

# EEHB 2024

The 5<sup>th</sup> International Conference on Energy  
Efficiency in Historic Buildings

7<sup>th</sup> – 8<sup>th</sup> October 2024

Singapore | Austria



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## EEHB 2024 Singapore Proceedings

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# Digital Applications for Conservation and Enhancement of Historic Buildings

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**Abstract** – The documentation and management of Historic Buildings are increasingly crucial actions, as heritage assets are very widespread and host a variety of functions, both public and private, that require conservation interventions respecting historical and cultural values and features, and at the same time the adaptation to energy efficiency standards, reduction of impacts on the environment and, in general, sustainable practices. In this context, the application of digital tools for the survey and modelling of cultural heritage becomes essential, both as a knowledge support and as a basis for the integration of data and information towards the definition of predictive models, characteristic behaviors and conservative strategies. The paper summarizes the outcomes of the INCEPTION research addressed to support experts and technicians to manage and analyze dimensional-morphological and scientific-technical data starting from H-BIM (Heritage Building Information Modeling) to be managed within the cloud-based platform grounded on semantic technologies, where information are integrated to geometries and are organized in data structures allowing a more comprehensive knowledge and understanding. Specific case studies support application examples.

**Keywords** – Digital documentation; H-BIM; Historical buildings; Semantic enrichment; 3D modeling for simulation.

## 1. INTRODUCTION

Today the application of digital tools for documentation, enhancement and restoration of historical buildings is more and more spread and crucial to develop conservation actions also in the framework of energy efficiency and sustainable practices. The role of digital technologies can be essential as a support allowing experts and technicians to manage and analyze dimensional-morphological and scientific or technical data to be integrated toward a more comprehensive knowledge and understanding, involving multiple disciplines.

In this direction, some experimentations have been investigated during the development of the European project INCEPTION - Inclusive Cultural Heritage in Europe through 3D semantic modeling [1], funded under the Horizon 2020 Programme. The results of the project, which ended in 2019, resulted in the INCEPTION Srl, Spin off incubated at the University of Ferrara, and are continuously developed and updated.

Within INCEPTION, advanced procedures for Heritage documentation have been performed and are under implementation by applying laser scanner and photogrammetry technologies [2,3], in order to manage 3D modes also processed in H-BIM (Heritage Building Information Modeling) environment [4]. In addition to geometrical features, data and information are organized in semantic structures, to be managed within the cloud-based platform grounded on semantic technologies. Semantic data associated with the models are collected, imported and linked to specific standardized ontologies to enable deeper understanding of Cultural Heritage architectural features and allowing the information integration and enrichment by users, in order to sharing knowledge and allowing new interpretation and understanding of 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 (International Foundation Classes standard), and all these data are collected on a cloud-based platform [5], allowing the “dialogue” among platform and applications.

Some specific case studies have been deepened focusing on digital innovation for the preservation of historical buildings. Palazzo Tassoni-Estense in Ferrara and the Istituto degli Innocenti in Florence (Italy) [6], the Tesla Museum in Zagreb (Croatia), and the Saint Nicholas Chapel in Obergum (the Netherlands) are the focus of survey and data processing procedures for testing different possible data management.

Different features and conditions of these buildings were particularly relevant for analyzing original configurations, also integrating technical information, diagnostic investigations and reports about previous restorations; condition assessment of structures, and managing of data regarding the structural performance; and developing asset management tools for maintenance purposes linking the information resulting from building inspection to the IFC model for technical analysis and decision-making.

The paper describes main outcomes from these research experiences, opening the discussion to the main innovation avenues traced today by the most up-to-date methodologies, technologies and tools concerning digital documentation and data assessment applied to Heritage.

## 2. BACKGROUND LITERATURE

Digital applications for conservation and enhancement of Historic Buildings are a research topic strongly interdisciplinary, involving different fields and knowledge. The State-of-the-Art includes innovations avenues concerning digital survey through different data capturing technologies, diagnostic procedures, conservation practices, and the very topical issue of Heritage at risk due to climate change [7].

