HBIM tool for preventive conservation of sensitive cultural heritage in museums: the SensMat approach

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Abstract

Technologies as IoT, sensors, data processing and BIM have changed the way we interact with the building's environment. A significant challenge is represented by the design of a unique open platform able to deal with different information sources and integrated BIM projects. In this framework the H2020 SensMat project aims to develop sensors, models and decision-making tools dedicated to monitoring the environmental conditions of buildings preventing the degradation of artefacts. The HBIM Layer represents the project workspace which integrates the museums BIM model with the information of the real-time monitored 3D objects as sensors and artefacts. Users can interact with different innovative management tools which could inform in real-time of possible vulnerabilities to the buildings and the monitored artefacts. The approach used in the project can be considered an example of how the integration of different technologies can represent a potential and innovative tool in the facility management industry.

Keywords: Heritage Building Information Modelling (HBIM), Internet of Things (IoT), Preventive Conservation (PC), Cultural Heritage (CH), Big Data, Digital Twin.

1 Introduction

The way we interact with the building environment radically changed thanks to significant developments technologies such as Internet of Things (IoT), wireless sensors, data processing/analysis and Building Information Modelling (BIM). Thanks to their flexibility and usability the use of sensors in ordinary buildings has become very popular ranging in several applications, as for example monitoring energy efficiency and thermal performance, hygrothermal properties of walls, air quality, heating controls. In this context, cultural heritage buildings take place with their critical needs regarding the preservation of artefacts and the environments where they are located. Indeed, one of the most critical aspect for a museum is represented by the monitoring state of health of its rooms and areas, which constantly may be exposed to climate changes or modifications of the level of pollutants that affects the building's health as well as the preservation of their cultural artefacts. As for sensors and IoT, the last decade has witnessed a great technological advancement in the three-dimensional and informative representation of buildings. At this regard BIM platforms represent an established tool to connect engineering, construction, architectural and management actors involved into a project. However, BIM and IoT integration represent a challenging open research issue, still far from being solved. Research is still moving first conceptual steps trying to overcome some inner obstacles represented by different architectures (as file formats and close systems which often are not openly usable) or different purposes for which originally the single approaches have been developed. BIM is a methodology used by experts and its information hardly reaches the individual users of the building; on the contrary, people or systems that use devices connected to the Internet constantly receive or exchange information about the surrounding environment. Trying to develop a unified interface is consequently a big challenge and the possibility to design and build a unique open platform able to deal with the different information sources, as data deriving from wireless monitoring sensors integrated with building automation systems and BIM models, is definitely an attractive perspective. One of the current frontiers of study is the application of BIM to the historical built heritage. In this case it is often referred more specifically to HBIM (acronym for Heritage Building Information Modelling), as a process applied to existing buildings (monumental or not) which significantly increases the potential of the BIM method, extending its use to the creation of models not only considered as digital representations of their geometry, but as dynamics models enriched by different levels of information and intelligent and parametric objects. A significant example of research in this direction could be considered the HBIM Layer Platform, developed in the SensMat (Preventive solutions for Sensitive Materials of Cultural Heritage) project, funded from the European Union's Horizon 2020 research and innovation program, which represents a workspace where user can interact with a three-dimensional BIM model intimately coupled with a series of information related to the different 3D objects including real-time monitoring sensors and artefacts. At this regard, it is important to underline how the approach presented in this work is coherent with the pioneering application of Digital Twin for the preventive conservation of cultural heritage. The paper aims to focus the attention on the key functionalities of the HBIM Layer, which could be in the future enriched with specific algorithms and data analysis tools in order to obtain a fully simulation of a Heritage Digital Twin.

2 State of the art

The adoption of the Internet of Things (IoT) technology constitutes a significant step towards unified ICT Platforms for a variety of applications with the purpose to facilitate the integration between the digital and real dimension in an environment which is becoming increasingly smart. However, designing a general architecture for IoT is still a very complex challenge since such systems are characterized by the presence of several devices, technologies and services. In this framework, cultural spaces represent a promising application of such technologies, being IoT able to offer to visitors a totally new fruition and, at the same time, to collect different environmental information in order to monitor and preserve the environment itself (Chianese & Piccialli, 2014). Different examples of design and application of such services and technologies applied to Cultural Heritage environments could be found in literature. In (Manfriani et al 2021) authors introduced

