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DISSEMINATION, ASSESSMENT AND MANAGEMENT OF HISTORIC BUILDINGS BY THEMATIC VIRTUAL TOURS AND 3D MODELS

DIVULGACIÓN, EVALUACIÓN Y GESTIÓN DE EDIFICIOS HISTÓRICOS MEDIANTE VISITAS VIRTUALES TEMÁTICAS Y MODELOS 3D

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Highlights:

- Virtual tours of 360° scenes, linking thematic digital contents, are proposed as intuitive and versatile tools for smart documentation, conservation and protection of historical buildings.
- The role of 3D reality-based and computer-based models is discussed toward their integration and correlation within thematic virtual tours of 360° scenes.
- The power of immersive environments for sharing knowledge about conservation issues as well as for training users on safety measures in historic buildings is underlined.

Abstract:

The digitalization of the historical-architectural heritage for virtual reality (VR) applications is crucial within the contemporary scientific and technical debate for several reasons. In fact, beyond the exploration for education and entertainment purposes, the employment of three-dimensional (3D) reality-based and computer-based models and environments seems to be very promising both for performance assessment and for risk management. Particularly, in order to develop and validate smart, low-cost and user-friendly tools, which might work even in cases of limited time and budget, this paper is going to propose a methodological workflow based on thematic virtual tours of 360° scenes, which integrate a variety of informative contents and digital products as external hotspots/switches. The VR tours, where 3D models might play a key role for an accurate representation of relevant parts and/or analytical elaboration of further data, are conceived as flexible and scalable solutions; they support users, technicians and authorities through remote access, diagnosis of the state of conservation and communication of safety measures. The application of the proposed methods and techniques to a representative case study, the Norman-Swabian Castle of Gioia del Colle (Ba), South Italy, is presented in order to illustrate the achievable results and to highlight the benefit of innovative "digital" solutions for data collection, storage and communication, compared to the traditional "analogical" practices. In detail, a Web-GIS platform, developed within a previous research project, is integrated with direct links to three thematic virtual tours that provide added contents for inclusive dissemination (timeline schemes, aerial views, 3D sculptural and architectural details), performance assessment (diagnostic reports, decay maps, 3D reconstructions of technical components) and risk management (exit signs, help instructions, warnings). Thus, the VR tours, while documenting the state of the site realistically, might also act as host environments of digital products, at increasing complexity, all displayed according to an intuitive and accessible communication approach.

Keywords: virtual reality; 3D model; architectural heritage; inclusive dissemination; decay diagnosis; safety training

Resumen:

La digitalización del patrimonio histórico-arquitectónico en aplicaciones de realidad virtual (RV) es crucial dentro del actual panorama científico-técnico por varias razones. De hecho, más allá de su exploración con meros fines educativos y de entretenimiento, el empleo de modelos tridimensionales (3D) basados en la realidad y entornos computacionales se muestran igualmente como herramientas muy atractivas en la evaluación del desempeño y en la gestión de riesgos. Sobre todo, destaca su utilidad al desarrollar y validar herramientas inteligentes, de bajo coste y de fácil empleo, que puedan aplicarse incluso en casos con disponibilidad temporal o presupuesto limitado. El presente trabajo propone un proceso metodológico basado en los desarrollos de recorridos virtuales temáticos de escenas en 360°, que integran una variedad de contenidos informativos y productos digitales como conexiones externas/interruptores. Los recorridos de RV, donde los modelos 3D pueden jugar un papel clave para la representación precisa y/o el análisis de los datos más a fondo, se conciben como soluciones flexibles y escalables, que apoyan a los usuarios, técnicos y autoridades a lo largo de la divulgación pública, el diagnóstico del estado de conservación y la comunicación de las medidas de seguridad que sea necesario adoptar para la conservación integral del patrimonio histórico-arquitectónico. Con el fin de ilustrar los resultados alcanzables mediante la metodología propuesta y resaltar el beneficio de la innovación de soluciones "digitales" en la captura, el almacenamiento y la presentación de datos, en comparación con las prácticas "analógicas"

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tradicionales, estas técnicas y métodos se aplican a un caso representativo de estudio, el castillo normando-suabo de Gioia del Colle (Ba), sito en el sur de Italia. Concretamente, una plataforma Web-GIS, que se encuentra desarrollada dentro de un proyecto de investigación anterior, integra enlaces directos a tres recorridos virtuales que brindan contenidos para la divulgación inclusiva (esquemas de línea de tiempo, vistas aéreas, detalles arquitectónicos y escultóricos en 3D), evaluación del desempeño (informes de diagnóstico, mapas de descomposición, reconstrucciones 3D de componentes técnicos) y gestión de riesgos (señales de salida, instrucciones de ayuda y advertencias). Por lo tanto, los recorridos de RV, además de documentar de manera realista el lugar, pueden actuar como entornos de productos digitales, con una creciente complejidad, todos ellos representados de acuerdo con un enfoque de comunicación intuitivo y accesible.

Palabras clave: realidad virtual; modelo 3D; patrimonio arquitectónico; divulgación inclusiva; diagnóstico de deterioro; formación en seguridad

1. Introduction

The digitalization of the architectural heritage for virtual reality (VR) applications is crucial within the contemporary scientific and technical debate for several aspects. In particular, the integrated conservation of sites and buildings with historical and cultural value requires suitable measures, in order to safeguard their tangible and intangible characteristics, as well as to ensure their integration into social life by continuity of use. In this regard, virtualization and visualization technologies might offer powerful tools for knowledge dissemination, development and management within refurbishment and enhancement processes (Campanaro et al., 2016; Champion & Rahaman, 2020; Deligiorgi et al., 2021; Kadi & Anouche, 2020; Laing, 2020; Yang et al., 2020).

Particularly, there are countless VR applications of photorealistic reconstructions by three-dimensional (3D) models and immersive environments that integrate multimedia informative contents with the purpose to offer an alternative perceptive experience by increasing levels of interaction and customization (Arrighi et al., 2021; Bozzelli et al., 2019; Ferdani et al., 2020; François et al., 2021; Hajirasouli et al., 2021; Mah et al., 2019; Mortara et al., 2014; Smith et al., 2019; Walmsley & Kersten, 2019; Younes et al., 2017).

Nevertheless, beyond the exploration for education and entertainment purposes, the employment of VR systems and solutions seems to be very promising for more specialist aspects of the heritage conservation practice, as well. Among them, two appear very much relevant for the present research.

The former, concerning the assessment of the state of conservation, is currently under development by a variety of studies and applications for the historical-architectural heritage (Lee et al., 2019a, 2019b; Napolitano et al., 2018; Sánchez-Aparicio et al., 2020; Trizio et al., 2019). It refers to remote gathering and sharing among different stakeholders –technicians, authorities, operators– of data related to decay patterns and performance anomalies/defects of building components, in order to schedule monitoring, maintenance and repair activities. For this purpose, several solutions are proposed, including: virtual tours of 360° panoramic scenes; 3D reality-based models from terrestrial laser scanner (TLS) and/or digital photogrammetry survey; and 3D computer-based models from Computer Aided Design (CAD), Historic Building Information Modelling (HBIM) and digital rendering graphics (e.g. Cinema 4D). These solutions might be eventually connected with Geographic Information Systems (GIS) and typically enriched by referenced links to documents, checklists, technical reports and digital elaboration sheets.