At the forefront of these innovations avenues, the concept of digital transition involves not only major changes in data exchange tools and media, but also the development of new common strategies for the creation, enrichment and sharing of 3D models, particularly when the object of survey and representation is cultural heritage [8]. One of the most pressing needs is to create three-dimensional models that can describe as accurately as possible and collect as much data as possible about a physical object, a place, a building.

Research directions in the field of digital documentation and data assessment to improve energy efficiency of historical buildings involve more and more the application of new sensors based on 3D computer vision to record thermal information in a three-dimensional space to develop energetic monitoring methodologies [9]. Thermal computer vision-based technologies can be a powerful support in heritage condition assessment and to outline conservation strategies, especially for historic buildings where specific destinations and uses require a careful balance between indoor and outdoor conditions, not to compromise the condition of materials and decorative features, or in museum applications, which require permanent control of the microclimate in exhibition rooms.

Smart sensing process for visualizing the performance of heritage buildings through HBIM platform is an additional application currently widely faced, also due to the increasingly applied parametric modelling of heritage buildings. HBIM modeling first requires the choice of the Grade or Level of Accuracy within the Level of Geometry according to different survey and modeling scopes and different actors involved in the different phases (i.e. restoration, Energy Efficiency, Finite Element Analysis, etc.) [10]. Data integration is topical also for documentation at urban

level, defining a three-dimensional database, which incorporates spatial models and energy information, with the final goal of merging heterogeneous information to interpret the overall framework and to design sustainable development scenarios. Recent studies are analyzing the development of platforms merging GIS (Geographic Information System) and BIM through CityGML data models, for supporting multi-scale analyses, ranging from urban to building level [11].

The need to develop increasingly targeted strategies for documenting and monitoring historical heritage - both listed, monumental, and widespread - stems from the amount of historic buildings in use that need to be upgraded, both for conservation reasons and for sustainability needs (environmental, economic, etc.), reducing environmental impacts. New tools and strategies are needed for both asset owners and managers, in order to optimize the overall asset management during the entire building life cycle. In this direction, Digital Twins are more and more analyzed to improve and upgrade, to protect heritage and also to meet regulatory requirements. The integration of HBIM and Building Performance Simulation (BPS) tools for data-driving the energy improvement is one of the most relevant topics in this direction also allowing predictive simulations [12]. Multi-criteria analysis tools allow comparing different interventions for energy improvement through dynamic, accessible, and sharable Digital Twins.

The potential of Digital Twin lies in the holistic approach (different data from different sources, in an integrated vision) as a support for tools for enhancing performance-based management with targeted strategies and advanced data analysis [13].

The ECTP (The European Construction, built environment and energy efficient building Technology Platform) Heritage and Regeneration Committee outlined the Horizon Europe 2022-2027 Position Paper [14], clearly stating that to pursue sustainable and resilient cultural heritage, huge opportunities are offered by digitalization as major driver to improve the preservation, maintenance, retrofitting, access, and promotion. Objective 2 - Digital built heritage for preservation and inclusiveness focuses on specific priority areas, such as: multidimensional digitalization through an overall integration of digital technologies, interpretation, digital preservation and remote access, data management platforms with robust models and data management procedures, digital tools to improve performance forecasting and monitoring before and throughout the lifecycle.

Several EU funded research projects are focused on energy renovation of heritage buildings, starting from the EU Seventh Framework. The project 3ENCULT [15] was aimed at bridging the gap between conservation of historic buildings and climate protection, facing energy efficient retrofit to increase comfort for users and for heritage collections, reducing energy demand. The Horizon 2020 project RIBuild [16] summarized the latest research on internal insulation in historic buildings transforming it into guidelines for decision making concerning the possible use of insulation in historic buildings. Task 59 - Renovating Historic Buildings Towards Zero Energy [17] was focused on the development of a knowledge base on how to save energy in renovation of historic and protected buildings in a cost efficient way, identifying the energy saving potential for protected and historic buildings according to different typologies, and integrated and replicable procedures to maintain the heritage value increasing energy efficiency. The Interreg Europe project VIOLET [18] faces the challenge to create a building culture consistent with modern requirements of reinstatement and conservation for improved energy usage and reduced carbon emissions, without endangering architectural heritage. The Horizon 2020 project REZBUILD - Refurbishment decision making platform through advanced technologies for near Zero energy Building renovation [19] put at the center of the society potential to tackle environmental issues regarding energy-inefficient buildings the collaboration between different stakeholders in the building renovation value chain, by developing a platform interconnecting in real time the key steps of a tailored retrofitting plan.