a remote monitoring and decision system in Palazzo Doria-Tursi Museum, in the Paganini Hall, in order to monitor the conservation conditions of the so-called "Cannone" and "Sivori" violins. The system allows the monitoring and characterization of the environmental fluctuations inside the exposition room and the effect of passive control with silica gel cassettes inside the conservation/display cases. Furthermore, the definition of the safe bands (SBs) helped to introduce alarm logics with immediate feedback to the conservators. In (Mora et al 2021) authors presents an HBIM (Historic Building Information Modelling) approach for the preventive conservation of one of the most representative Spanish heritage places that is The General Historical Library of the University of Salamanca. The methodology exploits the latest advances in inspection protocols, digitalization tools as well as wireless monitoring networks. All these information are integrated in the HBIM environment by using ad-hoc families and interoperable communication protocols that allow obtaining a complete knowledge of the conservation status of the site. Additionally, the approach uses KPI (key performance indicators) in order to evaluate the environmental conditions of the different assets presented in the site. In (Chianese et al 2013) authors proposed a prototypal framework architecture offering an integrated approach to cover multiple issues represented by enriching the collection of available information about artworks, structuring heterogeneous information in a unified model, stimulating visitors proposing innovative ways to enjoy cultural goods. An interesting project is the one presented in (Amato et al 2013), which exploits the Internet of Things technologies in order to make objects of a museum exhibition able to "talk" during users' visit and capable of automatically telling their story using multimedia facilities. A particular Wireless Sensor Network, using Bluetooth technology, is able to sense the surrounding area for detecting user devices' presence. Once a device has been detected a multimedia story of the closest museum objects is delivered to the related user. Another challenging theme associated to IoT technology is the preventive conservation of Cultural Heritage. The conservation of artefacts in museums is an issue of particular interest because every artwork undergoes certain deterioration with time. Such degradation depends on the type of material and it is caused by the combined effects of different parameters such as temperature, light, relative humidity, pollutants and human factors. In this framework the use of IoT allows remote monitoring and management of data collected from sensors making it possible to control the environment of the collections trying to minimize the deteriorations of artefacts. For example, in (Perles et al 2018) authors present an IoT architecture specific for Heritage Preservation needs. In particular, authors designed a solution to produce the minimum impact in the artwork, achieving a lifespan of more than 10 years. In (Alsuhly & Khattab, 2018) authors develop an IoT based system for museum indoor ambience monitoring and control. In the proposed system, the information about the artefacts' environment and their safety conditions are collected in real time and sent to a gateway where are pre-processed and aggregated before being relayed to a cloud where they are stored and analysed. According to the results of the analysis proper decisions are sent automatically to the actuators in order to set the best museum ambiance conditions or in the worst case to fire alarms. A manual actuator remote control is also available to the museum managers through a web- based interface. In (De Brito et al 2008) authors tested an experimental Wireless Sensors Network for the automatically and continuously monitoring of the museum environment, identifying the recurring problems and compared this system with related solutions. An interesting overview about the sensors used for the environmental monitoring in museums is provided in (Bacci et al 2008), in which authors highlighted the importance of innovative tools such as early-warning systems, passive sensors, dosimeters, and dedicated devices that can help in risk assessment and in the prevention of environmental damage. Authors also pointed out how these tools are required to complement the conventional methods for environmental monitoring, since in some case they are designed to detect effects which cannot be measured by standard instrumentation as for example degradation phenomena induced by the action of many environmental factors.
At the same time, a very current research topic is the one concerning the development of Digital Twin for the preventive conservation and management of cultural heritage, leading to combine the world of HBIM with that of IoT technologies. The general definition of the Digital Twin was given by (Glaessgen & Stargel, 2012), defined as an integrated multiphysics, multiscale,

probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, history, etc., to mirror the life of its corresponding twin. Recently (Hou et al 2021) conduct a literature review to investigate theoretical and practical links between applications of digital twin and heritage facilities management. The results show that the numbers of studies on digital twin application in the disciplines of architecture, engineering, construction and operation is rapidly growing. Indeed, the heritage facility management industry needs digital solutions to deal with problems related to performance monitoring and predictive maintenance, which could be actually supported using Digital Twins. (Angjeliu et al 2020) proposed a strategy for the development of the simulation model for Digital Twin applications in historical masonry buildings, using as case study the Cathedral of Milan, showing the possibility of developing numerous operations related to assessment and maintenance. The contribute of (Rasheed et al 2020) highlights the important role of the Digital Twins not only to provide real-time information for monitoring and decision-making but also for a predictive maintenance based on simulation of the future performances of the structure. All these values point out the great potential of application of Digital Twins in built heritage management, energy evaluation and preventive conservation strategies.

3 The SensMat project and the HBIM Layer Platform

The SensMat project (Preventive solutions for Sensitive Materials of Cultural Heritage) is founded from the European Union's Horizon 2020 research and innovation program and, as shown in Figure 1, aims to develop and implement effective, low cost, eco-innovative and user-friendly sensors, models and decision-making tools, as well as recommendations and guidelines to enable prediction and prevention of degradation of artefacts as a function of environmental conditions. The consortium consists of 17 main partners, including universities, research institutes, software engineering and management companies, museums as well as curators, scientists and conservators. As stated in the previous paragraphs, preventive conservation (PC) emerged as an important approach for the long-term preservation of sensitive cultural heritage (CH), notably for mobile artefacts, those displayed or stored in harsh environments and for small and medium-sized museums.

