IoT and BIM Interoperability: Digital Twins in Museum Collections

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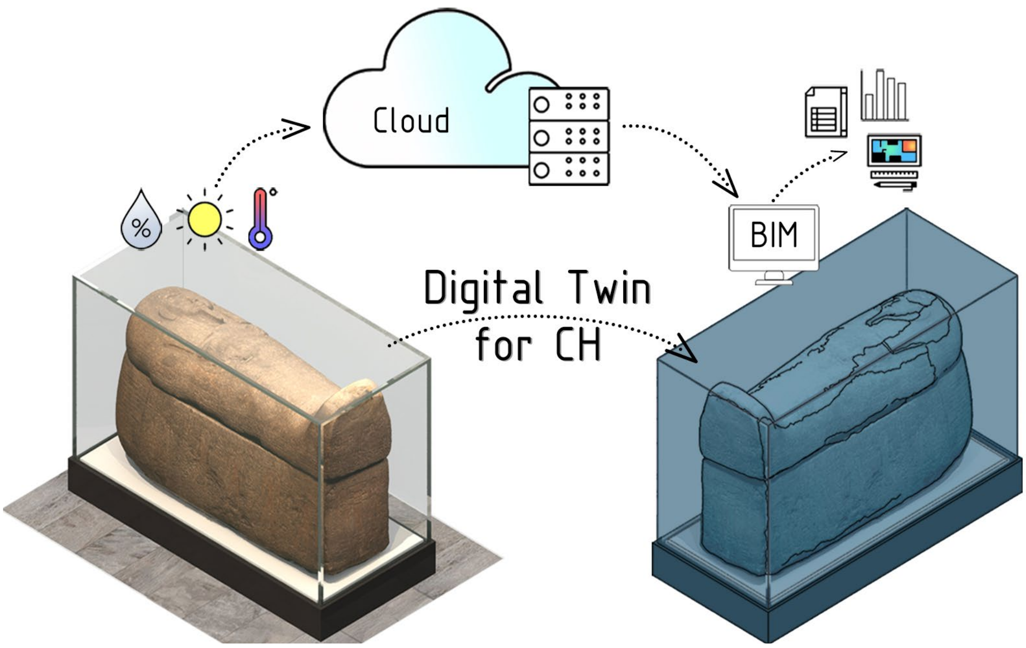
Abstract

According to the 2017 International Council of Museums (ICOM) guidelines, data on museum collections must be stored in a secure environment, supported by backup systems that allow access by all legitimate users, complete and unique identification, and description (associations, provenance, condition, treatment and current location) of each object are required.
Concerning these indications, it is therefore, a priority to establish precise protocols for the preventive conservation and analysis of data concerning not only the identity of the asset or the information collected during its study, but also how it is preserved.
This paper proposes a digital framework for the management of museum structures and collections, integrating Building Information Modelling (BIM) methodologies for the preservation and visualization of data with Internet of Things (IoT) methodologies for its collection and analysis.

Keywords
IoT, BIM, museum collections, interoperability, digital twin.



doi.org/oa-845-c223

Introduction

Museums are very complex bodies that perform various tasks, as summarized in the definition of the International Council of Museums (ICOM): "A museum is a permanent non-profit institution serving society and its development, open to the public, which acquires, preserves, researches, communicates and exhibits the tangible and intangible heritage of humanity and its environment for education, study and enjoyment" [Suay, Peter 2017].

As denoted by the definition, its functions – though varied – are directly related to both the material and the intangible heritage of humanity. Reasoning about material heritage it is easy to understand that over time museum collections will deteriorate. There are different reasons for this deterioration: environmental conditions, vandalism and the natural degeneration of materials. To stop – or at least slow down – the rate of deterioration of artifacts, collections are kept in constantly controlled microclimate where the conditions (of temperature, humidity and light) are appropriate to the material of which the work is composed [Jalpa, Biswajit 2016]. It follows that to prolong the life of museum collections, the monitoring, collection and processing of data regarding the environmental conditions of the museum and individual display cases is among the most important tasks.