The latter, concerning the risk management in pre-event and under-emergency scenarios, is not specifically developed for the historical-architectural heritage, but rather for the built environment in a broader sense (Hsu et al., 2013; Li et al., 2018; Lovreglio, 2020; Mavrogianni et al., 2015; Zhu & Li, 2021). It relies on virtual environments, generally coming from 3D computer-based models within animation and motion design applications (e.g. Unity 3D), where several hazard conditions are simulated in order to instruct and guide different profiles of users –rescuers, occasional visitors, and frequent occupants– on evacuation drilling, rescue operations, use of safety devices and recognition of hazard sources, among the others.

The review of the state of the art reveals how the above-mentioned aspects might greatly benefit from the innovative "digital" approach compared with the traditional "analogical" practice, in terms of integration of multiple issues, procedures and actors, usually featuring the heritage refurbishment and enhancement processes. In fact, as far as the assessment of the state of conservation is concerned, such an approach might enable the remote direct observation and investigation on accurate and informative replicas, as well as the effective and efficient management of miscellaneous data, with highly desirable impacts on communication and coordination among different disciplines and professionals.

Similarly, within the risk management, the approach might provide the users with intuitive and pervasive ways for behavioural self-training, addressing appropriate actions and decisions in hazard conditions, as an alternative to common info-graphics. Furthermore, the increase of awareness and preparedness of the occupants is crucial in specific cases, such as public access to historical buildings, where two critical conditions might occur. On the one hand, the visitors show low familiarity with the sites and, thus, have difficulties in recognizing obstacles and dangerous factors, as well as in reacting properly to the presence of other people, high densities, and overabundant environmental inputs. On the other hand, the configuration of egress paths end exits and the localization of safe gathering areas and protection devices might be not conventional, as a derogation of current prescriptions for listed buildings in view of the preservation of their original characteristics.

Additionally, from the review of the state of the art, it can be observed that virtual environments and models are generally targeted on exemplary pilot applications, featured by high morphological and constructional complexity, where expert computational procedures for representation and integration of multi-level informative contents and digital products are involved. However, for the widespread historical-architectural heritage, it is paramount to develop scalable solutions from basic configurations, in order to make them suitable for common practice activities, where time, resources and budget are limited.

Consequently, virtual tours of 360° panoramic scenes are herein proposed as main "host" environments for the reproduction and remote access to the sites, taking into account that they fulfil several remarkable requirements: (i) they are acquired and elaborated by low-cost tools and timesaving procedures; (ii) they are able to describe the colour and texture characteristics of the architectural surfaces leading to realistic visual communication; (iii) they integrate external documents and references; and (iv) they do not involve specific expertise for implementation and management in view of collaborative design processes. However, these virtual tours might be combined with more elaborated 3D reality-based and computer-based models, in the form of digital products directly accessible by hotspots/switches or, alternatively, as elaboration tools for developing data and results, then schematically displayed within the tours.

In the light of the above-mentioned issues, the present paper is going to propose and validate a methodological framework for the creation of VR tours of historical architectures, where 360° panoramic scenes are enriched by informational content and digital models. The tours, referring to three different and complementary thematic axes, *Inclusive Dissemination*, *Performance Assessment* and *Risk Management*, are meant to act as intuitive and versatile tools for smart documentation, conservation and protection of heritage buildings and sites.

2. Methods and tools

The proposed methodological framework moves from the main results of the project "3D-IMP-ACT. VR and 3D experiences to IMProve territorial Attractiveness, Cultural heritage, smart management and Touristic development", funded under the Cooperation Programme Interreg IPA CBC Italia-Albania-Montenegro and ended in December 2020. In detail, within the project, a Web-GIS platform was developed (De Fino et al., 2020), where archaeological and architectural sites in the reference territories were made remotely accessible by several informative contents and digital products. The informative contents, including texts and pictures that referred to the typological, historical and architectural characteristics of the heritage sites, were structured as entities of a geo-database that might be inquired by spatial and parametric keys. Moreover, the digital products relate to representations of the constructional evolution, photorealistic 3D reconstructions and multimedia sources, all accessible as links to virtual tours of 360° spherical photos of the interior and exterior spaces of the building/place of interest.

Thus, based on the above-mentioned platform, which was mainly addressed to tourists and visitors for immersive and inclusive enjoyment of a virtual network of transnational assets, an extent of achievable objectives and employable tools is herein proposed. Particularly the diagnosis of the state of conservation and the residual performances, as well as the implementation of strategies and measures for the safety of use, are included as additional domains. Moreover, further development concerns the identification of roles and functions that 3D models might play, based on different acquisition, elaboration and interrogations modalities.

Specifically, the methodological framework (Figure 1) relies on the creation of three different thematic virtual tours of 360° spherical photos, connected to the Web-GIS platform and related to *Inclusive Dissemination*, *Technical Assessment* and *Smart Management,* as previously stated. The first tour is a digital replica for the remote visit of the site and consultation of historical and architectural information. The second tour acts as the environment for sharing specialist elaborations toward survey and investigation of pathologies and obsolescence phenomena, also based on diagnostic data and thematic decay maps. The third tour is a tool for communicating instructions and recommendations addressing appropriate behaviours under emergency.

In detail, in the *Inclusive Dissemination* virtual tour (*VT_ID*), the 360° special scenes represent the current state of the places, including rooms and areas where public access is limited because they are reserved to internal personnel (offices, service spaces…), they show critical safety conditions (risk sources, architectural barriers…) or they need to keep controlled microclimatic parameters for conservation issues (hypogeal structures…). The first thematic virtual tour is associated with three categories of hotspots/switches to external links, which are marked by specific icons and meant to extend in time and space the physical fruition of the site:

- *ID1. Timeline:* Schemes and models of the historical evolution, namely 2D/3D graphic restitutions and/or photo-galleries of the main transformation phases as documented by available bibliographic and archivist records;
- *ID2. Aerial View:* Video shootings by Unmanned Aerial Vehicles (UAVs), in order to make visible parts with reduced or obstructed observation "from the ground", for high distance or interposed physical obstacles, as well as to offer a different perspective of the site, e.g. roofs, external areas and surroundings.
- *ID3. Details:* 3D models of sculptural and architectural details, in the form of coloured point clouds, for direct and interactive exploration of shapes, colours and textures of relevant parts from the cultural point of view.

In the *Performance Assessment* virtual tour *(VT_PA),* the 360° spherical photos enable the interrogation of three further categories of contents, supporting the assessment of occurring pathologies and previous restoration/conservation works:

- *PA1.Decay:* Graphic maps of the main surface alterations, as photo-edited 360° panoramic scenes for the internal rooms and textured orthophotos for internal and external facades.
- *PA2. Diagnostic:* Reports related to experimental measurements for diagnostics and monitoring of structural and environmental parameters by non-destructive and semi-destructive techniques.