Just mentioning a few significant examples, it is possible to highlight how the State-of-the-Art on digital applications to foster sustainable approaches in heritage management is very complex and articulated. In this context, the digital documentation and data management strategies supporting any integration of applications focused to different uses are particularly addressed.

### 3. HERITAGE DOCUMENTATION AND SEMANTIC MODELING

In 2018 the European Year of Cultural Heritage was celebrated to recognize the existing interest of Europe on Cultural Heritage. The entire Horizon 2020 framework program invested more than €500 million, in order to start to capitalize on the many research results achieved over the years. After that, with the “Declaration of Cooperation on Advancing Digitisation of Cultural Heritage” [20], signed by 24 EU Member States in April 2019, the joint efforts in European initiatives were even more consistent and articulated on three pillars: the 3D digitization of Cultural Heritage (pillar I); the re-use of digitized cultural resources to foster citizen engagement and innovative use in other sectors (pillar II); enhanced cross-sector, cross-border cooperation and capacity building (pillar III). Following such intention, several activities have been developed both to facilitate the 3D digitization and to offer a common environment for storing, accessing, and using the collected data.

The European Commission tasked the DCHE (Digital Cultural Heritage and Europeana) Expert Group to the development of guidelines on 3D cultural heritage assets. The Expert Group elaborated a list of 10 basic principles and a number of related tips for each of them geared toward cultural heritage professionals, institutions and regional authorities in charge of Europe's cultural heritage. The principles were published in August 2020 [21]. This topic was further investigated in the “Study on quality in 3D digitization of tangible cultural heritage” [22] that demonstrates how complexity and quality are essential in determining the necessary effort for a 3D digitization project to achieve the required value of the output. In short, the study highlights how there are no internationally recognized standards or guidelines for planning, organizing, setting up and implementing a 3D data acquisition project for any size of asset; quality parameters refer to different stages of the 3D digitization process; and thus, there is a pressing and urgent need for a technical specifications and guidelines [23].

On the other hand, specific actions pursued the achievement of an enhanced valorization of 3D digital data. Between 2019 and 2020, Europeana established the Task Force “3D Content in Europeana”. The Task Force analyzed valuable content on 3D digitization of cultural artefacts at large, in the perspective of their integration in Europeana, also discussing a number of related issues such as, for example, data formats, standards and storage of the models [24]. The effort precluded the explicit need made clear by the Digital Europe Work Programme 2021-2022 [25] foreseeing the creation of Data Space for Cultural Heritage: an European common data space to provide support to the digital transformation of Europe’s cultural sector, and foster the creation and reuse of content in cultural and creative sectors. It will build on the current Europeana platform, vastly expanding the current 3D functionalities. The improvement in 3D data management will be not only qualitative but also quantitative, since the “Recommendation on a common European data space for cultural heritage” [26] published by the Commission in November 2021 suggest the 3D digitization of all monuments and sites at risk, and at least 50% of the most visited ones, by 2030.

Careful documentation is therefore the crucial answer for any conservation or regeneration action to be implemented on historic buildings, considering in particular that there are limitations for the implementation of retrofit measures (for reasons of restrictions, compatibility of interventions, etc.), therefore retrofitting historic buildings requires detailed planning in order to guarantee that the case-specific variables are thoroughly considered [27].

EU funded research projects focused on energy renovation of heritage buildings shortly described before, converge on the need for a set of joint actions, including the improvement of documentation and monitoring methodologies, and the introduction of specific evaluation tools.

In this framework, the development of semantic-aware digital modeling can be an effective basis for meet the requirement of data integration and assessment for heritage assets, as experimented during the INCEPTION project in conceiving a platform able to support data associated with relevant information, and in experimenting possible applications in some heritage contexts.

