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TOWARD A BIM-CENTRIC DIGITAL TWIN FOR SUSTAINABLE MUSEUM OPERATION: THE MACA LIVING LAB CASE STUDY

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Abstract

Digital Twins (DTs) couple BIM and IoT for sustainable building operation, yet many implementations remain siloed, hard to scale, and difficult to interpret. This paper presents a stepwise DT prototype for an environmental-education facility, integrating indoor/outdoor sensing (CO_2, PM, temperature, humidity, occupancy) with a Revit BIM model. A Dynamo–Python pipeline maps cloud time-series to shared BIM parameters, enabling in-model visualization, threshold alerts, and KPI reporting. Initial deployment delivers the sensing-and-display setup and a reusable BIM data schema ready for automated synchronization. The lasting contribution is a replicable BIM-centric implementation method for room- and zone-level monitoring in sustainable cultural buildings.

Introduction

DTs are increasingly recognised as dynamic digital representations that are continuously updated by data streams from the physical asset and used to support monitoring, analysis, and decision-making throughout the lifecycle (Grieves and Vickers, 2017; Fuller et al., 2020). In the built environment, DT research has accelerated as BIM (Building Information Modelling), while rich in geometry and semantics, remains essentially static and insufficient to represent operational conditions required in operations and maintenance (O&M) (Sacks et al., 2020; Jiang et al., 2021). A common response is to integrate BIM with Internet of Things (IoT) sensing, cloud data platforms, and analytics to produce operational DTs capable of performance tracking, anomaly detection, and optimisation (Eneyew et al., 2022).

Despite the rapid growth of BIM–IoT DT prototypes, the literature consistently highlights limitations that hinder repeatability and scaling: (i) interoperability and semantic misalignment between BIM schemas and heterogeneous IoT platforms; (ii) fragile, project-specific mapping between sensor identifiers and BIM elements; (iii) ad-hoc synchronisation pipelines that are difficult to maintain; and (iv) limited support for how stakeholders interpret and act on DT outputs (Pauwels et al., 2017; Boje et al., 2020). Recent literature confirms that these issues remain central, especially where heterogeneous data structures, non-standardised integration procedures, and weak information governance limit the transition from data collection to operational decision support (Tang et al., 2019; Mannino et al., 2021; Liu et al., 2025; Zhang et al., 2025). Several contributions argue that semantic enrichment and standards-aware information management are necessary for DT ecosystems to become reliable beyond prototypes (Boje et al., 2020; buildingSMART International, 2023). Recent work on BIM-IoT-enabled smart and sustainable buildings shows that real-time monitoring, in-model visualisation, and sensor-linked dashboards are increasingly common, but that maintainable integration logic and robust spatial contextualisation remain insufficiently clarified, particularly in existing buildings and operational settings (Valinejadshoubi et al., 2021; Piras et al., 2025). Standards and positioning efforts (e.g., Industry Foundation Classes (IFC) and ISO information management frameworks) stress that DT value depends on disciplined information modelling, governance, and transparent data exchange mechanisms rather than tool-specific integrations (ISO, 2018; ISO, 2018a; buildingSMART International, 2020). This direction is also coherent with ongoing CEN/TC 442 standardisation efforts on digital twins in the built environment, which emphasise the relationship between BIM, structured information, and interoperable exchange environments (CEN/TR 18077, 2024; EN 18162, 2026).

Cultural and educational buildings introduce additional challenges and opportunities. Retrofitting sensing infrastructure in existing museums must minimise invasiveness and accommodate visitor flow, while the DT can simultaneously support operational decision-making and public sustainability awareness through "human-in-the-loop" feedback (Turco et al., 2022). In this context, indoor environmental quality (IEQ), including thermal-hygrometric comfort and air quality, becomes a dual objective: protecting occupants (often children) and turning the building into a learning environment. For particulate matter (PM2.5, PM10) and other pollutants, internationally recognised guideline thresholds provide a robust reference for interpretability and alerting logic (World Health Organization, 2021).

