |
| Possibility to add and modify annotations and filled regions, in different layers |
| The integration and use of web viewers and graphic supports |
| Degradation mapping, with annotation tools, simultaneously to the use of the platform |
| The possibility of inserting and cataloguing of heterogeneous data within the tour, and the possibility of inserting annotations |
| Ease use, graphic intuitiveness, exhaustive diagnosis |
| Possibility of contextual control of multiple information systems and digital contents |
| Possibility of remote inspections; information contained in a single workplace |
| Possibility of manual annotation |
| The ability to use annotation tools |
| **What are, in your opinion, the digital weakness of the VERBuM platform?** |
| The information layers, useful for the project and for monitoring the information over time, would be implemented according to a specific knowledge project |
| Operation of the platform linked to the use of internet |
| The switch between scene could be improved with an interactive map |
| Absence of a time reference of the inserted metadata |
| In on-desk use, viewing images is difficult because they cannot be enlarged |
| Initial interface inconsistent with the theme, lack of a summary index of the contents, lack of quantitative data and absent analytical modules |
| Missing experimentation about flexibility of the platform to adapt it to particular needs that arise during the analysis of the various case studies in order to avoid software obsolescence |
| There is no possibility to move directly to a scene using a map |
| Non-interactive hotspot display map |
| Limited interactivity with switch hotspot in map |

The internal evaluation of the VERBuM VE, where technical features established in Design stage and added in Development and Application stages by project partners allow to increase the potentialities of the platform according to the experience of the partners themselves and tests conducted during the structuration of the architecture and its implementation. This gave the result of a tool and a process almost ready to be regularly used in project teams, as expressed by the preferences of the respondents. Nevertheless, the test should be administered to a wider sample of respondents, going beyond national boundaries, and explore what they think about the use of Virtual Tour tools, such as VERBuM VE, within the BIM-based workflows.

#### 4.1.1 SWOT analysis

The study of literature review and the VERBuM validation activities, illustrated in Section 3, have been useful to identify weaknesses, threats, strengths and opportunities of the VERBuM technology and the process (SWOT analysis). Some authors (Rysanek et al., 2017; Poux et al., 2020) stated that the processing of three-dimensional models from laser or photographic scans, as well as the creation of accurate HBIM models of historic buildings, can be unsustainable processes for some process actors, in terms of time and costs, as engineering and architecture services costs and instrumentation and software applications costs, as well as limitations related to the impossibility of acquisitions in inaccessible and dangerous environments.

The virtual environment, built starting from a Virtual Tour of reality-captured 360° photos and augmented with digital contents, represents an opportunity to mitigate the above-mentioned challenges and face the transition to the use of BIM for existing buildings, allowing access and perception of the construction site/building in three dimensions through a variety of immersive experiences. The study of the as-is and as-damaged state can be carried out safely if the environments are at high risk for health and safety (inaccessibility, dangerousness). The application of the process is effective for sites characterized by critical operating conditions. At the same time, the methodology could find high potential in post-disaster emergencies where security conditions discriminate choices in planning the investigation process (Cantatore et al., 2020). In addition, the VE potentially facilitates the work activities management, making it possible to remotely control multiple construction sites, also having well organized and localized information available in a unique workplace.

Among the ones detected by interviewees, further strength point of the developed VE is the dual modes of widgets/hotspots insertion, assigning orientation and position: i) through the parameterization of the data by the user (assigning the spherical coordinates yaw - as rotation around the vertical axis, pitch - as the rotation around the transverse axis, and roll - around the longitudinal axis), ii) manual localization, directly interacting in the VR environment, this latter more effective and intuitive for non-specialist users (FIG. 10). The same modalities are extended to the activities of drawing, modification and repositioning of hotspots.

Indeed, the structure of the VE allows an adaptive interaction between technology and users, thanks to the possibility of sharing digital content produced with more usual methods (digital documents, videos, voice recordings) and other more innovative ones (BIM, 3D models texturized, point clouds, etc.) whose professional use depends on the technological maturity of the individuals and the work group. Furthermore, the use of the VE does not require all operators to have specialist software products, prone to the need for updating, technical skills for use, to share the acquired knowledge and start collaboration.