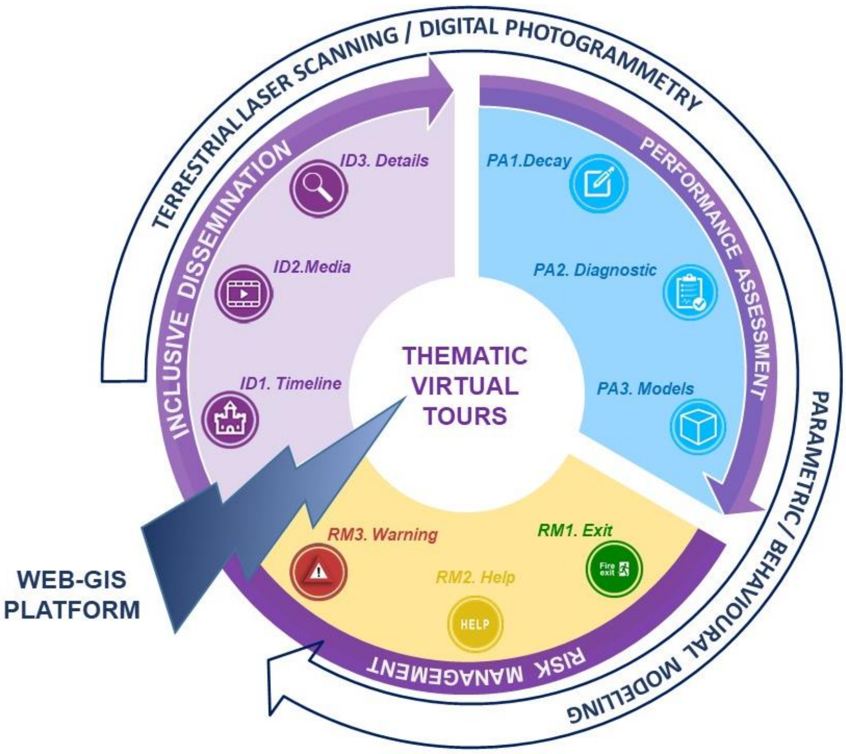


Figure 1: Methodological workflow.

- *PA3. Components:* 3D models of constructional and technological elements, as coloured point clouds, texturized polygonal meshes and computer graphic objects, for analysis of parts supporting the understanding of ongoing functioning mechanisms and crisis phenomena.
- In the Risk Management virtual tour (VT_RM), the 360° spherical photos are edited to report the egress paths through photo-editing tools and to highlight the distribution connections to the designated safe places. Furthermore, they refer to three further categories of external links, conceived to highlight provisions and behaviour models useful for guaranteeing the safety of use to visitors who are unaware of the distributive-functional layout of the building:
- RM1.Exit: Signs and maps guiding the users along the egress paths in emergency situations, including the location of the emergency exits, the indication of the fastest route and the identification of the elevators that can be used for the transport of stretchers.
- RM2. Help: Operating instructions on the location and use of any protective devices present on site;
- RM3. Warning: Representation of permanent spatial and technical elements that can limit the easy and quick escape flow, causing delays in the escape times and/or overcrowding in some points (gates of limited width, stairs with non-compliant tread-to-riser ratio, physical obstacles related to exhibition installations...).
- The main typologies and file formats of the above-mentioned external contents and products are listed in Table 1 for the three thematic virtual tours.
- As previously highlighted, the methodology includes the acquisition, elaboration and interrogation of 3D models of the artefacts, with increasing levels of complexity, both for the realization of digital products visible in the tours and for development of analytical procedures for data treatment and parametric/behavioural simulations, whose results are schematically displayed within the tours themselves.
- In particular, 3D reality-based products for digital terrestrial and aerial photogrammetry, eventually integrated by TLS, might be directly linked within the *VT_ID* e *VT_PA* for the reproduction of sculptural and architectural details (*ID3*) and constructional and technological elements (*PA3*). Moreover, they might be used to extrapolate information related to geometry, colour and texture for decay mapping (*PA2*), eventually based on semi-supervised routines of training and segmentation (De Fino et al., 2019; Galantucci & Fatiguso, 2019).
- Furthermore, 3D computer-based models from digital graphics (e.g. CAD) and parametric modelling (e.g. HBIM), eventually elaborated by manual or semi-automated conversion of the above-mentioned photogrammetry and TLS products (Bruno et al., 2018), might be exploited in order to make visible constructional and technological elements (*PA3*) in the *VT_PA*. In this case, compared to 3D reality-based models, the representation is less realistic and more simplified from the architectural point of view. However, it might better fit the morphological and typological description of technical parts (connection nodes, multi-layered stratigraphie…) and the digital classification and segmentation (division of a system in sub-systems, reproduction of evolution phases…). Besides, the 3D parametric models might support behavioural-based studies and simulations of risk scenarios –fire, intrusion, terroristic attacks…– and, thus, address the development of signs (*RM1*), instructions (*RM2*) and alerts (*RM3*) for virtual training within the *VT-RM*.

Table 1: Data typologies and formats.

Code	*Typology*	*File formats*
ID1. Timeline	2D/3D schemes and photo-galleries	.MP4, .JPEG, URL
ID2. Aerial views	Shootings by drones	.MP4
ID3. Details	3D models of sculptural and architectural elements	.MP4, URL
PA1. Decay	Edited 360° photo/ Orthophoto with decay patter	.JPEG (360° photos)/ .PDF, .JPEG
PA2. Diagnostic	Reports/Graphs/Diagrams of results from diagnostic tests	.PDF, .JPEG
PA3. Components	3D models of technical and constructional elements	.MP4, URL
RM1.Exit	Edited 360° photo with egress paths/ Documents and maps with egress/exit paths	.JPEG (360° photos)/ .PDF, .JPEG, .MP4, URL
RM2. Help	Instructions of protection systems (documents, videos)	.JPEG, .PDF, .MP4
PM3. Warning	Overlayered textual indications of layout features (stairs, openings, doors)	.JPEG

- It is worth mentioning that the photorealistic 3D models, which are used to reproduce sculptural and architectural details *(ID3)* and constructional and technological elements *(PA3)*, might be displayed within the virtual tours according to two approaches. The former relies on video-animations (.MP4), thus with no interaction by the users, and it might be adequate whenever the purpose is the description of a specific aspect of the product (e.g. integration of different parts) or the process (e.g. elaboration phases) or if the user might show low confidence with interface functions (e.g. pupils). The latter is based on the web publication (URL) of coloured point clouds (.LAS) and polygonal or texturized meshes (.OBJ, .FBX, .MTL, .glTF) by webGL viewers, both proprietary and open source. In this case, more expert tasks are enabled, including measurement, view change of the layout space, extraction of sections and hide/show options for elements or groups of elements, depending on the selected webGL viewer (e.g. Potree for point clouds and Sketchfab, 3DHOP, Three.js for meshes) and relative implementation of customized calculation codes. The same approaches apply when parametric models are used to reproduce constructional and technological elements (PA3), whereas the interaction by webGL viewers (BIM 360 Autodesk, BIMx Graphisoft, BIMvision and xeokit-bim-viewer) enables access to the relational structure among objects and relative properties, measurement, visualization of thematic drawings, extraction of sections and exploded views, insertion of comments and review notes.
- Finally, within the above-described correlation between virtual tours and 3D models, the required system scalability is achieved. In fact, based on the extent of the reproduced parts and relative complexity of elaboration and interrogation, the 3D models might be specifically developed for the virtual tours or rather integrated if available for different purposes in the refurbishment and enhancement processes (design management, structural analysis…). Consequently, their unavailability, even if affecting the completeness and richness of the augmented contents, do not compromise the efficacy and effectiveness of the "host" virtual environments, that are just additional components.

3. Case study

In order to illustrate the main functionalities and results that can be achieved through the use of thematic virtual tours, the case of the Gioia del Colle Castle, Province of Bari, Puglia Region, is reported below.

The artefact, built under Norman domination in the 11th century AC on a Byzantine nucleus dating back to the 9th century AC, reached its definitive configuration as a military fortification under the Swabian Reign of Frederick II, who promoted the construction of numerous and emblematic castle works in Southern Italy throughout the 13th century. In fact, the Emperor provided for the final arrangement of the structure, with a fairly recurrent configuration at the typological level: quadrangular plan with a central courtyard and four corner towers; development on two levels, with ground floor for service areas and first floor for noble rooms; magnificent and elegant decorative details, as in the case of the ashlar of the façades, the frames of the openings, the monumental staircase in the internal courtyard and some halls on the noble floor.