This paper reports a DT setup designed as a progressive, stepwise implementation for a museum Living Lab, the Italian (MAcA) Museo A come Ambiente based in Turin, where sensing infrastructure, data management, BIM preparation, and automated synchronisation are introduced in a controlled sequence. The current phase focuses on the area where the sensing infrastructure and visitor-facing displays are deployed, so that the end-to-end sensing-data-BIM pipeline can be validated, establishing the technical foundations required for scaling it to the full asset. While the five-layer architecture provides the overall DT framework for structuring sensing, data management, integration, digital representation, and stakeholder interaction in the museum case study, the main contribution of the paper lies in its BIM-centric implementation for maintainable room and zone level monitoring, where spatial contextualisation, progressive deployment, and stakeholder interpretability must coexist. More specifically, the contribution lies in the combination of persistent spatial identifiers, room-zone-level data binding, a writable shared-parameter schema, an incremental snapshot-to-live synchronisation logic, and a dual representation strategy in which BIM supports spatial-semantic contextualisation while external platforms support longitudinal analytics. The paper does not present a generic BIM-IoT monitoring platform, but an early-stage operational DT prototype whose advancement lies in making room-/zone-level climate monitoring more maintainable and interpretable through persistent spatial identifiers, BIM-native contextualisation, and interoperable state transfer. Accordingly, the paper illustrates (i) the BIM model and shared-parameter data schema, (ii) the configured cloud-to-BIM synchronisation pipeline, and (iii) intended use cases together with a KPI-driven evaluation strategy.

Case study and project context

The case study is the Living Lab established at MAcA, which is the first museum in Europe entirely dedicated to environmental issues, offering interactive exhibits, labs, and educational trails aimed at spreading environmental culture and supporting experiential learning. The museum (Figure 1) is in the north-west of Turin and in a post-industrial regeneration area facing Parco Dora with an overall surface of 3,500 square meters, including indoor and outdoor areas. It comprises two architectural bodies, a historic building and a newer volume, connected by an internal garden.

Figure 1: MAcA museum overview

Lying within the Po Valley, a densely populated and industrialised basin, particulate matter (PM) and other pollutants frequently exceed regulatory thresholds due to adverse meteorological and morphological conditions that reduce atmospheric mixing, especially in winter (ARPA Piemonte, 2024). Thus, MAcA is a meaningful testbed for setting up a DT focusing on indoor/outdoor microclimate and air quality awareness. Visitor-facing interpretation can connect measured values to broader environmental challenges, while operational monitoring can support comfort and risk mitigation in crowded educational spaces (World Health Organization, 2021). MAcA also provides an excellent "human–data interaction" environment as its mission explicitly targets schools and families through hands-on education. Furthermore, the museum runs structured programmes designed for school audiences. In 2024 it hosted over 34,400 visitors with 26,400 people coming from schools and groups (Associazione A come Ambiente, 2024). This is particularly relevant for a DT aimed at linking occupancy patterns and IEQ conditions (e.g., CO_2, particulate matter, thermal-hygrometric comfort) as comfort and air quality have both health and educational implications.

The development of the MaCA Living Lab is under the umbrella of the European Project NODES Spoke 4 "Digital innovation toward sustainable mountain", promoting digital technologies and services to improve sustainability and resilience in mountain territories and connected communities (ECS-NODES, 2025a). In particular, the INTERFACE flagship which aims to support the regeneration and repopulation of mountain territories through models sensitive to ecological context and participatory approaches capable of adapting to changing environmental conditions (ECS-NODES, 2025b). The MAcA Living Lab is used as a demonstrator where BIM-IoT integration, data-driven communication and monitoring workflows can be validated in a controlled public building and then transferred to other contexts (e.g., schools, cultural facilities, and tourism infrastructures), consistent with the mission of Spoke 4 (ECS-NODES, 2025a; ECS-NODES, 2025b).

