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DIGITAL TWIN AND HBIM-TO-IOT FOR SMART MUSEUM MANAGEMENT – THE CASE OF THE DART MUSEUM CHIOSTRO DEL BRAMANTE

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Abstract

Among recent innovations in cultural heritage digitalization, Heritage Building Information Modeling (HBIM) is particularly relevant for museums, where managing both the “container” — a historic building or site — and its “contents” is essential. These spaces, often repurposed from their original functions, are shaped by how visitors interact with them over time. This study explores the integration of HBIM with IoT systems to collect, visualize, and analyze real-time sensor data within a unified digital platform. A prototype was developed and tested in the former convent of Santa Maria della Pace in Rome. The future impact of the research will contribute to create a “smart” museum by improving building management, monitoring environmental conditions, and supporting visitor navigation through exhibition spaces. This user-centered approach, based on observed preferences, enhances the visitor experience, promotes accessibility, and increases the museum’s cultural and social impact.

Keywords

Heritage Building Information Modeling (HBIM), Internet of Things (IoT), Smart Museum, Visitor Analytics

1. *Introduction*

The integration of cutting-edge technologies for the management of cultural heritage in the GLAM sector (Galleries, Libraries, Archives and Museums) is becoming increasingly important. One of the most promising aspects involves monitoring visitors and analyzing their movement flows, which helps optimize the visitor experience and prevent potential overcrowding or inadequate environmental conditions. This is in line with the concept of “digital twin”, defined as the digital representation of a real-world entity (a physical twin) and the streams of real-time data produced throughout its lifecycle (Boje, Guerriero, Kubicki, & Rezgui, 2020; Lucchi, 2023), generally via Internet of Things (IoT) devices (sensors, actuators, etc.), which can exchange data with other devices and systems over the Internet.

Numerous studies have already highlighted the benefits of applying advanced information technologies in museums, showing how the synergy between 3D modeling—especially in a BIM or HBIM (Heritage Building Information Model) context—and large-scale data collection through IoT systems facilitates the analysis of a building’s conservation status, the optimization of visitor pathways, and the management of extraordinary events (Tang, Shelden, Eastman, Pishdad-Bozorgi, & Gao, 2019). In this perspective, the information management approach of HBIM processes is integrated with a dynamic and constantly updated vision of cultural heritage, where the digital twin is regarded as an operational decision-support tool that enhances heritage protection while simultaneously strengthening cultural appreciation.

Recent studies further underscore this shift: for instance, Hamed (2023) demonstrates how HBIM can be employed as a knowledge-driven tool for conservation decision-making, specifically in the diagnostic modelling of heritage assets. Mazzetto (2024) provides a comprehensive review showing how Digital Twin paradigms, coupled with BIM and IoT, offer preventive-conservation capabilities by enabling real-time monitoring and lifecycle management. On the semantic front, Niccolucci et al. (2024) extend the concept of Heritage Digital Twin by incorporating sensor and activator ontologies, illustrating how digital documentation frameworks can become truly reactive and interconnected.

Complementary contributions have addressed museum-specific contexts: Angeloni (2023) explores the use of virtual tours to enhance digital access to collections, while Resta (2021) analyses their impact on visitor engagement and long-term audience development. Mezzino (2023) discusses digital visualization techniques that broaden cultural dissemination and support interactive experiences. In a similar direction, Angeloni et al. (2021) present the Co.ME. project, which developed a system for measuring and evaluating visitor behaviour in museums, transforming exhibition spaces into responsive environments. Together, these studies reinforce the trajectory towards integrated, heritage-sensitive digital environments capable of supporting both conservation objectives and enriched visitor experiences.

The use of HBIM for digitizing cultural sites has proven advantageous for systematic documentation, diagnostic analyses, and preventive conservation, as it aggregates three-dimensional surveys, textual sources, historical images, and sensor-based data into a single digital environment (Martinelli, Calcerano, & Gigliarelli, 2022; Yang et al., 2020).

Regarding dynamic data, research in this domain has also uncovered opportunities to streamline maintenance and conservation processes through automated alerts triggered by deviations in environmental parameters or structural metrics detected by on-site sensors (Baghalzadeh, Keivani, Moehler, Jelodari, & Roshdi Laleh, 2022).

Moreover, the emergence of IoT-driven solutions in museum and heritage contexts makes it possible to record real-time information on temperature, humidity, pollutant levels, and visitor presence (Torres-González, Rubio-Bellido, Bienvenido-Huertas, Alducin-Ochoa, & Flores-Alés, 2022; Trento, Wurzer, & Coraglia, 2019). Such continuous monitoring can improve both sustainability and safety, as building managers can visualize sensor data on interactive dashboards and rapidly address any anomalies (Martinelli, Calcerano, Adinolfi, Chianetta, & Gigliarelli, 2023). In addition, the ability to track visitor flows using Bluetooth Low Energy (BLE) or RFID (Radio-frequency identification) technologies offers curators and museum directors valuable insights for optimizing crowd management and designing tailored experiences (Verde, Romero, Faria, & Paiva, 2023).