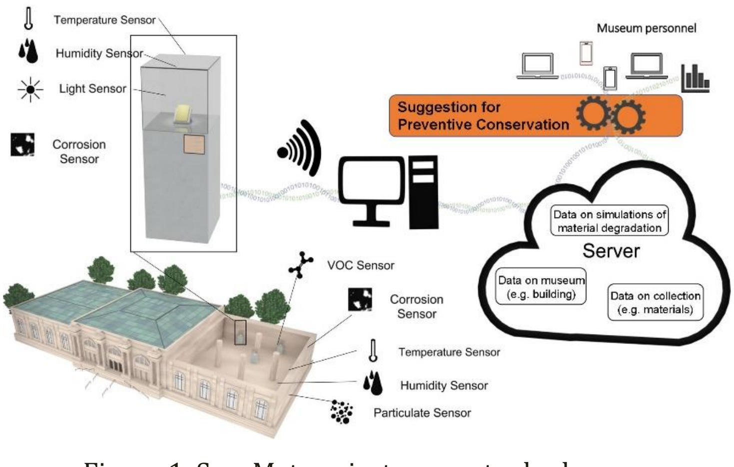

Figure 1. SensMat project conceptual scheme

The project involves demonstration of the developed platform in 10 case studies summarized in Figure 2 and represented by real small and medium building located in different EU countries, as museums, historical buildings, storage sites and workshops. Based on multiscale modelling, data management systems, collaborative platforms and sensor communication networks (IoT), museums stakeholders will be informed in real-time of possible dangers to their artefacts, thus reducing degradation risks and costly conservation treatment. At this regard, some of the project programs focus on the development and installation within each case study of a specific network of innovative sensors, grouped within nodes with the aim of measuring a series of parameters useful for the accurate monitoring of museum rooms. i.e. temperature, RH, visible and UV-A light, vibration, VOC.

Figure 2. SensMat project case studies

In this context the HBIM Layer Platform could be considered an innovative workspace where the structural and architectonical elements described by the three-dimensional representation of the buildings are combined with the different information included in the 3D or 2D objects characterizing the corresponding BIM model. At this regard, the designers included specific elements within the BIM model representing the real sensors and artefacts present in the museum and with which user can easily interact in order to find different types of information such as graphs of the measured parameters, KPI (key performance indicator), heatmap of the room and/or of the floorplan or simply data of the selected object (description, serial number, position in the museum, etc.). The interface of the platform is very intuitive: user can freely navigate the three-dimensional model of the museum, using the classic functions of a CAD model (rotation, shift, zoom, etc.) or alternatively he can use a tree-structure menu which allows the navigation of the model exploring the different levels of the building, the rooms of each floor and the several sensors and artifacts, choosing between a series of operations designed to access different levels of information.

Table 1. Some of the main features of the HBIM Layer Platform

Feature	Description
2D/3D Navigation	Display and navigation of the museum with common CAD aids tools (pan/rotate/zoom)
Model Browser	Possibility to browse the BIM model, navigating all its environments
Edit model #1	Possibility to edit existing museum spaces (add rooms, partitions, etc.)
Edit model #2	Possibility to add info, 2D/3D object, 2D picture and 3D spherical pictures

Create new sensor	Possibility to create new sensors specifying all related info
Create new artefact	Possibility to create new artefact specifying all related info
Display Graphs and Heatmaps	Possibility to access and display graph of real-time monitored parameters and/or floorplan/room real-time heatmaps
KPIs	Possibility to access, create and customize KPIs

4 Methods and data workflow

One of the principal innovative aspect which characterize the HBIM Layer Platform is its architecture which allows a full integration of BIM and IoT in a cloud-based environment. Figure 3 reports a schematic data workflow which simply explains how the architecture of the software has been designed. The several nodes with their sensors represent the IoT technologies placed in the museum, that constantly monitor the environments in which they are installed and where the artefacts are positioned. All the data coming from the node are transferred via Wi-Fi, Ethernet or GPRS to the web cloud services where the SensMat database is located. From this repository, by means of specific APIs developed in FORGE from Autodesk®, the information is then available in the HBIM Layer Platform, specifically in the BIM model of the building created using Revit from Autodesk® and previously uploaded.

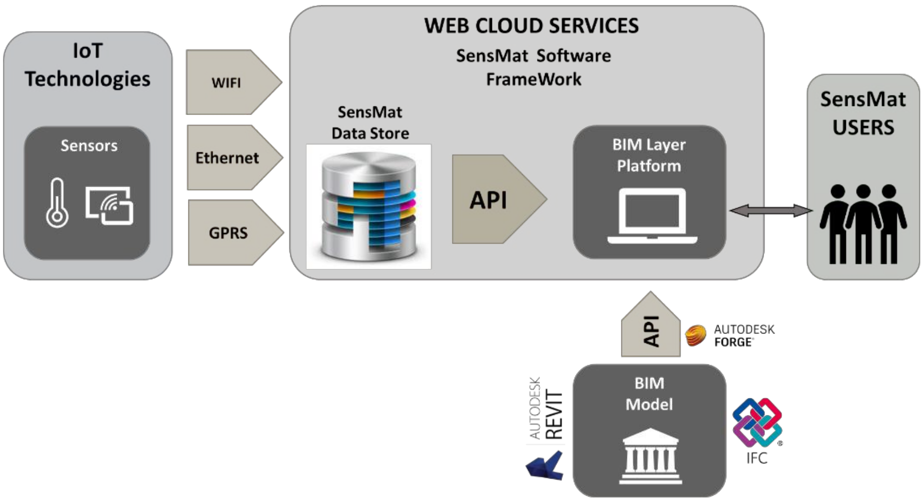

Figure 3. SensMat data workflow

The main goal for software designer has been the integration of data coming from the real world into a digital representation. At this regard, at sensors level, the information received directly from the field are then represented following a standard, named OGC SensorThings API, which provides an open, geospatial-enabled and unified way to interconnect the Internet of Things (IoT) devices, data, and applications over the Web. The following entities are defined:

- *Thing*: an object of the physical world (or an information) that is capable of being identified and integrated into communication networks;
- *Observation*: An observation matches is a data object.
- *Datastream*: this entity groups a collection of Observations measuring the same property and produced by the same sensor.
- *MultiDatastream*: it is an extension of Datastreams to handle complex observations when the result is an array. A MultiDatastream groups a collection of Observations and the Observations in a MultiDatastream have a complex result type.

For the purpose of SensMat project, every node is mapped with a *Thing*, *Datastreams* are used to store the nodes logs and the *MultiDatastreams* to store the devices data. At the BIM level, FORGE from Autodesk® has been used to graphically represent the case study model, in particular, including all its levels, floors, rooms and artefacts. An additional entity called *Node* was introduced, being the graphical representation of the node and which could be associated to multiple artefacts. The relation between *Thing* and *Node*, thanks to a common nomenclature, allows to integrate the physical world with the digital one, showing real data on the model representation. *Nodes* can be also associated to artefacts, allowing to gain a near real-time monitoring of the artefact environment.

5 Case study: the Styrian Armoury of Universalmuseum Joanneum

The Styrian Armoury belongs to the 21 departments and institutions of the Universalmuseum Joanneum, located in Graz (Austria). Today the Styrian Armoury contains 32, 000 objects from the 15th to the 18th centuries: armour, firearms and cannons, staff and edged weapons, bullet moulds and powder flasks stored on four floors with more than 2000 square metres of exhibition space. The collection is divided into different categories: (i) fire arms and accessories which is the most comprehensive in the armoury including 3,867 guns and 4,259 pistols and various types of accessories, (ii) artillery and accessories with 704 exhibits including wall guns, mortars, cannons, falconets, (iii) the edged weapons which contains around 2,414 items, (iv) the staff weapons with 5.395 items as halberds and pikes, fewer boar spears, couses, tardes, morning stars and glaives, (v) the collection of protective arms, shown in Figure 4, providing a clear picture of how soldiers protected themselves in wartime including around 3,844 items as helmets, armoured sleeves, shields and suits of armour.

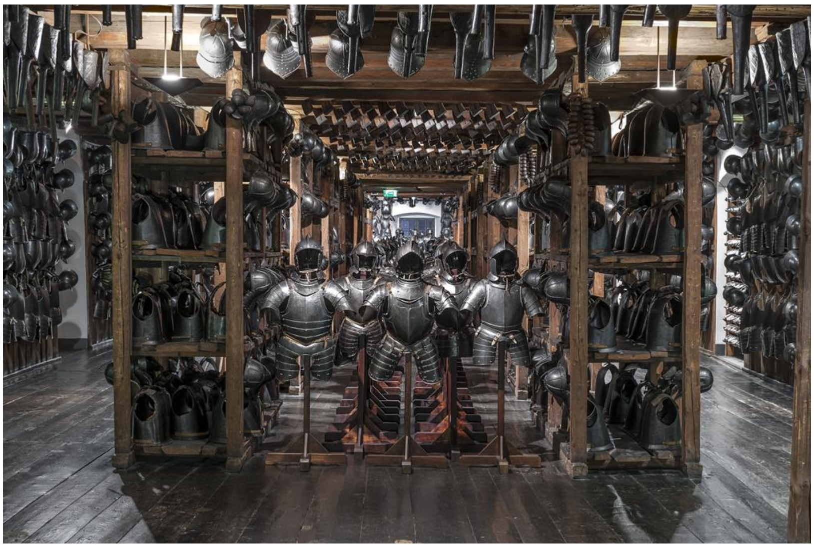

Figure 4. Some artefacts of the collection of protective arms

The first step of the research has been the definition of the geometry of the museum according to the different floorplans provided by the curator. The BIM model of the Armoury has been implemented in Revit from Autodesk® and, as shown in Figure 5, imported in the HBIM Layer Platform using its open-format Industry Foundation Classes (IFC).

The modelling of the several floors of the whole museum could be observed in Figure 6, which shows the North-West longitudinal section of the building. It can be observed how the different structural elements of the building have been modelled, both vertical (perimeter walls and internal partitions, columns) than horizontal ones (floor slab and pitched roof). In addition, the model has been also completed with various secondary elements such as windows, doors and a series of furniture complementary to the proper representation of the real building.