Methodology and DT architecture

This work adopts a replicable methodology to set up a BIM-centric DT for sustainable cultural and educational buildings, combining (i) a stable semantic and spatial backbone in BIM, (ii) a heterogeneous IoT sensing infrastructure, and (iii) an automated synchronisation workflow that collects time-varying measurements into BIM parameters for contextualized interpretation, alerting and reporting. The approach is consistent with DT literature that frames built-asset DTs as layered cyber–physical ecosystems, where separation of concerns supports scalability and long-term maintainability (Fuller et al., 2020; Eneyew et al., 2022), and where semantic enrichment and standards-aware information management are essential to move beyond fragile prototypes (Boje et al., 2020; buildingSMART International, 2023). The long-term target is a whole-building DT, while the deployed implementation focuses on the currently sensorised ground floor as an initial deployment domain to validate mapping rules, data schema, and interpretability before scaling additional spaces. The implementation framework is designed along five steps, better described in the following sub-sections.

1. Sensing and stakeholder interfaces.

2. DT system architecture.
3. BIM model and data schema.
4. Data integration and synchronization pipeline.
5. Intended use cases and evaluation strategy.

Step 1 - Sensing and visualization interface

The first step establishes DT's physical observability and its human-facing interaction points. At this stage, the monitored variables and sensing strategy are selected to capture IEQ and occupancy-related dynamics that are relevant to comfort, air-quality awareness, and operational monitoring. In parallel, the approach defines how the DT will communicate these measurements to different stakeholder groups through appropriate interfaces, ensuring that collected data can be interpreted and acted upon rather than remaining isolated technical signals. Detailed descriptions of the deployed sensing assets and stakeholder interface components are reported in Step 2 within the DT layered architecture. This dual interface setup addresses a common barrier in DT adoption, where monitoring data exists but are not effectively translated into decision support and stakeholder understanding (O'Donnell et al., 2013; buildingSMART International, 2020).

Step 2 - DT system architecture

Step 2 defines the DT architecture as a separation-of-concerns system and specifies the data contract that links physical sensing, cloud time-series identifiers and BIM entities. Currently, the system is framed as an early-stage operational DT prototype, combining a monitored physical environment, a spatial-semantic digital counterpart, updateable data links, and user-oriented interpretative outputs, while live cloud synchronisation is still being progressively activated. Although the current implementation uses Revit and Dynamo as the orchestration environment for BIM-native write-back and inspection, the architecture is not intended as a fully centralised DT repository: longitudinal measurements remain managed in the external time-series layer, while BIM stores selected operational states for spatial contextualisation, traceability, and communication. The DT architecture is structured in five layers (Figure 2).

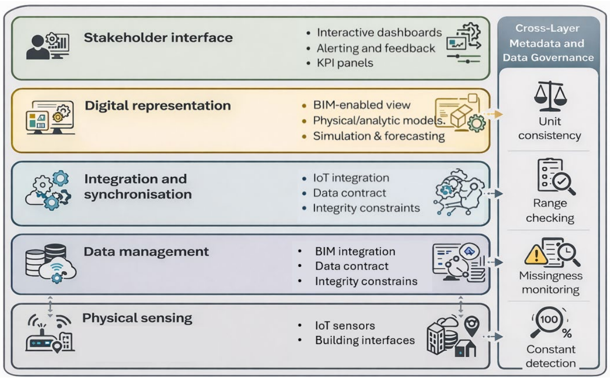

Figure 2: Layered DT architecture and data flow

This separation is widely adopted to support scalability and avoid tight coupling to vendor platforms (Fuller et al., 2020; Eneyew et al., 2022). Several contributions argue that semantic enrichment and standards-aware information management are necessary for DT ecosystems to become reliable beyond prototypes (Boje et al., 2020; buildingSMART International, 2023). In addition, the data contract includes explicit integrity constraints (e.g., unit consistency, range checks, missingness and constant-value detection) to prevent misleading interpretations and to support quality-controlled DT visualisations.

Physical sensing layer

This layer acquires IEQ and occupancy-related signals. The deployed devices measure indoor temperature, relative humidity (RH), carbon dioxide (CO_2), particulate matter (PM2.5, PM10), and occupancy indicators, complemented by outdoor boundary conditions via a weather station. The sensing stack combines KNX building automation devices and LoRaWAN (Long Range Wide Area Network) components to cover both stable IEQ monitoring and dynamic people-flow estimation. Sensor and device types, quantities, and monitored variables are summarised in Table 1 and are deployed across the sensorised domain to capture both environmental state and contextual drivers (occupancy/activity), enabling interpretation of microclimate variation as a function of use patterns. This heterogeneous configuration is designed to support both operational monitoring and educational interpretation by linking microclimate variations to occupant behaviour.

