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D10.2 – DIGITAL SOLUTION FOR THE MULTI-PURPOSE MONITORING OF ENVIRONMENTAL AND STRUCTURAL BEHAVIOUR OF BUILDINGS DEVELOPMENT FOR THE APPLICATION TO A REAL DEMO

SEPTEMBER 2025 | LIS

MULTICLIMACT

D10.2 - DIGITAL SOLUTION FOR THE MULTI-PURPOSE MONITORING OF ENVIRONMENTAL AND STRUCTURAL BEHAVIOUR OF BUILDINGS DEVELOPMENT FOR THE APPLICATION TO A REAL DEMO

Project Title	MULTI-faceted CLIMate adaptation ACTions to improve resilience, preparedness and responsiveness of the built environment against multiple hazards at multiple scales
Project Acronym	MULTICLIMACT
Contract Number	101123538
Project Coordinator	Rina Consulting S.p.A.
WP Leader:	ENEA

Deliverable	D10.2 – Digital solution for the multi-purpose monitoring of environmental and structural behaviour of buildings development for the application to a real demo
DoA	D10.2 – Digital solution for the multi-purpose monitoring of environmental and structural behaviour of buildings development for the application to a real demo
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REVISION TABLE

Version	Date	What
0.1		ToC
1.0	31/07/2025	First draft version for internal revision.
1.1		Prefinal version ready for coordinator quality check
2.0		Final version ready for submission

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Abbreviations and Acronyms

ACRONYM	DESCRIPTION
AI	Artificial Intelligence
API	Application programming interface
APK	Android Application Package
BIM	Building Information Modeling
BLE	Bluetooth Low Energy
CDE	Common Data Environment
CEIs	Civil engineering infrastructure
CIW	Climate Innovation Windows
CPS	Cyber physical system
DBMS	Database Management System
DES	Discrete-state, event-driven system
DLT	Distributed ledger technology
DT	Digital Twin
E&C	Engineering & Construction
EEG	ElectroEncephaloGram
EU	European Union
EWS	Early warning System
FoS	Factor of Safety
GW	Gateway
GPS	Global Positioning System
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
HRV	Heart Rate Variability
IAQ	Indoor Air Quality
IEEE	The Institute of Electrical and Electronics Engineer
IoT	Internet of things
IFC	Industry Foundation Classes
LCA	Life cycle assessment

MCU	Microcontroller unit
ML	Machine Learning
MVP	Minimum viable product
NDE	Non-destructive evaluation
NDT	Non-Destructive Testing
NRT	Near Real-Time
O&M	Operations and Maintenance
OTA	Over-The-Air
PAN	Personal Area Network or (WPAN: Wireless PAN)
PoA	Plan of Approach
PoC	Proof of Concept
PPG	PhotoPlethysmoGram
PPP	Public-Private Partnership
RC	Reinforced Concrete
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures
SE	Semantic Enrichment
SHM	Structural Health Monitoring
SRD	System Requirements Document
TCO	Total-Cost-of-Ownership
UI	User Interface
UX	User Experience
WSN	Wireless Sensor Network
XSS	Cross Site Scripting
LSTM	Long Short-Term Memory
GNN	Graph Neural Network
EN 1998-1	Eurocode 8 Part 1
EDA	Electrodermal Activity
VOCs	Volatile Organic Compounds
$PM_1/PM_{2.5}/PM_{10}$	Particulate Matter (sizes)
RH	Relative Humidity

CYPETHERM EPlus	CYPE energy simulation tool
CYPECAD	CYPE structural analysis tool
IEEE MetroLivEnv	IEEE International Workshop on Metrology for Living Environment
PANAS	Positive and Negative Affect Schedule
DOMX	IoT Node for environmental sensors
EmotiBit	Wearable biosensor device (brand)
V-Model	Development framework pairing each dev phase with a test phase
SDLC	Software Development Life Cycle
WP / WPs	Work Package(s)
T4.2 / T10.2 / T11.1	Task 4.2 / 10.2 / 11.1
KPI / KPIs	Key Performance Indicator(s)
UI/UX	User Interface / User Experience
IAQ	Indoor Air Quality
SHM	Structural Health Monitoring
XPS	High-performing, rigid foam insulation board
NaN	In computing, NaN standing for Not a Number
PCHIP	Piecewise Cubic Hermite Interpolating Polynomial
EPS	Expanded Polystyrene
PMV	Predicted Mean Vote
iOS	Apple Mobile Operating System
PWA	Progressive Web App
PCA	Principal Component Analysis

Executive Summary

Deliverable 10.2, "Digital solution for the multi-purpose monitoring of environmental and structural behaviour of buildings development for the application to a real demo," is a key output of the MULTICLIMACT project, funded by the European Union's Horizon Europe Program (2021–2027) under the Grant Agreement No. 101123538.

The main objective is to further enhance the LIS BIM-based platform (LIS-Platform) by integrating IoT sensor data for real-time monitoring of structural health, environmental conditions, and occupants' well-being in buildings.

The LIS-Platform is an advanced digital solution that integrates software, BIM, and IoT devices to enable intelligent, self-sensing structures. It addresses the diverse needs of stakeholders by enhancing resilience and adaptability to climatic and environmental challenges in the construction sector. Additionally, the platform connects with IoT wearable devices to collect physiological data from occupants while simultaneously monitoring environmental conditions, providing valuable insights into occupant health and well-being. Building on the design and development activities carried out in Task T4.2 and reported in Deliverable D4.2, this deliverable presents the progress achieved in Task T10.2, demonstrating the advancement of the LIS-Platform from Technology Readiness Level (TRL) 5 at the start of MULTICLIMACT to TRL 7. The software continues to operate as a web-based platform, consistent with the previous version, while an Android-based mobile version has now reached version 1.0.

To achieve the main objective, the following partners were involved in carrying out the tasks.

- UNICAM recommends sensors for Structural Health Monitoring and by providing BIM/CAD files.
- CYPE: Designs digital models and exports to the LIS-Platform, including energy simulation.
- ENEA: Integration of non-destructive testing data & evaluation of hygrothermal behaviour.
- LIS: Enhances BIM models by transforming them into dynamic, real-time representations.
- UNIVPM: Selecting sensors, testing & assessing environmental and physiological variables.
- UKA: Support environmental and physiological variables related to health and well-being.
- BRC: Promotes the LIS-Platform as a flagship solution within the MULTICLIMACT project.
- RINA-C: Support the overall task, by provide a comprehensive overview.

Key Results:

- The solution has been fully developed and finalized, tested in two separate *pre-pilot* phases, and is now ready for deployment in the project Italian pilot.
- Full Integration & Interoperability: Successfully integrated the BIM model, selected sensors, and data into the LIS-Platform.

Achievements:

- Mobile Application: Released the LIS mobile app for Android, including the BIM Viewer with all web features.
- LIS-Platform: Supports multiple users, groups, buildings with versioning, plus IoT devices and sensors (pilot-ready for deployment).
- The Data Analysis Platform, integrated into the LIS-Platform, includes AI/ML capabilities and supports navigation of BIM models, objects, sensor data, and clustering.

Initial findings have been presented in various peer-reviewed papers and articles.

1. INTRODUCTION

As with any structured project, a guiding framework or methodology is essential to ensure clarity, consistency, and alignment among all participants throughout the various project phases. Due to its reliability and structured, documentation-driven nature, the V-Model was selected as the overarching framework for this work. V-Model (Verification and Validation Model) is a software development life cycle (SDLC). This model is being applied across relevant Work Packages (WPs) within the MULTICLIMACT project, particularly in WP4, WP10, and WP11, where LIS is actively involved in Tasks T4.2, T10.2, and T11.1. The V-Model's typical validation phases are outlined is shown in Figure 1 and are organized around key documentation steps. This document, submitted as a formal deliverable, forms the foundation for Task 11.1 and supports both the development and part of the deployment phases of the Italian pilot within the MULTICLIMACT project.

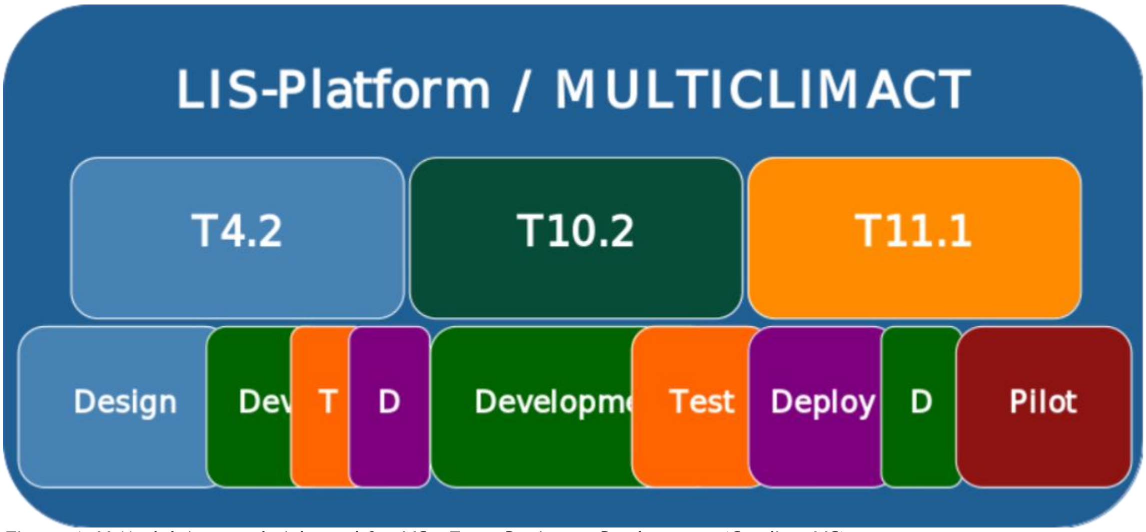

Figure 1. V-Model Approach Adapted for LIS - From Design to Deployment (Credits: LIS)

1.1. PURPOSE AND TARGET GROUP

The purpose of this deliverable is to track, document, and showcase the advancement of the LIS-Platform, elevating its Technology Readiness Level (TRL) from TRL 5, as established at the start of the MULTICLIMACT Project, to TRL 7. Achieving TRL 7 will demonstrate that the platform is operational in a near-real environment and constitutes the appropriate foundation for its full-scale deployment in a real-world scenario within the Italian Pilot. The selected site for this implementation is the Carmelitane building in Camerino (EX-Carmelitane), Italy. Through the integration of contributions from MULTICLIMACT project partners, a comprehensive digital model of the building will be developed and employed to manage and execute the Italian pilot. This model will enable project partners to adopt the LIS-Platform as the core BIM-based environment for generating semantically enriched models. These models will incorporate key performance indicators (KPIs) from multiple domains within the MULTICLIMACT project, with real-time sensor data providing live monitoring and adaptive response capabilities. Given the multidisciplinary nature of the project and the diverse expertise of the partners involved, specific responsibilities have been allocated according to each partner's domain.

1.2. CONTRIBUTIONS OF PARTNERS

The following table depicts the main contributions from project partners in the development of this deliverable. The contribution of each partner was important in drafting this document as the deliverable. All parts of the digital solution developed in this task and described in this deliverable were carried out by LIS; nevertheless, contributions from partners were evaluated during different design and development stages.

PARTNER SHORT NAME	CONTRIBUTIONS
LIS	Main content
CYPE	General document structure, Sections: 5.1, 7.1, 7.2, 7.3.
UNIVPM	Part Section 6, general revision of the document
UKA	Part Section 6
UNICAM	Part Section 4.2
ENEA	Section 5.4
BRC	Part Section 9
RINA-C	Part Section 5.2

Table 1. Contributions of Partners

2. OBJECTIVES AND EXPECTED IMPACT

The following table depicts the main contributions from project partners, their specific objectives, expected impacts, and group stakeholders.

PARTNER	OBJECTIVE	DESCRIPTION	EXPECTED IMPACT	TARGET GROUP/STAKEHOLDER
LIS	Lead development of platform and app; integrate BIM and sensor data, data analysis.	Integrated BIM model of Palazzo Fazzini and Carmelitane building. Connected platform to IoT sensors. Implemented data repository and clustering modules. Developed LIS mobile companion app and fully tested its connection with LIS-Platform.	Completed development.	Partners and all the stakeholders mentioned below.
CYPE	Provide BIM modeling tools and simulation of alternative scenarios	Developed BIM model export-ready for platform Supported scenario-based simulations	Allows “what-if” assessments (e.g. energy)	Problem owners, innovators, end-users, entities, municipalities, regions, institutions, universities, research institutions Building owners Public Administration
UKA	Contribute occupant health & wellbeing surveys	Uploaded occupant comfort & wellbeing	Enables assessment of	Researchers, public institutions, building managers

			occupant well-being	
UNIVPM	Support platform data ingestion and initial analytics	Integrated sensors to monitor building and its occupants from different perspectives: Environmental context (e.g., air temperature and relative humidity) - Physiological status (e.g., photoplethysmographic signal) - Building structural health (e.g., electrical impedance for SHM)	Real-time data flow into platform; validated data integrity; data processing pipeline	Researchers, public institutions, building managers occupants and caregivers
UNICAM	Assisted in sensor installation and details about the Carmelitane building eg. BIM/CAD documentation.	Provided detailed indications about the Carmelitane building for the pilot.	Contribution in developing a multidomain monitoring system	Researchers, public institutions, building managers and occupants
RINA-C	Support overall task.	Research the state of the art for BIM-based platforms and explain the integration between the CREMA tool and the LIS-Platform.	Provide a comprehensive explanation and facilitate a deeper understanding of the CREMA Tool, particularly its features and integration within the LIS-Platform.	Partners, Public.
ENEA	Support on non-destructive testing data. Evaluating the hygrothermal behaviour.	Provided non-destructive data for testing. Palazzo Fazzini. Evaluating the hygrothermal behaviour with a new measurement campaign for the Carmelitane building.	Improve the level of resilience of the system of interest considering the current and expected risk scenarios	Civil Protection, Municipalities, building managers, building owner
BRC	Communicate platform use and align demo with stakeholders needs	Prepared dissemination content on platform and app usage	Enhances visibility, uptake potential, stakeholder feedback loop	End-users, region authorities, innovators

Table 2. Partner-specific Objectives, Outputs & Expected Impact for T10.2

3. OVERALL APPROACH

3.1. STRUCTURE OF THE DELIVERABLE

This document serves as the deliverable D10.2 of the MULTICLIMACT Project. In certain sections, the content has been simplified from previously referenced documents that do not require full chapters in this document. For more detailed information, please refer to the appendix, external links, or request the full documentation. We have focused on including the most relevant parts, as the original documents may be beyond the scope of this deliverable.

3.2. MOSCOW ANALYSIS

MoSCoW analysis is a prioritization technique used in project management to help teams categorize requirements, tasks, or features based on their importance. The term "MoSCoW" is an acronym where each letter represents a priority category:

- MUST have: Critical requirements that are essential for the project's success. Without these, the project would fail.
- SHOULD have: Important requirements that are not vital but add significant value. These can be omitted, if necessary, but it would affect the project's value or performance.
- COULD have: Desirable requirements that are nice to have but not essential. These can be included if time and resources permit.
- WON'T have (this time): Requirements that are agreed to be out of scope for the current phase or release but may be considered for future iterations.

Since most of the partners were new to the methodology, their contributions to the design phase (Task 4.2) were broken down into smaller components, linked to partner dependencies. The 'accepted' status indicates that these contributions were formally validated at the beginning of the MULTICLIMACT Project. Following Task 10.2, the 'progress' status is used to track their evolution.

The following table, first introduced at the beginning of the project during the design phase (Task 4.2), is now being further developed as part of the development phase (Task 10.2).

P/TASK	ACCEPTANCE STACIAO TUS	DESCRIPTION	PRIORITY	PROGRESS
LIS_1	Accepted	A web app enabling users to define and assign roles, provision new nodes and integrate into the building.	MUST	done
LIS_2	Accepted	Data processing to extract actionable information regarding building structural health monitoring, environment quality, wellbeing. *	MUST	done
LIS_3	Accepted	Management of different device models and sensors (3rd party) in the web app and API	SHOULD	done
LIS_4	Accepted	UI/UX for data visualization and analysis with basic ML models in the web app.	MUST	done
LIS_5	Accepted	Generic notification system in the web app. Early warning system included. *	MUST	done
LIS_6	Accepted	Implementing data integrity guarantees in the System Architecture.	SHOULD	done
LIS_7	Accepted	Users can interact with the building; view sensor data and notifications related to the building itself.	MUST	done
LIS_8	Accepted	Implementing an interoperability layer (the system must communicate and interact with other platforms).	MUST	done
LIS_9	Accepted	Capability to generate reports and export data in PDF/CSV formats.	SHOULD	done
LIS_10	Accepted	Implementation of researcher user roles (read-only access, pseudonymized information).	SHOULD	done
LIS_11	Accepted	Support multiple devices as IoT sensor nodes, e.g sensor and actuators, support multiple	SHOULD	done

LIS_12	Accepted	API backend enabling read and write operations on the database of the web app with authentication	MUST	done
LIS_13	Accepted	Gateway collecting data from multiple devices and sending them to the LIS-API. [depends on #12]	MUST	done
LIS_14	Accepted	Mobile app implementing essential features from the web app.	COULD	done
LIS_15	Accepted	Password-less authentication (WebAuthn API) for users.	COULD	done
LIS_16	Accepted	Generation of reports in the mobile app and capability to export and send them via email, using external apps.	COULD	done
LIS_17	Accepted	ML & AI Algorithms	COULD	done
LIS_18	Accepted	Automatic recall for emergency services (dangerous situations, earthquakes, medical issues, fires, and flooding events) with auto-generated voice.	COULD	In progress
LIS_19	Accepted	Automatic basic labeling, and basic pattern recognitions for SHM, and quality of living*	COULD	done
LIS_20	Accepted	BIM model	WON'T	-
UNIVPM_1	Accepted	Sensors specifications: type of data and requirements for integration in LIS-Platform	MUST	done
UNIVPM_2	Accepted	Functions for health and well-being	MUST	In further progress within T11.1
UNICAM_1	Accepted	Indications about the typology of sensors to adopt in seismic monitoring system on a building scale	MUST	done
UKA_1	Accepted	Inclusion of subjective assessments regarding health, well-being & perception of the environment	COULD	done
BRC_1	Accepted	Adding the LIS information of the innovation in climate innovation windows	MUST	done
BRC_2	Accepted	Developing a stakeholders engagement plan, initiative for proper end user for this type of innovations	MUST	done
BRC_3	Accepted	Capacity building plan/activity for universities representative and existing innovators in the online market CIW	MUST	In progress WP16
RINA-C_1	Accepted	Support overall task.	SHOULD	done
ENEA_1	Accepted	Type of data and requirements for integration in LIS-Platform	MUST	done
ENEA_2	Accepted	Inclusion in the historical data feature of damage assessment data, obtained by correlation of advanced nondestructive testing (ultrasonic tomography and sonic measurements) and destructive testing	MUST	done
ENEA_3	Accepted	Development of a replicable methodology for the assessment of mechanical properties of building material after extreme actions such as earthquake	COULD	Testing integration with LIS-Platform (delay pilot change)
CYPE_1	Accepted	Integration of BIM models for Fazzini demo case: architecture, sensors and structure simulation.	MUST	done

Table 3. MoSCoW Analysis & Progress

3.3. SYSTEM REQUIREMENTS

In this paragraph, a brief introduction to the system requirements will be provided, although these were already described in Task 4.2 of the MULTICLIMACT Project.