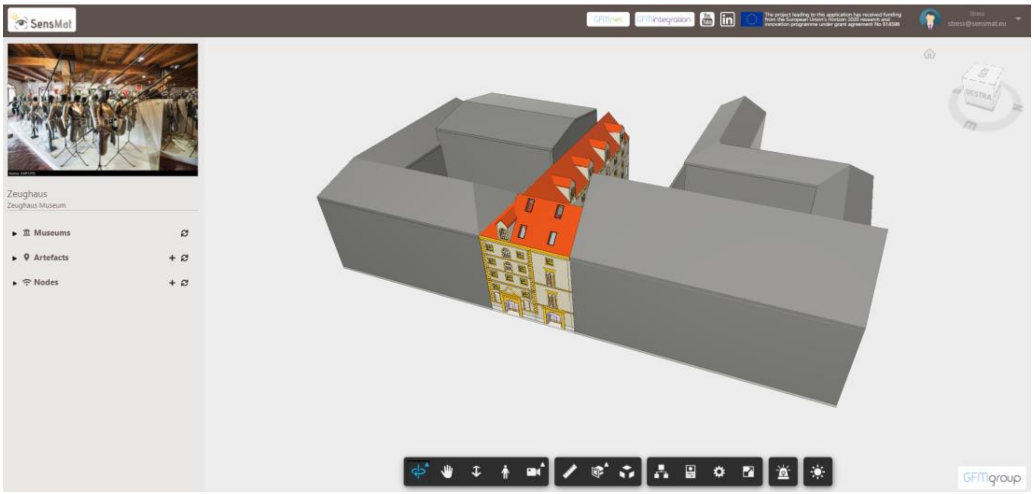

Figure 5. Main interface of the HBIM Layer platform: The Styrian Armoury

Figure 6. HBIM model of the museum, North-West longitudinal sections of the building

Finally, the BIM model was enriched by the presence of accurate 3D objects representing some of the monitored artefacts and the real sensors located in the museum. Regarding the latter, every physical box - called node - has been exactly reproduced in the model considering their geometrical dimension and the different sensors contained inside. The museum is actually characterized by the presence of four nodes, each of them positioned in a different position. Table 2 gives some details about their ID, position and the monitored parameters. For instance, Figure 7 shows a detail of the real node *SMUSEUM10* positioned at the fourth floor.

Table 2. Details of the nodes actually positioned in the museum.

Node ID	Position	Monitored parameters
SMUSEUM4	First floor	Temperature, vibration, light and VOC
SMUSEUM5	Second floor	Temperature, vibration, light and VOC
SMUSEUM6	Third floor	Temperature, vibration, light and VOC
SMUSEUM10	Fourth floor	Temperature, vibration, light and VOC

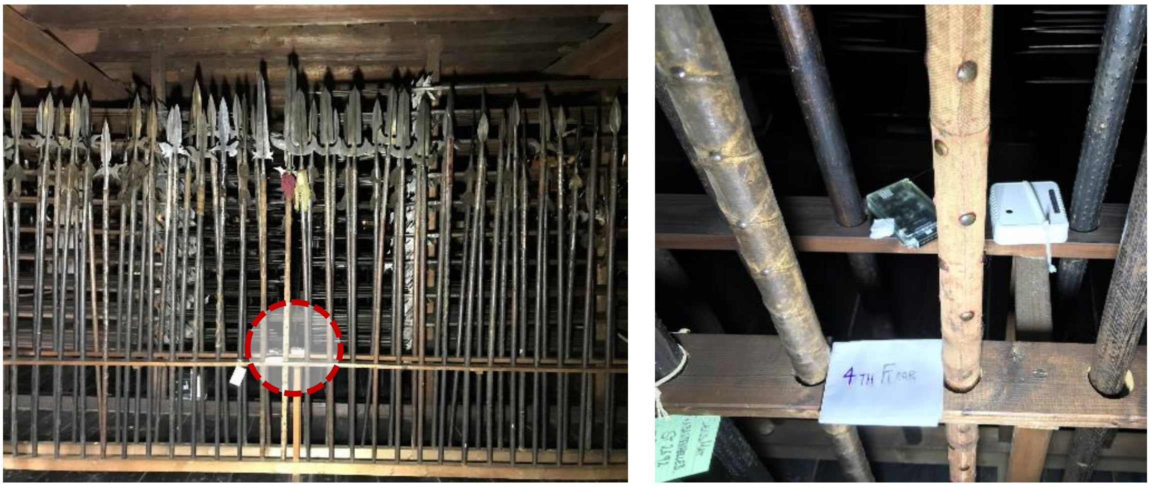

Figure 7. Example of monitoring sensor located at fourth floor.

In order to better organize all the information about the sensors actually present in the museum and at same time to provide a standardized database for future installations, a specific BIM Library for sensors has also been developed. The database contains a series of data collected from sensors including: (i) identity data (model, manufacturer, geometrical dimension, product documentation, etc.), (ii) technical data (measurement range, accuracy, sensitivity, etc.), (iii) electrical data (power supply, voltage), (iv) sensor and node pictures. This information is directly linked to the specific 3D object in Revit so that user can easily access them on the HBIM Layer Platform, where the whole BIM model is uploaded, for their needs of maintenance or management purposes.