Research initiatives such as the DIGItal LABoratory (DIGILAB) of the European Research Infrastructure for Heritage Science (E-RIHS), emphasize the benefits of sharing methodological frameworks and standardizing technological tools across multiple sites at regional or national levels (Bertrand, Loïc et al., 2020). By establishing a platform for data repository, curation, access, reuse, with specific services on dynamic data acquisition, heritage managers and scientific teams can pool diverse sensor data, 3D documentation outputs, and diagnostic results, thereby creating robust datasets for large-scale comparisons and more comprehensive analyses. This open, collaborative model responds to growing demands for sustainable preservation strategies in a context where resources, skills, and expertise often need to be scaled across entire territories (Bucciero et al., 2024).

Overall, the literature on digital twin solutions in cultural heritage environments indicates a shift from static models to continuously updated systems that capture multifaceted data in real time. This evolution enhances the responsiveness of interventions and supports deeper engagement with the historical, artistic, and social dimensions of cultural heritage. Although technical and organizational challenges still arise—ranging from interoperability between different software platforms to the long-term maintenance of sensor networks—the promise of a fully integrated HBIM-IoT ecosystem portends more informed, agile, and inclusive approaches to heritage conservation and enhancement.

In this context, the current study has developed an innovative platform that combines the HBIM approach with IoT systems, with the aim of enhancing museum management and addressing issues related to accessibility, safety, and prevention in the event of public health emergencies. At the core of the platform is a Bluetooth Low Energy (BLE) sensor network that tracks visitors' positions and routes inside the museum in real time. These dynamic data streams are then integrated into an HBIM model, which serves as a central repository for the building's 3D geometry—acquired through laser scanning or photogrammetry—together with historical, archival, and diagnostic information. This unified digital environment supports the planning of maintenance activities, guides preventive conservation efforts, and informs strategies for visitor flow management. Compared to previous

HBIM–IoT initiatives described in the literature, the originality of this work lies in: (i) the customisation of the platform's functionalities for a heritage museum context, integrating architectural semantics, historical data, and dynamic visitor-flow information; (ii) the monitoring objective, centred on behavioural and spatial analytics rather than only environmental or energy parameters; and (iii) the IFC-based interoperability that ensures dynamic data from BLE sensors can be visualised and queried in real-time within the HBIM environment. The selected case study is the complex of the former convent and the Chiostro of Santa Maria della Pace in Rome, an extraordinary example of Renaissance architecture. It demonstrates how combining HBIM models with an IoT-based sensor network can improve not only conservation and safety aspects but also the overall museum experience.

2. *Materials and methods*

This research combines several categories of tools and technologies to acquire and process geometric data, develop the HBIM model, and implement the IoT-based sensor network.

2.1 Survey Instruments

The geometric survey was conducted using a combination of terrestrial laser scanners and drone-based photogrammetry. Two laser scanners were employed to capture the detailed geometry of the Chiostro of Santa Maria della Pace:

- Faro Focus 3D S 120, used for indoor and short-range scans, which provided high-resolution point clouds of the cloister's arcades and interior spaces.
- Z+F IMAGER 5016, featuring an HDR camera and an internal IMU, allowing for faster acquisition and partial registration of scans in the field for complex areas.

Additionally, a DJI Mavic Pro Platinum drone was deployed for photogrammetric image capture. The combined datasets (scanner and photogrammetry) ensured complete coverage of the cloister, former convent and adjoining spaces.

2.2 IoT Sensor Infrastructure and Data Visualization

To capture visitor movement in real time, a network of Bluetooth Low Energy (BLE) beacons was deployed throughout the exhibition spaces. These beacons detect signals from small wearable devices (or protectors) carried by visitors, recording the intensity of the signals (in dBm) and sending data via gateways to a central server. Bleb Technology Srl provided the hardware solution, offering low power consumption and easy deployment capabilities.

The project also involved Systema Srl for the development of the cloud-based platform that stores and processes sensor signals, mapping them onto the corresponding spaces in the HBIM model. A key software tool for visualizing this combined information is LynxEyeD, which loads the IFC model of the building and overlaps the incoming dynamic data (e.g., visitor positions, aggregated flow metrics) onto a 3D interface. This front-end provides an effective decision-support tool for operators, allowing them to monitor visitor flow and environmental conditions — if present — in real time, all within the digital representation of the building.

3. *Case study description*

The former convent and the cloister of Santa Maria della Pace in Rome were selected for this study due to its notable architectural complexity and its current function as a museum, managed by DART foundation. Currently, those spaces occupy much of the former convent annexed to the church of Santa Maria della Pace, as well as the celebrated two-level cloister designed by Donato Bramante in the early 16th century. While the church remains outside the museum's route, the cloister and the interconnected conventual environments form the core of the modern exhibition areas, administrative offices, and facilities.

Records indicate that a Dominican convent existed on this site prior to Bramante's intervention. Commissioned by Cardinal Oliviero Carafa around 1500, Donato Bramante reconfigured much of the central courtyard into the famed cloister, distinguished by arcades supported by pillars on the ground floor and a column-based trabeation on the upper level. Although classical orders such as Doric, Ionic, Corinthian, and Composite are all present, the Ionic order dominates in homage to the Marian dedication of the site.