Following the decline of the Swabians, from the advent of the Angevins, the Castle underwent a progressive decline, with the abandonment of the functions of defence and use for residential purposes, with a series of adaptations and modifications, including insertion of new openings on the external and internal fronts, leaning of additional volumes and division of the large rooms to allow the optimization of spaces and functions. However, when in the first half of the 20th century a restoration intervention was started to bring the monument back to its original splendour, the architect in charge Pantaleo, while foreseeing the reasonable removal of the inconsistent parts, carried out a series of arbitrary and stereotyped new creations, in the spirit of the "stylistic restoration" of the Medieval fortress, with the addition of single, double and triple mullioned windows in the courtyard, insertion of a loggia on the monumental staircase and arrangement of stone furnishings, such as the throne and fireplace in the main representation hall.

A further restoration, however, was required in the second half of the 20th century with the aim of making the building open to the public. It was directed by architect De Vita, who had to reinforce some collapsed portions, as in the case of the wooden roofs of the southwest side or the first floor of the north wing. Following this second intervention, in 1977 the Castle became the venue of the City Archaeological Museum, a destination which it still retains today.

Figure 2: Equirectangular panoramic photo of the interiors of the south-west tower. Castle of Gioia del Colle (Italy).

3.1. Inclusive dissemination VT

For the realization of the *VT_ID*, the entire castle was captured by panoramic photos with a Samsung Gear 360 camera, which uses two fisheye lenses with 15-megapixel sensors on both sides of the device to simultaneously capture two 180° views then recomposed in the 360° image.

In particular, the documentation was extended to all those areas that are normally not reachable by the public for safety reasons and/or architectural barriers, as in the case of the south-west tower, accessible only through a narrow spiral staircase, which leads to a reserved room (Figure 2), or in the case of all the roofs, from which it is possible to have a different perspective of the places.

Thus, all the panoramic photos were integrated into the virtual tour by software *Easypano Tourweaver 7.98®* and enriched by conventional navigation switches –building plan with direct access points to the tour scenes, links to previous and subsequent scenes according to a pre-set sequence, arrows leading to contiguous scenes– and by customized hotspots to the external contents.

As an example, with reference to the central courtyard, the virtual visitor can access some photo-galleries (*ID1. Timeline*), reporting the historical documents of the archives of the Apulian Museum Pole, where the configuration of the site before and after the stylistic restoration by architect Pantaleo in the early 20th century is displayed, including the removal of inconsistent parts and the insertion of some stereotyped elements (Figure 3).

Similarly, the user can visualize some videos by drone DJI Inspire T600, equipped by X3 FC35 camera *(ID2. Aerial View)*, with zoom-in details of the decorative elements and the architectural surfaces, even close to the top crowning cornice (Figure 4).

Finally, the tour is connected with 3D restitutions of architectural details (*ID3. Details*), elaborated by software Agisoft Photoscan v. 1.2.5 through photo modelling of pictures extracted by aerial videos and/or acquired by high resolution Canon EOS M3 24.2 camera, eventually mounted on telescopic bars for reaching parts in elevation. The 3D restitutions are available to the users as RGB coloured point clouds by free and open-source web-reader Potree®, enabling rotations, translations and direct measurements on the scaled object *(*Figure 5).

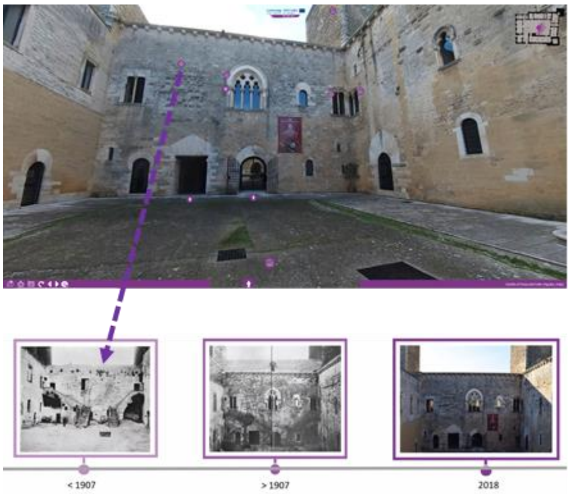
With specific reference to the 3D models of architectural details, it should be noted that they were produced specifically for the implementation in the virtual tour, also in consideration of the speed and agility of the acquisition and processing procedures on small-medium sized objects.

For this purpose, the selection of the images was always carried out ensuring an adequate overlap between adjacent photos –about 80% in both directions of the shooting plane– and verifying in post-processing the completeness of the model, obtained after the automatic execution of the well-known photogrammetric SfM (Structure from Motion) and MVR (Multi-View Stereo Reconstruction) routines for the elaboration of sparse point clouds, dense point clouds, polygon meshes and textured polygon meshes (Figure 6).

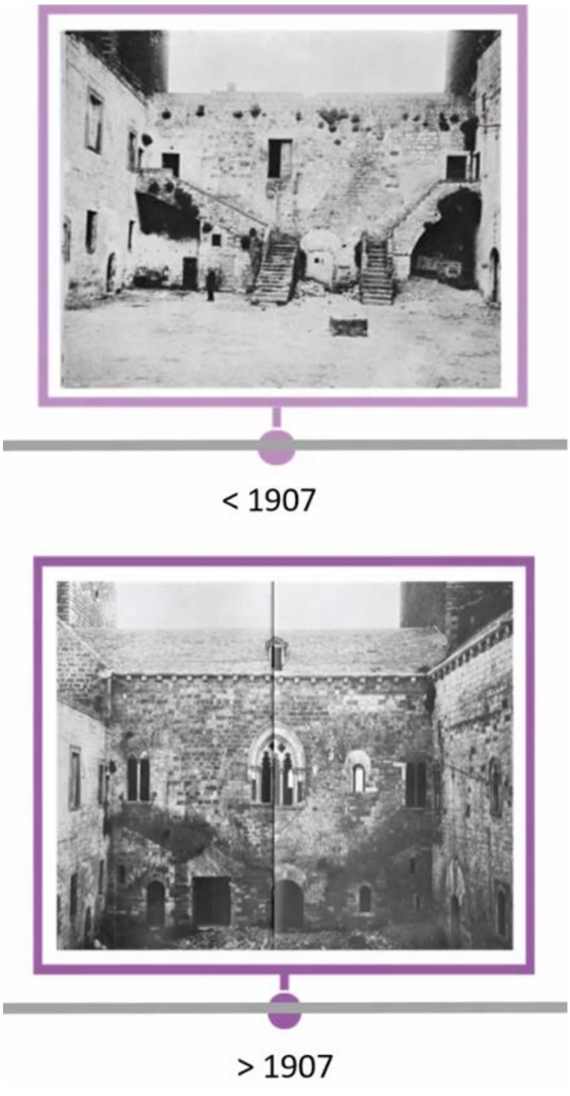
3.2. Performance assessment VT

For the realization of the *VT_PA*, the panoramic photos of the indoor environments of the *VT_ID* were modified by Adobe Photoshop v. 20.0.6 software for mapping the main surface deterioration patterns (*PA1.Decay*) where present, as in the case of the noble rooms on the west wing, affected by the collapse of the timber roofs in the 20th century and characterized by some cracks on the vertical structures (Figure 7).

This approach was not applied to the outdoor scenes, where the development in height of the internal and external façades and the consequent perspective deformation made the graphic representation more difficult to read.