Table 1: Sensing devices deployed in the Living Lab

Sensor type	Qty	Variables measured	Technology
Weather station	1	Outdoor temperature, illuminance, wind, rain	KNX
Outdoor humidity	1	Outdoor RH	Analog (0–10V / 4–20mA) / integration to BMS
Air quality probes	5	PM2.5, PM10	KNX
Indoor multisensors	4	Temperature, RH, CO_2	KNX
Presence/activity sensors	4	Presence/activity, illuminance, noise proxy; (some nodes also expose pressure/dew point signals	KNX
IoT controller/gateway	4	Fieldbus integration (RS485), device bridging metadata	LoRaWAN + RS485
3D ToF people counters	4	People counting / flow direction	LoRaWAN

Data management layer

Sensor measurements are stored as time series in a provider-managed cloud environment. This layer decouples high-frequency ingestion from downstream consumers and provides a single authoritative data source with timestamps and metadata (e.g., sensor identifiers, variable types). The cloud layer decouples sensor ingestion from downstream consumers and supports historical queries and auditing. For the current validation phase, an exported time-series snapshot is used to test the downstream DT linkage. Currently, programmatic access to these cloud time series is under activation. The paper focuses on the integration contract (identifiers, schema and workflow) so that ingestion can be activated without re-authoring the BIM model once API (Application Programming Interface) credentials and endpoints are available.

Integration and synchronisation layer

This layer operationalises the cloud-to-BIM bridge. The proposed workflow is based on Autodesk Dynamo (i.e., visual programming) combined with embedded Python scripts to (i) query the BIM model for persistent space-level identifiers (MAcA_SpaceId), (ii) construct authenticated API requests to retrieve time-series values, (iii) validate and preprocess records (timestamp checks, missing values, unit normalisation, optional aggregation), and (iv) write validated values into BIM shared parameters. The workflow is designed to be inspectable and modular, supporting gradual extension to additional sensors and variables (Eneyew et al., 2022). In the current validation phase, the integration layer operates in a snapshot-based mode using exported time-series datasets. The same modules are designed to transition to authenticated live API queries once endpoints and credentials are available.

In practice, the integration workflow is implemented as a Dynamo graph operating within the Autodesk Revit environment, where Python scripts are used to parse time-series snapshots, apply temporal filters and threshold logic, and write aggregated results directly into BIM shared parameters associated with spaces and zones. The visual programming layer supports transparency and inspection of the data flow, while embedded scripts encapsulate reusable logic for data validation and aggregation.

Digital representation layer

This layer hosts the DT's digital counterpart as a BIM-based operational interface. The Autodesk Revit model functions as the stable spatial and semantic reference where measurements are contextualised, aggregated by zones, and visualised through native constructs such as schedules, view filters and colour-coded overrides. This aligns with research showing that spatially contextualised performance interpretation improves the usability of measured data and supports diagnostics (O'Donnell et al., 2013).

The detailed implementation of the Autodesk Revit model, including modelling scope, shared-parameter schema, sensor-to-model mapping rules, and standards-aware design choices, is presented in Step 3.

Stakeholder interface layer

This layer provides human-facing interpretation for both staff and visitors. The Living Lab deploys five 27-inch displays driven by local mini-PCs, supported by supervision/webserver components, to expose simplified indicators and narratives derived from the monitored variables. This interface layer is treated as integral to the DT ecosystem as it acts as a Human–Data Interaction (HDI) layer that exposes IEQ and occupancy dynamics in near real time, improving interpretability and bridging the gap between measurements and actionability of DT outputs (O'Donnell et al., 2013; buildingSMART International, 2020).