In the V-Model, system requirements constitute a formal specification of the system's intended capabilities, encompassing its functional behaviour, performance criteria, interface characteristics, and security constraints, while remaining agnostic to implementation details. Articulated during the requirements analysis phase, these specifications provide the authoritative reference for subsequent design activities and serve as the validation baseline during system-level testing. These requirements were discussed and agreed upon during the first half of the first year of the MULTICLIMACT project. Extensive meetings were held, after which LIS drafted a Plan of Approach (PoA) that was shared with all task partners. Since most of the core implementation is based on the LIS Platform, LIS was able to progress independently with design and development, guided by the initial input and subsequent feedback from partners. For LIS, this approach was the most effective way to achieve high-quality results while incorporating the domain-specific expertise of various partners. The PoA document is available in the project's shared workspace and can be made public upon request.

3.3.1. SPECIFICATIONS USER REQUIREMENTS

- Web Application: Enable users to define and assign roles, provision new nodes, and integrate them into the building.
- Data Processing: Extract actionable information regarding building structural health monitoring, environmental quality, and occupant well-being.
- UI/UX: Provide an interface for data visualization and analysis with basic ML models integrated into the web app.
- Notification System: Include a generic notification system in the web app, with an early warning system (EWS) included.
- User Interaction: Allow users to interact with the building, view sensor data, and receive notifications related to the building.

3.3.2. TECHNICAL REQUIREMENTS

Based on the previously mentioned MoSCoW analysis, this table presents the technical requirements.

P/TASK	STATUS	DESCRIPTION	PRIORITY	PROGRESS
LIS_1	Web app enabling users to define and assign roles, provision new nodes and integrate into the building.	Cross platform and without installing anything on clients	MUST	done
LIS_2	Data processing to extract actionable information regarding building structural health monitoring, environment quality, wellbeing.	Data must be processed to extract relevant information	MUST	done
LIS_3	Management of different device models and sensors (3rd party) in the web app and API	Enable the integration of different devices from different vendors in the future	SHOULD	done
LIS_4	UI/UX for data visualization and analysis with basic ML models in the web app.	Users must view data in a user-friendly way	MUST	done

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LIS_5	Generic notification system in the web app. Early warning system included.	Notifications can alert people inside buildings and relevant users of the platform	MUST	done
LIS_6	Implementing data integrity guarantees in the System Architecture.	Data integrity is crucial and the better technologies ensuring it should be evaluated	SHOULD	done
LIS_7	Users can interact with the building; view sensor data and notifications related to the building itself.	UI to interact with the BIM model must be user-friendly	MUST	done
LIS_8	Implementing an interoperability layer (the system must communicate and interact with other platforms).	There is the need to communicate and interact with other diverse platforms	MUST	done
LIS_9	Capability to generate reports and export data in PDF/CSV formats.	This is a tool to export easily data	SHOULD	done
LIS_10	Implementation of researcher user roles (read-only access, pseudonymized information).	Researchers can access all data without privacy implications	SHOULD	done
LIS_11	Support multiple devices as IoT sensor nodes, e.g sensor and actuators.	Multiple and diverse devices will be connected to the platform in the future	SHOULD	done
LIS_12	API backend enabling read and write operations on the database of the web app with authentication	API can provide a secure and efficient way to save and access data	MUST	done
LIS_13	Gateway collecting data from multiple devices and sending them to the LIS-API.	The Gateway can send aggregated data from multiple devices in one time	MUST	done
LIS_14	Mobile app implementing essential features from the web app.	Increase the usability on mobile devices	COULD	done
LIS_15	Passwordless authentication (WebAuthn API) for users.	Enhance the authentication mechanism	COULD	done
LIS_16	Generation of reports in the mobile app and capability to export and send them via email, using external apps.	Convenient way to share data with other involved people	COULD	done
LIS_17	ML & AI Algorithms	AI can improve the analysis of data	COULD	done
LIS_18	Automatic recall for emergency services (dangerous situations, earthquakes, medical issues, fires, and flooding events) with auto-generated voice.	Useful function for emergencies	COULD	In progress
LIS_19	Automatic basic labelling, basic pattern recognitions for SHM, and quality of living.	Auto labelling can reduce times	COULD	done

Table 4. LIS's progress so far in line with the requirements.

3.4. INTERACTION WITH OTHER TASKS

The table below summarizes how this task connects to others.

TASK	DESCRIPTION	INPUT DATA	PARTNER (SRC)	OUTPUT DATA	PARTNER (DST)
T8.5	Subjective data from questionnaires	Survey data	UKA	GRAPHs	UNICAM/LIS
T8.5	Environmental and physiological data from sensors	Sensor type, data type	UNIVPM	Raw data (time series) for defining health and well-being synthetic indices	UNIVPM, UKA
T9.3	Thermo-hygrometric data from sensors at laboratory scale	Sensor type, data type	ENEA	Raw data (time series) for defining Thermo-hygrometric behaviour	LIS
T11.1	Environmental and physiological data from sensors	Sensor type, data type	UNIVPM	Raw data (time series) to be processed to enrich BIM Model	UNIVPM, LIS
T11.1	Test of the MULTICLIMACT solutions, exploiting the monitoring protocol and systems	Input data from LIS-Platform + factor type	LIS	Graphs	UNICAM
T11.1	SHM data from sensors	Sensor type, data type	UNIVPM	Raw data (time series) to be processed to enrich BIM	UNIVPM, LIS
T11.1	Data from sensors during seismic events	Sensor type	UNICAM	Time series	UNICAM
T15.1	Data from sensors during seismic events	Sensor type	UNICAM	Time series	UNICAM
T15.1	Thermo-hygrometric data from sensors at the building scale	Sensor type	ENEA	GRAPHs (time series)	UNICAM

Table 5. Interaction with Other Tasks - Data Flow (Inputs, Outputs, Sources, Destinations)

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4. BACKGROUND AND CONTEXT

The following paragraph presents the background and context that were taken into account as the initial status.

4.1. PREVIOUS WORKS (TASK 4.2 OUTCOMES)

Task 4.2 delivered the strategic design and prototype of the LIS-Platform, a BIM-based Smart Building OS engineered for near real-time multi-domain monitoring in Fazzini building in Camerino. The platform merges BIM models, IoT environmental and structural sensors, and physiological wearable data to evaluate building performance, occupant health, energy efficiency, and structural integrity.

Key outcomes included:

- Initial release of the Android-based LIS mobile app, offering IFC-model visualization, sensor data display, and on-site interaction in an alpha version using Flutter and Bloc architecture.
- Creation of the BIM model for Palazzo Fazzini building, enriched with non-destructive testing (NDT) results (sonic, ultrasonic tomography) and sensor typology.
- Modular platform architecture, supporting role-based access, multiple IoT and biosensor types, push notifications, emergency SOS features, and dynamic integration of live data into the BIM model (version control, event tracking).
- Sensor deployment specifications: structural monitoring via self-sensing ECC blocks and environmental monitoring with natural-based insulation panels and DomX IAQ sensors and sensors for physiological monitoring (Emotibit) chosen and provided by UNIVPM.
- Human-centric and resilience-focused metrics, combining environmental readings (temperature, humidity, CO_2, air velocity) with wearable physiological data (PPG, skin temperature) and psychological surveys (PANAS, perceived control).
- Data repository and dashboard capability, enabling partner access to key indicators—energy efficiency, structural health, thermal comfort, well-being—and underpinning scenario modelling and decision-support.
- Interoperability and integrity proof-of-concept, showcasing the LIS-Platform’s ability to integrate with ENEA’s Smart City Platform (UrbanDataset) and testing blockchain-based data integrity layers (PoC).

These outcomes set the technical and architectural foundation for D10.2, providing the blueprint for full development and deployment of the monitoring infrastructure including BIM, sensor networks, analytics, app interfaces, and stakeholder tools at the Carmelitane building.

4.2. CHANGE OF THE DEMONSTRATION PILOT

As with many projects, delays, changes, and uncertainties may arise, typically positioned on the right side of the risk matrix.

4.2.1. INITIAL PILOT: PALAZZO FAZZINI

At the start of the project, the LIS Platform was at TRL 5, and the LIS team was able to design and develop most of the modules and subsystems. To ensure optimal performance during both the development phase (Task 10.2) and the pilot phase (Task 11.1), an early setup was carried out at the LIS Office at UNIVPM. This helped build and configure the system for the pilot. Palazzo Fazzini, a former residential building in Camerino, was selected as the first Italian demo site to test the integration of structural and environmental monitoring within the LIS Platform. The pilot aimed to validate real-time data integration, interoperability, and stakeholder-oriented functionalities. The rationale behind the change of the demonstration site, also referred to as the Italian pilot, will be explained below.

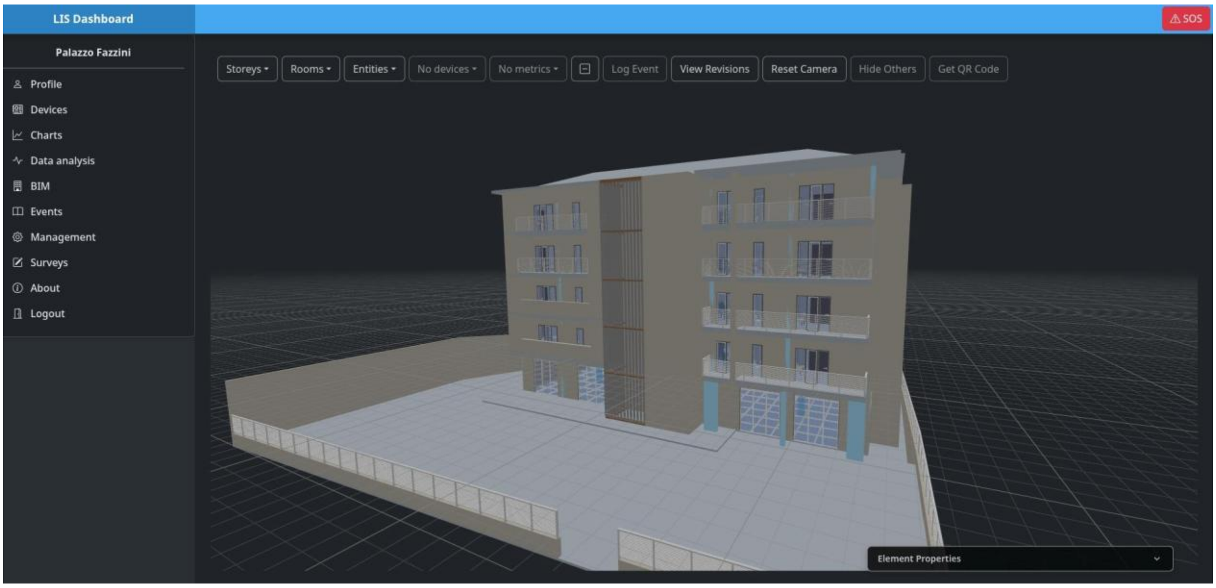

Figure 2. Palazzo Fazzini BIM model within LIS-Platform (Credits: LIS)

The design and part of the development for the Palazzo Fazzini were already undertaken during Task 4.2 of the MULTICLIMACT Project. However, as the change of the pilot became evident, it was determined that while some elements of the previous work may still be applicable, the majority will need to be redeveloped from the beginning.

Key Activities:

- BIM Model
- Using inputs from UNICAM and LIS, CYPE developed a semantic BIM model, exported in IFC format and integrated into the LIS-Platform to enable real-time data visualization and enrichment.
- Non-Destructive Testing (NDT) by ENEA
- Ultrasonic, sonic, tomographic, and pacometric tests on key structural elements. The results, including wave speeds and internal anomalies, were visualized in the LIS-Platform as heatmaps and versioned snapshots.
- Sensor Integration by UNIVPM & UNICAM
- UNICAM specified seismic sensors for structural health monitoring, while UNIVPM tested environmental, physiological sensors (e.g., PPG, CO_2, skin temperature) to monitor occupant well-being and sensors for the measurement of electrical impedance and free corrosion potential. These guided sensor deployment strategies.
- Platform & Mobile App Development
- The LIS-Platform prototype supported user roles, alerts, and event logging. An Android app enabled on-site viewing of the BIM model and sensor data, with browser access to model versions and test results.

Impact & Outcomes

- Full Integration: BIM, sensor data, and NDT results combined into a live, semantically enriched digital model.
- Interoperability: Features like IFC support, live streaming, and alerting proved platform flexibility.
- Stakeholder Value: The system addressed needs across facility management, civil protection, and research.

Foundation for Task 10.2

This pilot established the technical and operational basis for the next demonstration at the Carmelitane building. It validated core capabilities, including BIM-sensor fusion, NDT integration, and mobile-enabled interaction. As the MULTICLIMACT project progressed, it became clear that the pilot site was still not accessible. Consequently, the LIS team, together with the UNIVPM team, agreed to use the LIS Office as a testing lab for all components required by the project. This included wellbeing tests with wearable devices carried out under Task 8.5. This solution proved highly effective, as both Task 8.5 and Task 10.2 could be completed without delays. From this point forward, in this document we refer to the LIS Office as the *pre-pilot* or validation pilot.

4.2.2. FINAL PILOT: CARMELITANE BUILDING (EX-CARMELITANE)

Description

At the end of the 14th century, the Apostolic Chamber granted the site to the Servants of Mary, who built a church and convent there. In 1653, Pope Innocent X suppressed the convent, but it was soon re-founded and entrusted to the Discalced Carmelite Fathers. On that occasion, both church and convent were rebuilt according to designs by Father Gian Battista Bartoli, an architect. The convent remained active until the advent of the Kingdom of Italy, when it was confiscated along with other ecclesiastical properties. Over the following centuries, the building underwent diverse transformations: first as a Reformatory, then as a House of Correction, and later as a Re-education House for minors. The convent’s extensive vegetable garden was converted into an agricultural colony for young prisoners. In 1936, the church was restored and reopened for worship, while in 1967 the complex became the seat of the newly founded Academy of Fine Arts. The ancient convent garden was transformed into a public park, today known as Parco della Resistenza, located beneath the Albornoz fortress. It currently hosts university spin-offs and administrative offices of the University of Camerino, thereby reinforcing its relevance as a critical asset for both academic activities and the socio-economic fabric of the city.

Strategic Shift from Original Demonstration Site

The MULTICLIMACT Italian demonstration site underwent a strategic transition from the originally planned Fazzini student residence to the Ex-Carmelitane building. This change was necessitated by significant delays in the retrofitting works of the Fazzini residence, which were scheduled to commence after January 2025, creating potential risks for the project timeline and implementation of the MULTICLIMACT toolkit solutions. The shift represents a proactive adaptation to ensure the successful delivery of project objectives within the established timeframe. In-situ NDT data from the Palazzo Fazzini campaign (Task 4.2) were integrated into the BIM model and made accessible via the LIS-Platform. This allows continued analysis of the site, now designated as a second *pre-pilot* (Task 10.2). In summary, three different BIM models were created and are now stored in the LIS Platform.

- LIS Office at UNIVPM
- Palazzo Fazzini
- Carmelitane building (ex-Carmelitane);

Their development required three approaches: (i) static data represented in Figure 2 and its mathematical models during NDT as shown in

Figure 29. Heatmaps Generated from NDT Information of Palazzo Fazzini within the LIS-Platform (Credits: LIS)

(ii) dynamic data from sensors and IoT devices in Figure 19, and (iii) a final pilot where a mixed strategy was applied. Although this went beyond the scope envisioned in the Grant Agreement, several partners agreed to make an extra effort. As a result, the LIS team developed a version control system within the platform that enables switching between versions and navigating across different digital models. This functionality simplifies the understanding and use of each model, while creating a coherent environment for multipurpose and multidomain applications. To ensure that all components were developed correctly, a test site was established at the LIS Office (Task 4.2). This site later functioned as a validation pilot (Task 10.2) for dynamic data and the building’s behaviour, including indoor comfort, safety, security, and occupants’ well-being, with all data connected to the BIM model. A second *pre-pilot* was maintained strictly online, using data from the testing campaign to create a semantically enriched digital model with static data. This model can be accessed and studied through the LIS Platform.

Current Building Characteristics and Strategic Advantages

Figure 3. Location of Carmelitane building (Credits: UNICAM)

The Ex-Carmelitane building presents several distinct advantages for the MULTICLIMACT demonstration. Located in Camerino, Marche region, in the Mediterranean climatic zone characteristic of the hilly landscape of the Umbria-Marche Apennines, the building occupies a strategically significant position within the University of Camerino ecosystem. From a structural engineering perspective, the building presents an optimal case study for seismic resilience research. The historic masonry structure was renovated following the seismic events of 1997 (Marche-Umbria earthquake), demonstrating proven resilience during the devastating 2016 Centro Italia earthquake that severely impacted the region. Unlike many buildings in Camerino that suffered extensive damage during the 2016 seismic sequence, the Ex-Carmelitane building remained undamaged, validating the effectiveness of the post-1997 renovation works. The building's immediate accessibility represents a crucial operational advantage, as the selected rooms have been accessible since January 1, 2025, eliminating the delay risks associated with the original demonstration site. The demonstration will focus on two rooms on the first floor, each measuring 8.85 m^2, with identical south-west climatic exposure and internal characteristics, providing controlled conditions for comparative analysis of the MULTICLIMACT solutions. From an environmental systems perspective, the building is equipped with a conventional methane-fuelled radiator-based heating system. Neither mechanical ventilation nor active cooling is installed, with natural ventilation achieved through operable windows and traditional external shutters. The absence of real-time environmental monitoring systems further emphasizes reliance on passive comfort strategies and direct occupant control of microclimatic conditions. Ample daylight penetration and cross-ventilation enhance perceived indoor environmental quality. Although internal communal areas are limited, the presence of an extensive outdoor green space provides opportunities for social interaction and psychological restoration. The indoor environment is typically characterized by calmness and low occupancy density, with occasional peak crowding in laboratories. Average daily occupancy is estimated at approximately ten users. User-driven environmental regulation, primarily through the operation of windows and shading devices, supports individual adaptive behaviours and enhances resilience to environmental variability. These site-specific characteristics delineate key design imperatives for the implementation of the MULTICLIMACT framework. The Carmelitane building exemplifies a complex case in which constraints linked to heritage value, traditional construction systems, and low-tech environmental control necessitate a multifaceted approach to well-being assessment. The framework will therefore be customized to integrate subjective indicators, such as perceived thermal and visual comfort, as well as emotional resilience, with objective measurements derived from physiological data (e.g., skin temperature, electrodermal activity) and environmental sensors. These metrics will align with project key performance indicators (KPIs) that encompass architectural and system resilience, passive autonomy, and multi-level adaptation mechanisms (physiological, psychological, behavioural, and social).