### 3.1 Semantic-aware digital modeling

The enhancement of digital cultural heritage accessibility is the ability to access cultural contents and resources for as many people as possible by using ICT functionalities and applications, integrating different information in order to access cultural assets in many different ways and for many different purposes (management, research, diagnosis, monitoring, conservation and restoration procedures, education and enhancement). In this perspective, efficient 3D digitization methods, post-processing tools for an enriched semantic modeling, web-based solutions and applications to ensure wide access of heritage contents to experts and non-experts are the key results of the INCEPTION project, developed according to five main actions (fig. 1) to cover the main challenges and requirements in terms of changing role of digital models in the field of Cultural Heritage, semantic enrichment, interoperable formats, collaborations across disciplines and use and reuse of digital sources.

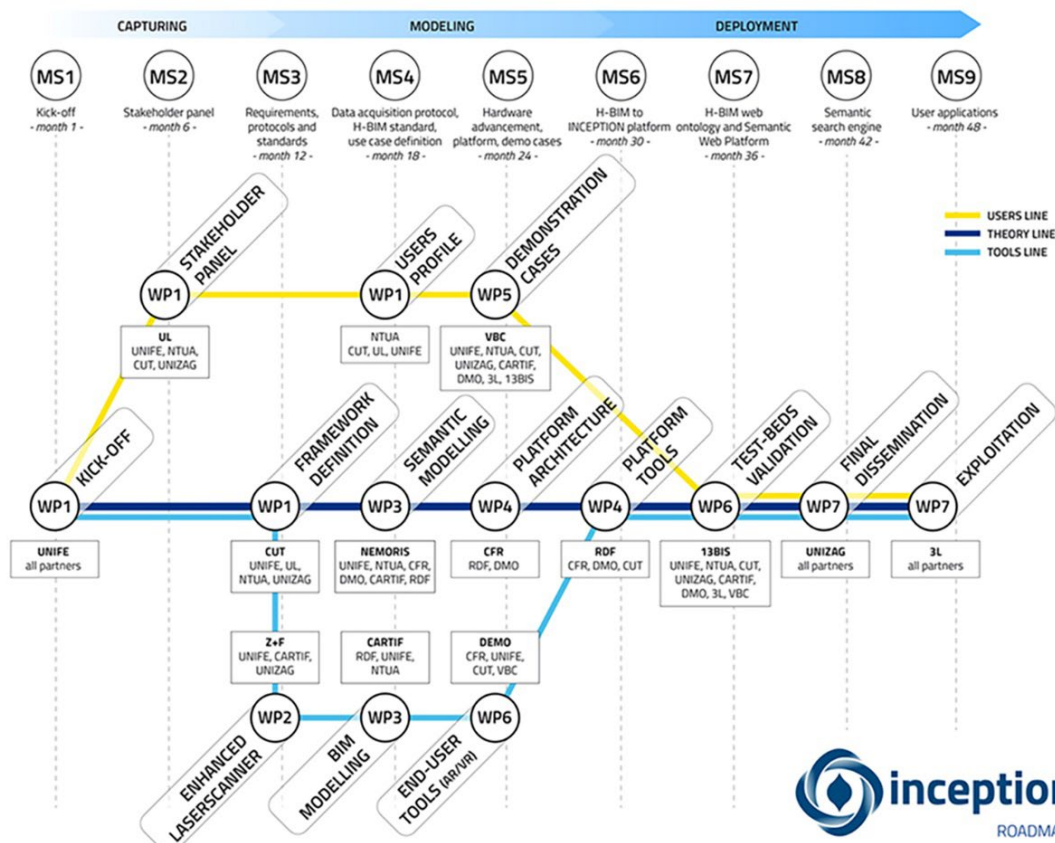


Figure 1. The roadmap of the overall project architecture

Within INCEPTION, the methodology to set up the cloud-based platform was based on semantic 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 analyzed 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 [28]. Semantic data associated with geometric models are collected, imported and linked to specific standardized ontologies to enable deeper understanding of Cultural Heritage and allowing the information completion and enrichment by users, in order to sharing knowledge and allow new interpretation and understanding of European cultural assets.

Applied methodology started 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.

