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From semantic-aware digital models to Augmented Reality applications for Architectural Heritage conservation and restoration

The paper presents the integration of Augmented Reality (AR) and Mixed Reality (MR) tools for the built Heritage management and control, both remote and on-site, and real time interaction, starting from a preliminary set of experimentation carried out for knowledge and tourism purposes. Within the framework of these experimentations, specific data inventories are related to the IFC model, and all these data are collected on a cloud-based platform, allowing the "dialogue" among platform and applications. Therefore, BIM integration is the first step of the procedure, considering a workflow where data capturing, digital documentation, and data modeling and aggregation are the entry level to manage applications able to give an added value in gaining the greatest technical benefit from digitization. Mapping the main features and the state of conservation is the second step, including geometric features, historical knowledge, documents and pictures related to materials, diagnostic analysis, etc.
Starting from AR applications developed on several case studies, including historical buildings, museums and a church, aimed at an immersive on-site navigation thanks to a set of additional information related to the digital model, experimentations oriented to technical uses are presented.
An extension of AR and MR applications for the analysis and interpretation of architectural heritage and technical uses can be an effective support in restoration, conservation and maintenance of historic buildings, by enhancing the real world through virtual objects and creating a new mixed reality environment for technical users.

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Keywords:
Architectural Heritage; Parametric modeling; AR/MR; Knowledge; Interpretation

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1. BACKGROUND

Nowadays technological evolution in the mobile devices and apps field can open up to many new opportunities, triggering at the same time new methodological challenges when these applications focuses on Cultural Heritage. Mobile applications and devices are increasingly widespread in different heritage fields and for different purposes. Anyway, the integration of Augmented Reality (AR) and Mixed Reality (MR) tools for the built Heritage management and control, both remote and on-site, and real time interaction can be further developed.
The state of the art and the scientific literature include an extensive discussion about these immersive technologies (Brusaporci et. al., 2017; Bertocci et. al., 2018), starting with the definitions and meanings given to the different dimensions of virtuality.
According to Bekele (Bekele et. al., 2018), an additional definition can be included within the virtual environment field: Augmented Virtuality. While Augmented Reality is indeed defined as a tool to enhance our perception and understanding of the real world by overlaying virtual information on our view of the real world, Augmented Virtuality aims at augmenting the virtual world with scenes from the real world. On the other hand, Virtual Reality allows the interaction with a digital environment without a means to interact with or see the real world, and Mixed Reality (Ioannides et al., 2017) aims at blending real and virtual environments.
Mixed Reality is the merging of real and virtual worlds to produce new environments and visualizations where physical and digital objects co-exist and interact in real time. Mixed reality takes place not only in the physical world or the virtual world, but is a mix of reality and virtual reality, encompassing both augmented reality and augmented virtuality. Mixed reality can be defined as "...anywhere between the extrema of the virtuality continuum, where the virtuality continuum extends from the completely real through to the completely virtual environment with augmented reality and augmented virtuality ranging between" (Milgram & Kishino, 1994).
Beyond, and as a priority for, the use of immersive applications, the approach to digitisation and semantic aggregation (De Luca, 2020) are at the heart of the creation of all the knowledge levels required for architectural heritage applications, particularly when they support conservation, management, enhancement and restoration processes. This issue needs to be faced considering all the opportunities offered by digital technologies, and the relations between interpretative models and reality, virtual reality, and augmented reality (Brusaporci, 2017).
Moreover, high-quality 3D digitization holds a great potential towards innovative solutions aimed at knowledge, conservation and enhancement of cultural heritage, as stated in the "Declaration of Cooperation on Advancing Digitisation of Cultural Heritage", signed to join efforts in a European initiative on the 3D digitization of Cultural Heritage (Cooperation on advancing digitisation of cultural heritage, 2019).
In this direction, the role of digital technologies can be essential as a support allowing experts and technicians to manage and analyse scientific data, contributing to conservation strategies, and, on the other, allowing general public and non-expert people to improve their knowledge and level of interaction thanks to applications in virtual environment (Mandelli et al., 2017).
Depending on the objective to be pursued by the digital model, different processes will be required for knowledge and representation, involving multiple disciplines (Münster, 2017).
Within the presented research framework, the use of applications for Augmented Reality and Virtual Reality started during the development of the European Project INCEPTION – *Inclusive Cultural Heritage through 3D semantic modeling* (Maietti et. al., 2020), and has been experimented also in other research contexts (Ferrari & Medici, 2017).
The INCEPTION project, started in 2015 and ended in 2019, was aimed at the semantic modelling of Cultural Heritage buildings using BIM to be managed through the INCEPTION platform for advanced deployment and valorisation of enriched 3D models for a better knowledge sharing and enhancement of European Heritage.
In this framework, the State of the Art includes several works as a reference and starting point to approach documentation, data collection, data management, and dissemination through integrated tools and platform (Apollonio et al., 2019; Potenziani et al., 2015; Champion & Rahaman, 2020), increasingly including data management through Building Information Modeling (Bolognesi & Fiorillo, 2019; Bianchini et al., 2016; Apollonio et al. 2017; Logothetis et al., 2018).
The main project result is the INCEPTION Core Engine (ICE), providing solutions for managing, visualising and archiving 3D or BIM models and all the related digital documents, aggregated by semantic technologies (Parisi et al., 2019). In particular, the ICE allows to realize an actual eXtended Reality (XR), as a mix of AR/VR/MR solutions. Thanks to tailored programming interfaces (APIs), INCEPTION enables the integration with e-travel and XR applications both for off-site and on-site use, even through mobile devices. The approach relies on retrieving on-the-fly, by the use of semantic queries, the contents hosted on the platform, starting from the BIM models developed, most of the times, for a specific purpose (Historic England, 2019; López et al., 2018). The availability of the right level of detail, accuracy and granularity is the key to be consistent with the storytelling and the information to be shared. Thanks to the semantic approach, each element of the model has a Unique Reference Identifier (URI) that allows to enrich these models with a virtually infinite amount of Linked Data and Open Data by the use of Semantic Triples.
Those technologies allow also a more effective immersive visualization of sites, objects and information, and improve the analysis of the assets by means of data and metadata integration (Messaoudi et al., 2018). Cultural heritage preservation, access, interpretation and understanding are the main purposes, together with the development of tools for decision-making and restoration processes (Centofanti & Brusaporci, 2013; Lo Turco et al.,2017).