Implementation of the Demonstration Framework

The demonstration addresses two key hazards: heat waves and seismic events, reflecting the dual climatic and geological vulnerabilities of the Umbria-Marche Apennines. Preparatory activities initially developed for the Fazzini site were re-applied to the Ex-Carmelitane building, ensuring continuity of project investments. The site serves as a testbed for the MULTICLIMACT toolkit, which includes 18 innovative, cost-effective, and easy-to-implement design methods, materials, and digital solutions. All preparatory activities originally developed for the first demonstration site were re-implemented by UNICAM for the Ex-Carmelitane building, including the creation of BIM models under Task T4.2. This approach ensured continuity with previous project investments while adapting to the new demonstration environment. The demonstration will generate valuable data for validating the effectiveness of integrated approaches to building resilience that address multiple hazards at multiple scales.

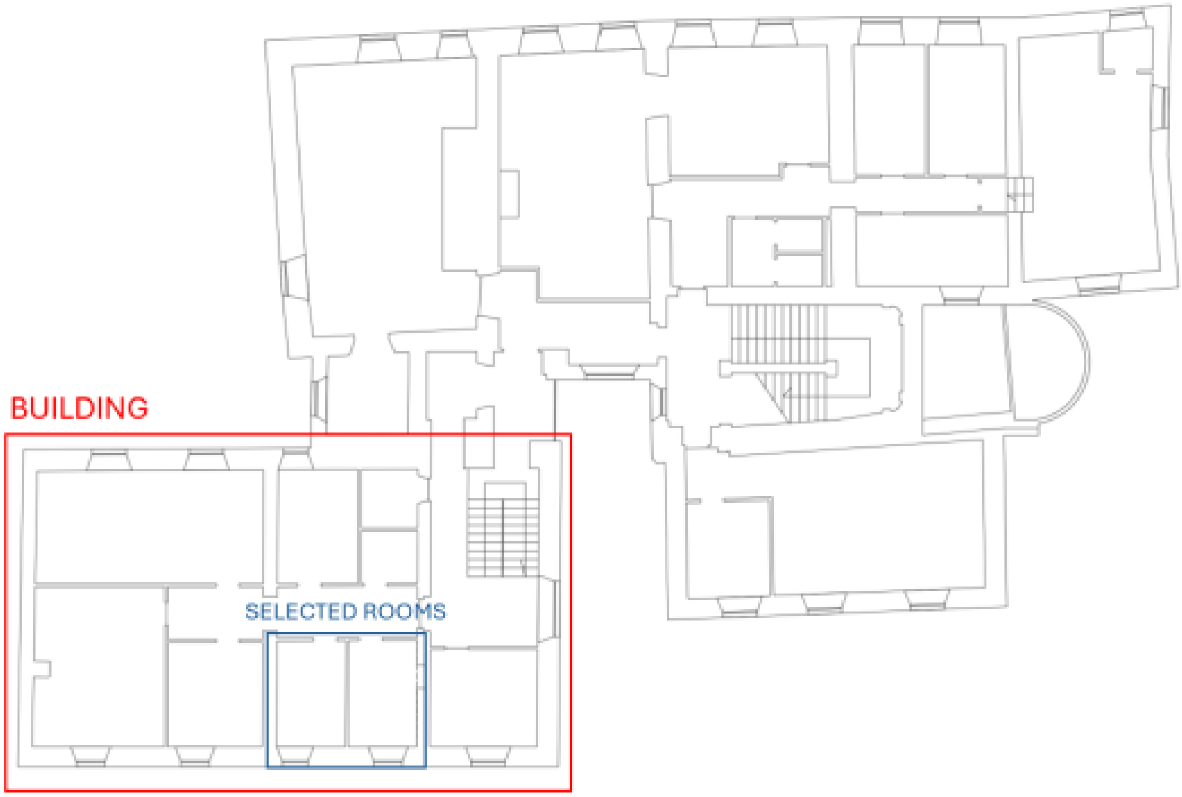

Figure 4. Portion of Ex Carmelitane building implemented in LIS platform and selected rooms (Credits: UNICAM)

Experimental Campaign

Two adjacent rooms on the first floor were selected for the comparative study Figure 5:

- Room 1(Conventional Retrofit): equipped with traditional petrochemical insulating materials (EPS, XPS).

- Room 2 (Innovative Retrofit): equipped with natural hemp fiber panels and a multifunctional mortar designed to enhance indoor air quality and quality of life. This room also integrates self-sensing blocks with embedded structural health monitoring (SHM) sensors.

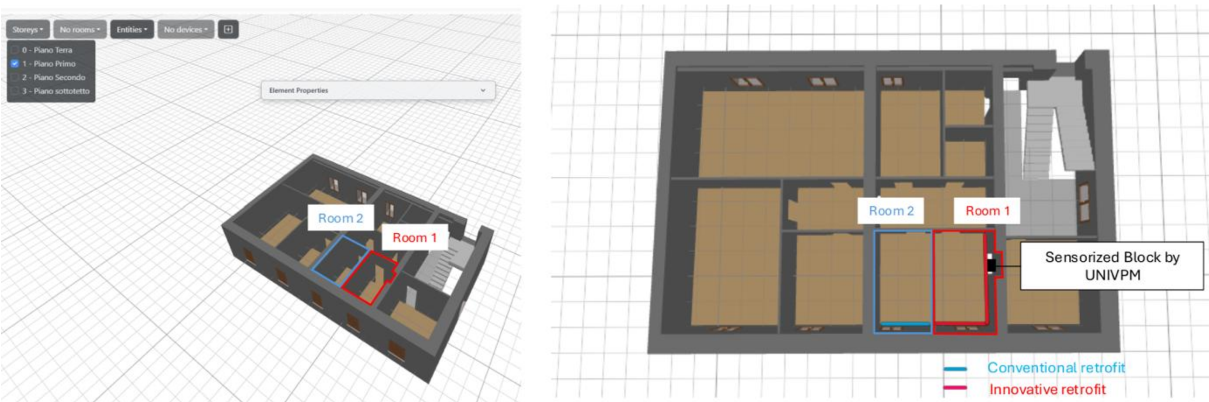

Figure 5. Experimental Campaign, comparative study (Credits: UNICAM)

Instrumentation and Data Acquisition

- Emotibit wearable device: measures electrodermal activity, skin temperature, PPG, ambient temperature, humidity, and motion data.
- DomX IoT sensor unit: monitors indoor air quality (temperature, humidity, VOCs, CO_2, PM concentrations, illuminance).
- Questionnaires: collect demographic data, comfort perception, affective states (PANAS), and clothing insulation levels.

Data are managed through the LIS Platform, which synchronizes environmental and physiological datasets in real time and supports multi-occupant experiments.

Implications and Perspectives

The Ex-Carmelitane demonstration highlights how historic buildings can serve as living laboratories for testing resilience-oriented technologies. The project advances three key objectives:

1. Scientific value: validating multi-hazard retrofit solutions that integrate environmental performance with human-centered indicators of comfort and well-being.
2. Replicability and scalability: providing evidence for the transferability of solutions across diverse climatic contexts, building typologies, and cultural settings.
3. Cultural and architectural integration: ensuring compatibility with traditional materials and construction features, thus balancing innovation with heritage preservation.

By combining passive strategies, reversible retrofit measures, and digital monitoring tools, the MULTICLIMACT framework establishes a reference model for sustainable, human-centered retrofitting of Mediterranean historic buildings.

In conclusion, the design requirements specific to the Camerino context are oriented toward improving energy efficiency and occupant well-being while safeguarding the architectural and cultural significance of historic buildings such as the Ex Carmelitane. Interventions must remain compatible with existing materials and constructional features to ensure the preservation of historic character. This necessitates a balanced strategy integrating passive environmental solutions and reversible retrofit measures that promote both sustainability and resilience without undermining architectural authenticity. Through this tailored approach, the MULTICLIMACT framework aims to establish a reference model for human-centered, sustainable retrofitting practices in Mediterranean heritage contexts. The building thus represents both a technical asset, given its resilience, accessibility, architectural features and a socio-cultural hub, reinforcing its suitability as a demonstration site for MULTICLIMACT. The strategic selection of this historic building, with its proven seismic resilience and immediate accessibility, ensures that the MULTICLIMACT demonstration can proceed without delay while contributing to the preservation and enhancement of Italy's architectural heritage. The project exemplifies how historic buildings can serve as platforms for innovative resilience technologies, bridging traditional construction knowledge with contemporary climate adaptation strategies. This comprehensive demonstration will provide essential evidence for the scalability and replicability of MULTICLIMACT solutions across diverse geographic, climatic, and building typology contexts, supporting the project's broader objective of mainstreaming climate resilience assessment and enhancement tools for public stakeholders and citizens throughout Europe.

5. WORKFLOW AND DEVELOPMENT

The current section outlines the practical implementation steps followed during the development of the digital solution for the Italian demonstration case, in line with the architecture defined in Task 4.2. It focuses on the creation and refinement of the BIM model, the integration with a CDE (Common Data Environment), and the preliminary simulations that support indoor comfort and structural monitoring. This workflow materialised into a digital twin of the Carmelitane Building (Ex-Carmelitane) in Camerino (Italy), aiming to consolidate real-time sensor data with analytical and physics-based models. This virtual representation is continuously fed with real data and linked to monitoring interfaces through the LIS-Platform. Special attention was placed on interoperability and data fidelity throughout the pipeline. To ensure a robust foundation, the modelling workflow was jointly developed by UNICAM, LIS and CYPE. Their coordinated efforts allowed for a spatially coherent IFC model where each building element and space could be unambiguously referenced in simulations and sensor mapping.

5.1. BIM MODELLING FOR CARMELITANE BUILDING

The digital twin architecture required a well-structured, IFC-based BIM model as a starting point. A collaborative modelling process was conducted using Autodesk Revit and IFC interoperability workflows. The core geometry and space configuration were iteratively refined, ensuring alignment with both simulation needs and real-world sensor installation requirements.

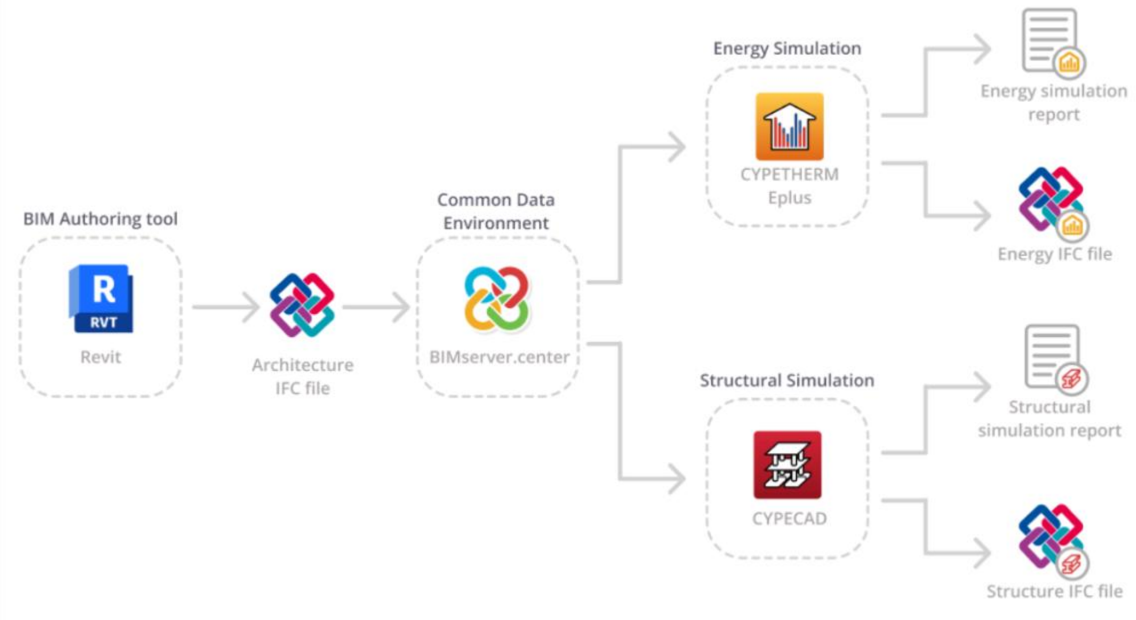

Figure 6. BIM Modelling Workflow for Ex-Carmelitane (Credits: CYPE)

5.1.1. ARCHITECTURE MODEL AND INTEGRATION IN CDE

The BIM model was created using Autodesk Revit, with reference data and support provided by UNICAM. Model elements were structured with proper classification of building elements (walls, floors, slabs, windows, and zones) to ensure compatibility with subsequent simulation and monitoring steps. The modelling phase had to address challenges such as incomplete building documentation and the need for accurate internal zoning. For this reason, the coordination between LIS (in charge of sensor planning), UNICAM (modelling and documentation), and CYPE (modelling, export strategy, and energy/structural simulation) was crucial. Software adaptations were necessary, as the use of common open standards alone was not sufficient. Best practices were applied in labelling rooms and spaces, making them easier to select and ensuring that data could be retrieved efficiently. CYPE used its own software suite, while LIS and UNICAM worked with Autodesk Revit to develop the BIM models. Interference checks and error reports were exchanged between partners to overcome potential deadlocks in later stages of development. Some elements are included in the section below, as they represent special considerations that may fall outside common industry standards.

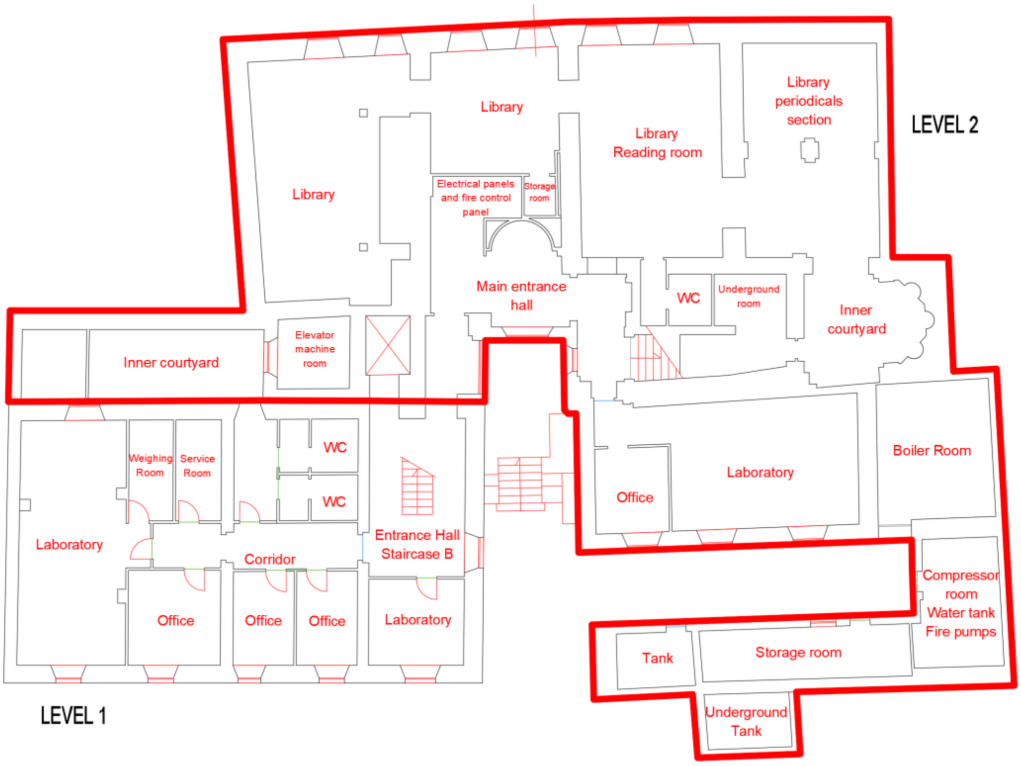

Figure 7. Image of Ex-Carmelitane level 1 floorplan. The zone marked in red was left out (Credits: UNICAM)

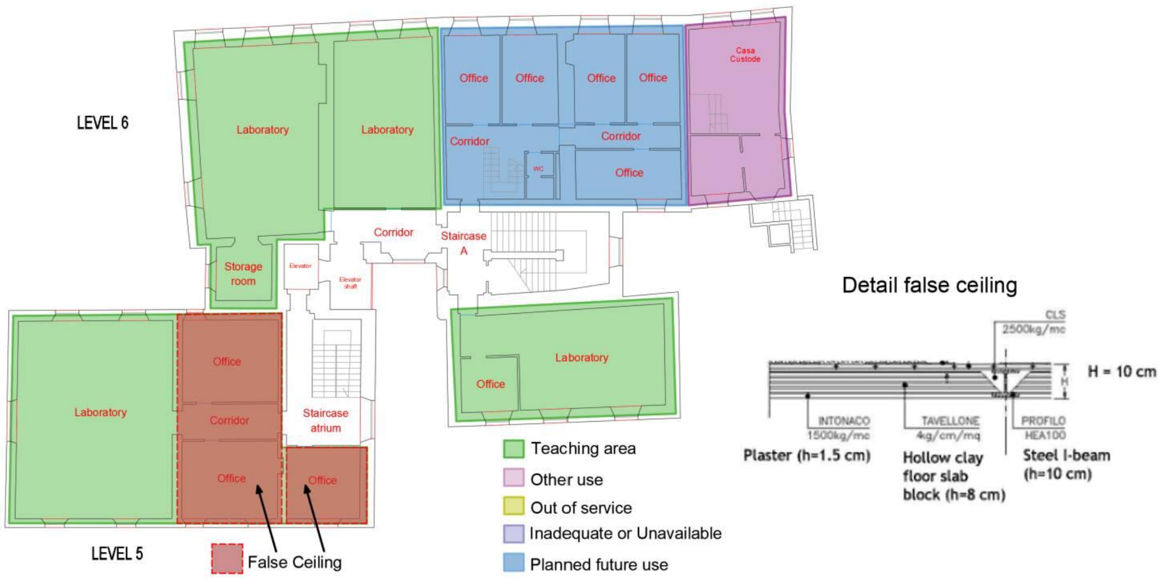

Figure 8. Ceiling constructive details provided for the BIM modelling (Credits: UNICAM)

The following special considerations were defined and implemented to ensure optimal execution:

- <u>Element Level Association:</u> All elements were properly associated between two consecutive levels, and no element extended beyond this range. For example, walls were bounded between Level 1 and Level 2, not from Level 1 to Level 4. This ensured the model remained organised and suitable for energy simulations.