Table 2: summarises the deployed visualization and supervision components

Component	Qty.	Role
LCD monitor (27'')	5	Visitor facing real-time visualisation; staff situational awareness
Mini-PC	5	Local compute for visualisation and interaction
Supervision/energy management software	1	Integration layer; dashboards; device management
Webserver for remote or local interface	1	Remote or local access; integration services

Step 3 - BIM model and data schema

The third step focuses on the design of the BIM model as a semantic backbone for operational data binding and defines a parameter-based data schema to support persistent integration of environmental monitoring information. The BIM model is intentionally developed to prioritise operational interpretability and long-term maintainability rather than geometric detail, in line with operations-oriented BIM practices in facility management contexts (Sacks et al., 2020; Jiang et al., 2021). At the current stage, the model encompasses the sensorised ground-floor spaces, with explicit room and zone definitions to ensure consistent spatial contextualisation, aggregation, and reporting of monitored conditions.

Rather than establishing a one-to-one linkage between individual sensing devices and BIM elements, the adopted strategy associates monitored variables directly with spatial entities. Each space acts as a semantic container for a predefined set of environmental parameters, enabling the aggregation of sensor data at the room or zone level. This approach reduces coupling between physical devices and the BIM model, increasing robustness to sensor replacement, relocation, or changes in the sensing infrastructure, while preserving spatial meaning and continuity of historical records (Pauwels et al., 2017; Boje et al., 2020).

The shared-parameter schema reflects this aggregation-oriented logic and includes space-level parameters representing monitored environmental quantities (e.g., temperature, relative humidity, CO_2 concentration, PM2.5, PM10, illuminance), along with a timestamp parameter recording the last valid data update. Additional boolean or state parameters are used to encode threshold-based anomaly conditions derived from recent time windows, supporting alerting and reporting without requiring persistent storage of full time series within the BIM environment. This schema enables BIM-native views, filters, and colour-coded representations once synchronised values are written to the model (O'Donnell et al., 2013). The parameters are designed to be writable by external automation scripts, enabling repeatable BIM updates without manual interaction. In the current validation phase, time-series snapshots imported from external data sources are used both to verify data-to-space mapping integrity prior to live ingestion and to test transferability toward open representations, including IFC property sets (ISO, 2018; ISO, 2018a; buildingSMART International, 2020).

The same schema was therefore mapped to a custom IFC property set (PSet_MAcA_IoT) through a DefaultUserDefinedParameterSets configuration, exporting room-level entities as IfcSpace objects with MAcA_SpaceId, timestamp, and selected IEQ variables (Figure 3). In the BAR zone, for example, Z_Bar - CO2, Z_Bar - Temperatura, and Z_Bar - Umidità were exported as Bar_CO2, Bar_Temperature, and Bar_Humidity, while the same logic was replicated for CUPOLA and VERDE. Outdoor variables remain in the time-series layer in the current phase; accordingly, the interoperable exchange model prioritises room-level indoor states through IfcSpace-linked custom properties, while external boundary conditions remain outside the primary IFC export. Currently the prototype focuses on writable implementation logic, stable spatial identifiers, and standards-oriented exchange of selected operational states rather than on bSDD for formal semantic harmonisation.

Step 4 - Data integration and synchronization pipeline

Building on the shared-parameter schema defined in Step 3, Step 4 configures the automated data synchronisation pipeline responsible for injecting time-varying environmental measurements into the BIM model. The workflow is implemented using Autodesk Dynamo in combination with embedded Python scripts and is designed to operate at the space and zone level rather than at the individual sensor level (Figure 4).

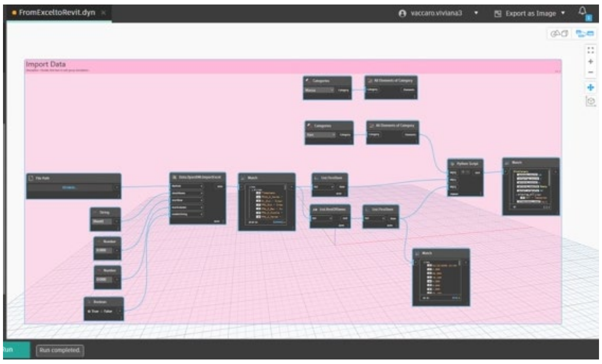

Figure 4: Dynamo based synchronization workflow

This design choice ensures robustness to changes in the sensing infrastructure while preserving the spatial interpretability of monitored conditions.