2. SEMANTIC-AWARE DIGITAL MODELING

Within INCEPTION, the methodology to set up the cloud-based platform was based on semantic

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technologies to allow portability and interoperability in knowledge management. As mentioned before and following a top-down approach, information about the target of the model are organized in a semantic structure in addition to the geometrical description. After having analysed the concepts of CIDOC CRM, a SKOS based vocabulary to cultural heritage buildings was developed. Then a SPARQL web service was deployed allowing to navigate between architectural concepts and understand specific parts of the model.

One of the core services of the INCEPTION platform is a web service to manage semantic information (Bonsma et al., 2018). Semantic data associated with the models are collected, imported and linked to specific standardized ontologies to enable deeper understanding of Cultural Heritage architectural characteristics and allowing the information completion and enrichment by users (Ausonio et al., 2018), in order to sharing knowledge and allow new interpretation and understanding of European cultural assets.

Applied methodology of the presented research starts from the creation of semantic-aware digital models, parametric models (H-BIM) semantically enriched in order to gather data and information related to materials, state of conservation, structural conditions, previous interventions, etc. Specific data inventories are related to the IFC model, and all these data are collected on a cloud-based platform, allowing the "dialogue" among platform and applications (fig. 1).

BIM integration is indeed the first step of the procedure, considering a workflow where data capturing and digital documentation, and data modeling and aggregation (in order to create accurate reality-based 3D models), are the entry level to manage applications able to give an added value in gaining the greatest technical benefit from digitization. Within this phase, an interpretative geometric representation of architectural shapes is essential.

Mapping the main features and the state of conservation is the second step, including geometric features, historical knowledge, documents and pictures related to materials, diagnostic analysis, etc.

More specifically, the INCEPTION platform consists of a framework of software tools and a set of programming interfaces (APIs) able to transform each element of an IFC (Industry Foundation Classes) BIM model into semantic RDF (Resource Description Framework) triples, storing them in a dedicated semantic triple store and linking them to metadata, documents and other linked data