Figure 8 illustrates an example of a node modelled using Revit showing some of its properties while Figure 9 shows the corresponding object in the HBIM Layer Platform as seen by a user.

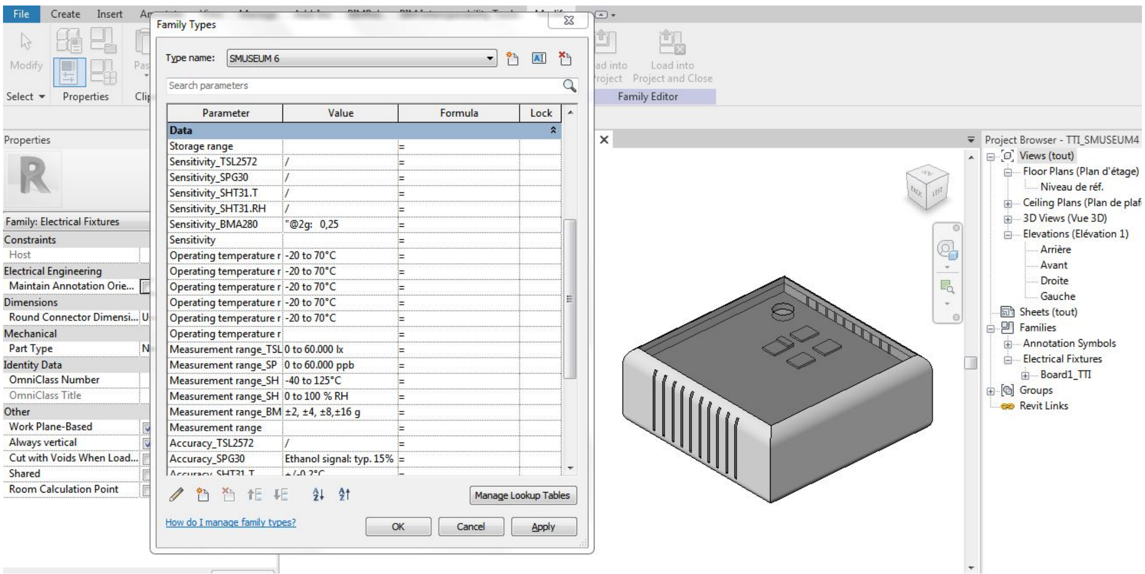

Figure 8. Modeling of the node *SMUSEUM* typology in Revit and some of the properties associated to the 3D object.

Figure 9. Detail of the *SMUSEUM* sensor typology in the HBIM Layer platform and some of the properties associated to the 3D object.

Figure 10 and Figure 11 show a comparison of the real environments of first and second floor of the museum, with their artefacts and sensors, and the corresponding HBIM model representation. The position of the node is highlighted using the dashed red circle.