BIM integration is indeed the first step of the procedure, considering a workflow where data capturing and 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. Within this phase, an interpretative geometric representation of architectural shapes is the essential basis for then mapping the main features and the state of conservation, 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 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 . 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.

Applications developed during the project have been further advanced by INCEPTION s.r.l., an innovative start-up company incubated as a spin-off at the University of Ferrara to offer support to the process of digitization, management, dissemination, enhancement of cultural heritage and built heritage, through products and services using BIM-based technologies and semantic-web platforms. The innovative core of the proposed innovation lies in semantically breaking down a building in its single constituent parts and elements, physical or functional, provided with properties and relations with other elements (physical and/or functional).

During the project development and the testing of semantic modeling and platform functionalities, specific case studies have been used to deepen application and data integration possibilities.

#### **4. CASE STUDIES DEVELOPMENT**

In order to test and apply the overall INCEPTION process, nine demonstration cases were selected from six European partner countries, including historical buildings, museums,

archaeological sites, and a church. A first experimentation has been tested on Palazzo Tassoni-Estense (fig. 2), in the historic city center of Ferrara. This historical building is an interesting case study, including parts reconverted to a new use (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. An interactive virtual tour has been designed for this historical building, using raster-based technical material for use via Web Browsing and HDM AllInOne, and has been realised with 36 of the 123 360° images acquired during the survey campaign.

In addition to the historical-architectural information, technical information on the restoration work carried out on the building and diagnostic investigations have also been aggregated as additional digital data exploitation, in order to display a set of technical information for additional purposes, including structural assessment, thermal analysis, and technical information.