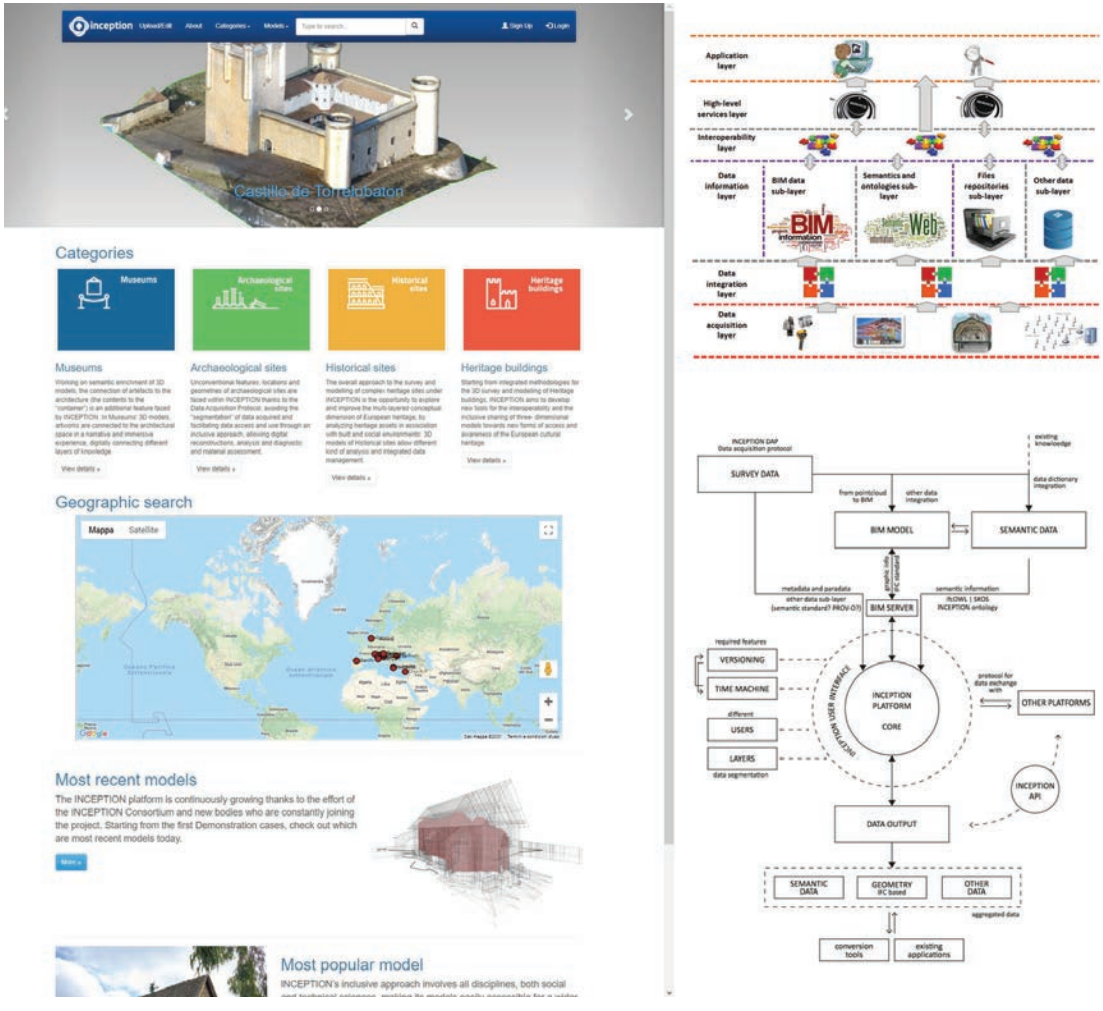

Fig. 1 - The INCEPTION platform: on the left the home page, combined with the data layers integration schema for the semantic enrichment of 3D models and the input and output data diagram, on the right.

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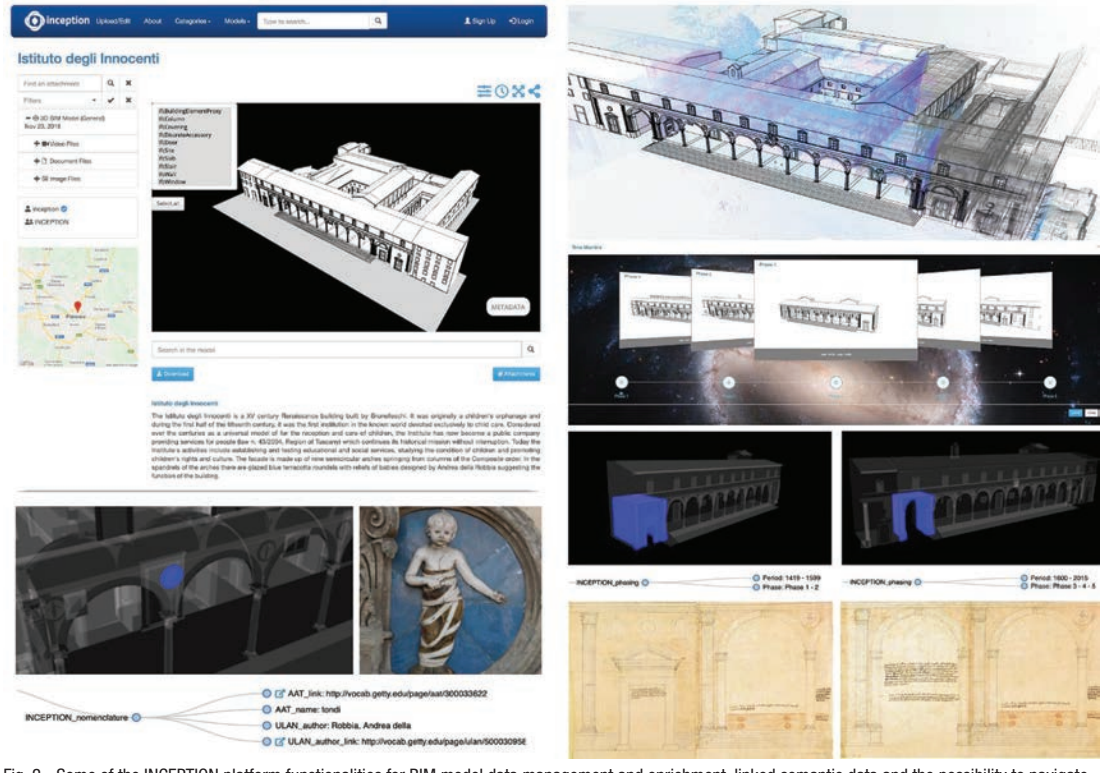

Fig. 2 - Some of the INCEPTION platform functionalities for BIM model data management and enrichment, linked semantic data and the possibility to navigate the model over centuries.