- Facade Walls: Facade and external walls were assigned the parameter "IsExternal" and marked as "*Boolean* = *yes*", to distinguish them properly in the energy model.
- Room/Spaces: Spaces were needed to be defined for each of the enclosed areas in the project to perform the energy simulation. For this, the "Room" tool in Revit was used. Rooms were exported as *IfcSpace* to maintain the correct spatial representation within the IFC model. Additionally, all spaces were modelled so that they adjoin the slabs (top and bottom) and walls completely. Also, they were not bounded to ceilings.
- Wall Composition: Walls were exported as solid entities without layers, parts, or individual components. This simplification of the geometry facilitates the simulation processes.

Spatial zones (rooms) were carefully delineated to allow correspondence with the subsequent simulations in CYPETHERM EPlus and semantic queries in the LIS-Platform. The main focus was on the definition of spaces and occupancy areas, which would later support the generation of energy demand indicators and comfort analytics. As mentioned above, special care was taken to have Rooms and building elements such as walls and floors, aligned by surface, to avoid computation and calculation errors for spaces in the Energy simulation.

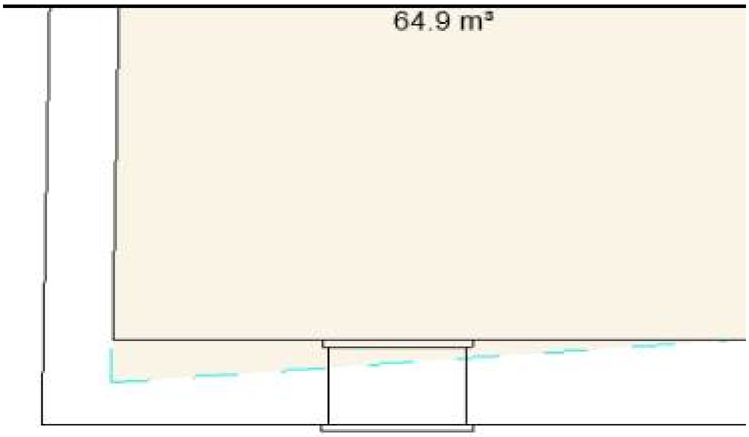

Figure 9. Room separator and wall misalignment error detected (Credits: CYPE)

For structural simulations, building elements were carefully modelled to serve as the foundation for the structural model in CYPECAD, where default solutions were assigned. Once the BIM model was finalized, the IFC file was uploaded to the BIMserver.center platform, which served as a Common Data Environment (CDE) and data exchange hub. This enabled CYPE to extract the building geometry and integrate data from both energy and structural simulations.

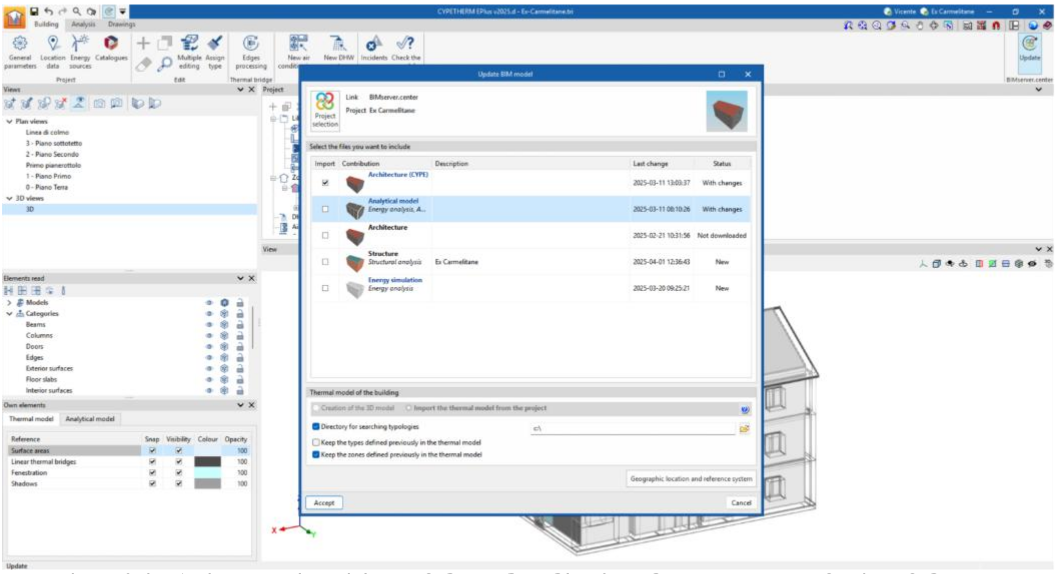

Figure 10. Loading of the Architectural model into CYPETHERM EPlus from BIMserver.cente (Credits: CYPE)

5.1.2. ENERGY MODEL FOR SIMULATION

An energy model was developed using CYPE's CYPETHERM EPlus tool, with the new integration of the Analytical Model definition tool, as developed in T4.3 and tested in T10.3. The workflow included defining thermal zones based on the BIM model, mapping material and thermal properties of building elements, and setting thermal thresholds.

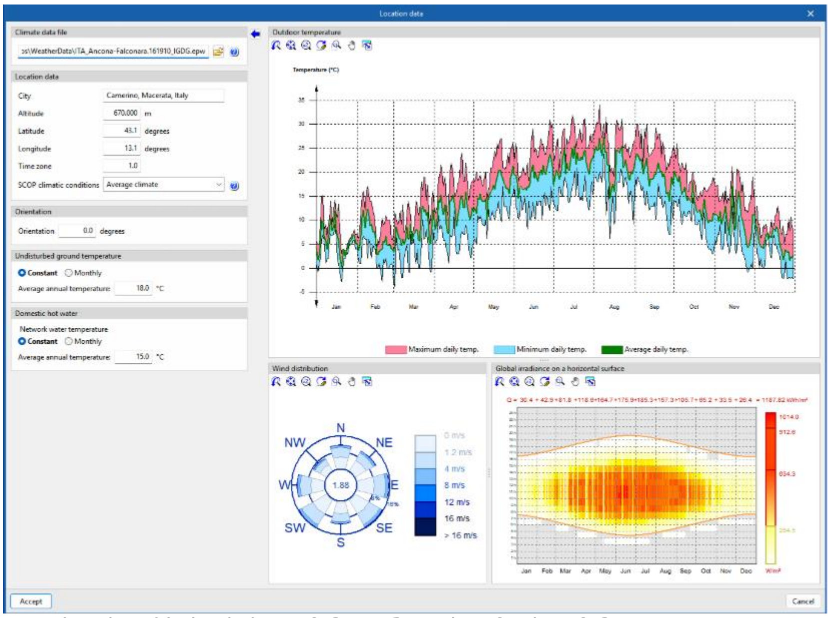

Figure 11. Camerino weather data file loaded into CYPETHERM Eplus (Credits: CYPE)

First, the weather file for Camerino was obtained from the Energy Plus Weather Data website and loaded into the software. This allowed for precise weather condition simulations for the building.

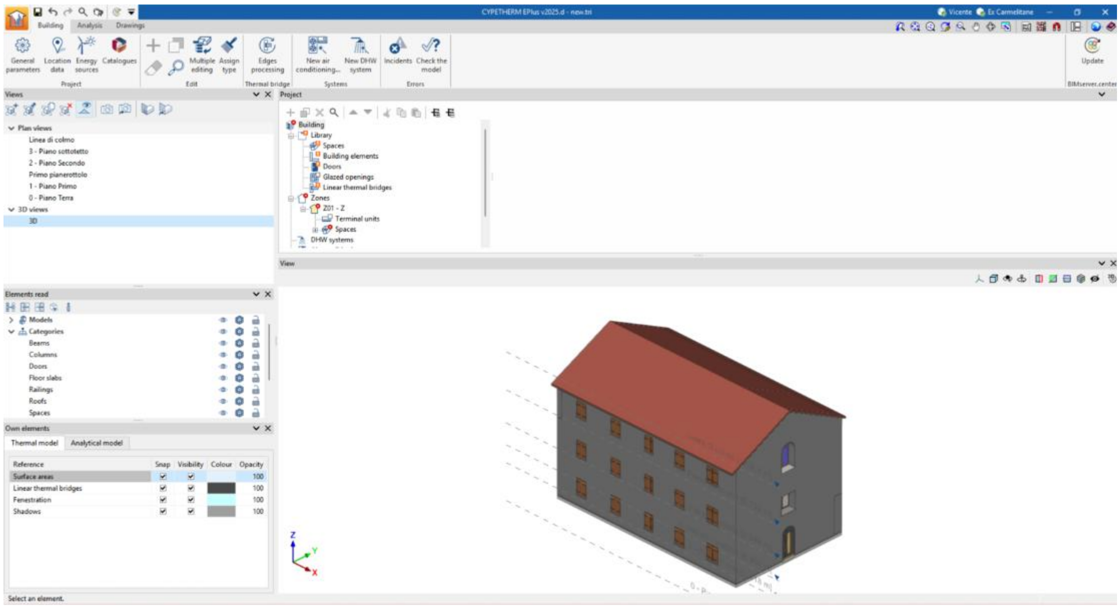

Figure 12. Architectural BIM Model imported in CYPETHERM EPlus (Credits: CYPE)

Once the Architectural Model was imported from BIMserver.center, the definition of material and thermal properties of building elements was carried out, as seen in Figure 8. Additionally, spaces, openings (doors and windows), thermal bridges, and thermal threshold such as set point and comfort temperatures were mapped, defined, and specified.

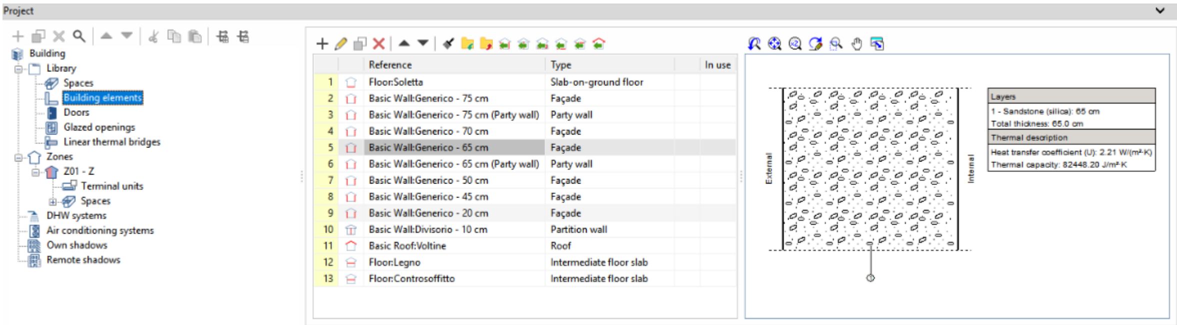

Figure 13. Material and building element mapping in CYPETHERM Eplus (Credits: CYPE)

The calculated values for heating and cooling energy demand of the Ex-Carmelitane building were found to be negligible, as no information of its conditioning systems and equipment was provided. However, the model was still used to simulate **internal thermal conditions throughout the year**. Data such as energy transfer and temperature evolution were the focus of the simulation.

5.1.3. STRUCTURAL MODEL FOR SIMULATION

A structural model of the Ex-Carmelitane building was developed using CYPECAD, CYPE's dedicated tool for structural analysis and design. The process began with the import of the architectural model, which served as a geometric reference for defining the primary load-bearing elements of the structure. Based on the architectural layout, a detailed structural model was constructed, including all relevant components: columns, beams, slabs, and load-bearing walls. Each element was defined with its corresponding material and geometric properties in accordance with Eurocode standards.

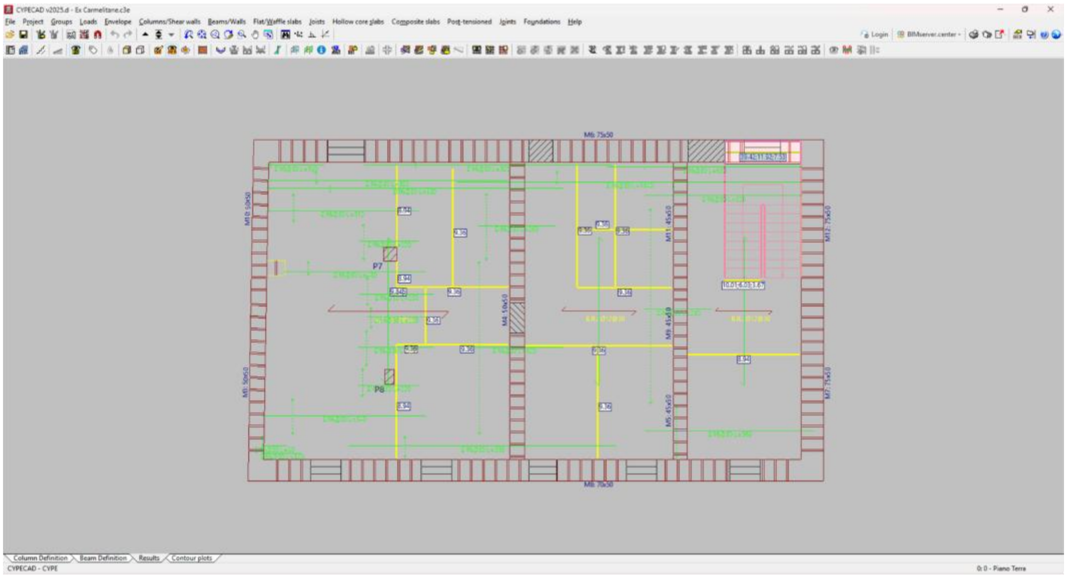

Figure 14. CYPECAD interface with the Beam definition of the structural mode (Credits: CYPE)

The modelling process included the definition of concrete and steel grades for all elements, structural zoning and floor distribution, modelling of vertical elements (columns, shear walls), and horizontal elements (floor slabs and beams) across all levels, and accurate mapping of architectural axes and spans, ensuring alignment with the original Architectural model.

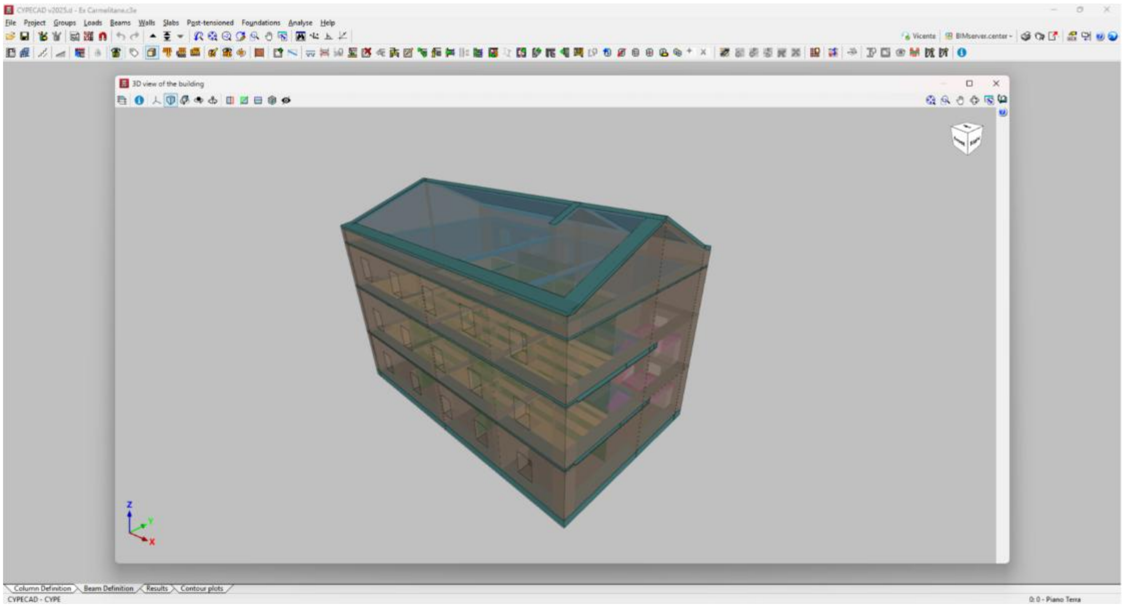

Figure 15. 3D View of the structural model in CYPECAD (Credits: CYPE)

The complete structural model was developed to assess the seismic resilience of the building under various load combinations, as seen in Figure 10. This included all the structural elements to perform the simulations in consideration with load cases (dead, live, wind, and seismic), Eurocode-based combinations, and modal spectral analysis (EN 1998-1). As with energy simulations, the intention was to feed the digital twin with structural metrics derived from both modelled and sensed data, enabling real-time comparisons and alerts.

5.1.4. TOWARD A DIGITAL TWIN: CARMELITANE BIM MODEL ON THE LIS-PLATFORM

The final BIM model, in IFC format, is hosted on the LIS-Platform. It will be enriched with data from environmental sensors, structural health monitoring (SHM) systems, and physiological sensors from wearable devices, as outlined in T8.5, presented at 2025 IEEE INTERNATIONAL WORKSHOP ON Metrology for Living Environment IEEE MetroLivEnv 2025[1] and (De Maio et al. 195).

Relevant contributions include:

1. "Enhancing the Built Environment Resilience: Integrating the MULTICLIMACT CREMA Tool, Sensing and Digital Solutions for Building Protection and Occupants' Well-Being Assessment", presented by Prof. Gian Marco Revel and authored by RINA, LIS, eCampus University, and UNIVPM.
2. "Development of a BIM-Based Platform for the Assessment of Indoor Multidomain Comfort", presented by Prof. Gloria Cosoli and authored by eCampus, LIS, UNIVPM, and UKA.

This integration is further detailed in the *pre-pilot* setup, including user interactions, scheduled events, and in-situ testing focused on hygrothermal performance. For testing purposes, two rooms on the first floor have been identified. These rooms will be retrofitted with special self-sensing energy-efficient components (EECs) for monitoring general structural health and external loads. The retrofitting will use a multifunctional mortar developed and patented by UNIVPM (Patent No. 102017000033750). This product serves as a multifunctional indoor finishing capable of passively reducing pollutant concentrations (including NOx, COx, O_3, and VOCs) and regulating relative humidity (RH) to enhance occupant comfort and health. It also features a low environmental impact, contributing to reduced building energy demand and improved indoor environmental quality.