The information system and the configured processes have common objectives with Building Information Modelling, such as the communication and sharing of information contents, but VERBuM has the advantages of the accuracy in representing the morpho-typological characteristics of the historic buildings, the ease of use, and the timeliness of upload/update information.

The potential of the tools and approach for analysing the transformations and interventions that have occurred over time are evident. The opportunity offered by the presence of archival information about the state of maintenance - at a given historical moment - supports the selection of conservation strategies with respect to the current state of conservation; it also expresses the potential opportunity to obtain qualitative information on the interventions undergone, obtaining immediately legible graphic results (Cantatore et al., 2020). A positive aspect of using VT, as a standalone tool or integrated with the BIM approach, is that it does not require tools with high computational performance (e.g. workstations) since the development of immersive solutions is mainly based on the use of raster information rather than 3D vector graphics (Ferrari and Medici, 2017).

The use of the VE can take place on-desk or on mobile devices, and through a headset, so if the headset device is unavailable or individuals have physiological difficulties (motion sickness), the possibility of consulting the digital contents remains inclusive.

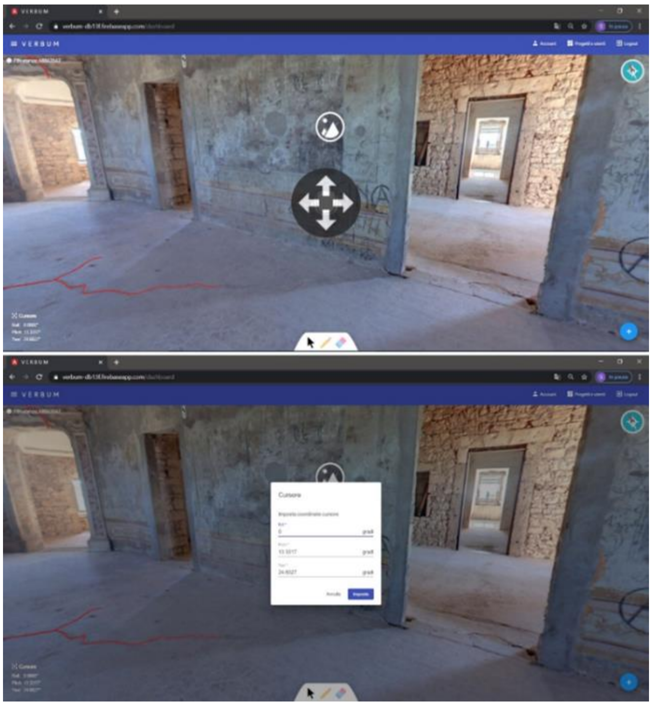

FIG. 10: Spherical coordinates for hotspot insertion

As this is a Virtual Tour accessible via web, it can be accessed via URL from additional digital platforms, whether they are dedicated websites or software that allow interactivity with hypertext links (as also granted in BIM software).

The use of digital contents becomes easier in the design and execution phases. The construction manager can consult administrative and technical documents directly on site. Maintenance activities also benefit from the consultation methods offered by the VTT as the maintenance instructions overlap the visible environment (Palmarini et al., 2018). Ultimately, information exchanged between the various individuals is enhanced (from the technicians in the collection of historical data, in the compilation of the survey forms, to the conservative authorities in the control of the choices)(Cantatore et al., 2020).

The information retrieval in BIM models presupposes that all users know where and how to find them, while in the VTT they are called up by interacting with specific objects, designed so that they communicate the type of content, connected with digital content and directly visible within a recognizable three-dimensional space. The possibility of inserting hypertext links to web pages allows to share and also make available the contents deriving from the laser scanning or photogrammetric acquisition campaigns (point clouds and polygonal and textured meshes) and the HBIM models, once published on specific platforms by the operators who have the resources and skills.