In this essay, we propose the definition of a computer architecture structured on different levels that collects, analyzes, classifies and stores environmental information. The system, based on an interdisciplinary relationship, is divided into three different layers, each with its complexities: the first layer is a hardware interface (client) that collects the museum's environmental data and transmits it to the server (cloud or edge); a second server management layer acts as an interface for analyzing the collected data; the last layer, stores locally the processing carried out on the data; this last layer is necessary to provide decision-making tools based on human-readable data to plan more conscious interventions.

A unique feature of the proposed work is the integration of IoT systems and BIM tools through the writing of flexible algorithms in the VPL (Visual Programming Language) environment. The possibility of saving the outputs in a BIM environment facilitates the possibility of linking the information of the building (container) with that of the collections (content) for active management of the museum's issues, improving its enjoyment. The data of the collections are included as BIM objects, the collected information is also included in nested BIM families and both are included in the HBIM model of the museum.

The built prototype can also work in real-time and combines the adaptability of IoT tools with the versatility of BIM tools. The possibility of storing and comparing, through thematic maps, information about exhibition spaces, collections and the museum could optimize the decision-making processes of museum activities, improving security and collection management.

Digital Tools and Environments

IoT – The Internet of Things (IoT) is the discipline that researches how to make objects from our daily lives communicate and coordinate intelligently to provide services, using the network, be it local or Internet. Using sensors and actuators as interfaces to the real world, IoT enables the remote monitoring and management of objects and their environment, providing them with digital interfaces, making them 'smart' and part of our lives. As through the digitisation of every step of the production processes now Industry 4.0 can predict errors in the production processes or possible malfunctions, today we see examples where similar monitoring and prevention processes also take place in the AEC sector. This constant monitoring can be exploited to manage the museum environment and thus improve the conservation and security of cultural heritage or its usability. The use of sensors connected to IoT gateways in monitoring the museum environment has many advantages over traditional monitoring: low cost, low visual impact, low energy consumption, high accessibility, no invasive hardware infrastructure, easy deployment of sensor nodes and the ability to continuously monitor and control the environment.

Machine Learning – One of the main objectives of Machine Learning (ML) is to train a machine to detect patterns in structured data and, consequently, to assess its quality and whether it should be trusted. The data to be analyzed, in this use case, comes from the readings produced by the different edge nodes' sensors. To date, numerous algorithms are available, together with their implementations, to perform these tasks. These algorithms have recently become easily accessible and performing enough to allow developers to integrate these solutions in the most diverse fields, and architecture is no exception. Given the reduced complexity of the problem, for this prototype, we opted to use the open-source Python library scikit-learn, which provides Python language implementations of the most popular ML algorithms. This choice allowed for fast prototyping with little performance impact.

VPL – Visual Programming Language (VPL) applications allow algorithms to be constructed by linking graphic elements that synthesize specific commands. These applications are increasingly being explored in the architectural field because they simplify modeling processes for the production of complex geometries. In this research field, they are used to create a connection between the output of ML processing and the BIM environment. The structuring of this connection in the VPL environment allows an *in itinere* verification of the process and quick customization of the interoperability parameters between the different platforms. The application chosen for the development of this connection is Grasshopper as there are already several plugins that allow communication with BIM platforms. The IoT infrastructure and the ML algorithms are developed in a traditional programming environment to ensure a shorter and more flexible workflow, supported by the availability of consolidated libraries for this type of operation.

BIM environment – Building Information Modeling (BIM) methodologies, widely used in the AEC (Architecture Engineering Construction) sector [Dore et al., 2017] worldwide, catalyze important collaborative processes and interdisciplinary ways of relating through data structures. These structures cover the whole life of the architectural artifact that is intended to be represented utilizing a digital model (National Institute of Building Science, vi. Glossary). The bibliography of the sector is full of examples where BIM is applied not only to new constructions but also to already constructed buildings. In this case, the focus is on maintenance, upkeep, restoration, and the archiving and management of information related to the asset, thus defining the research strand of HBIM [Murphy et al. 2013]. To specific derivations of the methodologies introduced above, new acronyms were born [1]. One of these specific areas, involving the integration of HBIM and Museum Facility Management models, is called MBIM [Tucci et al. 2019]. In the case of modeling [2] of a museum, given the nature of BIM processes, it may be interesting to experiment with the "reuse" of data from multiple information datasets for the elaboration of models with different themes and purposes.