(a)



(b)

Figure 3: *Inclusive Dissemination* Virtual Tour. Example of contents related to the category *ID1. Timeline*, including: (a) Panoramic scene of the courtyard west facade linking to a chronological photo-gallery; (b) Detail of two historic pictures documenting the configuration before and after the restoration by architect Pantaleo.

Figure 4: *Inclusive Dissemination* Virtual Tour. Example of contents related to the category *ID2. Aerial view*, including some pictures extracted from video shooting by UAV.

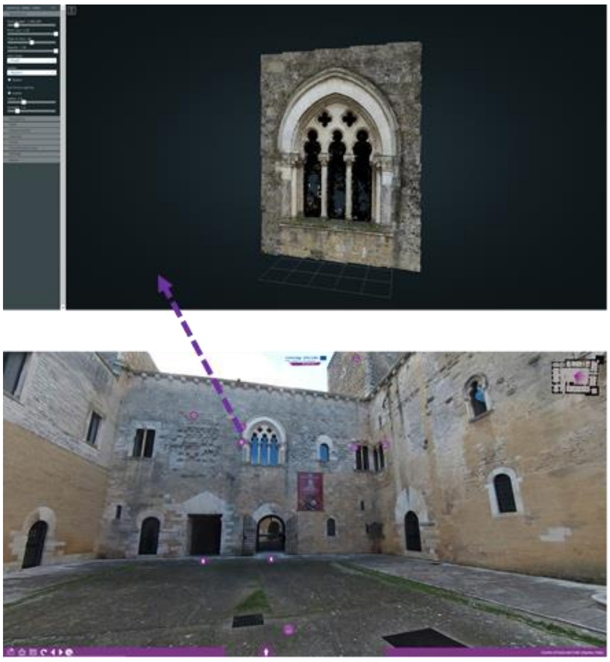
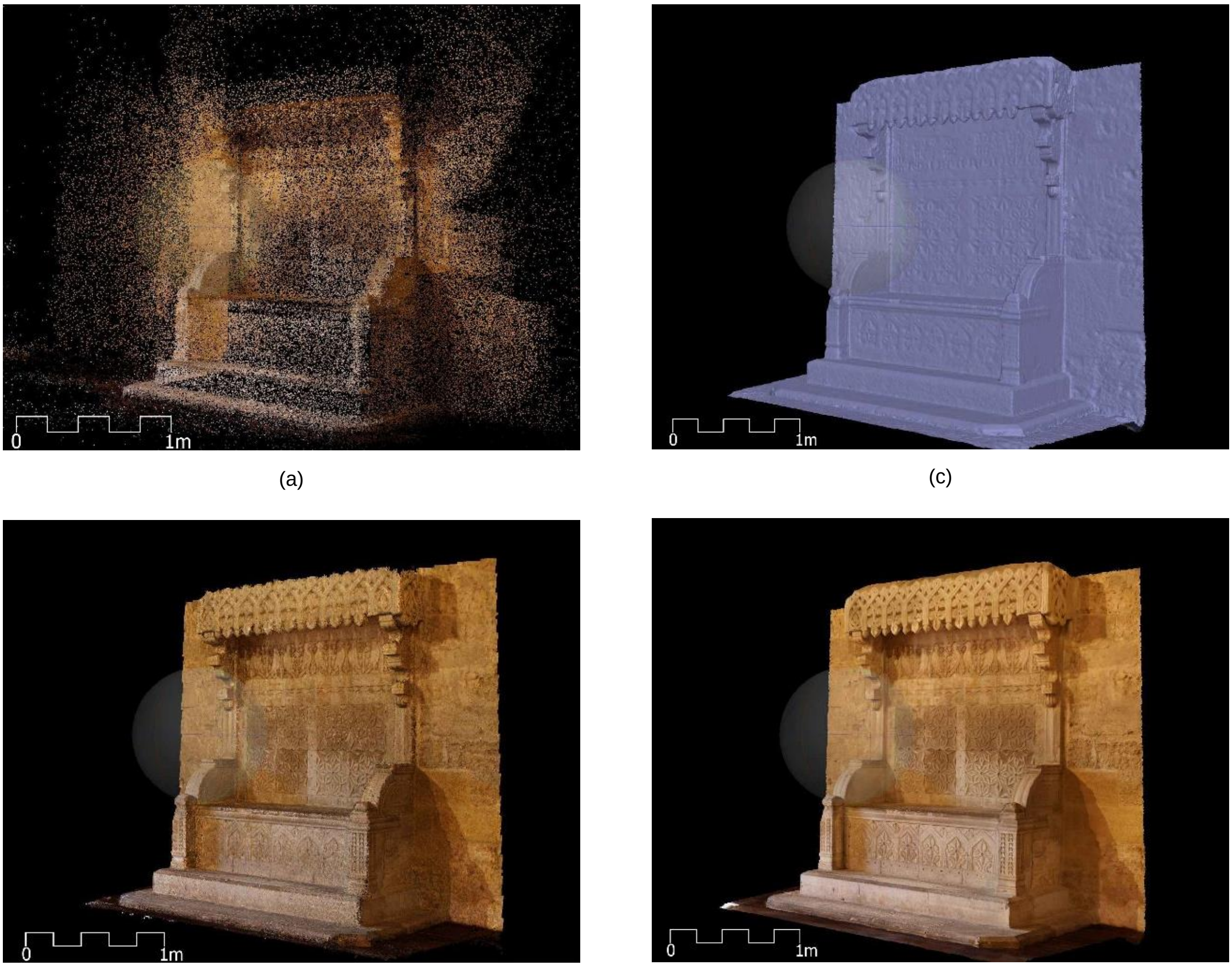


Figure 5: *Inclusive Dissemination* Virtual Tour. Example of contents related to the category *ID3. Details*, including a panoramic scene of the courtyard west facade linking the photogrammetry-based 3D reconstruction of the triple mullioned window.



(a) (c)

(b) (d)

Figure 6: Elaboration of 3D models: (a) sparse coloured point cloud, (b) dense coloured point cloud, (c) polygonal mesh, and (d) texturized polygonal mesh of the 20th century throne in the main noble hall.