The development of the web-based digital environment has proved to be faster, in contrast to the basic use of BIM applications and, above all, with BIM software's development with customized applications (plug-ins) through API or Visual Programming Language.

One of the disadvantages of the web-based virtual environment lies in the lack of functionality capable of supporting operators in decisions, through the implementation of analytical modules for the study of the entered information and, therefore, for performance simulations of the buildings. Furthermore, the integration with BIM-based applications takes place through information exchange in the form of files, rather than data/parameters. This aspect leads to define the VERBuM technology of digital maturity Level 2, on a scale that goes from 0 to 3 in the digital maturity model developed by Mark Bew and Mervyn Richards (2008), which aims to achieve interoperable information exchange, possible through standardized and shared data transfer within an integrated web-based system (Succar, 2009; Succar, 2010).

A threat to its development and diffusion could be distrust of the actual benefits of this innovative technology. However, training, communication and use tests are the strategies generally adopted in change management to lead to acceptance and address the initial limitations. Very frequently, customization and awareness of potentials are influenced by mandatory or optional use, but also if the use is perpetrated by superiors who influence the attitude of subordinates.

The opportunities are linked to rapid technological developments and human factors, such as predisposition and confidence, in the application field of VR, so much so as to intrigue the possibility that weaknesses become opportunities. The technological improvements of Virtual Reality in the construction sector will certainly continue to benefit from the transfer of results from other domains. Therefore, in the near future, it is expected that specialized products for the management of refurbishment and restoration, developed both in scientific research and in the market, could pose a threat to VERBuM. However, the flexible and modular nature of the product and the process facilitates the inclination to meet the technical-performance requirements of potential new users, identified through next market analyses.

#### 4.1.2 Threat mitigation strategies

The first strategy to mitigate threats related to distrust consists of introducing VR in academic training programs of students, so that they are prepared for the use of highly accurate virtual environments in academic lectures and workshop concerning the management of the building process. In this regard, the Virtual Tour of Masseria Don Cataldo was used in the Refurbishment of historic buildings course at Polytechnic University of Bari, to remotely proceed with the inspection and survey phases, during the pandemic period for COVID19. This test provided that VTT can be a valid tool to formulate the diagnosis of actual causes of decay and settlements, and support intervention decisions.

In addition, a dissemination plan of the project results and potential uses of the digital environment in conferences, sector seminars (restoration and conservation), and on-line engineering and architecture magazines was prepared and performed in order to expand the knowledge about this technological alternative for the management of restoration processes and, therefore, gradually consolidate awareness of use possibilities and promote its diffusion.

The use of the VERBuM product and process will certainly become more fluid and simple because the structures imposed by technology recursively model the interactions between operators, and in turn, the use of the same product is modelled by the interactions themselves. Therefore, working groups are advised to plan and perform use tests for smaller projects or to proceed with the application on an example case, before proceeding with its implementation in real contracts. In addition, the results of this project may converge within social and technical norms that will positively influence performance requirements and attitude for use.

Among the threats, the scarce integration of the VTT with BIM approach and reality-data capture models (point clouds and texturized meshes). Nevertheless, the VTT can be supportive to these other technologies, since the first stages of the project, when the BIM models and digital surveys deliverable are still not complete. In VERBuM VE this connection to the BIM approach and use of point cloud/meshes has been mitigated adding the functionality of opening URLs. Indeed, BIM models can be published on the web through BIM 360, BIMx, Autodesk viewer, etc., as well as point clouds and meshes can be published as webGL objects, using web-based viewers that convert large 3D point clouds/meshes into a web-based version via an HTML site (Potree, Threejs, Schetchfab, Poly, 3DHOP, etc.). Then, the sharing URLs can be inserted in the VERBuM VE in order to solve the weakness related to interoperability with BIM software and point clouds and polygonal textured meshes (FIG. 11).