This reorganization not only enhanced the architectural coherence but also created new internal routes for the resident community (Riccardi & Benedetti, 1981).

Over the following centuries, the convent underwent multiple expansions to accommodate liturgical, educational, and communal functions. Archival documents describe how additional rooms, service corridors, and even the partial addition of upper levels were introduced to respond to population growth and shifting priorities within the religious order. A few wings were extended vertically, altering rooflines and internal partitions. Others were reconfigured to serve as refectories or dormitories, leading to changes in window placements, staircases, and decorative schemes. By the 18th century, the complex had evolved into a multifaceted structure that blended Bramante's Renaissance interventions with Baroque and later modifications, producing a unique layering of styles and spatial typologies (Fig. 1). The most evident modifications concern the connections between the cloister and the adjacent buildings, with the addition of new wings extending along Via Arco della Pace and Vicolo della Volpe. Some portions of the complex have been incorporated into later structures, as evidenced by variations in floor heights and the arrangement of openings. Structural and masonry analyses also reveal the use of different construction techniques, testifying to the transformations that have occurred over the centuries (Riccardi & Benedetti, 1981).

Today, the DART museum operates throughout these formerly religious spaces, hosting contemporary art exhibitions, educational programs, and cultural events. The cloister is frequently used to display installations or serve as a gathering point, taking advantage of its grand proportions and architectural significance. Meanwhile, the upper floors—some of which result from older expansions—have been repurposed into galleries, offices, and visitor facilities. This dual dimension—an architecturally significant Renaissance structure functioning as an exhibition space—makes it an ideal context in which to test the integration of HBIM and IoT technologies. The variety of architectural elements, including loggias, vaulted rooms, and outdoor areas, required a combination of terrestrial laser scanning and drone photogrammetry for its survey. Furthermore, the museum context presented a unique opportunity to install Bluetooth Low Energy (BLE) beacons and wearable sensors for real-time visitor monitoring, thus aligning well with the project's

Fig. 1: Inner view of the cloister of Santa Maria della Pace complex, during the exhibition "INFINITY. Michelangelo Pistoletto. Contemporary Art."

implementation of an HBIM–IoT platform.

Taken together, these factors confirm the cloister and convent of the church of Santa Maria della Pace as a compelling case study for merging detailed architectural documentation, advanced surveying methods, and continuous monitoring of visitor flows. By adopting a data-driven workflow, the building's geometric information, historical records, and real-time sensor data are unified into a single digital environment, ultimately improving both management strategies and the broader understanding of this Renaissance masterpiece.

4. *HBIM modelling*

4.1 Geometric survey and documentation

The first step of the study involved documentation. Due to the complexity and articulation of the building, geometric data was collected via an integrated survey coupling different tools and methodologies, in order to cover the interior and exterior of the whole building, as well as its architectural style and decoration, with special care devoted to the exhibition spaces.

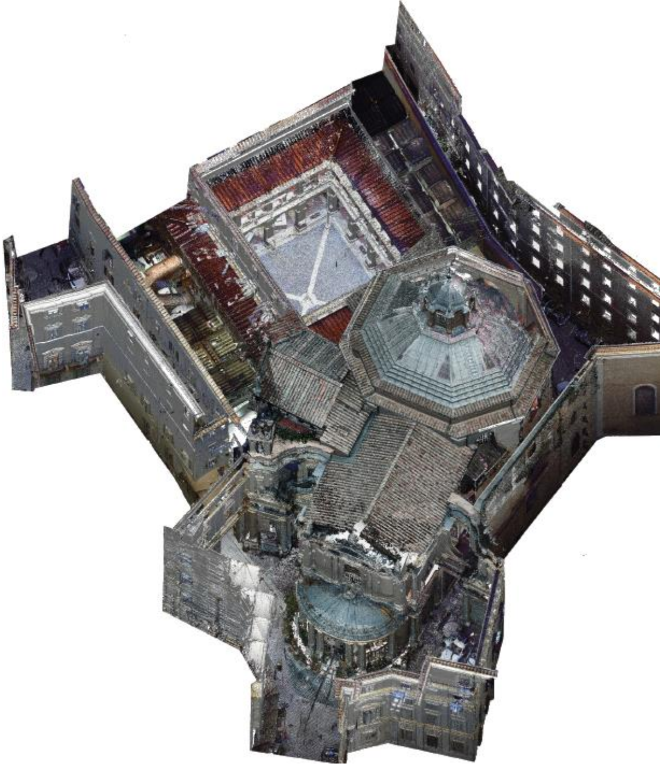


Fig. 2: Integrated geometric survey of the building.

The acquisition tools used include terrestrial laser scanner and drone photogrammetry, which allowed us to obtain a high-density point cloud, representing the geometry of the building in detail. Laser scans provided precise data on the morphology and dimensions of the spaces, while photogrammetry integrated additional information on upper floors, rooftops, and other surfaces not accessible from the ground.