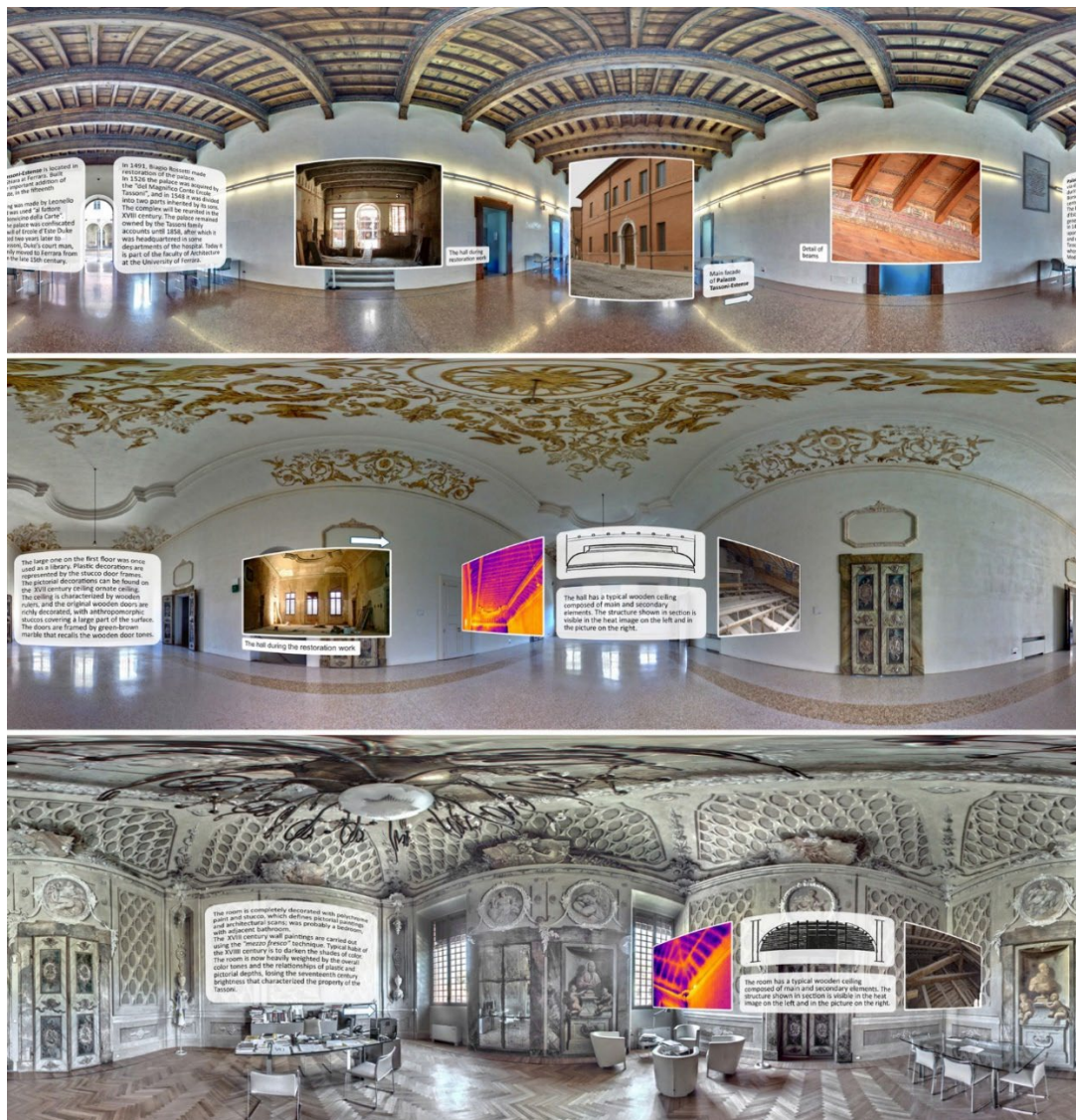
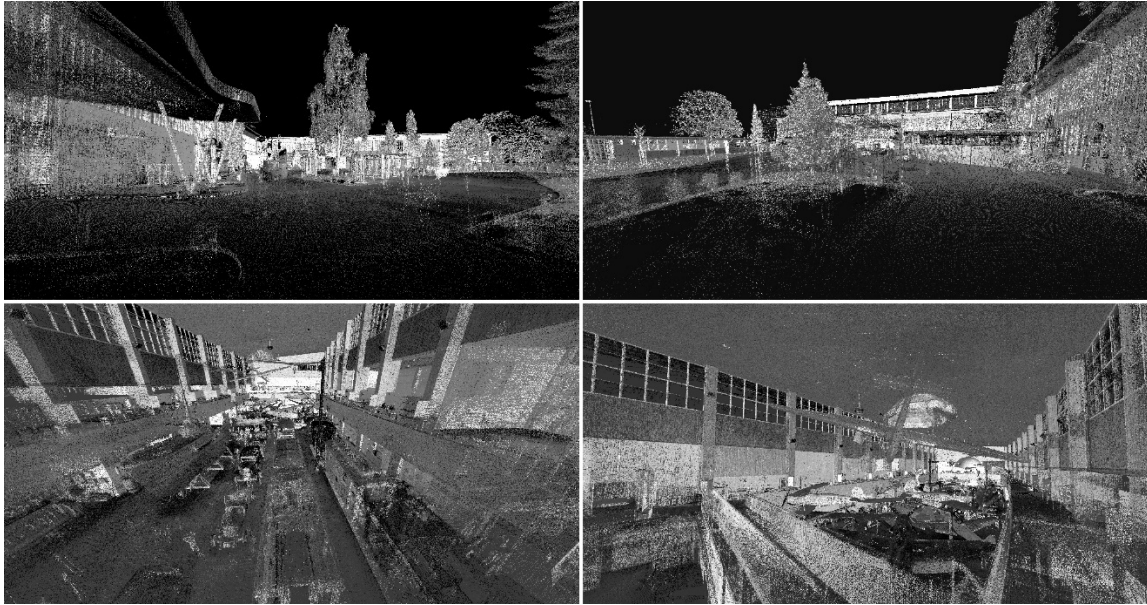


Figure 2. For the Tassoni-Estense Palace, an interactive tour has been realized, mainly using raster images in order to be easily used on-the-go by web browsing and All-in-one HMD. The source data are 36 of the 123 spherical images captured during the survey campaign buildings

Another building on which experiments and applications were performed is the Technical Museum Nikola Tesla in Zagreb. The museum includes a relevant scientific and educational center in the field of technical sciences. The entire structure was designed and realized 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 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 current significance.