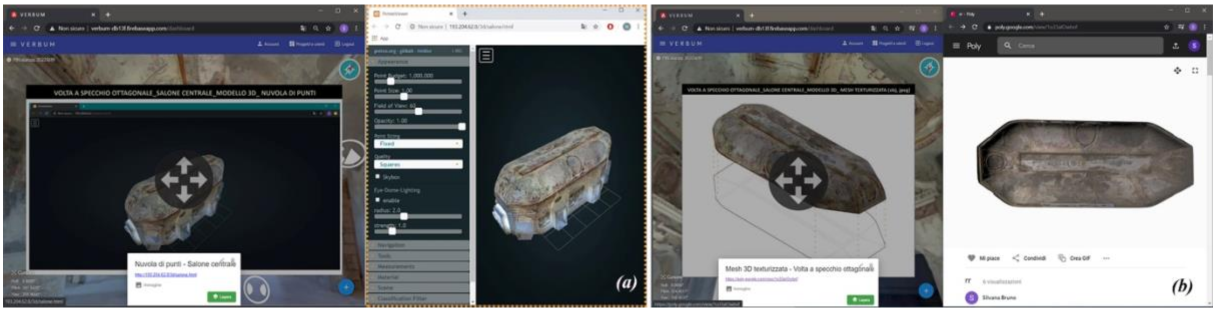

*FIG. 11: VERBuM application: visualization and analysis of point cloud (a) and texturized meshes (b)*

This last mitigation measure has been adopted in anticipation of future developments of the web-based platform. Indeed, the current architecture based on Virtual Tour will integrate further modules for consulting and sharing BIM models and photorealistic three-dimensional models within the same collaborative cloud-based application, working more as a digital twin of the historic building.

## 5. CONCLUSIONS

The digital transformation of the construction sector in the Industry 4.0 era is also involving cultural and architectural heritage conservation management. This paradigm change requires the development and assessment of integrated Information Technologies built around the potentialities and criticalities of the available ones, with the aim to create an instrumented and ready-updated virtual entity of the Built Environment, now defined as digital twin. Before approaching the development and implementation of all-in-one digital environment for digital twinning of cultural and architectural heritage, investigations are needed to identify methods and procedures for reality-based representations and data analysis. The VERBuM project tried to fill the gaps in this context of digital progression proposing a process and a product, that can be furtherly developed according to future technological evolution. The intention of introducing Virtual Technical Tours within the framework is derived by benefits of rapid updating of building representation, in full scale, with interconnected 360° photos, in the time-gaps until the end of point clouds, 3D meshed and HBIM creation. In addition, VERBuM product consents the user to create Virtual Tours through natural gestures on the web, aggregating heterogeneous three-dimensional representative elements. The VTT created can be easily enriched by adding information collected in real time from the centralized information system and shared between all the actors. The majority of respondents, from Italy, confirm VERBuM is a tool and process almost ready to be regularly used in project teams. Nevertheless, the test should be administered to a wider sample of respondents, going beyond national boundaries, and explore what they think about the use of Virtual Tour tools, such as VERBuM VE, within the BIM-based workflows. A future objective is creating semantic relationships between objects and properties (also decay patterns) contextually in point clouds, texturized meshes, 360° reality-based photos and HBIM models, in order to really connect the real world to the digital twin, used for real time simulations. A barrier to this further development of the virtual environment is that research about semantic segmentation of architectural heritage has been recently started and require future studies to have adequate methods to colour and shape features recognition of each building component (including decays) and programming codes, especially open source, to be added within the VE. These elements can become an integral and effective part of a digital twin of architectural heritage, a potential and ongoing research topic. Nevertheless, further research is required to create an all-in-one digital environment that will comprehend also building performance monitoring and early warning provision in case of anomalies or risk of damages and/or discomfort for occupants. Nevertheless, the distrust in use of a Virtual Environment in a refurbishment/restoration project could be an obstacle to the implementation of the Information Technology in regular practices, thus a dissemination and education plan may be a solution to overcome this threat.

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