Related Work

We are witnessing several innovations in the AEC sector: the well-established innovations of Industry 4.0 are being translated into the field of architecture and the need to build a Digital Twin of the building is becoming increasingly strong. Smart Buildings, introduced by Clements-Croome's research in 2004, have evolved into Cognitive Buildings and are now able to learn and predict user behavior [Ploennigs et al. 2017] The ability to integrate IoT data with a BIM model of the building could offer new decision-making tools for the Facility Manager to identify potential problems intuitively [Wong et al. 2005].
Given this strong need, it is also possible to identify several examples in the bibliography where IoT sensors are used to reduce the risk of possible damages produced by the interaction between heritage assets and their storage environments. Manfriani et al. describe a virtuous case study where such sensors are used to monitor part of a small museum collection of the City of Genoa dedicated to Paganini, concerning two historical violins. The proposed intervention, consisting of a remote control system based on web-cloud-IoT technology, re-

sulted in a cost-effective improvement of the conservation conditions of the objects for the museum institution; the study is still in progress [Manfriani et al. 2021].
A further application in this direction of considerable importance is the recent example of the Natural History Museum in London. The museum property is 100,000 square meters and there are 15,000 sensors inside measuring every aspect of the museum. This data helps the Natural History Museum team to protect both the building and its collection. This data is stored within a Digital Twin which aims to better inform how it maintains the collection and the environment for visitors [Richardson 2020].
In this area of application of IoT systems for the heritage sphere, it is noteworthy that the spread of increasingly accessible low-tech hardware and visual programming languages, with more user-friendly interfaces and a faster learning curve than traditional programming systems, have allowed architects, engineers and curators to experiment with new strategies for designing or monitoring built architecture.
In terms of design, KM Kensek confirmed the effectiveness of the Dynamo scripting language as a parametric design tool, successfully using data from Arduino environmental sensors (humidity, sunlight and CO2) as input to modify parameters of the BIM model related to the case study project [Kensek 2014]. M. Rahmani Asl et al. suggested that data from simulations can be employed as design criteria using BIM-based optimization frameworks; the framework is developed on Dynamo and collects sensor data from buildings to optimize building energy performance and spatial daylighting based on simulated environmental data [Asl et al. 2015].
Regarding the monitoring of the built environment, Delgado et al. reported sensor families in the BIM environment, positioned at the physical sensors, which can accommodate the temperature and stress values of the monitored structure read by the edge nodes. Also in this case, the connection between IoT and BIM environment was made through the Dynamo application. This approach provides for the dynamic visualization of key structural performance parameters and enables real-time updating, long-term data management and model transformation via the IFC format [Delgado et al. 2018].
There are also some interesting examples for monitoring the museum environment by hybridizing BIM models and IoT sensing. La Russa et al. modeled in Grasshopper's VPL environment Artificial Intelligence algorithms to manage the entrances inside some rooms of villa Zingali, previously modeled in BIM environment, to preserve certain hygrometric conditions inside some rooms [La Russa et al. 2020]. Instead, Pepe et al., within the SensMat project, modeled sensor families in a BIM environment and communicated them with real sensors through Dynamo. The developed framework was designed to be applied to museums with very different themes and architectures [Pepe et al. 2021].

Methodology

The various IoT-connected nodes along with their sensors are placed inside the museum at predefined locations. The nodes can communicate using different wireless technologies, e.g. through Wi-Fi, Zigbee, or 4G. Once the connection to the network is established, they can then proceed to send the sensors' readings data to cloud storage services.
The transmission of data from IoT sensors to the database is done using the MQTT protocol. This protocol is often used in industry due to its flexibility and efficiency. The Sparkplug B v 1.0 namespace [Links 2017] was used to structurally organize the MQTT topics on which the data is transmitted. An example of an MQTT topic adhering to the Sparkplug B standard is the following: "namespace/group_id/message_type/edge_node_id". In our use case the namespace variable is "spBv1.0" given the standard used. The group ID is used to identify the different rooms in the museum environment. The use of this parameter makes it possible to keep track of the position of the sensor and to carry out spatial queries within the database. The message type field assumes the value DDATA, indicating that the payload contains readings from the sensors. Finally, the edge_node_id field contains the unique ID of the connected IoT node. The data is then collected in a database based on the information con-