The collected data were processed separately, using the proprietary software for the laser scans and Agisoft Metashape to elaborate the photographic documentation from the drone, via the Structure from Motion process. The point clouds were registered using CloudCompare and Autodesk ReCap, resulting in a complete representation of the building, including underground spaces and roofs. Although the point clouds had different density characteristics—due to the different acquisition methodologies—the overall point cloud, thanks to a good overlapping value, presented tolerable deviations and an optimal degree of accuracy for the subsequent modeling in the HBIM environment (Fig. 2). Quantitative checks on the registered and integrated point clouds, performed using CloudCompare and Autodesk ReCap, revealed a mean deviation of ±3–5 mm for interior spaces and ±8–10 mm for roof structures and upper external areas not directly accessible from the ground. These values are consistent with the technical specifications of the surveying instruments employed: the Z+F IMAGER 5016 (accuracy ±1 mm at 10 m, ±2–3 mm at 50 m) and the Faro Focus 3D S 120 (accuracy ±2 mm at 25 m) for terrestrial scans, combined with high-resolution photogrammetric data acquired with a DJI Mavic Pro Platinum drone. The higher deviations recorded in roof areas are attributable to the lower density of control points and the reliance on aerial imagery. Overall, these results confirm the suitability of the integrated dataset for accurate HBIM modelling of complex heritage structures.

5. *Information modelling and semantic enrichment*

The second step of the study involved the HBIM modelling of the building, following the Scan-to-BIM approach, using the point cloud from the integrated survey as a "scaffold" on which to directly model objects corresponding to building elements (Radanovic, Khoshelham, & Fraser, 2020).

Recent advancements in the Scan-to-BIM domain have introduced automated and semi-automated segmentation techniques for the semantic enrichment of point clouds, aiming to reduce manual modelling time while improving classification accuracy. For example, Patil & Kalantari (2025) compare deep learning models (Swin3D, PointNeXt) to evaluate how segmentation accuracy impacts BIM reconstruction. Zbirovský & Nežerka (2025) present Cloud2BIM, an open-source pipeline that automatically segments walls, slabs, and openings, generating IFC-compliant models with minimal user input. A comprehensive review by Abreu et al. (2023) discusses procedural point cloud modelling and the limitations of current methods, such as occlusions and irregular geometries, while Song et al. (2023) propose A-Scan2BIM, an assistive system that auto-generates editing operations in Revit, reducing manual workload. These studies highlight the rapid progress of automation, while also showing that manual segmentation remains necessary for heritage contexts requiring high levels of interpretative accuracy.

For the present study, point cloud segmentation was performed manually within Autodesk Revit, following a Scan-to-BIM approach. Specific building elements (e.g., columns, vaults, decorative capitals) were identified and modelled directly from the registered point cloud, guided by the semantic classification defined in the Building Execution Plan. Manual segmentation was preferred in order to ensure the integration of historical, architectural, and diagnostic information that would be difficult to automate, and to preserve full control over the level of geometric detail required for heritage components.

An analysis of the building and the geometric survey, coupled with bibliographical and graphical documentation, supported its breakdown structuring into architectural elements (e.g. walls, floors, windows, etc.) based on the semantic classification of their formal and functional characteristics, as well as on the pre-set of behavioral rules of the BIM tool of choice. Each element was modelled separately as an object and assigned a specific Level of Information Need (LOIN), defined in accordance with ISO 19650 (ISO, 2018), specifying both the Level of Geometry (LoG) and the Level of Information (LoI)—that is, the quality, quantity, and granularity of both geometrical and alphanumerical information associated with it. This approach defined a hierarchical organisation of the building's components and systems, calibrated to the intended uses of the model: preventive conservation planning, real-time visitor flow analysis, and heritage documentation. For instance, structural components such as load-bearing walls and columns were modelled with high geometric detail and enriched with material and historical data, whereas non-structural elements like furniture were represented at lower geometric resolution but maintained essential identification and location attributes. This

Fig. 3: HBIM model section of the former convent and the Chiostro of Santa Maria della Pace in Rome.

selective definition of LOIN optimised modelling effort, avoided unnecessary over-detailing, and ensured interoperability with the IoT-based monitoring platform. This morphological and technical analysis of individual elements, and the corresponding segmentation of the point cloud, contributed to the understanding of the building as a whole, and supported the integration of data about the building's materials, construction techniques, and historical modifications in the HBIM model. A similar breakdown structure was assigned also to the exhibition spaces of the museum.

The HBIM modelling (Fig. 3) was developed in the BIM authoring tool Autodesk Revit, an object-oriented modeler which groups model objects into classes called “families”, sharing a common set of properties and a related graphical representation. A system of parametrical rules was defined to control the characteristics of each family, as well as the set of interdependent relations among objects that constitute their “behavior”; therefore, it was essential to create planimetric and altimetric constraints to manage the proportional relationships among the parts. System families, which are modelled inside the software with predefined behavior, were used to model the main constituents of the building's structure, such as walls, floors, roofs, etc. A parametric library of loadable families—modelled in a specific editor with greater flexibility—was defined for repeatable building components, such as windows and doors, highlighting the modularity and composition of the architectural language. Local families were used for single, non-repeatable objects, such as vault lunettes.