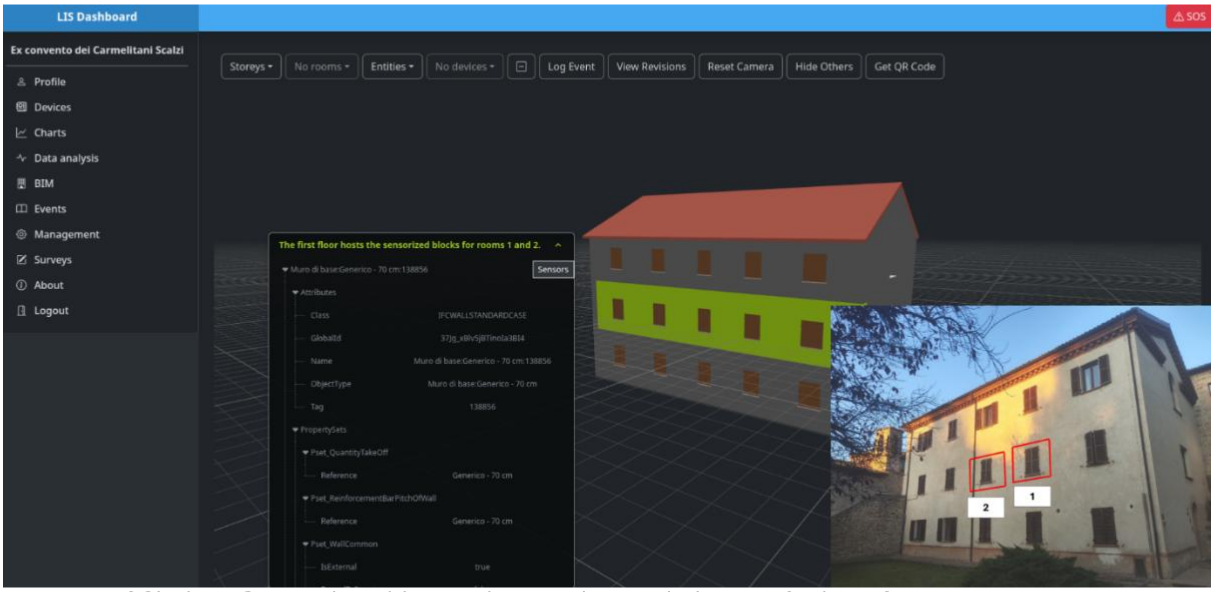

Figure 16. LIS-Platform. Rooms selected for retrofitting and sensor deployment(Credits: LIS)

Once the BIM model has been finalized, the file is uploaded to the LIS-Platform. While the changes may not be immediately visible, the majority of the updated information has already been embedded. In the two target rooms, digital placeholders have been incorporated and are prepared to be linked with the actual sensors upon installation.

[1] https://www.metrolivenv.org/

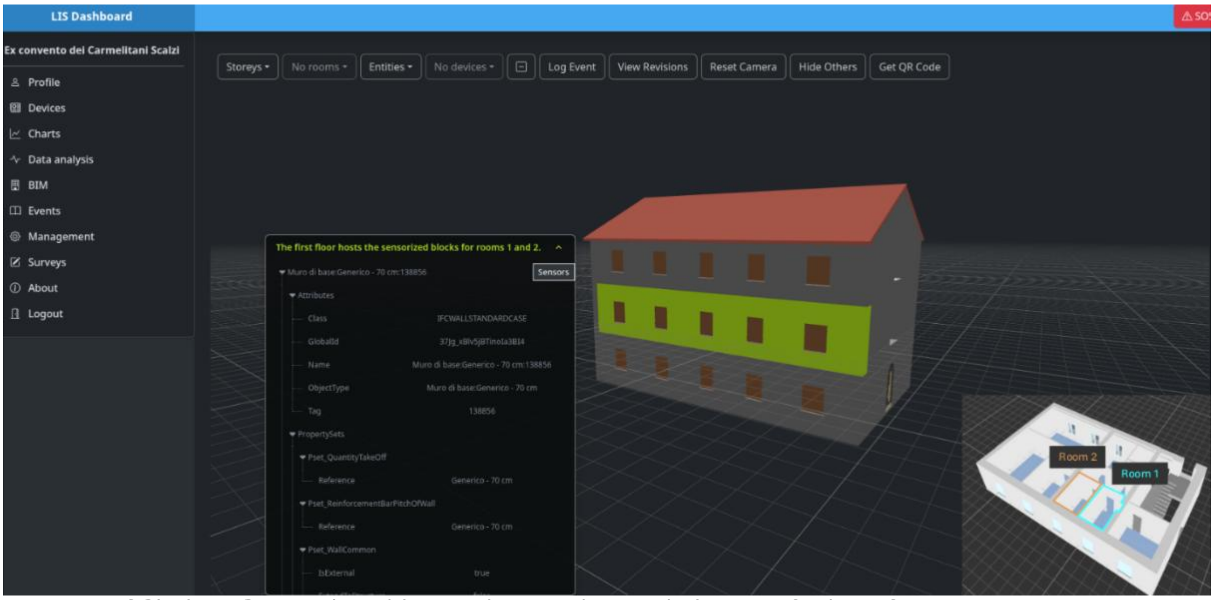

Figure 17. LIS-Platform. Rooms selected for retrofitting and sensor deployment (Credits: LIS)

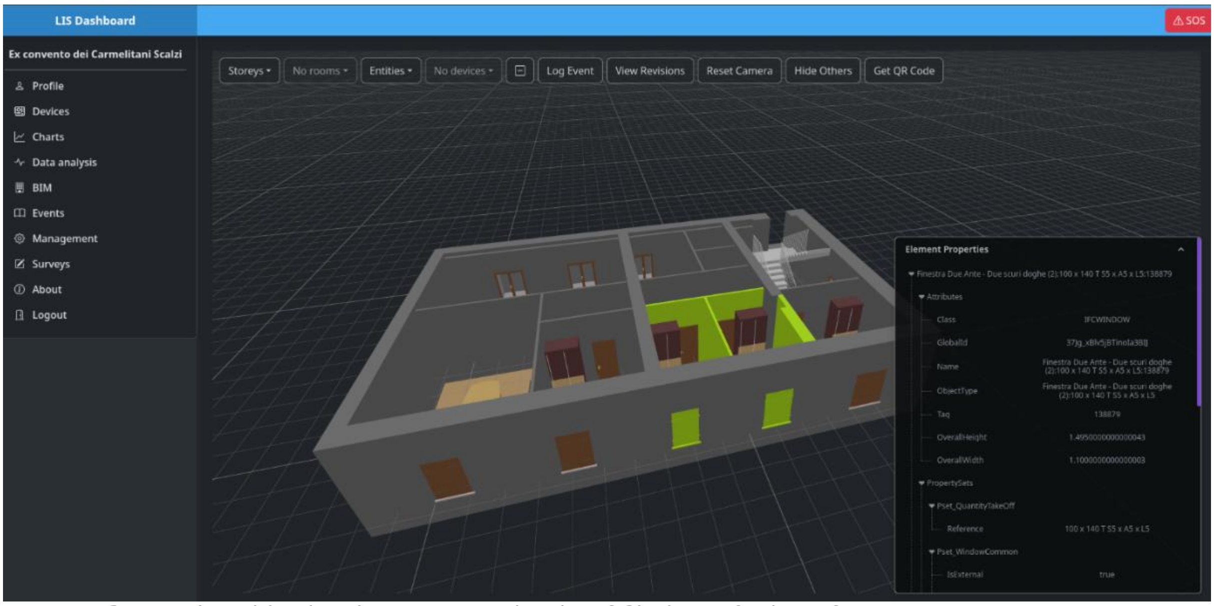

Figure 18. Rooms selected for the pilot overview within the LIS-Platform (Credits: LIS)

5.2. IOT INTEGRATION AND LIS DEVELOPMENT

The LIS-Platform functions as an IoT infrastructure integrating multiple connected IoT devices, creating a Smart Building Operating System. Running on a virtualized Ubuntu Linux 24.04 LTS instance, it supports various Linux-based components, such as web application servers and multi-level gateways. Embedded sensors enable smart structure capabilities, enhancing energy efficiency, asset management, and resilience to environmental hazards, facilitating informed decision-making.

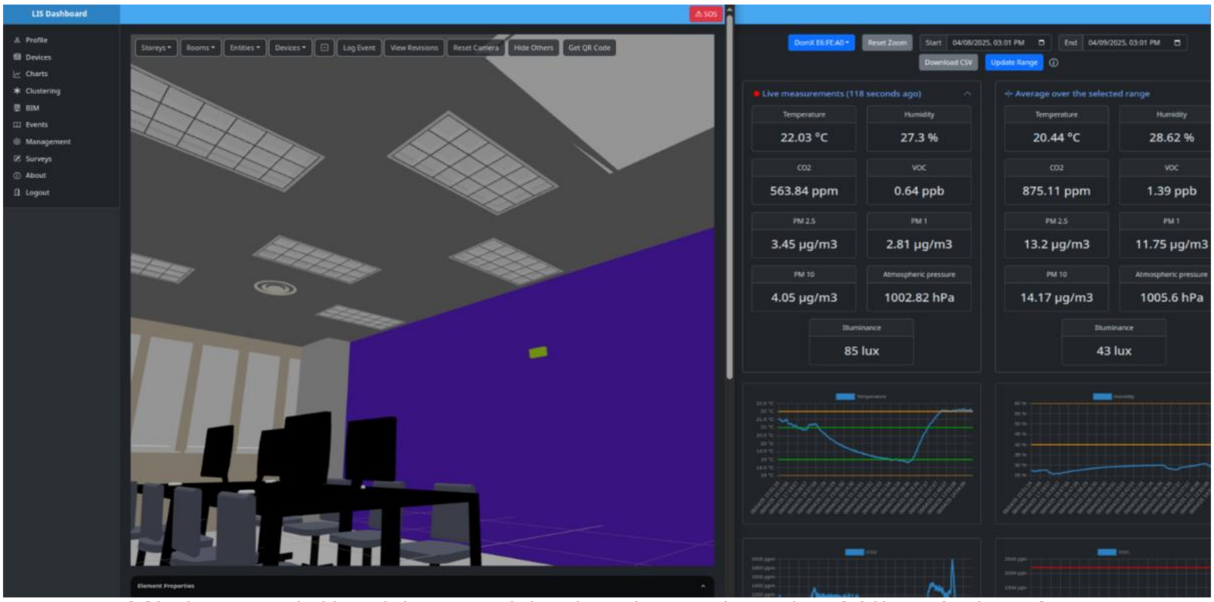

Figure 19. LIS-Platform main dashboard showing real data from the pre-pilot at the LIS Office. (Credits: LIS)

State-of-the-Art Review of BIM-Based Solutions

Building Information Modeling (BIM) has become a cornerstone in the architecture, engineering, and construction (AEC) sectors, enabling integrated digital workflows across the lifecycle of buildings. Contemporary platforms such as Autodesk Revit, Graphisoft Archicad, Trimble Connect, and Bentley iTwin provide robust environments for parametric modelling, multidisciplinary coordination, and performance-based design evaluation. Autodesk Revit, for instance, integrates with cloud-based services like BIM 360 and Insight, allowing for clash detection and preliminary energy simulations. Graphisoft Archicad, commonly used in European practices, promotes real-time collaboration via BIMcloud and ensures interoperability through open IFC standards. Similarly, Trimble Connect and Bentley's iTwin services extend BIM functionality into the infrastructure domain, fostering the development of digital twins capable of real-time data integration and performance monitoring throughout the building's operational phase. Despite these strengths, existing BIM solutions still present limitations in supporting renovation projects, especially in public or policy-driven contexts. The evaluation of social, environmental, and economic outcomes across multiple renovation scenarios often requires complex workflows and technical skills not typically accessible to non-expert users. These tools are generally geared toward detailed design and construction documentation rather than early-phase strategic decision-making, where multiple stakeholders, including public authorities, must assess trade-offs between performance, cost, and feasibility.

Positioning the LIS-Platform

Within this context, the LIS-Platform offers a significant contribution by bridging the gap between advanced technical modelling and accessible decision-making tools. Rather than replacing BIM platforms, LIS serves as a lightweight, web-based interface that enhances existing models and simulation outputs. It provides clear, comparative, and scenario-based insights to support informed decision-making. The platform includes an integrated BIM (IFC) viewer, allowing users to navigate models by storeys, rooms, or elements while accessing associated metadata and performance indicators. A key feature is the embedded dashboard, which can be extended to support multi-criteria decision-making (MCDA). This enables users to explore renovation scenarios based on predefined indicators such as greenhouse gas (GHG) reductions, primary energy savings, cost-effectiveness, and improvements in indoor environmental quality. Additionally, the LIS-Platform enables performance evaluation at both the individual building scale and across broader geographical areas through its interoperability with the ENEA Smart City Platform and the CREMA Tool. Unlike traditional BIM authoring tools, LIS simplifies the exploration of alternatives through user-friendly filtering and comparison features, making it suitable for both technical experts and public decision-makers. Beyond energy and renovation considerations, the LIS-Platform is well-positioned to incorporate climate resilience indicators, which are becoming a critical component of sustainable building strategies. In this context, integration with the CREMA tool (Climate Resilience Maturity Assessment), also developed under the MULTICLIMACT project, creates valuable synergies.

In the field of building design and infrastructure resilience, the LIS-Platform and the CREMA tool represent two complementary systems. The LIS-Platform supports planners and decision-makers by offering detailed insights into building performance, energy efficiency, cost-effectiveness, and greenhouse gas (GHG) reductions. The CREMA tool, on the other hand, is designed to assess and recommend resilience and adaptation strategies for buildings and infrastructures, ensuring their ability to withstand and recover from adverse events. Specifically, the CREMA tool allows users to input asset descriptions, select relevant hazards for a given location, and assess the vulnerability and risk of different buildings. The resulting data and analysis are then passed to additional modules for further evaluation, including economic loss estimation, cost-benefit analysis, and identification of adaptation solutions.

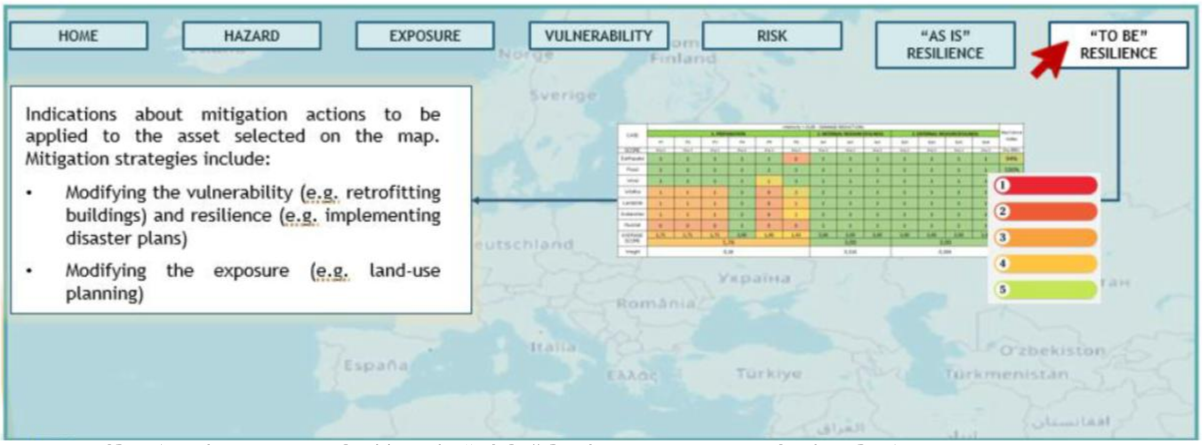

Figure 20. CREMA tool - Navigation Dashboard – "TO BE" Resilience assessment (Credits: RINA)

The IoT paradigm is founded on interconnected and interdependent entities, where relationships go beyond individual objects to include the mutual influence of their properties. As connectivity expands, systems evolve from isolated components into dynamic networks, with information flow becoming central to their operation (Alderson & Doyle, 2010; Barabási, 2009). This transformation redefines the concept of platform functionality, as seen in the LIS-Platform, by extending its capabilities beyond the constraints of physical 3D space. It extends the capabilities of BIM models by managing semantic enrichments and can serve as a robust framework for twinning systems, enabling the development of fully-fledged digital twins.

LIS-Platform system architecture

In terms of network architecture, the LIS-Platform is designed with a multi-layered structure that broadens the definition of a platform. It evolves from being purely software-based to encompassing IoT/CPSs and WSN. The layers are outlined in their simplest form below.

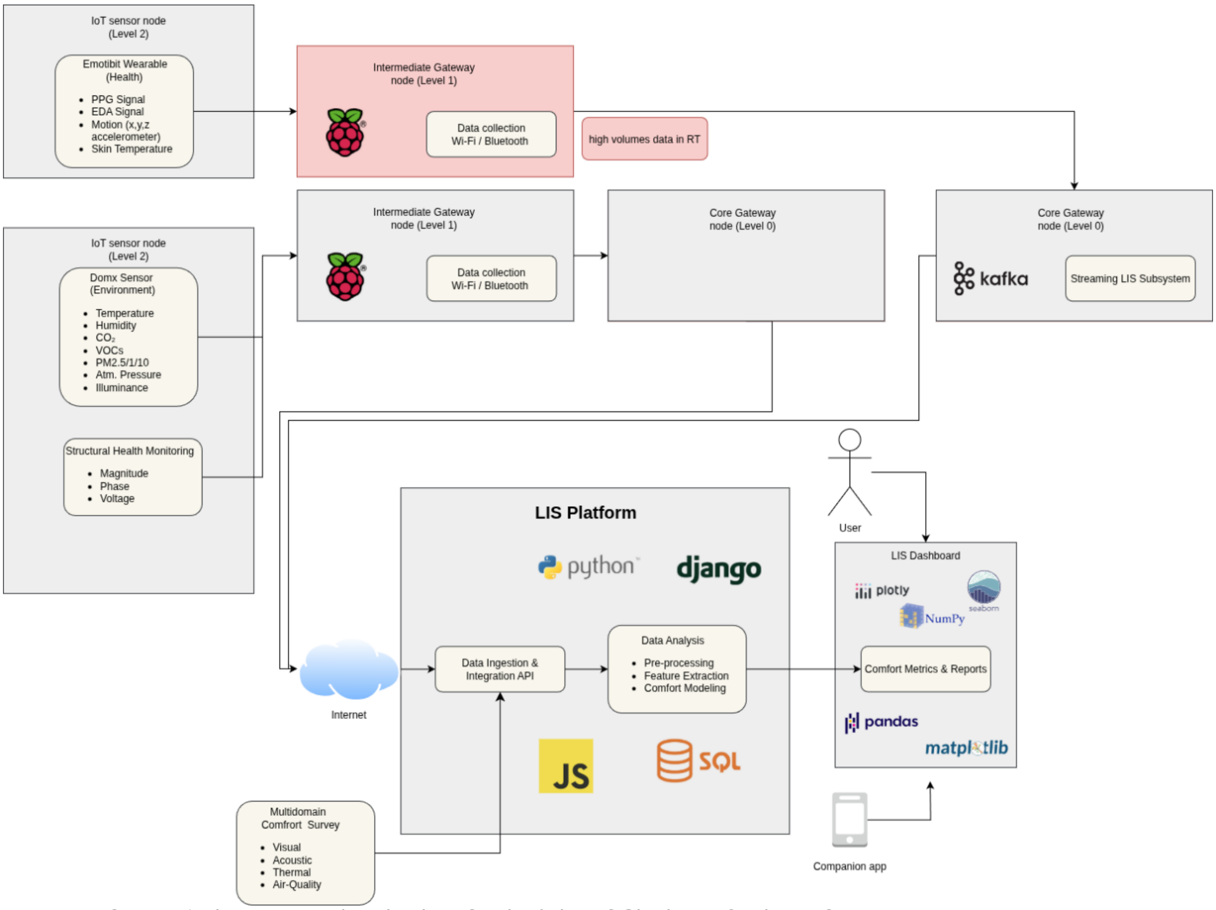

Figure 21. System Architecture and Technology Stack of the LIS-Platform (Credits: LIS)

Gateway Nodes

Gateways (GWs) connect and translate data across various networks. Organized in multiple layers for redundancy and security, these nodes collect real-time sensor data via wireless technologies, including BLE, transmitting securely to a central API for further analysis.