The synchronisation pipeline performs four main functions: (i) retrieval of structured monitoring data from external sources (currently via spreadsheet-based snapshots, with cloud-based time-series endpoints planned); (ii) temporal filtering and preprocessing of measurements, including timestamp parsing, unit normalisation, and aggregation over configurable time windows (e.g., rolling 24-hour periods); (iii) evaluation of threshold-based conditions to identify anomalous

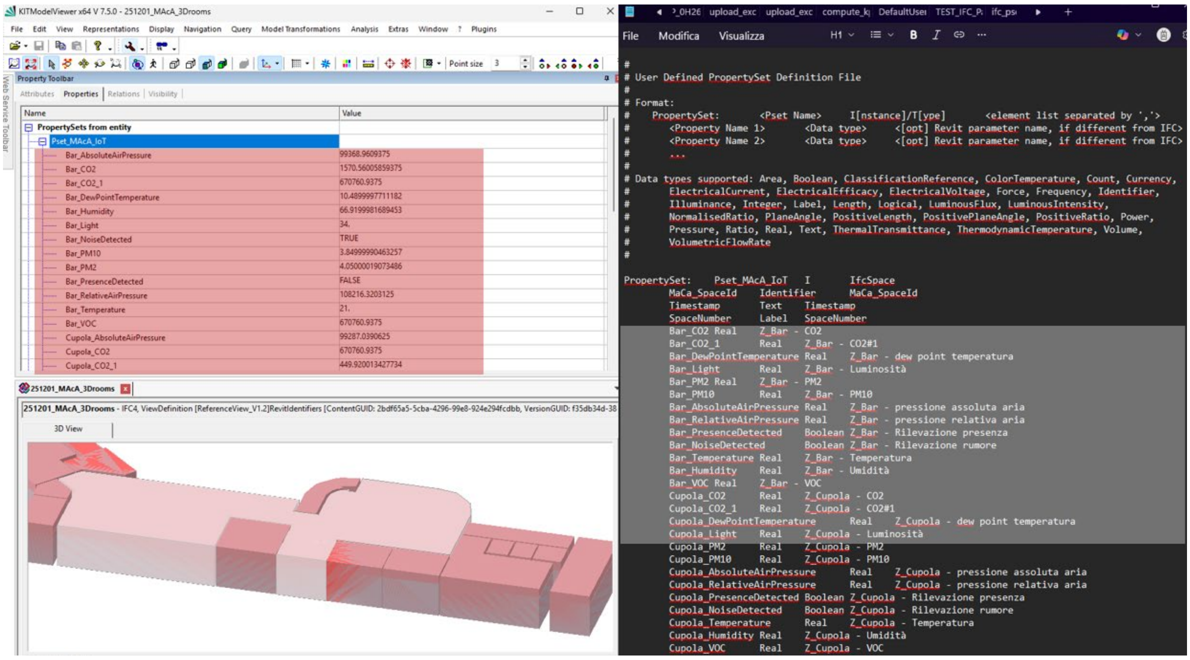

Figure 3: Custom PSet_MAcA_IoT definition and IFC-based export of room-level monitored states