(fig. 2). These data are reassembled in a 3D model, navigable by means of a simple modern web browser (HTML5 + WebGL).
The main aspect is the advanced use of the cloud platform connected to on-site mobile applications. This allows gaining available information, to be visualized during inspections and updated when additional analysis are performed. The connection platform-apps allows the continuous updating of information (pictures, documents, texts, historical documentation retrieved, etc.). When new information are available on the platform, AR app can display and manage all new data.

3. AUGMENTED AND MIXED REALITY TOOLS FOR CULTURAL HERITAGE

The connection among H-BIM and Virtual and Augmented Reality applications is part of the current research debate, since it is more and more crucial the opportunity to manage three-dimensional information systems including information and data according to different levels of knowledge, to be virtually explored thanks to immersive digital environments (Banfi & Oreni, 2020).
Even if personal devices as smartphones and tablets nowadays allow fast processing and enhanced visualization, also extending to VR and AR thanks to the incorporated camera, and the videogame technology allows the interactive visualization of complex heritage sites in an immersive experience, the content still remains the main concern (Apollonio, 2009).
Huge efforts like the London Charter (Denard, 2012) has been carried out in the past years in order to ensure reliable 3D reconstructions (Hermon & Niccolucci, 2018) but only few of them fully comply with it.
In order to somehow solve this shortcoming, the INCEPTION platform indeed is focused on making available certified historical sources and all the reliable pieces of information that could be useful even for technical, managerial, maintenance, conservation and development aspects of cultural heritage, also exploiting XR. This approach, together with the specifics APIs above mentioned for the integration between the structured data inside the INCEPTION platform and the development of XR Apps by third party companies, relieves creative industries from the burden of painful searches in archives and eases collaboration between different disciplines, technologies and research fields (Di Giulio et. al., 2020). As a matter of fact, several experiments have been carried out in the field of ludic/touristic and edutainment through VR and AR applications, testing the "static" and "dynamic" methods of data access to the platform.

3.1 EXPERIMENTATION FOR TOURIST AND KNOWLEDGE PURPOSES

Case studies developed under the European project INCEPTION include historical buildings, museums and a church. The main purpose of this experimentation was to develop an immersive on-site navigation thanks to a set of additional information related to the digital model.
A first experimentation has been tested on Palazzo Tassoni-Estense (fig. 3), in the historic city centre of Ferrara. This historical building is an interesting case study, including parts reconverted to a new use (in fact it hosts the Department of Architecture of the University of Ferrara), and rooms in their original configuration both from an architectural-structural and decorative point of view.

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An interactive virtual tour has been designed for this historical building, using raster-based technical material for use via Web Brosing and HDM AllInOne, and has been realised with 36 of the 123 360° images acquired during the survey campaign (Cannella, 2013).
In addition to the historical-architectural information, which becomes an in-depth level of knowledge to be explored during the virtual tour, technical information on the restoration work carried out on the building and diagnostic investigations have also been aggregated. Therefore, the virtual tour opens to additional digital data exploitation, at visual level, in order to display a set of technical information for additional purposes.
These experimentations have been deepened on the case study related to the Istituto degli Innocenti in Florence (fig. 4). Virtual tour on SS. Annunziata Square, Time Machine reconstruction of the façade on SS. Annunziata Square, Virtual tour of the museum (focused on paintings and artefacts) were developed targeting tourists, visitors of the museum and scholars, through mobile and desktop VR applications.
Another building on which experiments of Virtual and Augmented Reality applications were performed is the Tesla Museum in Zagreb.
Technical Museum is one of the most visited Museums in Zagreb. The museum presents a relevant scientific and educational centre in the field of technical sciences. The entire structure was designed and constructed as a timber structure and it represents a rare existing example of European engineering concept of expo-halls timber structures with large span from the early 20 century. Technical Museum of Zagreb was founded on the model of existing large scientific and technical museums in the world; it is a complex museum of science and technology. The aim of digital modelling and applications development was to provide interactive access to museum exhibits as well as to museum