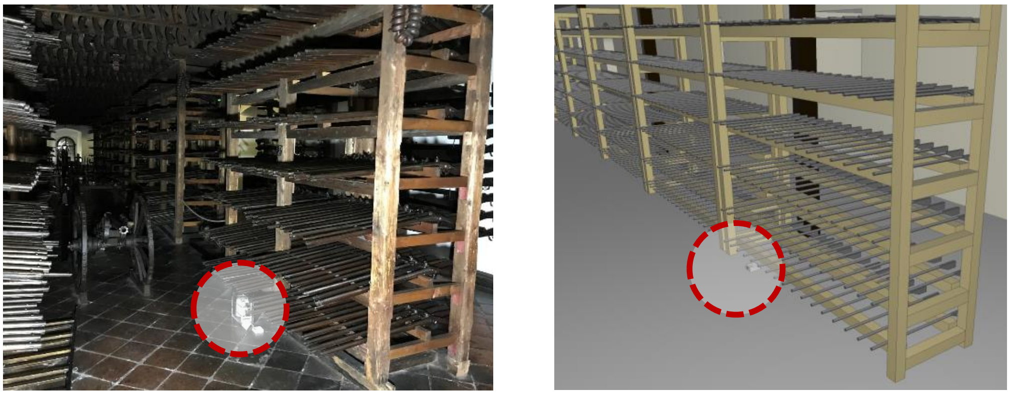

Figure 10. Comparison of museum first floor: real monitored room vs HBIM model

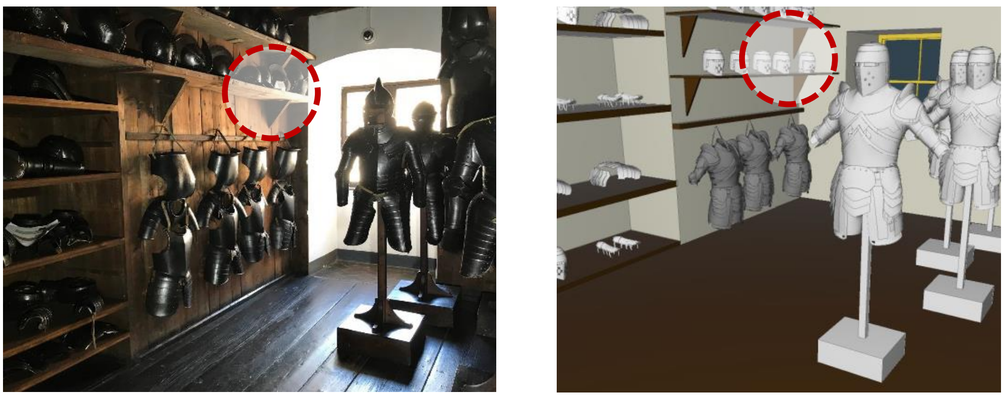

Figure 11. Comparison of museum second floor: real monitored room vs HBIM model

Figure 12 shows an example of a graph that user can visualize by selecting the corresponding sensor functionality from the tree menu. In general, graphs can be set according to the chosen parameter and the monitoring period that can be selected from the associated calendar. In this specific case, the graph shows the real-time variation of the temperature measured by the sensor *SMUSEUM10*, located at the fourth floor, in a period of 2 weeks.

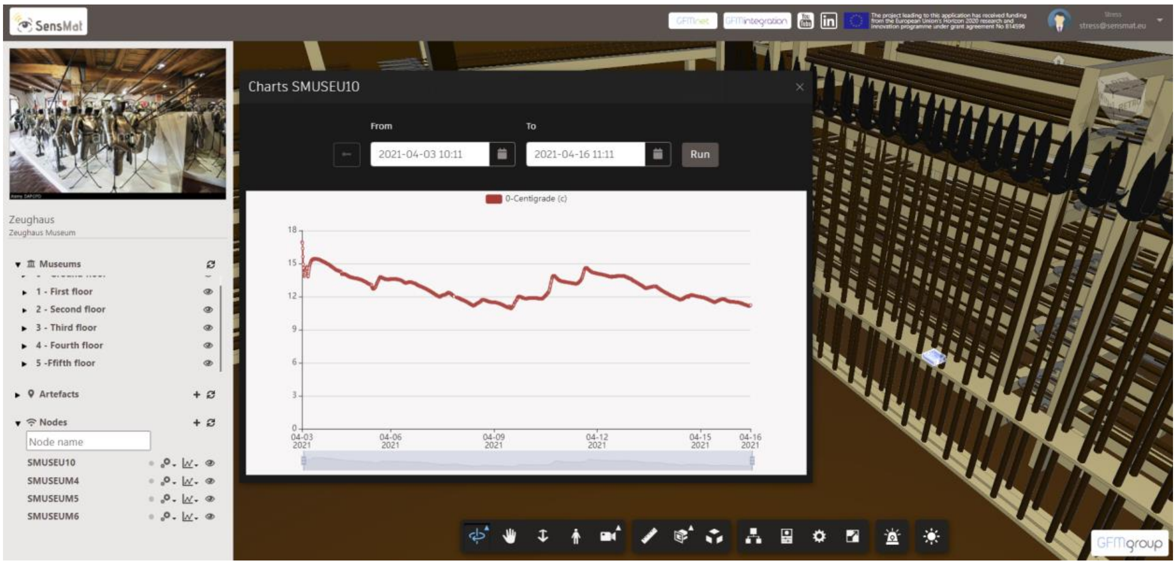

Figure 12. Node *SMUSEUM10*: graph of the monitored temperature at fourth floor

Finally, Figure 13 presents another interesting functionality of the platform that is the possibility for user to visualise, selecting the appropriate function from the tree menu, the entire heatmap of a specific floorplan. In that case, the heatmap of third floor is shown. This feature is very important as it allows the user to globally display the temperature of an entire floor in order to facilitate the identification of any critical issues. Furthermore, if necessary, the same function can be applied to individual rooms of the building if, for example, the curator is only interested in displaying the temperature of a single portion of the museum rather than the entire floor.