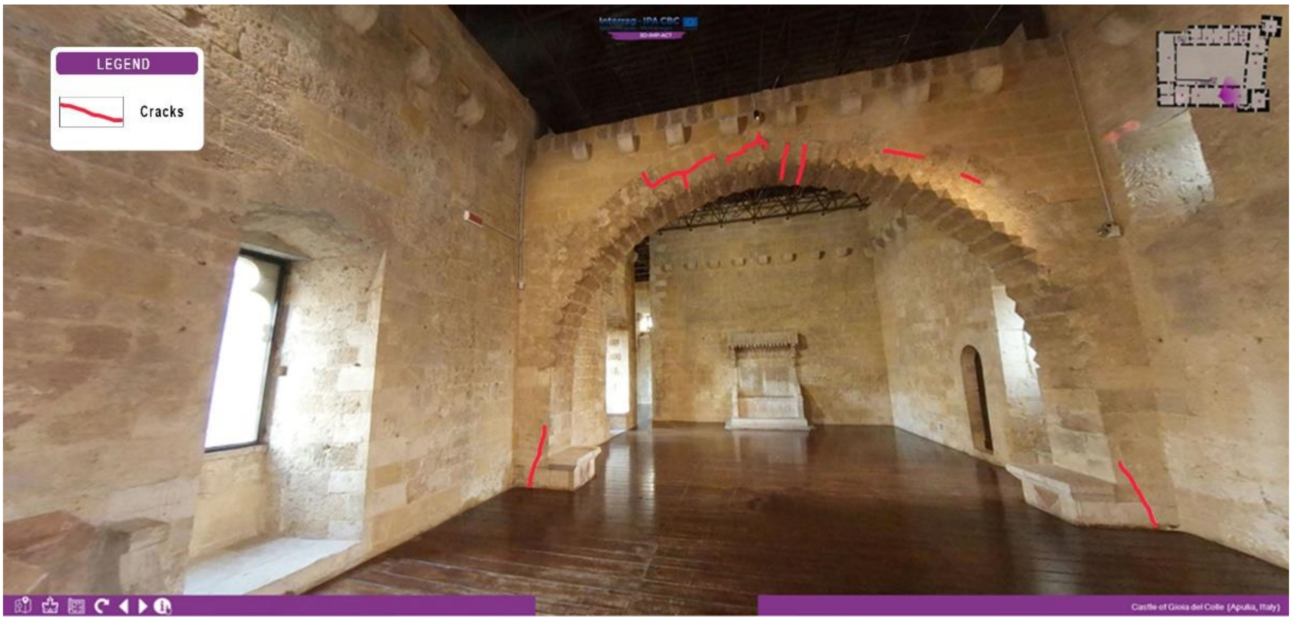


Figure 7: *Performance Assessment Virtual* Tour. Example of a panoramic scene of the main noble hall, modified for decay mapping.

Figure 8: *Performance Assessment Virtual* Tour. Example of an orthophoto of the west courtyard facade, modified for decay mapping.

Alternatively, the external surfaces were mapped using some orthophotos (*PA1.Decay*), as extracted from coloured point clouds. These mappings, carried out in compliance with the nomenclature in Italian code UNI 11182 "Cultural heritage. Natural and artificial stone. Description of the alteration -Terminology and definition" (UNI, 2006) , as well as on the international guidelines "ICOMOS-ISCS (2010). Illustrated glossary on stone deterioration patterns" (International Scientific Committee for Stones, 2010), document the good state of conservation of the masonry surfaces, with moist areas due to rainwater infiltration, presence of vegetation, biological colonization and formation of black crusts.

Nevertheless, the above-mentioned phenomena seem to produce different effects on the surfaces due to the different façade materials, resulting from replacement, restoration and consolidation interventions over time, in particular in the 20th century (Figure 8).

Moreover, the presence of damp patterns and the diversity of the constructive characteristics of the stone blocks are also the main evidence from the thermographic survey, carried out on the external and internal façades (*PA2. Diagnostic*), with areas at higher apparent temperature, in correspondence of materials featured by great porosity (i.e. tuff) and/or affected by detached plaster (Figure 9). Finally, the thematic tour was enriched with links to 3D models of constructional and technological elements *(PA3. Components*), to support the analysis of specific diagnosis aspects.

Among these, the construction of the reticular truss roof, introduced by architect De Vita to replace the collapsed timber structure and currently debated for possible conservation, was particularly useful. The Building Information Modelling of the metallic modular roof, as of the entire complex, was carried out by *Autodesk Revit 2019®* software, based on the TLS survey, carried out by Faro Focus 3D X130 and elaborated by *Autodesk Recap Pro 6.0®* software, for more general and accurate reproduction of the building morphology (Figure 10).

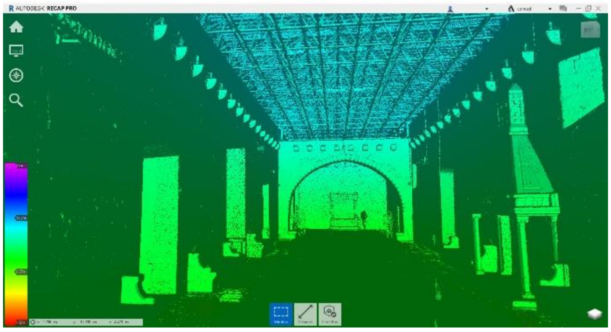
In this case, the 3D models, used for extracting orthophotos for mapping purposes, resulted from digital photogrammetric acquisitions similar to those described for the *VT_ID*, also in consideration of their photorealistic representation of the surface alterations. On the contrary, the restitution of the technical details benefited from the availability of the overall geometric survey, certainly more suitable for accurate representation than the realistic texturized meshes acquired via photogrammetry. In particular, the most significant elements of the BIM model are made available by links to the web publication in Autodesk Viewer 2021*,* which allows comprehensive analysis of the parametric objects, through axonometric views and transversal sections, as well as navigation and query of properties and graphic sheets, available in the model itself.

3.3. Risk management VT

For the implementation of the *VT_RM*, risk scenarios deriving from fire propagation simulations were employed. In particular, as for the *VT_PA*, the panoramic photos of the *VT_ID* were edited with Adobe Photoshop v. 20.0.6 to display the egress paths and exits towards identified safe places (*RM1.Exit*). Floor plans *(RM1.Exit)* were also attached, showing the fastest route, fire safety signs, detection and extinguishing systems, fire-fighting compartments, emergency exits, and the lifts that can be used to transport stretchers. The same type of component can call up video instructions about emergency exits (Figure 11).

The Castle shows many elements, where the derogation to standard solutions is allowed by national regulations about fire prevention in listed buildings open to the public. These building elements of potential vulnerability are critical in emergency and evacuation situations because they can involve delays in pre-movement times and dangerous overcrowding conditions. In these situations, the legislation requires measures for information of occasional visitors and training of frequent occupants, including instructions about the employment of warning systems. In particular, openings and passages whose widths are smaller than the regulatory thresholds (<90 cm), stairs with non-compliant tread-to-riser ratio and excessive lengths of dead-end corridors compared to the corresponding risk profile –type of occupants and building materials– have been brought to the attention through the *RM_VT* (*RM3.Warning*) (Figure 11). In the event of a fire, it is essential to be ready to use the protective devices, whose location and use instructions must be made known. Therefore, information sheets and explanatory videos were disclosed (*RM2. Help*) (Figure 12).

Figure 9: *Performance Assessment Virtual* Tour. Example of thermograms of the surfaces of the courtyard.



(a)

(b)

Figure 10: Main noble hall (Fig. 7): (a) Point cloud in false colours about elevation; and (b) relative parametric BIM model.

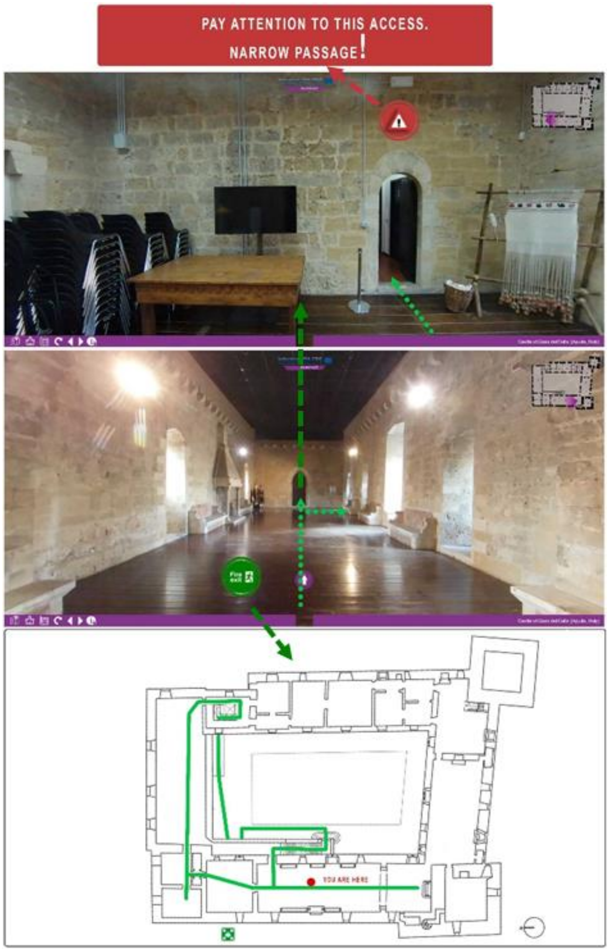


Figure 11: *Risk assessment Virtual Tour.* Example of egress paths within the 360° photos and interactive maps. In addition, critical elements are noticed via textual instructions.