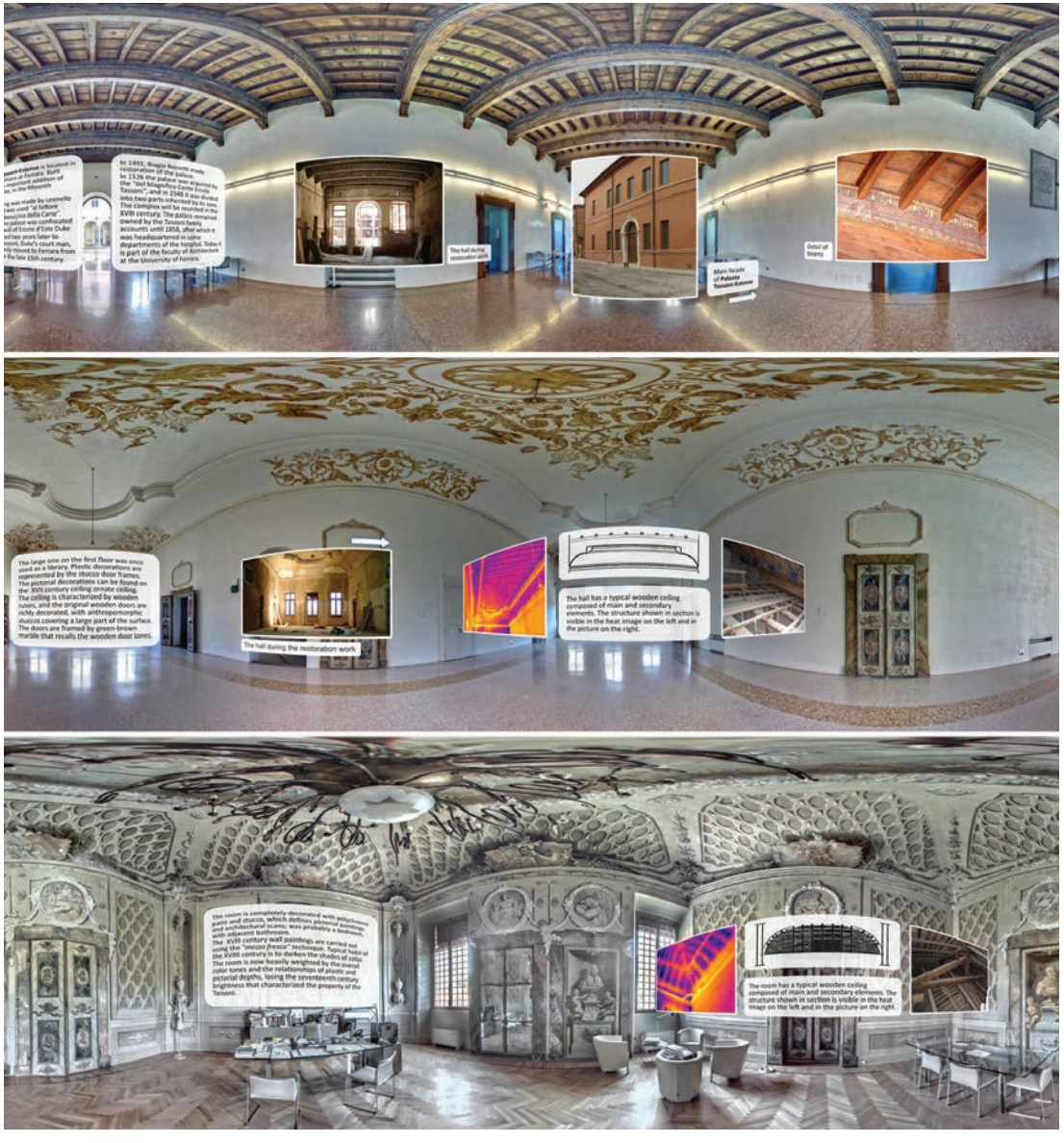

Fig. 3 - For the Tassoni-Estense Palace, an interactive tour has been realized, mainly using raster images in order to be easily used on-the-go (it doesn't require high CPU level or bandwidth) by web browsing and All-in-one HMD. The source data are 36 of the 123 spherical images captured during the survey campaign.

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Fig. 4 - Virtual Reality applications developed for the Istituto degli Innocenti in Florence. On the left, the virtual tour of the museum focused on artefacts, on the right, the SS. Annunziata Square and Time Machine reconstruction of the façade.

building itself. A research experimentation was related to the new skin, in order to develop interactive thermal pictures presenting the development of technology and its significance in modern world.
The architectural H-BIM modelling of the Museum (fig. 5) and its supporting structure was carried out using Autodesk Revit 2018 software. The model was developed organizing the available pieces of information in the most appropriate way to represent the state of conservation of the building, even storing the result of performed analysis (as a numerical value or as external documentation). In this way, the achieved Level of Development of the BIM model went even beyond the LOD 500 (as-built stage for the American Institute of Architects). Creating a digital model for management and maintenance means, in fact, that model can be continuously updated and implemented over time to record changes made during maintenance (as foreseen by the Italian regulation UNI 11337:2017 with LOD G). A detailed explanation of the creation of the BIM model can be found in (Rajčić et al., 2019).
Furthermore, in order to make those model actually updatable, models were exported in IFC 2x3 to be uploaded onto the INCEPTION platform, where have been converted to TTL and enriched both semantically and with attachments of different types (PDF files, structural reports, thermographs, images, 3D models, etc.). A detailed description of this process in available in (Maietti et al., 2020).
For the application of Augmented Reality, together with the Museum curator some objects were chosen to be enhanced with this technology inside the museum, including one of Tesla's coils (fig. 6). The smartphone application was developed in Unity environment, using Vuforia's image recognition technology as a starting point for the content. The