Federated models were developed for different sections of the building, depending on the Level of Information Need of most model objects, and also on modelling logistics (e.g., diachronic development of different parts, depending on evolving data acquisition). The cloister was modelled separately, with higher detail, and great care was devoted to the representation of the architectural order of Donato Bramante's design. The former convent, currently housing the museum and exhibitions, although morphologically simpler, underwent many transformations over time, resulting in a significant heterogeneity of spaces and building elements: for example, most of the rooms are located on different elevation levels and present different vaulted systems, and there is a great variability of windows. Therefore, the modelling of

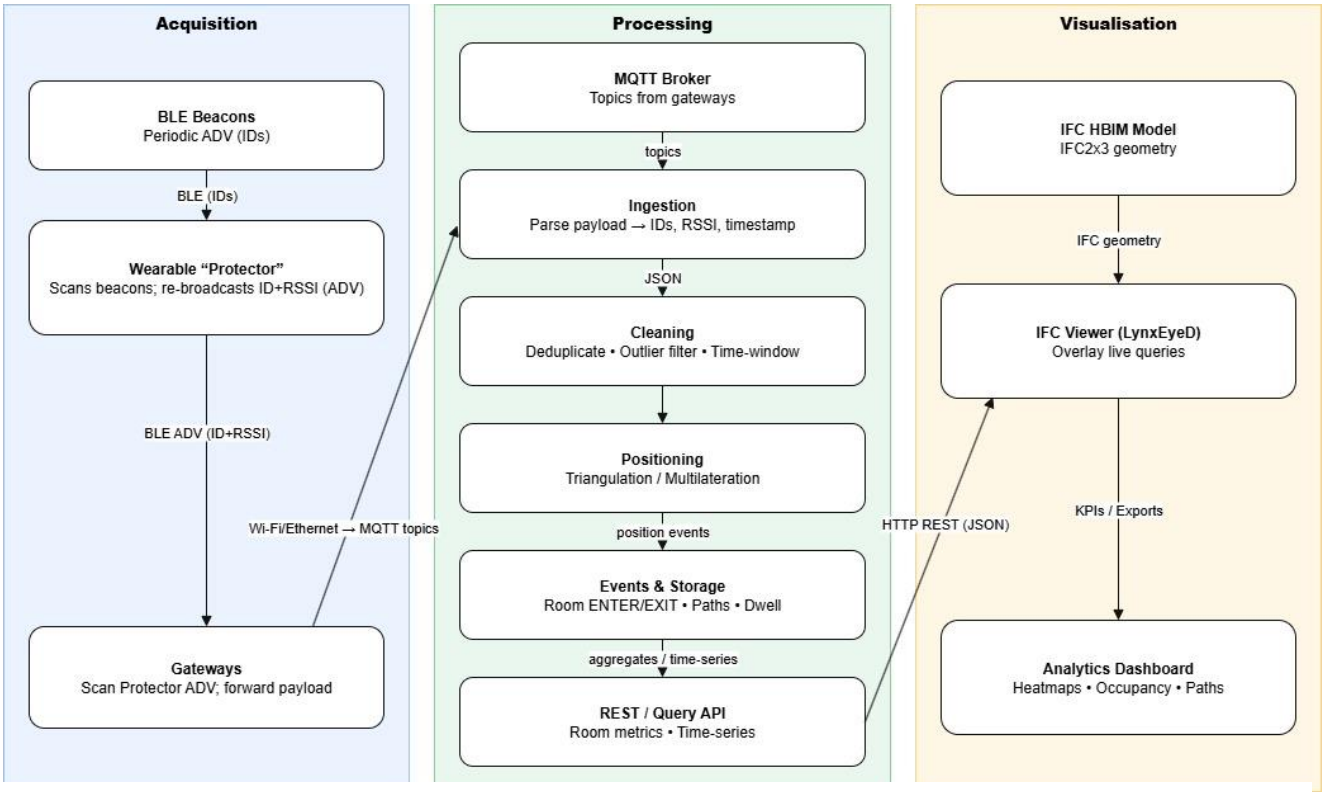


Fig. 4: Three-layer architecture and data flow of the IoT–HBIM platform, showing components, communication protocols (BLE, MQTT, REST, IFC) and the integration of sensor data into the HBIM model for real-time visualisation and analytics.

horizontal and vertical connections, entrances and paths, as well as loadable and local families, required special attention.

This whole process is intrinsically linked to the end use of the HBIM model and requires balancing the geometric accuracy and semantic fidelity of model objects against the corresponding architectural elements. Clarity about model uses guided technical decisions during point cloud segmentation and modeling, ensuring that the final model is not only accurate, but also adequately usable (fit) for its specific purpose.

The semantic enrichment of each model object was performed by associating collected data related to historical development, materials, building systems, and current condition through custom properties, including textual descriptions, reports, and links to external resources. The documentation and preservation of historical information within the HBIM model ensures that the historical context and importance of the analyzed architectural elements are easily accessible and properly documented.

The principal model use of the study is the development of the HBIM-IoT platform, going beyond the functionality of HBIM as a static "hub" of data collected during the life of a building, by enabling the dynamic management of real-time information from different IoT devices. To this end, the model was exported into the IFC2x3 format.