tained in the MQTT topic and the payload. The data once in the database is then processed by an ML pipeline whose purpose is to remove outliers. There are different approaches in the literature to solve this kind of problem, but considering the nature of the data, a simple Isolation Forest algorithm is robust enough [Zemicheal et al. 2019]. Once the outliers have been removed the data is ready to be stored and queried by the HBIM client. . The connection between the database and the VPL environment is made via HTTP APIs. The data, which can be selected according to spatial and temporal interval criteria, are downloaded locally to be managed by the VPL platform. The interoperability of the data collected and those modeled in the BIM environment is guaranteed by the Rhino.Inside Revit plugin. The relationship between the physical edge node and the digital family is guaranteed through the assignment of unique IDs during installation.
The main objective of this framework is to spatialize the data collected from the real world in a digital environment to obtain specific thematic representations.

Development

For the development of this prototype the selected case study is not real, the BIM model used is the model of Alvar Aalto's Villa Mairea reconstructed from bibliographic sources in Revit. It can be seen from the images of the model how, in addition to the structural elements of the building (perimeter walls and internal partitions, columns, floor and pitched roof), it was also completed with a series of complementary fixed furnishings that could simulate a museum environment (Fig. 1). Finally, within the BIM model, some families of 3D objects representing some of the real monitored edge nodes that could be located in the museum were inserted. Concerning the latter, each node was reproduced in the model considering their real geometric dimension.
It was assumed to place one node in the environments Room A and Room B and two nodes inside the environment named Living due to its dimensions. During their installation it is possible to label each node concerning its topology. Fig. 2 provides the details that each node communicates with the cloud service (ID, location and monitored parameters). To create a solution that would be repeatable in real projects, and to better structure the information related to the installed sensors, each family was enriched with specific parameters related to the individual components such as model, manufacturer, size, power supply needed, precision, measurement accuracy.

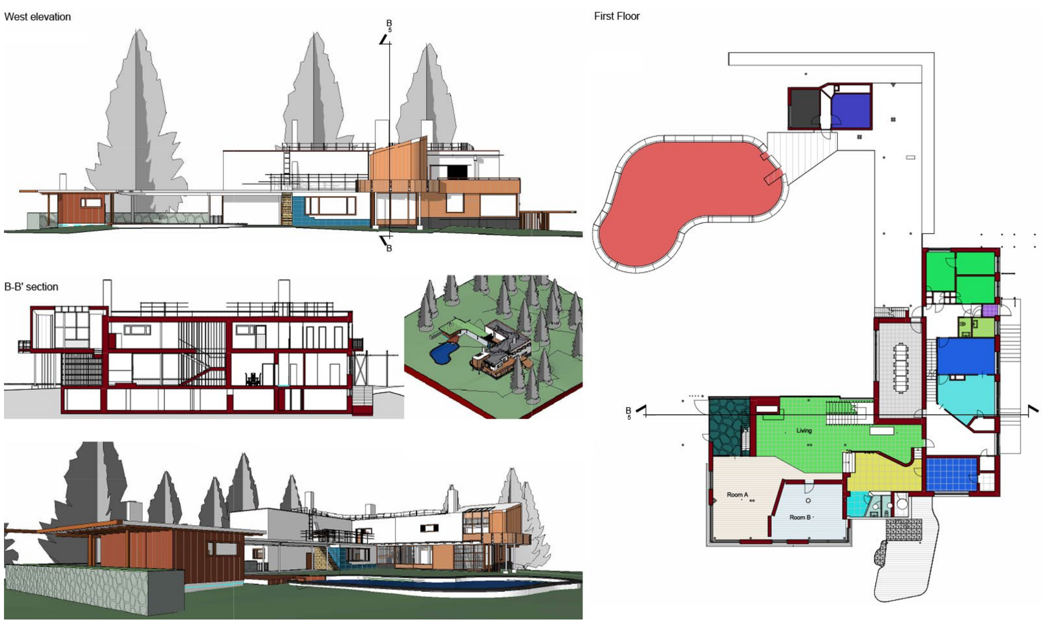


Fig. 1. BIM model of Alvar Aalto's Villa Mairea.