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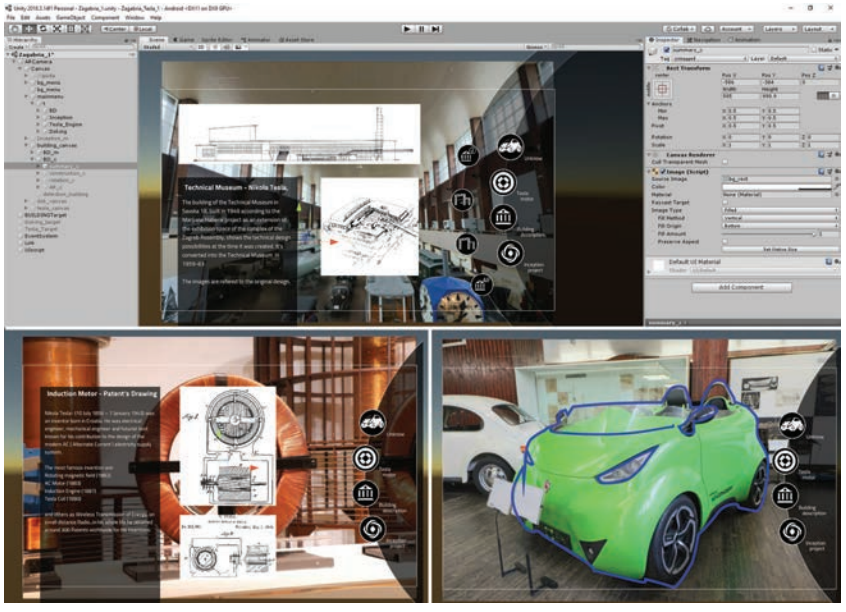

Fig. 5 - The historical and technical documentation attached to the H-BIM architectural and structural model of the Tesla Museum by the use of the INCEPTION platform can be retrieved even in VR environments in order to create more effective experience of a virtual tour.
Fig. 6 - Visualization of the function of the AR app that enhances the structure by superimposing it, dynamically and in real time, inside the big room.

two- and three-dimensional contents are directly and dynamically taken from the INCEPTION platform and usable also on the 360° images.
In this case, the AR application is focused on the museum experience. In fact, multiple objects are exhibited within the museum and the accurate data capturing performed on some of them allowed to enrich the BIM model. Those information can be retrieved on the fly from the platform, exploiting the INCEPTION APIs, in order to provide the museum visitors with an "augmented" experience.

4. MIXED REALITY ENVIRONMENT FOR TECHNICAL USERS

The case studies presented above explored the use of Virtual and Augmented Reality applications mainly for the immersive use of digital models for tourism, or knowledge purposes. The opportunity of creating augmented content in digital environments also allowed for the integration of technical information, such as reports about the restoration site at palazzo Tassoni-Estense or images of diagnostic investigations carried out on the building. In this way, historical information is combined with technical information to create virtual explorations that exploit the digital environment to link specific information to specific rooms or parts of the building.
In the case of the Tesla Museum in Zagreb [1], the BIM model becomes crucial as it allows the structure of the building to be explored focusing on condition assessment of the structure, or to manage data regarding the structural performance.
While structural and condition assessment of the Museum were performed, a 3D model was created using UAV photogrammetry and laser scanning techniques. Starting from the 3D survey, the BIM model of the Technical Museum has focused on modelling complex timber structure, as well as architectural i.e. non-structural elements such as roof, floor and curtain walls.
BIM elements were used to model cross and longitudinal trusses of the main hall and side halls, with appropriate definition of the top and bottom truss chords as well as tension and compression diagonals. All trusses are modelled parametrically to facilitate ease of future modifications either of individual beams or the entire truss element types as groups. Multi-part column elements were modelled using column BIM elements with bracing elements for diagonals and horizontal elements. Roof supports are modelled as beam systems.
Starting from the BIM model enriched with further data on the platform, two applications have been

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developed. From one side, a VR app allows the user to virtually navigate the exterior of the building using an immersive view where to take advantage of the digital experience by hiding unnecessary elements that distract from the understanding of the building itself. Furthermore, the user has also the chance to switch off the architectural elements focusing just on the timber structure (fig. 7): an unusual and extraordinary possibility offered by the in-depth digitalization.
With integration of all of the data in BIM model, it is possible to simulate future interventions by foreseeing consequences of bad design and/or inappropriate retrofitting.