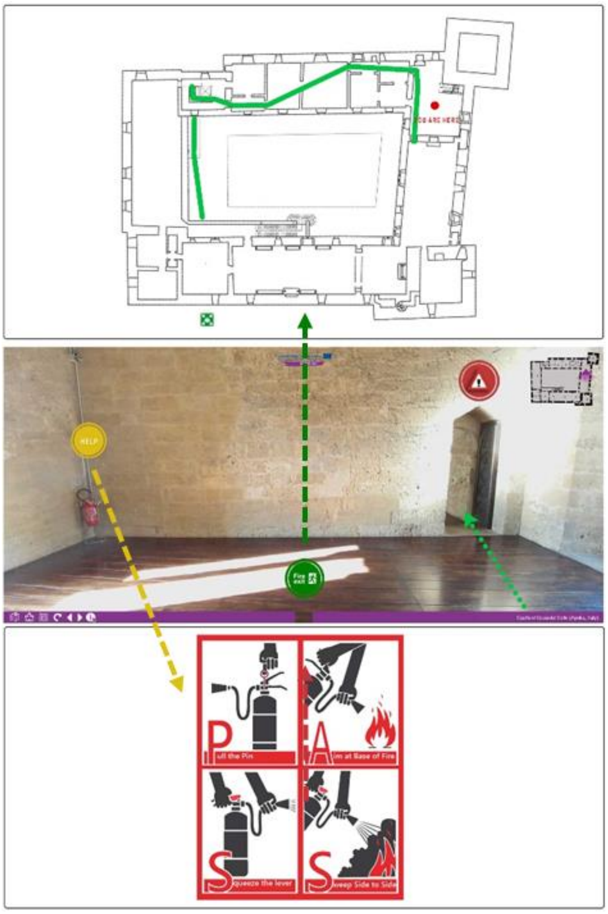


Figure 12: *Risk assessment Virtual Tour.* Example of instructions about protection devices.

In the specific case, the 3D models were necessary for simulations, which results were made usable in the tour. In particular, the escape routes were determined by agent-based simulations (ABM) performed in BIM-oriented software for wayfinding according to the Fire Safety Engineering approach. Behavioural design, applied to historical-architectural buildings through ABM, aims at the conservation of the architectural heritage and life safeguarding. The simulative approach of the human flows and interaction with each other and with the environment is based on predictive models of behaviour, such as the Social Force model where each user is represented as an agent subjected to attractive and repulsive forces.

The role of the BIM in the simulation is fundamental for its parametric structure including geometric, material and performance data of the entire building and furnishings (Figure 13). On the one hand, this information is required to define obstacles and spatial constraints to human movement and, on the other hand, to simulate the fire propagation according to the type of combustion reaction and the fire resistance properties of materials, including thermal capacity, surface temperature and emissivity.

The 3D model, as mentioned, was created starting from the point cloud acquired with laser scanning and processed in Autodesk ReCap Pro 6.0, in its building and architectural components, with a metric accuracy compatible with the representation scale 1:50 but with a level of detail and information close to LOD 500 for the elements that are needed for fire simulation (walls, furnishings, openings, flat and vaulted floors, including the truss) and human behaviour. In fact, the geometries of windows and some architectural components have been simplified in Autodesk Revit 2019. The model was imported into the Pyrosim v. 2019.1 (*Thunderhead Engineering*) Fire Dynamic Simulator (FDS) software in the interoperable *.IFC format, preserving the parameters. The next step of behavioural modelling of agents in escape required the exchange of the proprietary file format of Pathfinder application (also developed by Thunderhead Engineering).

The emergency routes plans, imported into the *RM_VT*, are graphic elaborations exported in *.PDF from the HBIM that represents the fire signs and protective devices. The videos of the users' flows obtained from the agent-based simulations are likewise imported as a component (RM1.Exit) (Figure 14). Since the 3D model reporting fire signs and protection devices is available, the same was loaded in the *RM_VT*, once published via the web with *Autodesk Viewer*®, in order to have an overall perception of the building (Figure 15).

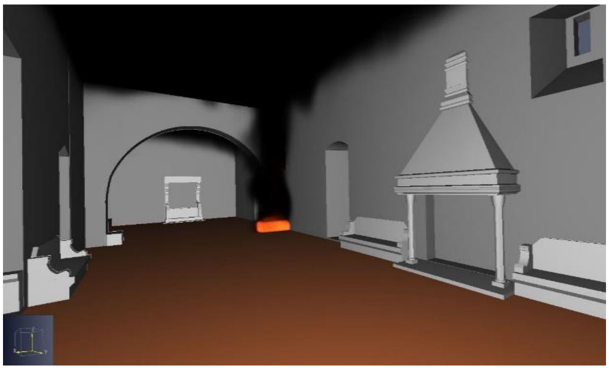


Figure 13: Risk assessment Virtual Tour. Sala del trono. Example of fire source in Agent-based simulation (ABM) with BIM.

Figure 14: Risk assessment Virtual Tour. Central courtyard. Example of human-human-building interactions in Agent-based simulation (ABM) with BIM.

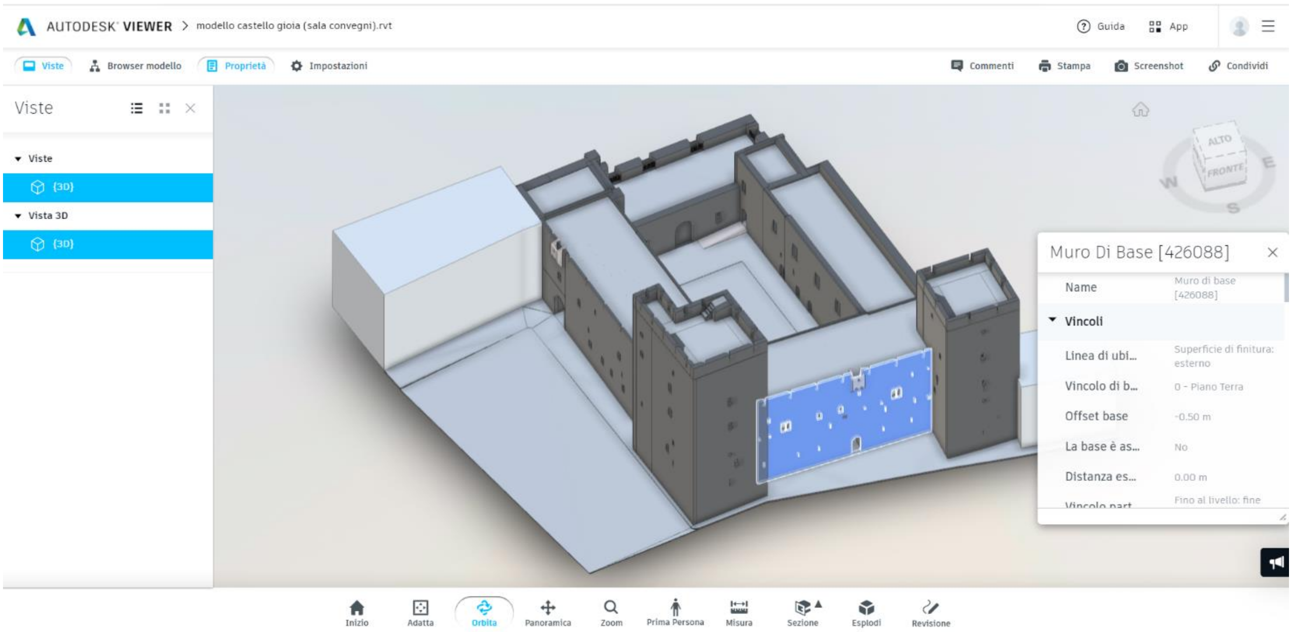


Figure 15: Risk assessment Virtual Tour. BIM model reporting overall egress paths and protection devices.