Sensor Nodes

Sensor nodes or external nodes, including sensors, interact with the LIS-Platform to expand data collection, command reception, and system functionality.

IoT Sensor Nodes (Level 2)

IoT devices ("leaf nodes") equipped with MCUs gather environmental data. Due to limited storage, these nodes temporarily buffer data before wireless transmission (BLE) to intermediate gateways.

Intermediate Gateway Nodes (Level 1)

Single-board computers (SBCs) aggregate data from multiple IoT nodes. Positioned strategically for redundancy, they provide persistent data buffering and communicate over a local intranet.

Core Gateway Nodes (Level 0)

Central network nodes deployed per floor or functional area. They interface between the local intranet and wider internet, perform preliminary data analysis, and manage OTA software updates for lower-level nodes.

Web Application

A web-based management platform offering dashboards for device, building, and user management, data visualization, anomaly notifications, reporting, and data export (CSV/PDF). It implements distinct roles (owner, technician, researcher) with role-based data access controls compliant with applicable regulations

API

A new API will enable secure read/write access to the web app's database. It will feature strong authentication (MFA or token/key-based) to ensure only authorized users and partners can access sensor data. The API will collect data from core gateways and support third-party integrations to transform raw data into insights.

UX/UI Design

The platform interface will be user-friendly, intuitive, and accessible. Dashboards and charts will allow users to filter data by features and time, making the platform usable even for non-technical users.

Data Management

A built-in data analysis module enables partners and researchers to apply machine learning, update models, and conduct real-time studies directly on the platform.

Database Management (DBMS)

A relational SQL database will be implemented with data redundancy and backup strategies to ensure data integrity and high availability.

Mobile App

A lightweight mobile app will provide core platform features and emergency notifications. It will use BLE broadcasting to detect user location via nearby IoT sensors.

Testing Strategy

All software components will undergo automated and manual testing using unit tests and GitHub Workflows, both before and after deployment.

5.3. DATA PLATFORM DEVELOPMENT AND CONNECTIVITY

Designed for climate resilience and occupant-centered monitoring, the LIS platform enables real-time visualization and interaction with comfort KPIs and SHM through a unified, context-aware interface.

5.3.1. INTEGRATED BIM–IOT FRAMEWORK FOR BUILDING MONITORING (TASK 10.2)

The confluence of Building Information Modeling (BIM) with Internet of Things (IoT) sensing and analytics is enabling increasingly sophisticated systems for real-time monitoring of indoor comfort and resilience. For instance, recent frameworks have successfully combined BIM spatial data with live temperature and humidity readings to compute Predicted Mean Vote (PMV) in real time, visualizing comfort heat maps directly within BIM environments [1]. Building on this, digital-twin frameworks have emerged that merge BIM, IoT, and machine learning to support predictive control of indoor environments. One such study integrates BIM-derived geometry with real-time sensor data to calculate simplified PMV (sPMV) and employs a hybrid Prophet–LSTM model for forecasting environmental conditions and enabling model predictive control (MPC) of HVAC systems via a web-based platform [2]. There is also a growing body of work focused on occupant-centric digital twins, where user feedback is incorporated to personalize comfort models. One high-impact project developed a semantic digital twin by integrating a linked building data model, continuous smartwatch feedback, and sensor logs. This enabled richer occupant-specific decision support tools directly tied to BIM zones and sensor data [3]. On personalized thermal comfort modelling, the Build2Vec methodology shows the value of combining BIM spatial context with longitudinal comfort feedback via a GNN model. It achieves 14–28 % improvement in predictive accuracy over conventional baselines by leveraging spatial-temporal proximity patterns in occupant feedback [4]. Reviewing broader trends, a systematic analysis of European case studies confirms that digital twins built on BIM + IoT are increasingly used in the operations & maintenance (O & M) phase, distinctly improving energy efficiency and occupant comfort. However, the deployment of such systems in existing buildings is constrained by data availability, model completeness, and interoperability challenges [5]. Collectively, these academic studies illustrate the current state-of-the-art in BIM-enabled comfort analytics: multi-modal sensing data feeding real-time pipelines, thermal comfort computation (PMV or sPMV), predictive analytics powered by machine learning, and occupant feedback loops all linked to BIM geometries. These systems support dashboards and tools that contextualize environmental conditions within the digital twin framework.

The Live Information System (LIS) platform developed under MULTICLIMACT extends this paradigm for climate-resilient, occupant-centered monitoring. It connects structural, environmental, and physiological sensors to a central BIM-platform. All data streams converge in the building's digital twin, enabling real-time visualization, querying, and interaction with comfort and building health metrics in an integrated, context-aware interface.

Integrated System: We describe a digital twin platform that fuses BIM and IoT. The system architecture consists of multi-layer IoT hardware and software, a database, analytics engine, and visualization front-end dashboard.

Data Acquisition: Environmental and structural sensors collect real-time building data. Wearable physiological sensors can optionally capture occupant data and feedback.

Data Repository: All sensor data stream into a centralized time-series database. Open-access APIs and dashboards within the LIS-Platform enable project partners to query and visualize the data.

Analytics Engine: The engine computes comfort metrics from the environment, SHM and physiological data, continuously updating the building model based on user request. Unsupervised clustering groups data features according to comfort levels.

Visualization & BIM Integration: A 3D BIM viewer overlays sensor readings on the building model. Interactive dashboards display historical trends and live data. For example, colouring IFCSPACEs by temperature or CO_2 levels.

Stakeholder Access: Facility managers and engineers use the tool to monitor comfort and building health; occupants can receive feedback on indoor conditions. All partners can access the shared data and reports through web dashboards or APIs. Researchers can download the data for local analysis based on their requirements.

This task focuses on building a data based rich digital twin platform for indoor comfort and structural monitoring. A digital twin[2] is a virtual replica of a physical asset; when paired with IoT sensors it provides real-time, context-rich data about the asset. Here, the digital twin comprises the building's BIM and live data feeds. By integrating BIM and IoT, the system aims to continuously monitor indoor environmental conditions and occupant well-being, and to support in future optimized HVAC control. Prior work shows that linking BIM to sensor networks enables comprehensive monitoring: for instance, one approach "integrated BIM information models and IoT systems aimed at the collection, processing and visualisation of environmental data[3]" in real time In our task, we build on these concepts to define a flexible reference architecture and implement each component (sensors, data flow, analytics, AI, visualization) in a co-creative framework that serves project partners.

5.3.2. REFERENCE FRAMEWORK AND OBJECTIVES OF TASK 10.2

Task 10.2 is framed by standards for interoperability and an open-data mindset. We adopt neutral formats (e.g. IFC) so that BIM models and sensor data can be combined. For example, using IFC has

[2] Autodesk

[3] https://www.itcon.org/

been proposed to improve accessibility of BIM data to IoT and automation systems. The objectives of Task 10.2 include:

- **Define System Architecture:** Specify a modular architecture (hardware and software) integrating BIM, sensor networks, communication layers, and databases.
- **Install and Integrate Sensors:** Deploy environmental sensors, structural sensors, and optional wearable sensors.
- **Develop Data Repository:** Create a secure data platform to store streaming data. Provide APIs or dashboards so that all public partners can query historical and real-time data.
- **Implement Analytics:** Compute comfort indicators from the collected data and use machine-learning techniques. Apply k-means[4] clustering and ML algorithms.
- **Visualization & BIM Integration:** Build user interfaces that overlay sensor data on the BIM model. For example, integrate colour zones into the 3D model viewer aps.autodesk.com case.rpi.edu.
- **Stakeholder Accessibility:** Ensure facility managers, engineers, and occupants can easily use the system. Provide role-based views (maintenance dashboards, occupant feedback tools) and open data access for research.

5.3.3. SYSTEM ARCHITECTURE (BIM, IOT, DATA FLOW, DATABASE)

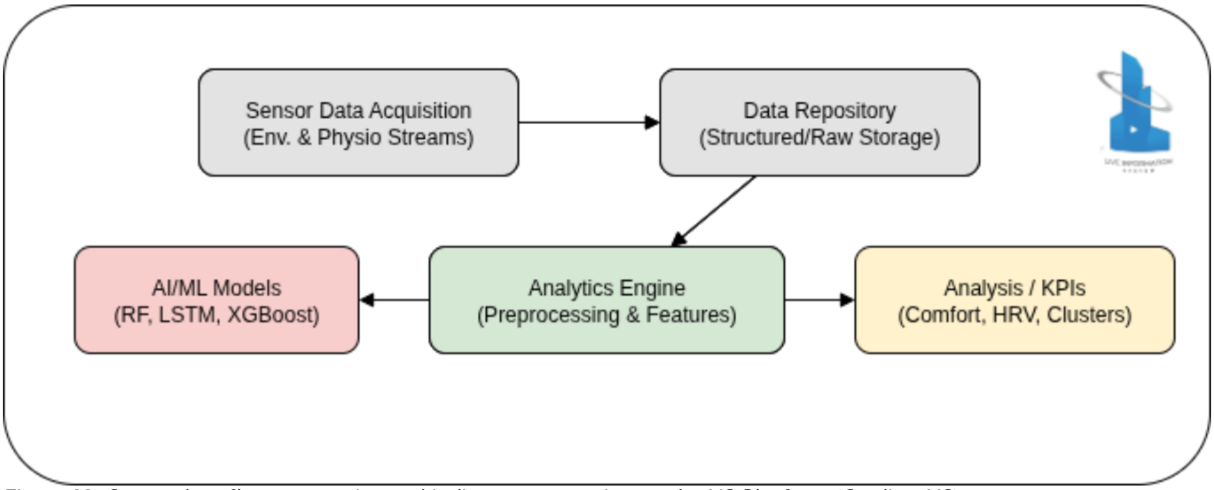

Figure 22. Sensor data flow, processing and indicators extraction on the LIS-Platform (Credits: LIS)

The LIS-Platform is built upon a modular, data-driven architecture designed for real-time acquisition, processing, and analysis of multi-domain sensor data, including environmental, structural health monitoring and physiological streams. The architecture emphasizes interoperability with BIM models, machine learning integration, and extensibility for research and monitoring applications. As illustrated in *Figure 19*, the architecture consists of five core functional components:

Sensor Data Acquisition

This layer includes all IoT endpoints responsible for capturing live data. Environmental sensors (e.g. temperature, relative humidity, CO_2, PM, VOCs) and physiological wearables (e.g. heart rate, EDA, skin temperature) continuously monitor the indoor environment and occupant response. All signals

[4] By default, kmeans uses the squared Euclidean distance metric and the k-means++ algorithm for cluster center initialization. https://www.mathworks.com/help/stats/kmeans.html

are time-synchronized and streamed using lightweight protocols HTTP API or WebSocket that transmit data from sensor to LIS server.

Data Repository

Raw and structured data are stored in a centralized data repository. This repository supports both real-time ingestion and historical retrieval. All records are tagged with temporal and spatial metadata, enabling linkage to specific rooms or BIM elements. The system is designed to support interoperability through standard APIs and query interfaces. In the following figure the end-user UI for the data repository is shown. Researchers can upload physiological data, and the platform takes the corresponding environmental and/or structural data from LIS database and matches them to the physiological ones. The researcher is given the option to keep the data private to themselves or share it with other building's members.

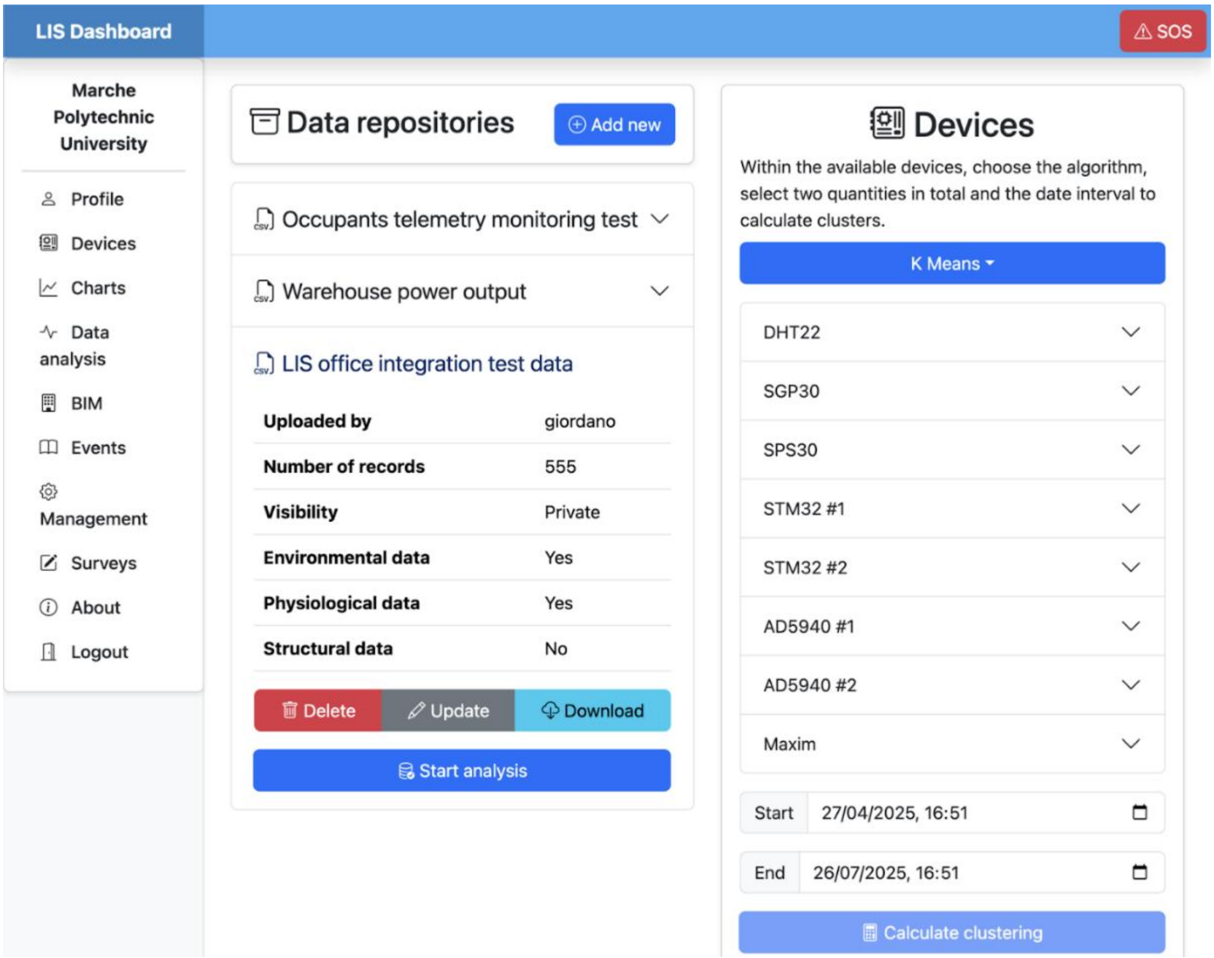

Figure 23. Data Analysis within the LIS-Platform (Credits: LIS)

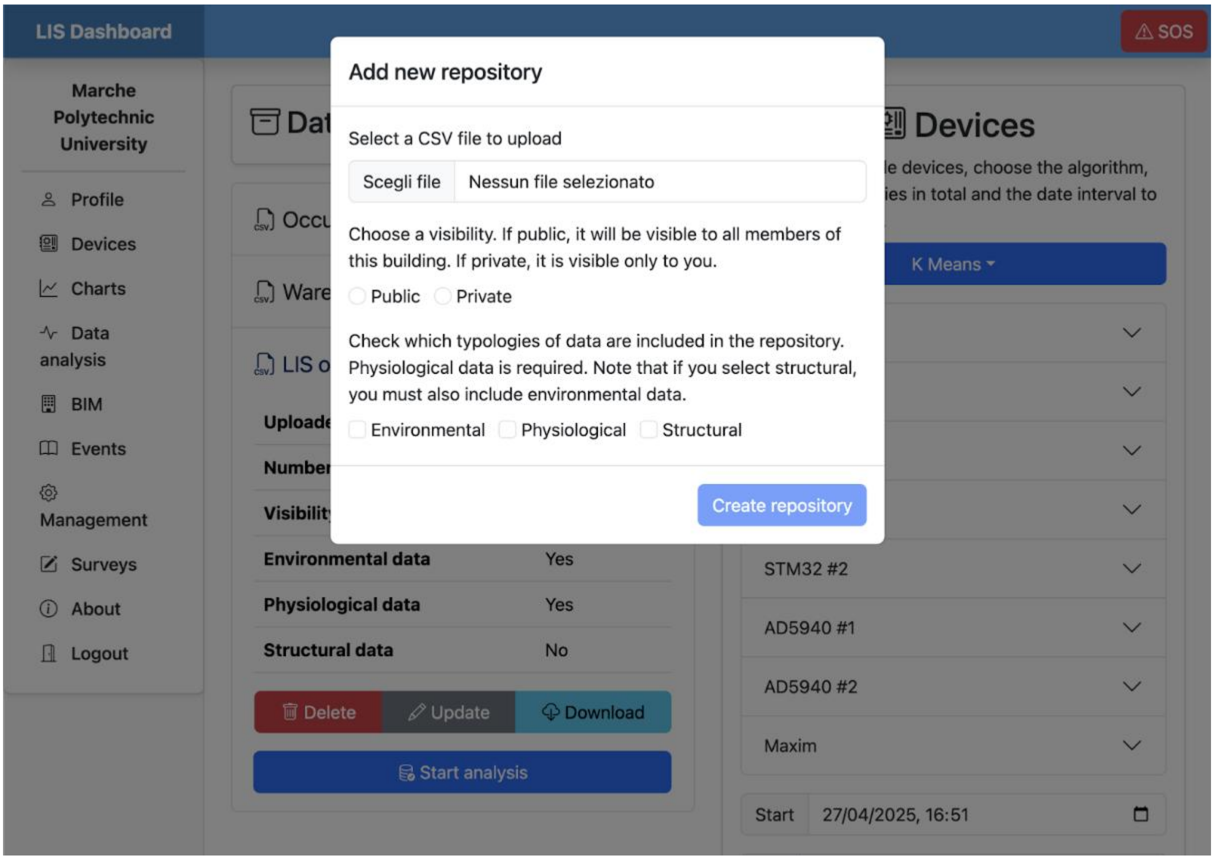

Figure 24. LIS-Platform: Data analysis and repository upload (Credits: LIS)

Analytics Engine

This intermediate layer acts as a data processing hub. It handles preprocessing (resampling, filtering, cleaning), feature extraction (e.g. HRV, PMV, thermal indices), and initial data alignment between environmental and physiological streams. The engine transforms raw signals into analysis-ready features for further computation and visualization.