6. Design and implementation of the integrated HBIM–IoT platform

The current study aimed to integrate static, heritage-specific information with a dynamic framework capable of acquiring and visualizing real-time visitors flow measurements. This requirement led to a modular, tiered architecture that spans three main layers.

- Data Acquisition Layer – BLE beacons and wearable devices gather raw signal measurements, which are forwarded to a central server via gateways.
- Data Management and Processing Layer – A cloud-based environment processes the incoming signals, estimating positions and mapping them to the building's HBIM geometry.
- Data Visualization and Integration Layer – The HBIM model (in IFC format) is paired with an application (LynxEyeD) that overlays the processed sensor data on a 3D interface.

Figure 4 provides a consolidated schematic representation of these layers, showing the main components, the data flows between them, and the formats used. This diagram integrates both the physical architecture and the logical workflow, offering a comprehensive view of how sensor data are acquired, processed, and visualised within the HBIM environment.

The following sections detail how each layer was implemented in the case study, from the physical deployment of BLE devices to the data handling pipeline and final visualization.

6.1 Implementation of the Sensor Network

A network of Bluetooth Low Energy (BLE) beacons was installed in key areas of the building—such as galleries, corridors, and transitional nodes—to minimize coverage gaps. BLE was chosen over Wi-Fi, RFID, and UWB for its low energy consumption, suitability for thick masonry walls, and balance of accuracy and cost. Unlike Wi-Fi, BLE beacons offer reliable signals in complex architectural spaces with minimal energy impact. Each beacon emits signals at set intervals, while visitors are provided with protector devices that detect these broadcasts (Fig. 5). Gateways, positioned in unobtrusive locations, collect the Received Signal Strength Indicator (RSSI) readings from multiple beacons and push them to a cloud-based server.

Because of the building's Renaissance architecture features, such as thick masonry walls, arches, and columns, a systematic calibration phase was critical to account for signal interference and optimize beacon placement. During this phase, the research team conducted field measurements comparing actual distances between beacons and protectors against the corresponding RSSI readings.

Any discrepancies between measured distances and signal-based estimates were analyzed to adjust beacon transmission power and refine the formulas used to convert RSSI values into distance estimates.This process also identified any "dead zones" or areas with excessive signal overlap, prompting the repositioning of certain beacons to achieve consistent coverage across all monitored rooms.

As a result, the final configuration balanced low power consumption with reliable detection ranges. The gateway devices gather calibrated RSSI data from multiple beacons in real time, then

Fig. 5: Experimentation of the HBIM-IoT sensor network for tracking visitors.

forward it to the project's central server, where additional algorithms map each reading to a specific location in the building's HBIM model.

6.2 Data Collection and Analysis

Once the BLE gateways receive signal-strength readings from the protector devices, they send these data—along with beacon IDs and timestamps—to a central server using a secure network connection. The system then carries out multiple steps to transform raw measurements into actionable spatial information.

All incoming data records are assigned a unique identifier. Each record typically includes:

- Timestamp: The moment the beacon registered the Protector's signal.
- Protector ID: A unique code for each wearable device.
- Beacon ID(s): The specific hardware modules that detected the signal.
- RSSI (signal strength) values.

A preprocessing routine discards incomplete or contradictory entries (e.g., signals arriving out of expected time sequences) and performs basic formatting. Any anomalies, such as rapid jumps in location, are flagged for further examination to avoid artificially skewing subsequent calculations.

The next phase applies multilateration algorithms that approximate the protector's position within a local coordinate system based on beacon coordinates established during the survey stage. If at least three beacons detect the same wearable within a close time interval, the system compares the RSSI-derived distances among them to infer (x,y) coordinates in relation to the building's ground plan. In more open areas, four or more beacons may detect the signal, further refining accuracy.

Because the geometry of the former convent and cloister can create interference patterns, a calibration table—resulting from the earlier field tests—is consulted to ensure that raw RSSI values are interpreted consistently. This calibration step helps account for architectural obstacles such as thick masonry or vaulted ceilings.

After position estimates are established, each coordinate is associated with a specific room or zone in the HBIM model. The IFC export contains boundaries (footprints, walls, polygons) for each distinct area. The system checks which boundary polygon or volume contains the computed (x,y)—and occasionally (z)—coordinates. When a match is found, the system produces a “location event” that records:

1. The assigned room or zone ID (as defined in the HBIM model).
2. The protector’s approximate position within that space.
3. The timestamp of the event.

This approach ensures that each reading seamlessly aligns with the architectural semantics present in the HBIM. In practice, museum operators see the aggregated results not as raw coordinates, but as visitors located in a named room or corridor, precisely as designated in the model.