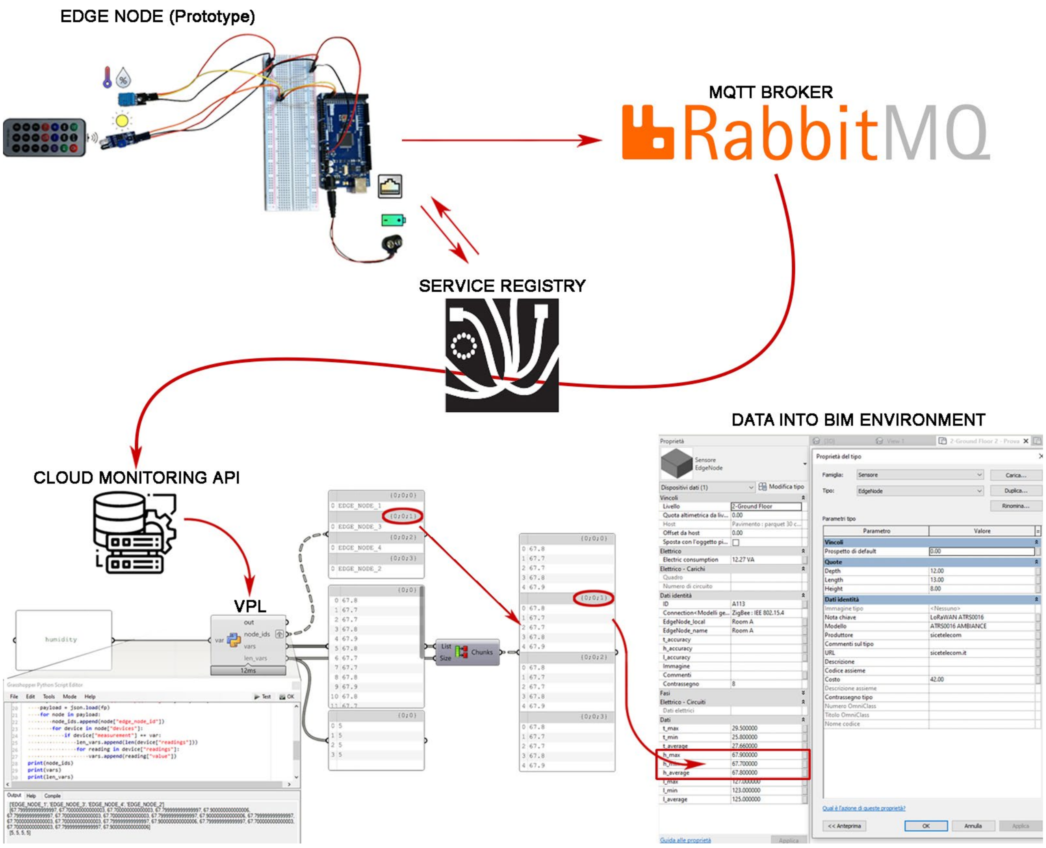


Fig. 2. Interoperability scheme between the different environments.

The code in the VPL environment is divided into three sections (Fig. 3). In the first section, once processed, the data is downloaded locally through a special cluster written in Iron-Python within the Grasshopper application. Each data query downloaded is preceded by the ID of the device. Once the ID has been recognized, the algorithm, using the data tree structure of the application, divides the data into a list of lists and consequently each branch of the data tree is associated with the correct sensor family previously inserted in Revit. The second portion of the algorithm is used to carry out further processing on the data and to make a local copy updated at the time of download in table format. In the third section of the algorithm it is possible to produce graphical displays that the user can view by selecting the corresponding sensor feature from the tree menu, or, as shown in Fig. 4 it is possible to simultaneously view the entire heatmap of a specific floor plan and the readings of individual cabinets or rooms (depending on the group of sensors selected). This feature is very important as it allows the user to view the temperature of the entire floor globally to facilitate the identification of any criticalities.

Conclusion

This paper presents the results of the first research born from the collaboration of a research group of the Department of Architecture and Design of the Politecnico di Torino and the LINKS Foundation Centre. The objective of this first research is to critically evaluate the potentialities derived from the hybridization of BIM systems and IoT technologies to improve museum management. The main characteristics of the workspace and the outputs that can be obtained were presented. The main difference between similar frameworks developed for ordinary building management and the proposed framework developed for museum management is the ability to represent the relationship between building and artwork, between container and content, a specificity that offers many insights for research.