AI/ML Models

Processed features are fed into machine learning models hosted within the LIS-Platform. These include supervised models (e.g. Random Forests, XGBoost, LSTM) for comfort prediction, as well as unsupervised techniques (e.g. K-means clustering) to detect recurring patterns in user response or room conditions. These models are trained using data collected from test campaigns or real deployments and support incremental retraining. Initial results contain data from pre-test that took place in LIS office in collaboration with UNIVPM for experimental data collection, pre-processing and analysis (Cosoli et al., in press).

Analysis and KPIs

The output from the analytics and ML modules is used to derive actionable indicators and comfort metrics. These include HRV time series, comfort scores, IAQ exposure profiles, cluster groupings, and anomaly flags. Results are accessible through interactive dashboards, allowing users to monitor real-time conditions and derive high-level insights.

5.3.4. INTEGRATION WITH BIM

A core architectural feature of the LIS-Platform is its native integration with Building Information Modeling (BIM), enabling a spatially aware and semantically rich framework for data visualization, contextual analysis, and predictive modeling. The platform is designed to interface directly with the digital model of the monitored building, typically provided in Industry Foundation Classes (IFC) format. This open, standardized schema ensures compatibility across BIM tools (e.g., Revit, Archicad, BIMserver) and facilitates consistent mapping between real-world sensor data and virtual building elements. Each sensor, whether environmental (e.g., temperature, CO_2, light) or physiological (e.g., wearable tracking devices) is registered in the platform with metadata that includes its spatial coordinates and functional mapping to specific IFC entities (e.g., IfcSpace, IfcWall, IfcSystem). This association enables two key capabilities:

- Semantic enrichment of sensor data, by linking time-series measurements to architectural context (e.g., Room 2.14, South Façade, HVAC zone A).
- The resulting digital twin acts as a live, data-driven replica of the physical building. Unlike a static BIM model used purely for design or construction, the digital twin dynamically reflects the building's operational state, including indoor environmental quality, energy performance, and human-centered indicators like thermal comfort or heart-rate variability.

This integration supports:

- Heatmap visualizations, showing gradients of temperature, CO_2, or discomfort across the building as shown in the next figure.
- Anomaly detection in context, e.g., flagging a sensor reading outside of its normal range and immediately localizing it to a BIM-linked object.

Figure 25. Heatmap Visualization via the Zone-Aware Interface in the LIS Platform (Credits: LIS)

Technically, the LIS-Platform achieves this through a middleware layer that connects the real-time analytics engine to the BIM viewer. This ensures that spatial-temporal analytics can be visualized, navigated, and filtered by any stakeholder, engineers, facility managers, or researchers directly within a 3D, zone-aware interface.

5.4. SENSOR INTEGRATION AND HYGROTHERMAL MONITORING IN THE CARMELITANE BUILDING

The LIS-Platform will integrate data from sensors installed by ENEA in the Carmelitane Building. The measurement campaign is scheduled to begin in September 2025. Sensor data will be made accessible to the LIS-Platform via SFTP, and a dedicated API will ensure interoperability and seamless data integration. Hygrothermal testing will be conducted in parallel with material characterization to analyse changes in composition and moisture sorption after the material's maturation. The objective is to assess the impact of these changes on hygrothermal performance. Numerical simulations will complement the experimental results, using sensor data streamed to the LIS-Platform to recreate and validate the observed behaviours within the platform itself.

The experimental setup for hygrothermal measurements will be specifically defined for the Carmelitane Building. Sensors will be installed on both surfaces of selected wall assemblies. They will be fixed in position using adhesive rubber at the edges to prevent moisture infiltration, ensuring full adherence to the wall surface. The sensor covers will be made of breathable material to prevent condensation and maintain accurate measurements. ENEA has purchased sensors for thermo-hygrometric monitoring (fig24) inside the walls. The sensor has a relative humidity measurement range: 0÷100% - Temperature measurement range: from -40 to +80°C.

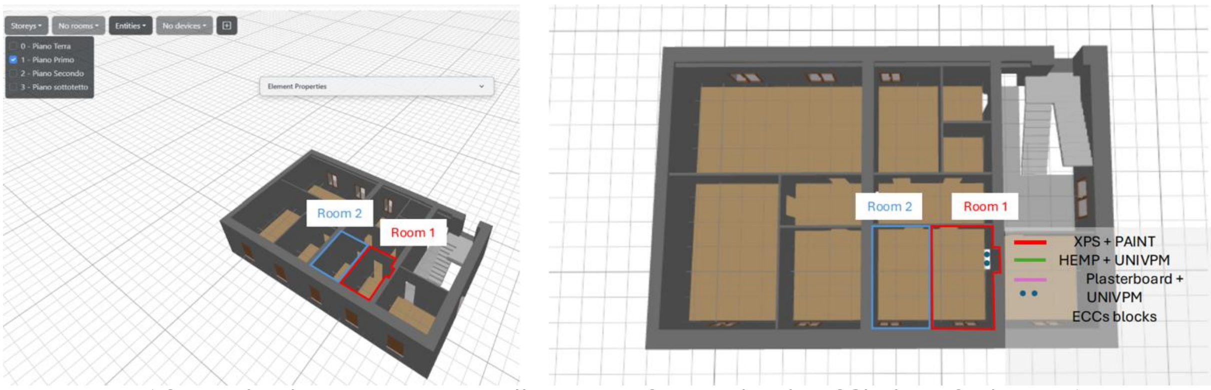

Figure 26. ENEA Sensors for Thermo-Hygrometric Wall Monitoring Connected to the LIS Platform (Credits: ENEA)

The sensor network has been operationally tested and synchronized with the central system for remote management of continuous data collection and in continuous Figure 26. *ENEA Sensors for Thermo-Hygrometric Wall Monitoring Connected to the LIS Platform (Credits: ENEA)*. Figure 27. *Installation Diagram of Thermohygrometric Sensors on Insulated Walls (Credits: ENEA)* shows the installation diagram of the thermohygrometric sensors on the insulated walls made of XPS (red) and lime hemp (green).

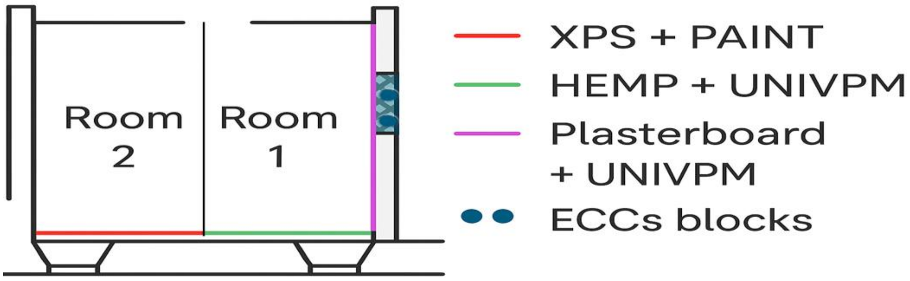

Figure 27. Installation Diagram of Thermohygrometric Sensors on Insulated Walls (Credits: ENEA)

Figure 28. External control unit for measuring weather parameters (Credits: ENEA)

The monitoring system also includes the use of an external control unit (fig.26) for measuring weather parameters, equipped with an outdoor temperature and relative humidity probe with a relative humidity measurement range: 0÷100% - Temperature measurement range: from -40 to +80°C.

5.5. PLATFORM SECURITY

The LIS-Platform takes all-encompassing approach to security. It starts from the security of the Django web framework, on which the LIS-Platform is built upon.

Application security

Protection against common attacks like cross site scripting, cross site request forgery, SQL injection, clickjacking, are enabled and we take advantage of all. We also take advantage of the secure password storage and complexity requirements offered by Django. When developing the Platform, we implement best security practices such as:

- Validating all user input and non-user input (like cookies and HTTP headers) avoiding making assumptions that data is trusted.
- Encrypting all connections to the LIS-Platform via HTTPS with secure encryption configuration and revoking device credentials in case those as sent insecurely via HTTP.
- Avoiding all third-party content and forbidding it entirely via Content Security Policy, which improves both security as well as privacy.
- Removing referrer information (site the user is coming from, i.e. the LIS-Platform) when navigating away from the site.
- Processing user-uploaded IFC files inside an isolated instance that has no access to the LIS-Platform database, by removing network access as well as file system access to the database files.
- Leveraging standard web APIs like Content Security Policy and Trusted Types to provide strong mitigations against XSS and other data injection attacks.
- Running the LIS-Platform itself inside an isolated instance with minimal access to the OS to protect it from other software on the system as well as the OS from it.

Data security

Several security measures are in place to avoid data disclosure or loss. Every instance of data, whether it be sensor data, IFC files (or derivatives), event logs, device logs, user logs, is authenticated and requires specific privileges to access at the granularity of single users. Since access controls can be bypassed with software vulnerabilities, programming best practices are being followed to limit those or mitigate the impact, such as validating all user and non-user input, avoiding third-party content in web pages to improve privacy and reduce the impact of supply-chain attacks, add software mitigation and containment. When data is transmitted, it is always encrypted in transit using default HTTPS security with no fallback to legacy encryption. In case of hardware or software fault corrupting data, we rely on backups taken multiple times a day which can be quickly restored with few commands. Such unexpected event would also be detected by our continuous status check monitor which immediately notifies multiple people for them to address the downtime, ensuring data availability. Backup are stored in a different datacentre than the one where the LIS-Platform is running and are encrypted before being sent in such a way that the remote destination has no access to them even if the storage is hacked while a backup is taking place. Finally, the LIS-Platform also avoids having unnecessary data in the first place, and as such, it automatically deletes logs older than 90 days.

Authentication security

The LIS-Platform has implemented passwordless authentication using passkeys to provide enhanced security and protect users against phishing attacks. Compared to passwords, passkeys use public key cryptography to avoid pitfalls associated with shared secrets. The user credential manager, which may be a smartphone, computer, software password manager, USB/NFC token, stores a private key, while the LIS-Platform only stores a public key. The public key is useless without the private key shall the service ever being breached. During login, the user authenticator proves possession of the private key without revealing it. The LIS-Platform allows multiple passkeys per-member each requiring verification (usually biometric verification or PIN entry on the authenticator) making the passkey a self-contained 2FA form, thus streamlining login without typing an additional OTP or waiting for an SMS. Currently, the passkey is an optional addition to the password.

6. PRELIMINARY EXPERIMENTAL STUDY AND RESULTS

The additional *pre-pilot*s required extra effort, time, and resources. Other components, such as the development of the dynamic survey within these tasks, were also carried out using the LIS budget, without requesting any additional adjustments or resources from partners. This approach was taken to ensure progress, avoid delays in other modules, and preserve the value of the work already completed under Task 4.2.

6.1. PRE-PILOT SETUP OVERVIEW

In the initial phases of the project, two *pre-pilot* setups were established:

- Palazzo Fazzini (formerly recognized as the initial pilot site) (Candigliota et al.2025)
- LIS-Office, located within the UNIVPM Building (Cosoli et al. 2024)

Palazzo Fazzini in Camerino was initially selected as the primary pilot site. A substantial portion of the pilot’s development, including integration for structural and damage assessment, was carried out under Task 4.2. Although the pilot location was later reconsidered, the development had already progressed significantly. Initial in-situ testing and data collection were successfully completed in collaboration with ENEA. Following these results, the project transitioned to a fully digital environment. All testing data were preserved and managed within the LIS-Platform to ensure continuity, traceability, and long-term usability. As both destructive and non-destructive testing (NDT) data are uploaded to the LIS-Platform, each dataset is permanently linked to the corresponding object within the digital model. This ensures that the data remains associated with the object, even when the IFC model is downloaded and used externally. This ensures that the data remains associated with each object, even when the IFC model is downloaded and used externally. For example, Column 13 has already been selected, and the colour scheme in the 3D environment indicates the presence of linked data, as shown in the figure below. The model can be oriented, and by clicking on the object, users can access the associated properties and method. Each object is assigned a unique ID, which can also be generated as a hyperlink or QR code. This allows any stakeholder to directly access the BIM model with the object pre-selected. If linked data are available, the stakeholder is taken directly to the object's properties and can input numerical values or other information, such as maintenance reports. Updates to the BIM model are automatically synchronized with other stakeholders through the LIS-Platform, and outputs remain cross-compatible with formats such as IFC.

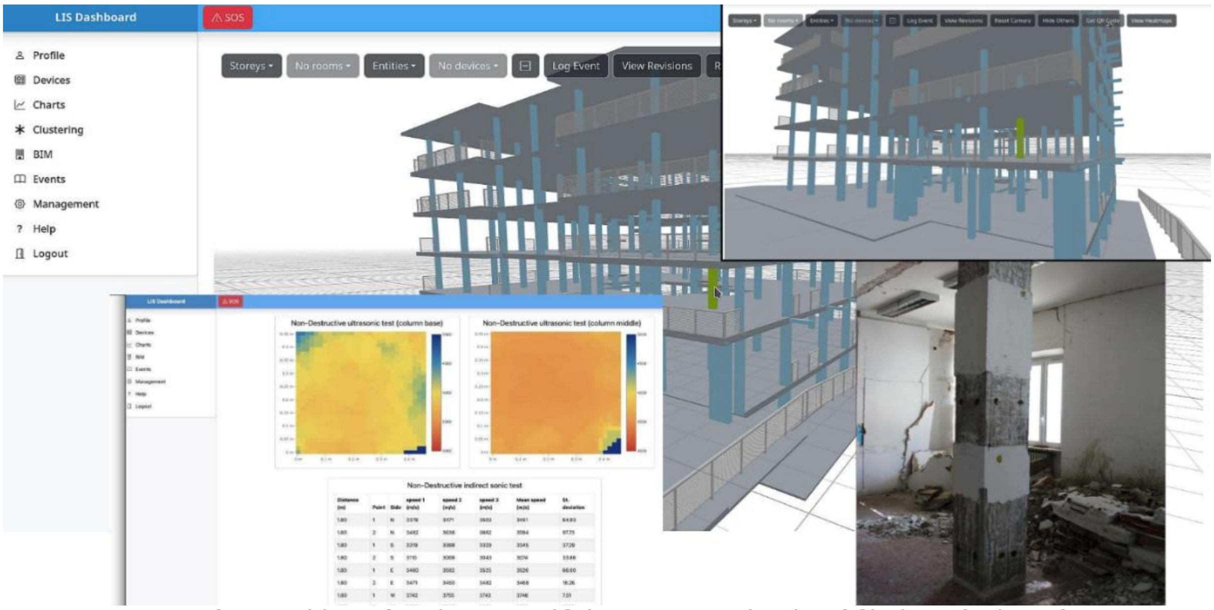

Figure 29. Heatmaps Generated from NDT Information of Palazzo Fazzini within the LIS-Platform (Credits: LIS)

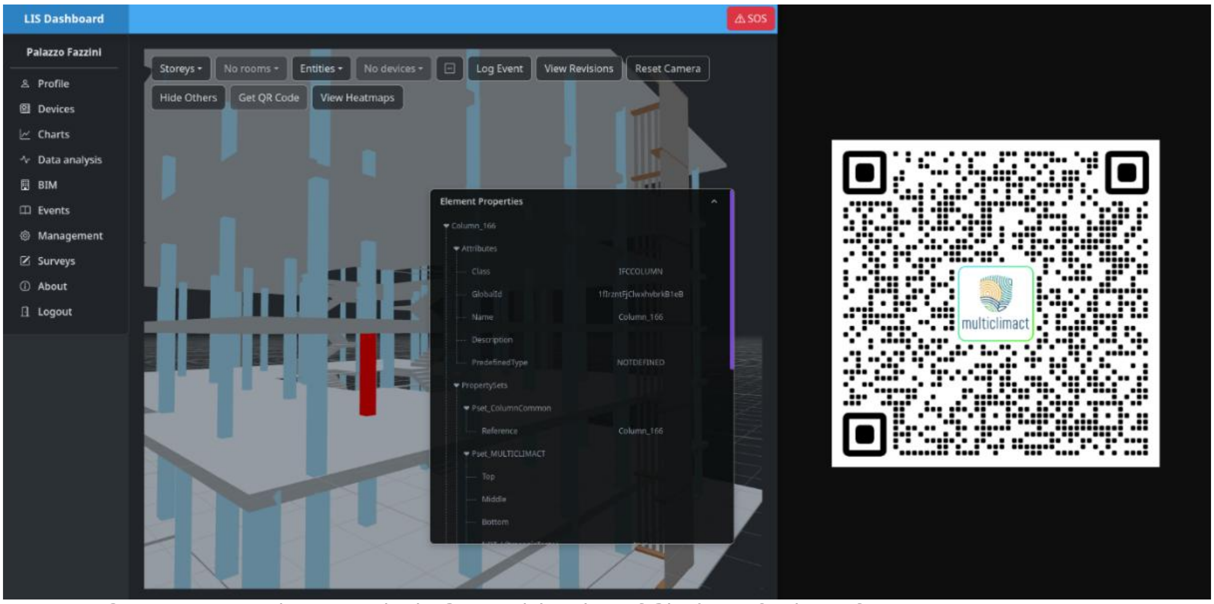

Figure 30. Direct access to objects inside the BIM model within LIS-Platform (Credits: LIS)

In Task 10.2, the automatic synchronization of BIM model updates for all stakeholders was further enhanced by enabling operators and researchers to modify objects directly within the model—without the need to download files or open additional applications. Each object can be assigned a unique link or QR code, allowing users to upload testing campaign results or other relevant information straight into the model. These inputs are instantly visible to all stakeholders in real time. Consequently, building administrators and owners can easily navigate through all changes, filtering and tracking updates by object, category, or model version. This streamlined process greatly enhances collaboration, transparency, and data management across the entire building lifecycle.