All location events flow into a relational database that stores the visitor’s path over time. Some fields commonly included are:

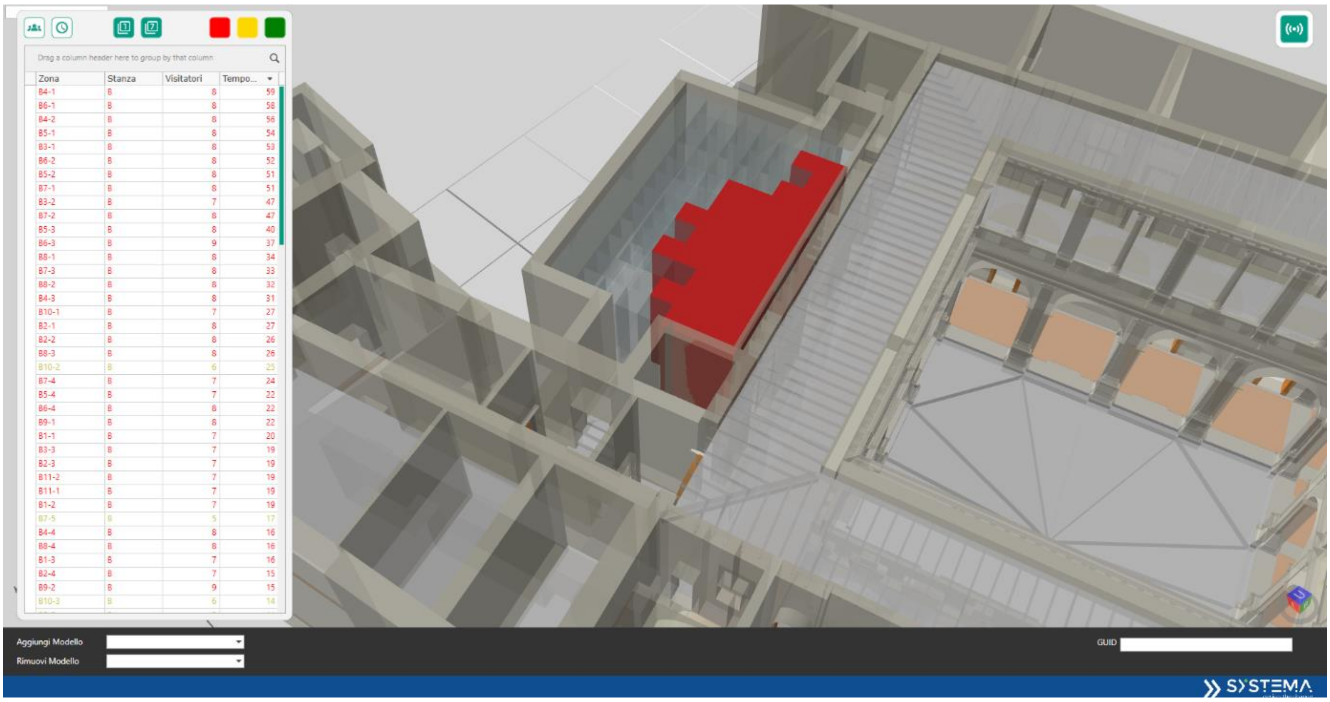
- Event ID (unique primary key).
- Protector ID (reference to the visitor’s wearable).
- Timestamp.
- Zone/Room ID (linked to the IFC-based model element).
- Distance or Accuracy Metric (if any).

Periodically, the system processes these location events to derive higher-level insights:

- Occupancy: Counting how many protectors there are in each area at a given time.
- Dwell Time: Estimating how long a visitor remains in a specific zone.
- Path Reconstruction: Linking consecutive events for the same protector to build a time-sequenced route.

Queries can filter results by date, time range, or zone, generating real-time dashboards or historical usage patterns. For instance, daily occupancy peaks might highlight a need to open additional galleries, while extended dwell times in certain exhibition rooms may suggest increased visitor interest in specific displays.

Though the core objective focused on visitor flow, the system architecture can readily accommodate additional sensors (e.g., temperature or humidity), provided they share the same local coordinate system and room definitions. In that case, each measurement can be tagged to the corresponding IFC zone, enabling correlative analyses—such as comparing occupant density with environmental conditions.



Zona	Stanza	Visitatori	Tempo...
B4-1	B	8	59
B6-1	B	8	58
B4-2	B	8	56
B5-1	B	8	54
B3-1	B	8	53
B6-2	B	8	52
B5-2	B	8	51
B7-1	B	8	51
B3-2	B	7	47
B7-2	B	8	47
B5-3	B	8	40
B6-3	B	9	37
B8-1	B	8	34
B7-3	B	8	33
B8-2	B	8	32
B4-3	B	8	31
B10-1	B	7	27
B2-1	B	8	27
B2-2	B	8	26
B8-3	B	8	26
B10-2	B	6	25
B7-4	B	7	24
B5-4	B	7	22
B6-4	B	8	22
B9-1	B	8	22
B1-1	B	7	20
B3-3	B	7	19
B2-3	B	7	19
B11-2	B	7	19
B11-1	B	7	19
B1-2	B	7	19
B7-5	B	5	17
B4-4	B	8	16
B8-4	B	8	16
B1-3	B	7	16
B2-4	B	7	15
B9-2	B	9	15
B10-3	B	6	14

Fig. 6: Visualization of the HBIM-IoT platform for real-time monitoring of visitor flows.

This extensibility sets the foundation for a more comprehensive digital twin, incorporating building performance, security, and preventive conservation data into the same HBIM-based framework.