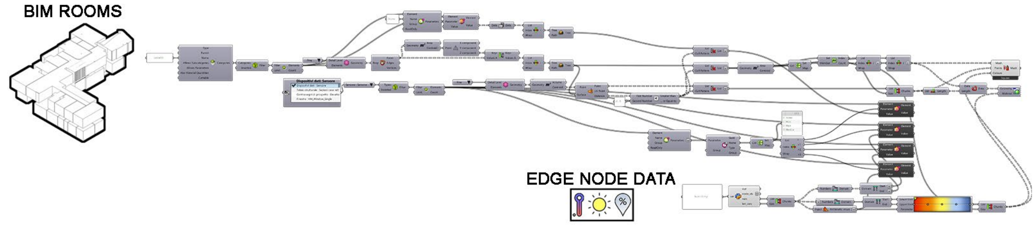


Fig. 3. Part of the code in VPL environment for connection with BIM environment.

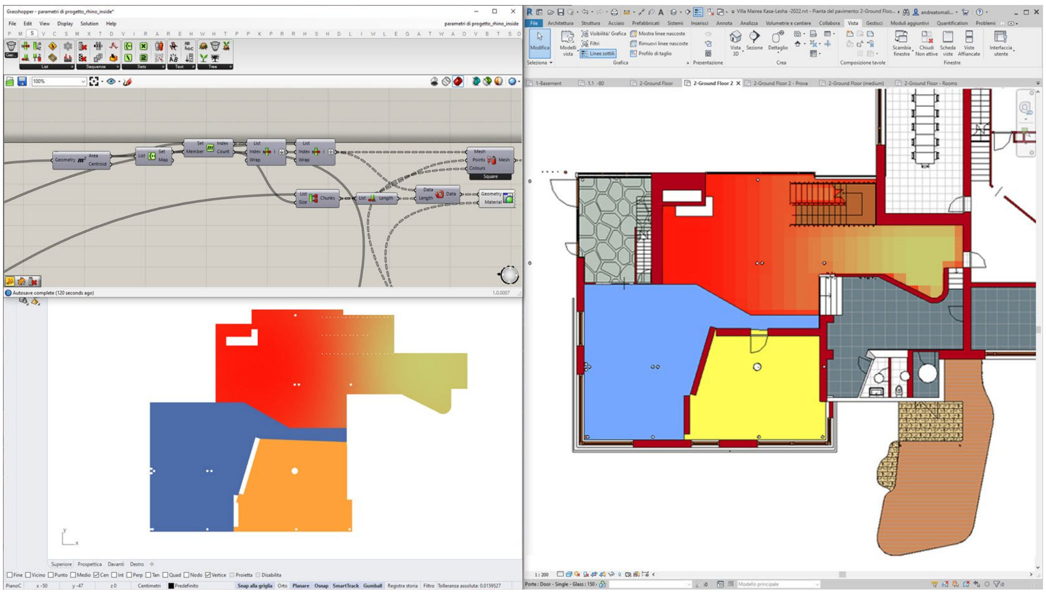


Fig. 4. Creation of heatmaps and visualization of data on a BIM model.

The potential of an integrated system that associates IoT information in traditional design environments, although in the prototype phase, is nevertheless considerable. During this first experimentation, some criticalities have been noticed that still need to be addressed: the installation of edge nodes in the halls must foresee protocols that eliminate human error (one could insert the group of sensors in the wrong place or assign an incorrect ID); the development of algorithms in a VPL environment, although suitable for a prototype phase, is not suitable for an operational tool open to museum staff; the creation of heatmaps should be carried out through a user interface that is simpler and closer to the skills of a curator. Once these critical issues have been resolved, the research group will go on to identify a real case study on which to apply this methodology.

Notes

[1] HBIM: Heritage/Historical Building Information Modeling; BHIMM: Built Heritage Information Modelling/Management [Della Torre 2016]; EBIM: Existing Building Information Modelling [Edwards 2017]; B(H)IM: Building(Heritage) Information Modelling [Simeone et al. 2014].

[2] The term modeling refers to the cognitive process that leads to the construction of a model. A model is a mental or theoretical representation containing the essential structure of objects or events in the real world.

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