*Figure 3. Point clouds of exteriors and interiors of the Technical Museum Nikola Tesla in Zagreb, obtained by 3D laser scanner survey as the basis for the development of the H-BIM model*

The architectural H-BIM modelling of the Museum (Fig. 3) and its supporting structure was carried out using Autodesk Revit 2018 software. The model was developed organizing the available 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) [29]. 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.). The two- and three-dimensional contents are directly and dynamically taken from the INCEPTION platform and usable also on the 360° images.



Figure 4. The historical and technical documentation attached to the H-BIM architectural and structural model of the Tesla Museum through the INCEPTION platform

An additional demonstration case focused on the application of Virtual tools for technical uses, is the Saint Nicholas Chapel (Oberghum, the Netherlands), developed to test the site management use validation of a cultural heritage asset by introducing the tools for maintenance purposes within the INCEPTION platform (Fig. 5).

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.

In 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 of BIM requirements have been defined specifically for the Saint Nicholas Chapel demonstration case.



Figure 5. 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

The application related to this experimentation is the Asset Management tool (DEMO RE Suite) developed by the INCEPTION partner DEMO (fig. 6): 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 foresees 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. 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 [30].

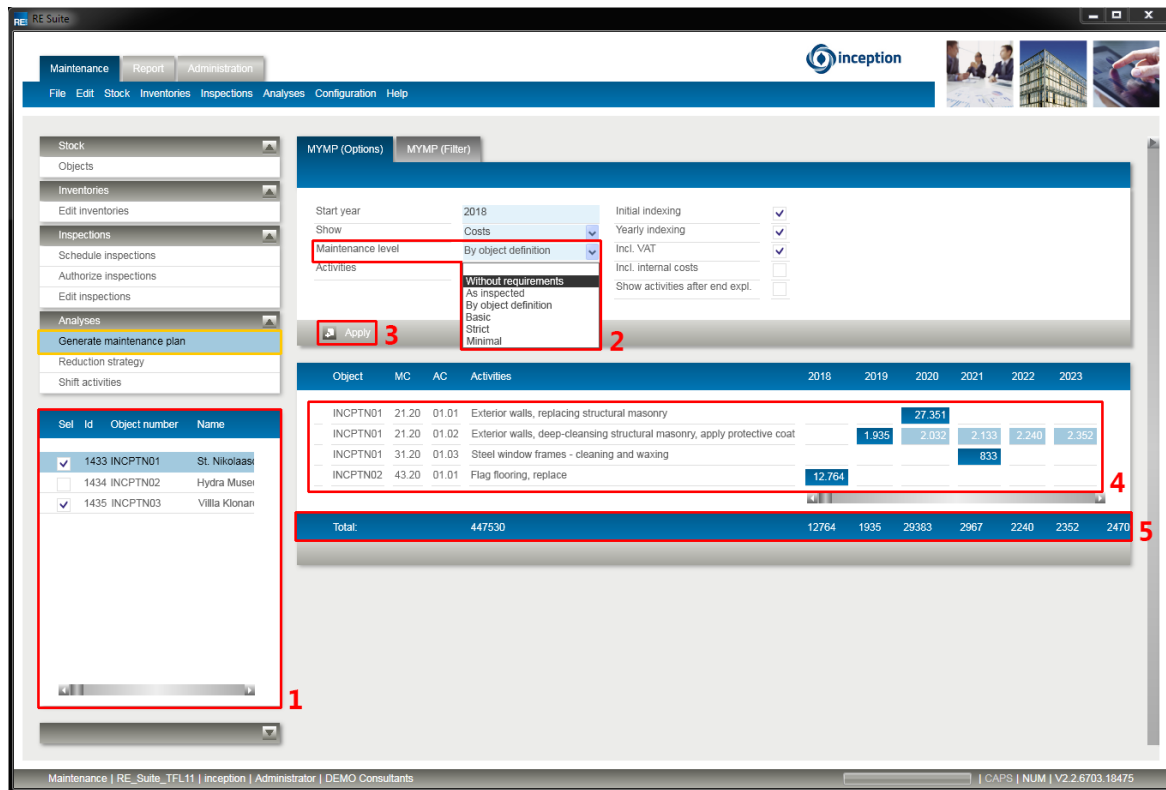


Figure 6. View of some functionalities of the assessment Asset Management tool (DEMO RE Suite) used for on-site condition assessment during the INCEPTION project development