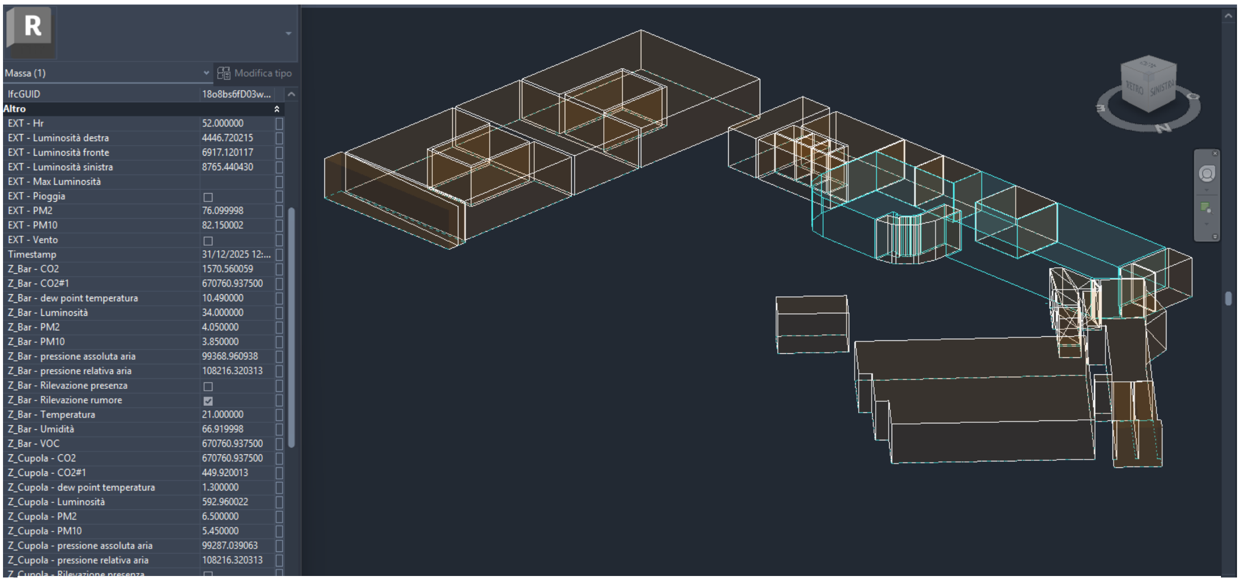

Figure 5: BIM contextualisation of monitoring data via shared parameters

environmental states; and (iv) writing of validated and aggregated values directly into predefined BIM parameters associated with rooms or zones, including measured quantities, last-update timestamps, and alert indicators. Rather than persisting full time series within the BIM environment, the pipeline selectively materialises operationally relevant summaries (e.g., maximum values over the last 24 hours and corresponding alert states). This approach enables BIM-native constructs, such as drafting views populated with automatically generated text-based annotations, view filters, and colour-coded overrides, to function as lightweight operational dashboards, supporting spatially contextualised interpretation of building performance without overloading the model with high-frequency data (Figure 5) (O'Donnell et al., 2013).

Within this workflow, Dynamo scripts directly write alert summaries and exceedance information into dedicated drafting views, allowing the BIM model to function as a self-contained, read-only operational reporting interface without relying on schedules or external dashboards.

At the current stage, live cloud access has not yet been activated; however, the synchronisation workflow is fully implemented and executable. Once data endpoints and authentication credentials are provided, the pipeline can be enabled without requiring modifications to the BIM model or its parameter schema, as the data-to-space association logic is already embedded in the operational configuration defined in Steps 2 and 3. This separation between model structure and data access supports incremental deployment and facilitates the progressive evolution of the system toward a fully operational DT. In this configuration, the time-series layer remains the authoritative source for longitudinal measurements and temporal analytics, while BIM hosts selected synchronised states for spatial-semantic contextualisation and operational interpretation.

Step 5 - Intended use cases and evaluation strategy

The last step of the methodology defines the intended DT capabilities and the evaluation protocol to be applied as integration progresses from snapshot-based validation to live synchronisation. The proposed DT supports three complementary functions: (i) operational observability of IEQ at zone level through continuous sensing; (ii) BIM-centric contextualisation, where monitored values are linked to spatial entities via persistent space-level identifiers (MAcA_SpaceId) and shared parameters; and (iii) stakeholder communication, where technical measurements are translated into readable indicators for educators, visitors, and facility staff. Evaluation is defined as an intended, KPI-driven strategy to be executed once live synchronisation is enabled, structured along three dimensions:

1. Pipeline performance and data reliability: quality criteria for time-series ingestion (latency, completeness, integrity);
2. Spatial correctness and interpretability: SpaceId mapping correctness; clarity of schedules and colour-coded views for staff;
3. Stakeholder usefulness: qualitative feedback on readability, perceived utility, and support to operational or educational decisions.