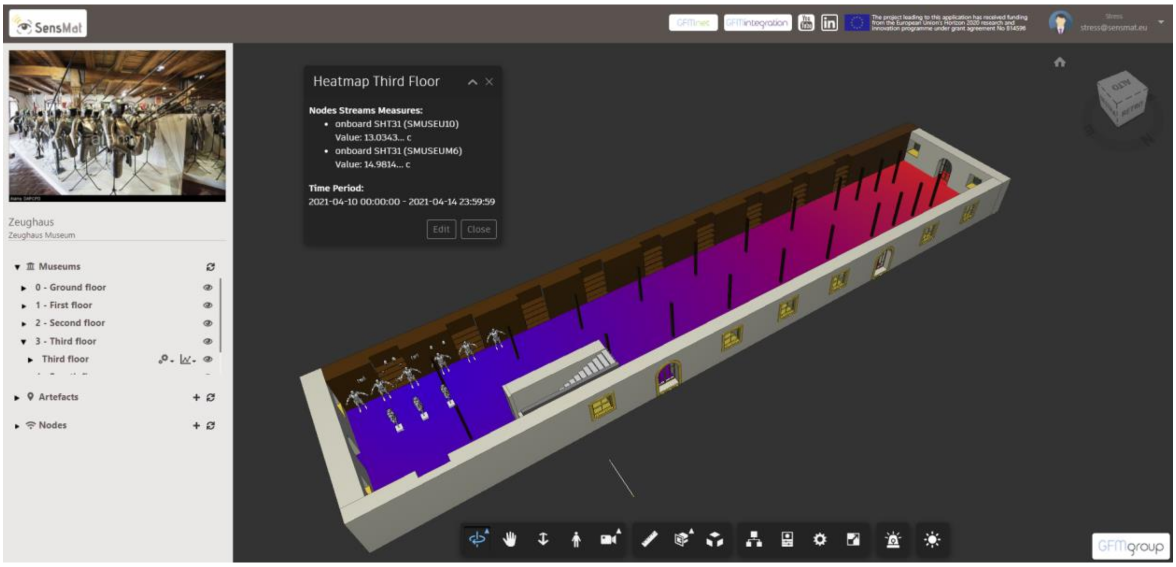

Figure 13. Example of floorplan heatmap of the museum third floor

6 Conclusion

This paper presents the results of a work carried out to develop an innovative platform, called HBIM Layer, specifically designed to integrate the established methodology of Building Information Modelling (BIM) with the great advancement in the use of Internet of Things (IoT) witnessed in the last decades. As well known in literature, BIM represents a modern tool to connect all the actors involved into a project, on the other hands the use of low-cost sensors has become very popular, allowing research and applications in a wide range of disciplines. However, the integration of these two different, but complementary, worlds represent nowadays a challenging open research issue. Recent years have been characterized by a growing interest in the application of BIM methodology for the management of the information needed for maintenance and assessment of historical buildings and museums. One of the main differences between ordinary buildings and museums is the relationship between the buildings and artworks contained inside, which represents a specific element of research. Indeed, cultural heritage buildings are characterized by special needs regarding the preservation of its artefacts and the environments where they are located. One of the most critical aspect for a museum is represented by the monitoring state of health of its rooms and areas, which constantly may be exposed to climate changes or modifications of the level of pollutants that affects the building's health as well as the preservation of their cultural artefacts. It could be affirmed that nowadays preventive conservation emerged as an important approach for the long-term preservation of sensitive cultural heritage and the artefacts contained into historical buildings as museums. At this regard, the HBIM Layer Platform could be also considered one of the first example of integration of an Historical Building Information Modelling (HBIM) with all the real-time information deriving by sensors and IoT technologies.

Moreover, a current research topic is the one concerning the development of Digital Twin models for the preventive conservation and management of cultural heritage, which lead to combine the potentiality of HBIM with IoT technologies, in order to obtain a virtual twin of the real monitored structure. The main advantages of this approach are connected to the possibility, thanks to the large amount of data available, to carry out a series on innovative operations related to assessment and maintenance of the structures, including simulations of their performances considering different real or theoretical scenarios. All these values point out the great potential of application of Digital Twins in built heritage management and preventive conservation strategies.

The HBIM Layer has been developed in the SensMat (Preventive solutions for Sensitive Materials of Cultural Heritage) project, funded from the European Union's Horizon 2020 research and innovation program. The project, with participation of more than 17 main partners, aims to develop and implement effective, low cost, eco-innovative and user-friendly sensors, models and decision-making tools, as well as recommendations and guidelines to enable prediction and prevention of degradation of artefacts as a function of environmental conditions. The platform permits a user-friendly management and monitoring of all the elements of a building, thanks to a navigable HBIM model (created using Revit from Autodesk®) enriched by the presence of 3D object representing the artefact and the sensors located in the museum. The features of the platform have been illustrated using the case study of the Styrian Armoury belonging to the Universalmuseum Joanneum, located in Graz (Austria), which contains about 32, 000 objects from the 15th to the 18th centuries. The HBIM model of the building was created using Revit from Autodesk® and uploaded into the platform, along with a series of 3D objects representing the sensors and artifacts contained in the museum. As shown in the previous paragraphs, user can quickly access to a series of data regarding the real-time monitoring of the several rooms and floors of the museum, as well as a series of information about the status of the different sensors and artefacts. Thanks to the use of intuitive and efficient graphs and heatmaps the curator has the possibility to obtain a chronological overview of the variation of all measured parameters, being thus able to easily identify possible anomalies or critical situations of the whole system. In addition, it is always possible to update the HBIM model, by means its IFC file, to accommodate temporary or permanent changes in exhibition spaces and variations in the elements contained, whether sensors or artifacts.

In conclusion, the present work showed the results obtained in the development of the HBIM Layer platform, a tool which combines the benefits of BIM modeling and real-time monitoring through IoT technologies. In particular, the main features of the workspace have been presented as well as showing how user can navigate the three-dimensional model and access a range of information inherent to the artifacts and data deriving from the sensors.
The future development of the platform will include algorithms and tools, i.e. artificial intelligence or machine learning routines, dedicated to the specific needs to obtain a complete Heritage Digital Twin in order to guarantee a fully innovative experience of management of cultural heritage buildings and their artefacts.

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