By transforming raw signal inputs into IFC-referenced location events, the proposed approach ensures that real-time visitor data is consistently anchored to the building's documented geometry and semantics. This architecture provides operators and stakeholders with immediate, room-level insights, thereby enhancing daily management and strategic planning within the museum environment.

6.3 Implementation of the Visualization Platform

The platform's visualization environment builds on the IFC export of the complex of Santa Maria della Pace, which contains all architectural elements and spatial boundaries previously modeled in Autodesk Revit. Early in the development process, project staff ensured that the beacon locations used for visitor-tracking were consistently aligned with their corresponding geometry in the IFC, thus avoiding mismatches once the system went live. This alignment step guarantees that when the server computes a protector's position, the user interface can accurately overlay that position onto the three-dimensional representation of the building.

Within LynxEyeD, the IFC file is loaded at startup to generate a 3D scene reflecting the building's walls, floors, roofs, and other architectural features. Each room or zone in the IFC bears a unique identifier that matches the relational database records. As location events arrive in real time from the server, the application places or updates "markers" in the correct positions, effectively showing users how visitors move within the building. If several protectors are detected in a single room, the system can aggregate their markers to indicate overall occupancy, and it may display a color scale to convey areas of higher concentration or extended dwell times.

The LynxEyeD platform allows the real-time overlay of visitor tracking data onto the HBIM model, visualizing their spatial distribution within the museum. Through advanced analysis tools, it is possible to generate a heatmap of the most frequently visited areas, providing a clear indication of high-traffic zones and movement dynamics within the exhibition space.

Operators can examine both immediate and historical views of visitor flow by switching between a live mode and a playback mode. In playback mode, LynxEyeD replays previously stored events in chronological order, enabling museum staff to visualize how circulation patterns changed over a specific time window, such as a particular day, an exhibition, or even an hourly segment. This replay capability opens opportunities for in-depth evaluations, such as identifying congestion issues that recur at the same time each day or analyzing how exhibit layouts affect the way visitors navigate the space (Fig. 6).

From an interaction standpoint, the software's user interface offers straightforward methods for panning, zooming, and selecting elements of the 3D environment. Operators can click on rooms or markers to view real-time metrics such as instantaneous occupancy or time-based statistics derived from the aggregated dataset. When the system detects that an area has surpassed a predefined threshold for visitor density, LynxEyeD can highlight the zone or generate an alert, allowing staff to act promptly to maintain comfort and safety.

Beyond these immediate benefits, the platform can also generate summary analytics that offers insights into broader trends, including average stay times in certain spaces, the most heavily trafficked routes over an entire day, and correlations between several factors influencing visitation. Since all data are mapped directly to the IFC model, museum managers can interpret these analytics while preserving the architectural and historical context of each zone.

7. Conclusions and future developments

This study has highlighted how HBIM platforms and Internet of Things systems can interrelate in the domain of cultural heritage management. Originally conceived to address information exchange issues over the life cycle of a building, BIM provides data storage and sharing solutions that support design, implementation, and operational phases. The experiments conducted on monitoring visitor movement within a museum context, together with their results, confirm that integrating HBIM and IoT is a promising strategy for enhancing conservation practices and information management throughout a building's life cycle—particularly in its operational stage.

The analysis also investigated the need to extend or adapt BIM's information system to manage model data across time, reflecting the building's evolutionary narrative and the activities taking place within it. By merging an HBIM model (documenting original Renaissance elements, subsequent modifications, and current usage) with continuous IoT-based monitoring, the study underscores how data-driven heritage management can reconcile historical authenticity with the evolving needs of a modern museum.

The system developed enabled real-time monitoring of visitor movements, yielding a heatmap of the most frequently visited areas. By doing so, it allowed for a deeper understanding of visitor behavior dynamics, influenced by both architectural and organizational factors, thereby providing museum managers with a powerful tool to analyze visitor needs and improve their experience. Furthermore, the visualization platform offers interactive features for the museum's operational management, illustrating how technological innovation can contribute to the sustainable enhancement of historical sites.

Based on these findings, we can affirm that the proposed study has demonstrated the effectiveness of combining HBIM and IoT for cultural heritage management. By employing advanced technologies, museums can achieve more efficient operations and an improved visitor experience, ultimately becoming more accessible, interactive, and effective.

Looking ahead, future developments will focus on three main directions: (i) integrating environmental sensors (e.g., temperature, relative humidity, illuminance, pollutants) and energy-management modules into the same IFC-based visualisation environment, enabling comprehensive monitoring of both visitor behaviour and building performance; (ii) enhancing predictive analytics to support short-term operational decisions, such as opening secondary galleries or adapting wayfinding when occupancy thresholds are likely to be exceeded; and (iii) introducing advanced visitor-interaction features, including personalised tours with context-aware content delivered via BLE beacons or AR devices, tailored to interests inferred from dwell-time patterns. In parallel, micro-climate and crowding data will be linked to preventive-conservation protocols, allowing managers to anticipate risks for sensitive spaces and schedule targeted interventions. These upgrades will extend the platform's capacity from monitoring and analysis to proactive decision-making, contributing to both the sustainability and the experiential quality of cultural heritage sites.

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