## 5. RESULTS AND DISCUSSION

The presented research and experimentations are just a part of the activities developed by INCEPTION in the field of digitization and assessment of heritage buildings. Innovation, sustainability, and preservation are today strongly related to the possibility of relying on digital reconstructions with a level of accuracy proportionate to the modelling purposes, and of being able to handle large amounts of data, which must be analyzed in an integrated manner, each historic building being unique, and thus having to make case-by-case choices when proposing regeneration strategies.

The case studies presented are only part of the application tests developed within INCEPTION, and refer in particular to the knowledge and management needs of technical stakeholders, providing decision-making tools for restoration, conservation and maintenance of historic buildings by collecting, structuring, analyzing and disclosing data related to the buildings and their surroundings.

The use of 3D semantic BIM should indeed be facilitated and more widespread among professionals in charge of heritage conservation, supporting on-site technical assessment and remote analysis to determine, and enhancing the understanding of refurbishment interventions, in a predictive way, assessing technical risks, monument protection regulations, cost management, and socio-functional building performance [31].

The INCEPTION platform, based on the Inception Core Engine (ICE), allows a semantic approach, for easily exploring BIM and HBIM models and the web and accessing other contents. ICE interprets each element of a 3D model as a single entity that can be connected to a specific knowledge, transforming all the geometries of a 3D model of a monument or a site into semantic triples that connect one element to another using specific predicates, defined in a dedicated semantic ontology. The 3D models have to be provided in the form of a Building Information

Model (BIM) as an IFC (Industry Foundation Classes) standard file. Once the models and related information are transformed into triples, all of these are stored in a semantic triple store that is accessed via HTTP through a dedicated Apache Fuseki SPARQL server. ICE technologies can power web applications that allow users to enrich their models with new semantic metadata. Indeed, the web client allows to enrich the models with new data and attachments (e.g., pictures, thermographic images, 3D models of specific details, videos, etc.), all related to the model or a specific geometrical element.

Similarly, the Core Engine allows not only enriching the model but also easily navigating it together with semantic metadata and attachments. Three different modes are natively included in the ICE: IFC, texture and hybrid views. The IFC view mode allows to select geometric elements, filter them by levels or classifications and query their metadata, while the texture mode does not present selectable elements but offers a visualization capable of offering an intuitive material understanding. The hybrid mode superimposes the previous ones by means of an editable transparency layer and allows you to select IFC geometric elements enriched this time by their real appearance. It is also possible, for each element, to access its metadata [32].

## 6. CONCLUSION

The outlined research framework and activities highlight the increasing relevance of digital tools for heritage documentation and restorations, and the need to increase applications able to support sustainable practices.

Starting from the main outcomes of the INCEPTION projects, new research directions have been furtherly explored by the Horizon 2020 project “4CH – Competence Centre for the Conservation of Cultural Heritage” [33], applied and funded under the Work Programme Europe in a changing world – inclusive, innovative and reflective Societies (Call - Socioeconomic and Cultural Transformations in the Context of the Fourth Industrial Revolution - H2020-SC6-Transformations-2018-2019-2020), and completed at the end of 2023. The application developed under 4CH addressed the requirement by the European Commission to set up a European Competence Centre aiming at the preservation and conservation of European Cultural Heritage using new state-of-the-art ICT technologies. Concerning Heritage 3D models, 4CH further develops the main outcome of INCEPTION for documenting, monitoring and visualizing 3D BIM models of the built heritage, by applying advantages of 3D and Semantic Web technologies, fostering data connections and knowledge sharing and accessibility.

Also within this project, the Inception Core Engine allowed the exploration of HBIM modeling enriched with semantic data to connect tangible and intangible information, opening to interoperability with other resources. Future research direction will be driven by the development of the European Competence Centre, towards new abilities to acquire knowledge and interact with Cultural Heritage, merging digital evolutions and sustainability.

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