An additional demonstration case focused on the application of Virtual tools for technical uses, is the Saint Nicholas Chapel (Obergum, the Netherlands) [2], developed to test the site management use validation of a cultural heritage asset by introducing the tools for maintenance purposes within the INCEPTION platform.
For the 3D acquisition, a mid-range 3D laser scanner was used together with additional sensors (HDR-RGB and IR) and a short-range 3D laser scanner for high resolution capturing details of bas-reliefs (e.g. pulpit) and structural/architectural elements. Data has been captured with most possible consistency of the outside and inside structures of the building, the bell tower and all the other accessible environments. Further, thermal imagery was captured from key view positions inside and outside the building.
I this case, next to the 3D parametric modelling, the semantic part consisted of inspection data (e.g. assessment grade, repair priority, type of component defect) that would help at developing a semantically enriched 3D model of the heritage building, integrating additional documents related to the technical survey (i.e. pictures of defects, interventions and costs) for proper decision-making. Then, a set

Fig. 7 - Through the use of the Twinmotion (Unreal Engine) platform, an off-site virtual reality navigation experience has been realized on the architectural complex of the museum in relation to its timber structure.

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Fig. 8 - The Asset Management tool (DEMO RE Suite) used for on–site condition assessment of the Saint Nicholas Chapel in Obergum, the Netherlands, and management of assets with embedded BIM software.

of BIM requirements have been defined specifically for the Saint Nicholas Chapel demonstration case.
The application related to this experimentation is the Asset Management tool (DEMO RE Suite) developed by the INCEPTION partner DEMO: it is a software solution used for condition assessment on–site and management of assets with embedded BIM software. The main aim of the tool is to leverage the existing data in BIM to expedite and enhance the quality of building inspections. The solution provides the possibility to not only assess the building condition, but also to optimize the conservation maintenance planning according to different needs. This experimentation foresee the creation of the IFC model based on 3D data capturing to be stored on the platform; the Asset Management tool retrieves this model to be used for building inspection based on the BIM object decomposition according to the applied technical norms for condition assessment. The tool links the information resulting from building inspection to the IFC model, and then the inspection results are uploaded to the platform (fig. 8). The semantically enriched IFC model is stored on the INCEPTION Platform. This enriched model can be used for further technical analysis and decision-making using the Asset Management tool or other relevant software tools.
A scan-to-BIM procedure has been also applied on the Castle of Torrelobatón (Valladolid, Spain), starting from 3D photo-based scanning by means of a drone and from 3D laser scanning of the exterior and interior of the Castle [3]. The resulting H-BIM model has been divided into the multilingual representative elements of the European defensive architecture from the XV century so far according to the Getty-AAT.
The 3D semantic H-BIM model can be also linked with diagnostic tools, like IR sensors or cameras, wireless communication devices and sensor data in general; therefore, temperature and humidity data of the southern wall have been recorded in a static and dynamic way, and correlated with the reflectivity indexes for possible early assessment of humidity.
At the same time, demonstrating one more time an effective data re-use, the same 3D model that was hosting diagnostic data, has been also used for creating an immersive environment, bridging the gap between XR environments for technicians and tourists (fig. 9). In fact, high-quality textures captured by the photo-based scanning can be use both for detecting pathologies and for offering citizens with an off-site immersive navigation of the castle.

5. CONCLUSION

Currently, with several forms of accessibility changing due to the pandemic outbreak, digitisation is becoming an effective solution in making monuments and cultural sites virtually accessible to people. Therefore, improving VR/AR/XR policies and experiences will become more and more essential for empowering the cultural heritage sector with its digital transformation. The relevance of digital platforms, tools and virtual experiences is now at the forefront of public minds and many institutions are increasing or moving activities online.
However, the INCEPTION project demonstrated how the development of online platform tailored

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on specific needs (i.e., historical buildings, monuments and sites in general) still requires significant efforts. Digital technologies, including HTML5, 3D WebGL viewers, Semantic web technologies, VR/AR/XR and eventually AI technologies, are rapidly evolving and can provide a huge range of possibilities for technicians and creative industries as developers of applications and contents, as well as for citizens enjoying the Cultural Heritage in a new way. Nevertheless, starting every time from scratch or from the rough technology can make the task even too challenging. For this reason the experiences presented in this paper made use of the INCEPTION platform as a one-stop repository of semantic contents (that can be accessed by APIs developed for the purpose) and of easy-to-use environments and VR/AR technologies (such as Twinmotion and Unity+Vuforia). The latter are not to be intended as representing the state-of-the-art in the sector but rather an example of achievable results.
Only in this way, these tools can give a significant advantage in sectors where the interpretation of the elements is very complex (i.e., archaeological context). Cultural Heritage preservation and conservation activities do not need to outgrow the capabilities of digital devices and computing resources. Rather, they require a multidisciplinary synthesis by means of ontological archiving and flexible repositories. In the end, we make the the best use of AR/MR tools when they help to manage, enrich, use, preserve and disseminate heritage sites and buildings in an easier and more effective way.