4. Discussion

The application to the case study of methods and tools, as introduced in Section 1 and described in Section 2, helps outline some remarks on the advancements of the state of the art and future research improvements.

Firstly, it should be highlighted that the development of thematic virtual tours, which result from the same layout of panoramic scenes although they can be explored separately, strengthens the recalled optimization of costs and resources that are reasonably priced and easy to use tools are enabled, if compared to more sophisticated 3D solutions (Bozzelli et al., 2019; Ferdani et al., 2020; Hajirasouli et al., 2021; Younes et al., 2017). For the Castle of Gioa del Colle, with more than thirty rooms, two working days of one operator were needed for the acquisition by the 360º camera of redundant images, later selected based on the best light conditions throughout the day, and for the following elaboration of the basic sequence within the virtual tour editor, ready to be integrated with the digital products afterwards.

Moreover, a common visualisation environment of the site/building, where only the typologies of hotspots/switches to external links vary depending on the specific purpose, offers an effective tool for transversal interrogation, taking into account that the thematic contents and products are very much likely to overlap and interact within the overall process of safeguarding and valorisation. In fact, from the operational point of view, it should be considered that the territorial bodies in charge of heritage assets, such as local governments, associations and superintendencies among the others, might greatly benefit from a coherent and comprehensive collection of their cultural, architectural, technical and functional characteristics, in order to address compatible and effective protection and improvement actions. Nevertheless, from the conceptual point of view, assuming that dissemination, assessment and management of historical sites/buildings involve multi-disciplinary and multi-faceted aspects, the virtual tours are conceived as separate in order to give modularity and versatility to the system, even though cross-references are implicit. For instance, understanding a decay pattern (VT_PA) might require consultation of videos surveying inaccessible parts by drones (VT_ID); getting an overview of ongoing activities of analysis and diagnosis (VT_PA) by non-experts users, such as visitors involved in a virtual touristic visit (VT_ID), might be a useful way to make the public aware of the cultural value of the asset, also by showing the commitment of the managing authorities to conservation and protection actions; providing help, warning and exit signs (VT_RM) through the same tool of the informative tour (VT_ID), facilitates people in getting familiar with places that are generally complex and unknown.

The above-mentioned integrated approach is new, compared to previous works, as documented in the most recent literature and based on virtual tours of panoramic scenes for divulgation (Mah et al., 2019) and diagnosis (Napolitano et al., 2018; Sánchez-Aparicio et al., 2020; Trizio et al., 2019). Moreover, it gives an added value to the application to risk management, where computer graphics environments are generally used (Zhu & Li, 2021) instead of photorealistic scenes, although the perception of the real surfaces and spaces might empower the associations between places and emergency risks/facilities.

Such a vision is further addressed by the integration of the virtual tours with a Web-GIS platform, collecting a variety of texts and pictures referred to the typological, historical and architectural characteristics. In addition, all the digital added contents/products of the tours might be stored as entities of the relational geodatabase, too. This possibility, which was already applied to the former project 3D-IMP-ACT, could be a further improvement of the present study, particularly for those records, such as diagnostic reports on construction materials/elements or 3D models, that might be analysed and compared across different case studies, through spatial and parametric interrogation of the geographic information system. Finally, as the future development of the proposed workflow and application, the validation should be supported by the results of feedback questionnaires, structured to provide a metric for usability, effectiveness, motion sickness, sense of presence and realism of the virtual environment (Mastrolembo Ventura et al., 2020), as well as retention and self-efficacy for training purposes under emergency (Chittaro & Sioni, 2015; Falconer et al., 2020; Lovreglio et al., 2018; Rahouti et al., 2021).

5. Conclusions

The proposed methodological framework moves from the motivation of addressing approaches and solutions, as acknowledged by the scientific community for the digitalization of the historical-architectural heritage, according to an integrated vision. In fact, it aims at taking into account all the aspects, which merge in the refurbishment and enhancement processes and might most benefit from the virtual site representation, the systematization of different data for typology, discipline and restitution mode, as well as from the intuitive communication among the stakeholders. Furthermore, the methodology is focused on the definition of flexible and accessible tools, which might apply even in common practice applications, where time, resources and budget are limited, being understood that a configuration at increasing levels of complexity is highly desirable to meet specific requirements.

Consequently, the paper has developed and validate VR environments, remotely and/or onsite accessible, that are centred on the creation of virtual tours of 360° panoramic scenes, since they seem to fulfil a series of valuable requirements: acquisition and elaboration by low-cost tools and timesaving procedures; capability to describe shapes, colours and textures of the architectural surfaces leading to realistic visual communication; possibility to store and display a variety of external informative contents and digital products. Particularly, the virtual tours have been herein focused on three thematic areas: (i) *Inclusive Dissemination* that extends the physical visit to the understanding of the historical-constructional stratifications and the exploration of parts with limited accessibility, for location at high altitude, private functions, presence of architectural barriers and dangerous conditions; (ii) *Performance Assessment* of the state of conservation, through the correlation among decay maps, diagnostic investigations and details of technological and structural elements, including those from previous transformations and modifications; (iii) *Risk Management*, through communication and training of appropriate and aware behaviours in emergency situations.

Nonetheless, all the informative contents and digital products connected to the thematic virtual tours as hotspots/switches, while contributing to the aforementioned purposes, are conceived as additional components of the central host environment and, as such, can be selected consistent with the needs and availabilities of the specific application.

In particular, such flexibility applies to the use of 3D reality-based and computer-based models, which are proposed both as products that can be directly explored and interrogated through referenced external links or as processing tools for the elaboration of data and results, then displayed in a schematic way. They certainly constitute an added value with respect to the development of the thematic axes. Even so, their unavailability does not affect the validity of the methodological workflow, limiting only the complexity and specialization of the application.

Nevertheless, in the case of historical-architectural heritage, it should be noted that, like 360° spherical photos, 3D reality-based models from digital terrestrial and aerial photogrammetry offer extraordinary possibilities of documentation and analysis of morphological, formal and material characteristics of surfaces and volumes, that are typically heterogeneous, irregular and composite, with limited use of hardware and software tools. Likewise, the described process demonstrates how more elaborated computer-based parametric and predictive models enable specialist assessments on assets, features by interconnected technical, environmental and social factors.

Finally, it is worth underlying the need to focus on goals and strategies, rather than on techniques and tools required for their achievement, in order to develop effective and feasible solutions, which are fully consistent with the requirements –understanding of inherent characteristics, interpretation of phenomena and mechanisms, correlation of multi-disciplinary issue and transmission of cultural values– that are distinctive of the refurbishment and enhancement processes of the historical-architectural heritage.

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