KPI logic and indicator interpretation will be grounded in recognised guidance for air quality and comfort, while preserving transparency on assumptions and data provenance.

Discussion

The first results support the feasibility of the proposed BIM-centric DT approach. A one-week monitoring excerpt sampled at 15-minute intervals was used as a testbed to verify end-to-end linkage between time-series measurements and the BIM environment, and descriptive statistics indicate meaningful room/zone-level IEQ dynamics. The test confirmed the successful population of shared parameters, timestamps, and alert-related fields from external records, showing that monitored values can be spatially contextualised in BIM without relying on full time-series storage within the model. This is relevant because the proposed logic reduces dependence on device-specific BIM bindings and supports more robust room- and zone-level interpretation under sensor replacement or reconfiguration. The validation also confirms that data-quality assurance and metadata governance (e.g, covering variable naming, units, channel definitions, and consistent cross-zone mapping) are first-class DT requirements before thresholding logic or public-facing indicators are operationalised (Boje et al., 2020; buildingSMART International, 2023). Accordingly, the workflow incorporates integrity checks on units, ranges, missingness, and constant values to reduce misleading interpretations and false alerts. On the integration side, a proof-of-concept BIM linkage was achieved: DT fields were instantiated as shared parameters in Revit, and a Dynamo-Python workflow was configured and tested to connect the exported snapshot to BIM parameters, enabling automated population and BIM-native representations. This confirms BIM's role as a spatial and semantic backbone for operational data binding, supporting zone aggregation and "where/which space" reasoning that complements conventional dashboards and improves interpretability of measured performance (O'Donnell et al., 2013). In this respect, the contribution is not the generic coexistence of BIM and IoT, but a more maintainable operational logic in which monitored values are bound to persistent spatial entities rather than to device-specific model objects, reducing fragility under sensor replacement or reconfiguration and enabling interoperable room-level state externalisation through IFC. A key implication is that the DT should be implemented as a dual representation system: BIM-based views for spatial traceability and contextual diagnosis, and time-series dashboards for temporal analytics, comparisons, and anomaly cues. Thresholds for alerting and exceedance logic will be anchored to authoritative guidance and widely adopted standards, including WHO guidance for particulate matter (World Health Organization, 2021), (ASHRAE, 2023; ISO, 2025) for thermal comfort, and CO_2 used as a ventilation/occupancy proxy with known limitations (Lu et al., 2022). In this direction, the installed museum screens, currently limited to vendor-default static content, will be progressively repurposed to display curated near real-time dashboards aligned with acquisition frequency, using read-only visualisations, role-based access control, and content governance. Overall, the main scaling challenges are robust metadata and point naming, systematic data-quality assurance, secure and maintainable cloud access, and stakeholder-oriented visual design for public-facing displays.

Conclusions

This paper presented a BIM-centred, stepwise framework for integrating, contextualising, and operationally interpreting environmental monitoring data in a living-lab setting. Through the MAcA case study, the work showed how a DT can be implemented by using BIM not as a passive geometric repository, but as an active semantic interface for spatially grounded monitoring, alerting, and reporting. Rather than pursuing a device-centric or fully control-oriented architecture, the proposed approach intentionally operates at room/zone level, aligning data representation with practical facility-management reasoning and stakeholder interpretation.

The contribution lies not only in the use of a five-layer DT framework, but in its BIM-centric operationalisation for room- and zone-level monitoring, combining persistent spatial identifiers, a writable shared-parameter schema, an incremental path from snapshot-based validation to live synchronisation, and preliminary IFC-based transferability. In the current implementation phase, this approach has been validated through snapshot-to-BIM integration using a Dynamo-Python workflow, confirming that BIM-native views can support early operational interpretation without requiring invasive model re-authoring. The study also indicates that effective DT adoption in cultural or public buildings depends on balancing technical integration with interpretability, governance, and maintainability. In this configuration, BIM is not treated as a fully centralised repository of DT information, but as a spatial-semantic interface coupled with external time-series infrastructures and interoperable exchange mechanisms. Future work will extend live cloud ingestion, consolidate IFC-aligned interoperable exchange, and refine role-based interfaces for operational and public-facing use.

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