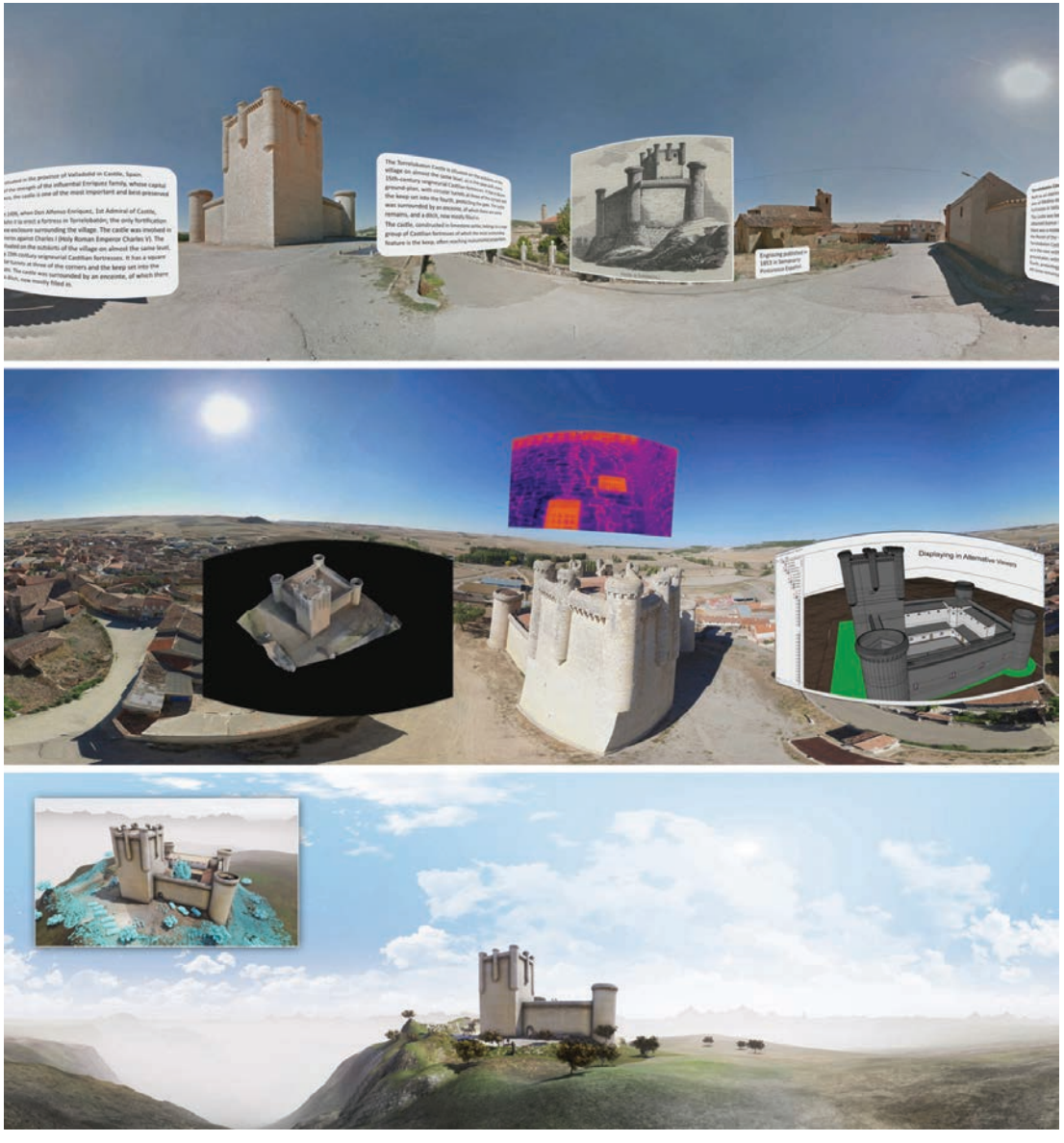

Fig. 9 - The 3D model of the Castle of Torrelobatón in Valladolid, Spain, was used to be linked to diagnostic tools, for documentation purposes and for creating an immersive environment, bridging the gap between XR environments for technicians and tourists.

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NOTE

[1] The demonstration case related to the Nikola Tesla Technical Museum in Zagreb has been developed together with the University of Zagreb, Faculty of Civil Engineering, partner of the INCEPTION project.

[2] The demonstration case focused on Saint Nicholas Chapel, Obergum, the Netherlands, has been developed with DEMO Consultants BV, partner of the INCEPTION project, who developed the software tool for Cultural Heritage Asset Management to be connected to the INCEPTION platform.

[3] The survey and modeling procedure on the Castle of Torrelobatón in Valladolid, Spain, has been performed by Fundación CARTIF, partner of the INCEPTION project.

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