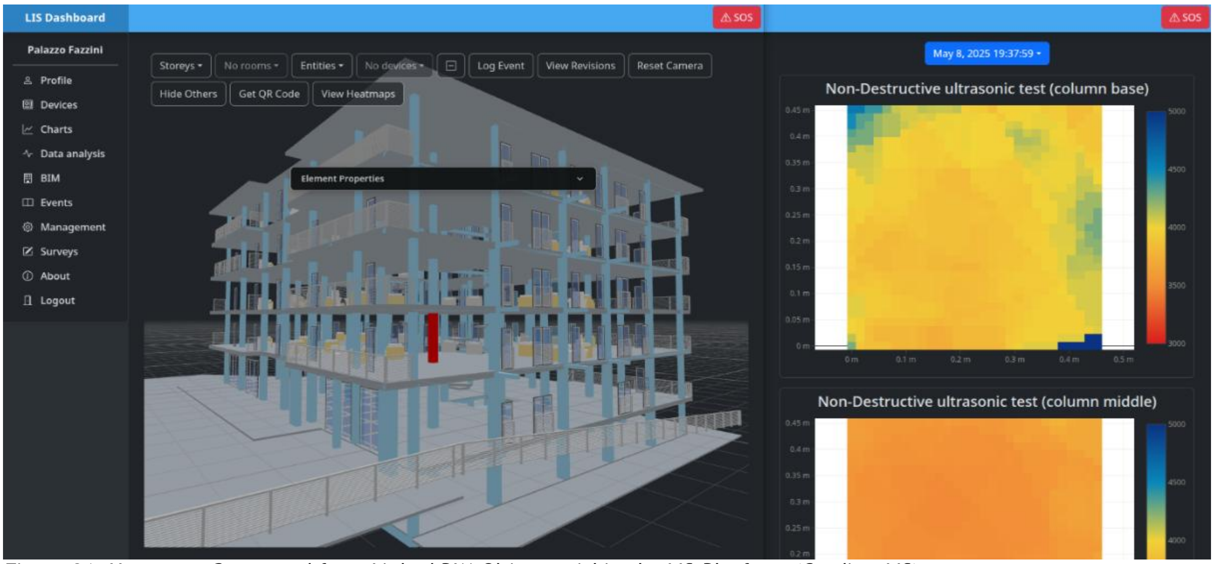

Figure 31. Heatmaps Generated from Linked BIM Objects within the LIS-Platform (Credits: LIS)

The process places particular emphasis on the professional roles involved, both during on-site operations and throughout maintenance activities. It aims to streamline procedures and ensure immediate access to relevant information. As shown in the figure, each update allows for the generation of a QR code linked to a specific object. This code can be shared directly with the responsible operator, either as a link or an image. This method enables real-time updates to the BIM model and, by extension, to a Digital Twin (DT). This approach allows operators to access only the relevant section or object without the need to interact with the entire digital model, which is often resource intensive. As a result, workflows are simplified, and all stakeholders remain informed of any modifications made. The resulting BIM model becomes a continuously updatable model, maintaining a dynamic link to the physical asset and its characteristics. This ensures the preservation of its long-term value while supporting adaptability for future users with diverse needs and objectives.

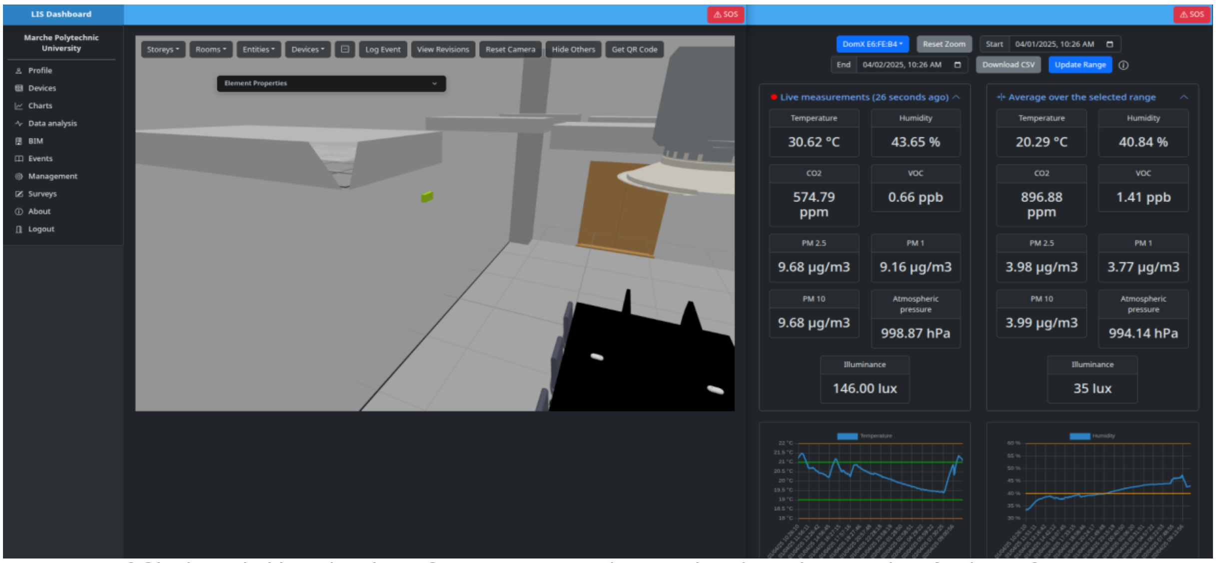
Figure 32. LIS-Platform dashboard with IoT-BIM connection and sensor data from the pre-pilot (Credits: LIS)

In parallel, a second *pre-pilot* was carried out at the LIS-Office. This installation included a full suite of environmental sensors, SHM systems, and biosensors integrated with wearable devices tested by LIS personnel and UNIVPM researchers. All environmental, physiological, and SHM data were collected in real time and streamed directly to the LIS-Platform. Through this integration of IoT/CPS devices, the collected data was automatically embedded into the BIM model, enabling stakeholders to analyse performance, develop hypotheses, and plan future interventions for the full-scale pilot. A comprehensive testing campaign focusing on the correlation between physiological and environmental data is detailed in Task 8.5. A summary is presented here, with an emphasis on the technical implementation aspects within the LIS-Platform.

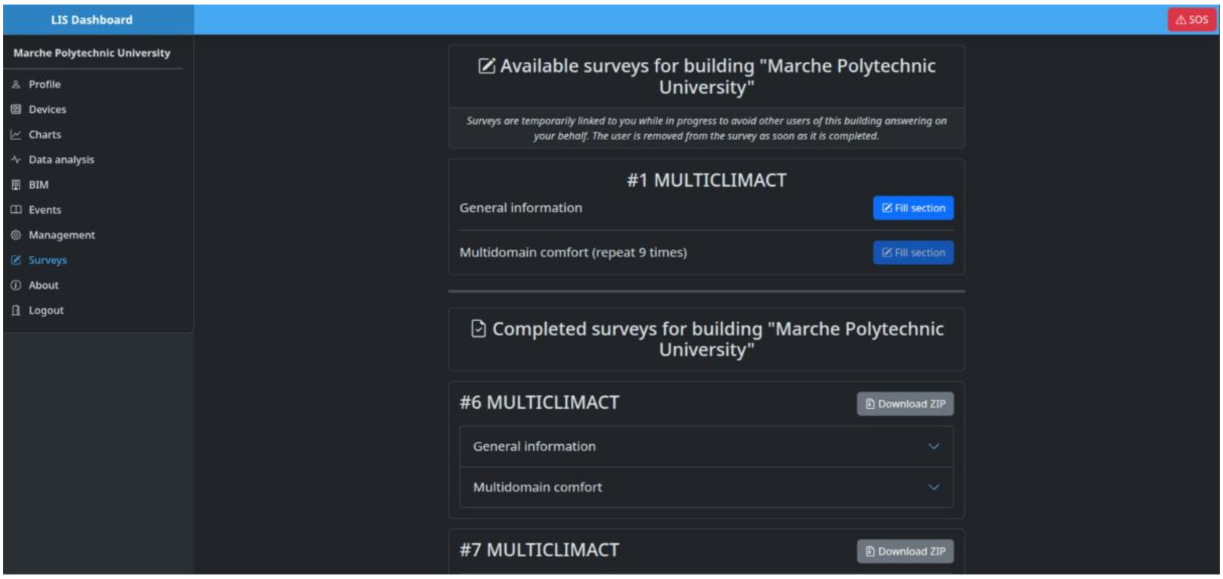

Figure 33. Material and building element mapping in CYPETHERM Eplus (Credits: LIS)

Dynamic survey tool

In collaboration with UKA and UNIVPM, a survey campaign involving volunteers was conducted. Given that much of the sensor data was already accessible through the LIS-Platform, a new integrated and dynamic survey tool was developed. This tool enabled the collection of subjective comfort-related data and was directly linked to real-time physiological and environmental sensor inputs. The dynamic survey tool provided precise timestamping of participant responses, along with corresponding environmental and building conditions. This tool was developed outside the grant agreement of the MULTICLIMACT project. Nevertheless, the partners involved adopted it as a substitute for traditional methods, such as handwritten records and conventional survey tools (e.g., forms). The idea and its implementation demonstrated strong performance, enabling the precise identification of specific moments in time and across domains, thereby providing a deeper understanding of indoor environmental adaptation and occupants' well-being. This capability makes it a valuable tool for studying behavioural adaptations, stress responses in emergency scenarios, and informing decisions related to the design and planning of multidomain interventions both for renovation and the development of future buildings. This pilot comfort study was conducted as a *pre-pilot* of the LIS-Platform ahead of the Camerino demo deployment; the tests were performed in agreement with the WMA Declaration of Helsinki[5] and was approved by the UNIVPM Ethics Committee. Fifteen volunteers (8 men, 7 women; ages 23–55) performed standardized office tasks over ~2.5 hours while wearing wearable sensors. Data were captured by the LIS-Platform in three synchronized streams: physiological signals, ambient environmental readings, and in-situ surveys. This controlled office campaign aimed to validate the end-to-end LIS data pipeline and generate initial insights into multimodal comfort, thereby supporting readiness for the full deployment.

6.2. DATA COLLECTED

The fixed DomX sensors continuously monitored the indoor environment, capturing parameters such as air temperature, relative humidity, CO_2 concentration, volatile organic compounds (VOCs), particulate matter (PM_1, $PM_{2.5}$, and PM_{10}), atmospheric pressure, and illuminance. The corresponding averages of these measurements are presented in Figure 34.

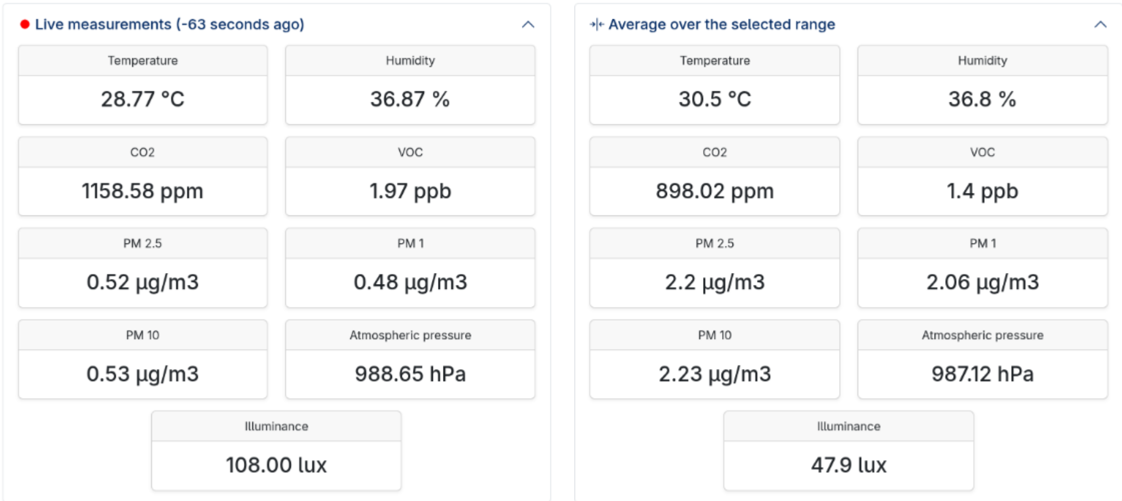

Figure 34. RT measurements within the LIS-Platform (Credits: LIS)

5 https://pdf-it.dev.acw.website/please-and-thank-you?url=https://www.wma.net/policies-post/wma-declaration-of-helsinki/&pdfName=wma-declaration-of-helsinki

Structural Sensors: Sensors that measure structural health conditions about electrical impedance (modulus and phase) and free corrosion potential of building integrated in sensorized blocks as in Figure 35 and Figure 36,along with their corresponding average values.

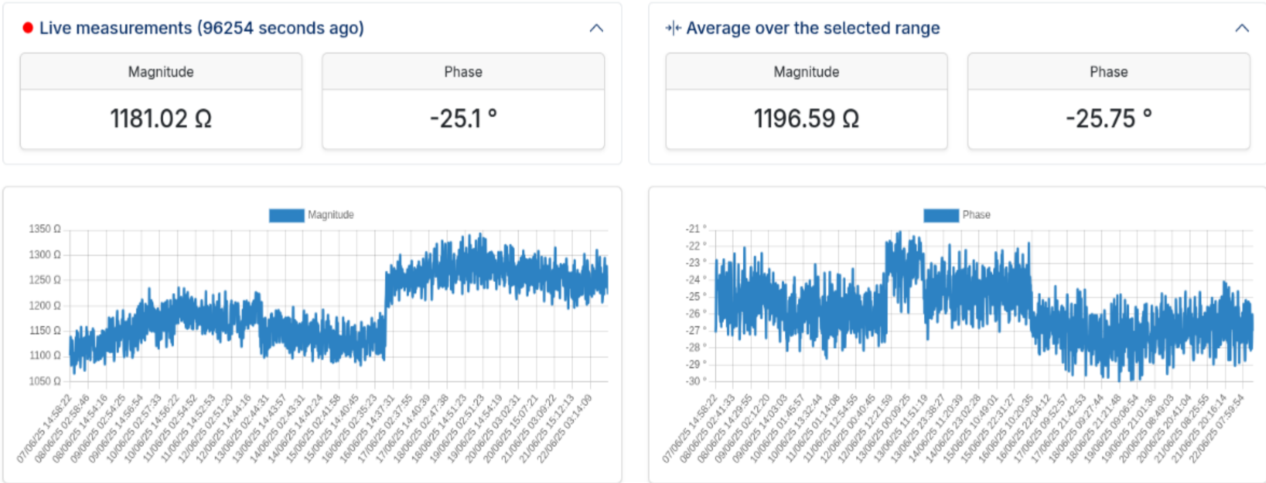

Figure 35. RT measurements for SHM within the LIS-Platform (Credits: LIS)

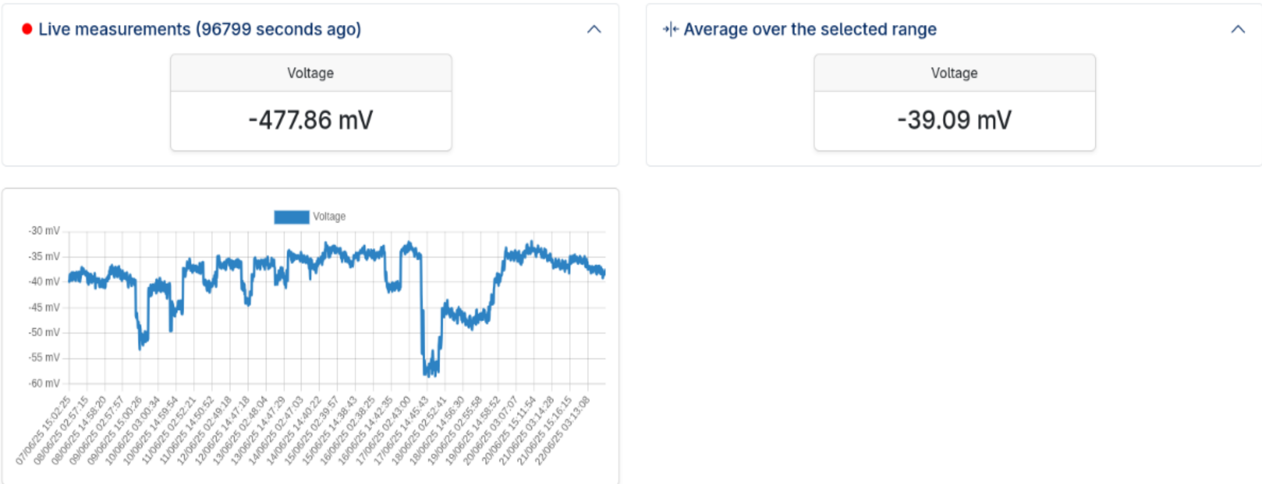

Figure 36. RT measurements for SHM within the LIS-Platform (Credits: LIS)

Physiological Wearables: To capture occupant comfort or stress, wearable devices record physiological data. EmotiBit wearables recorded electrodermal activity (EDA), photoplethysmography (PPG, providing pulse-rate metrics), tri-axial accelerometer, and skin temperature. These continuous streams capture participants' autonomic and activity-related responses.

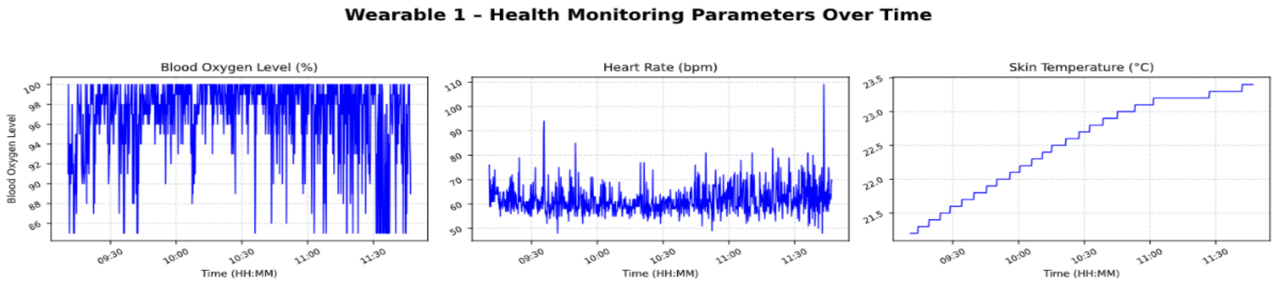

Figure 37. Physiological data within the LIS-Platform (Credits: LIS)

Subjective surveys: Repeated in-situ questionnaires collected self-reported comfort and perception ratings. These covered demographics, health and four comfort domains (visual, acoustic, thermal, and air-quality) on Likert scales. The surveys allow mapping subjective comfort to objective measurements. Each data stream was logged as timestamped CSV and uploaded via the LIS-Platform to the analysis server. The campaign thus provided a rich multimodal dataset combining physiology, environment, and human feedback.

6.3. DATA COLLECTION AND SYNCHRONIZATION METHODOLOGY

All raw data were automatically ingested into the LIS-Platform's database. To synchronize streams, a unified timeline was established using UNIX timestamps. Specifically, each data file was indexed by time, duplicates or null timestamps were removed, and all streams were aligned in ascending chronological order. A tolerance window of ~40 milliseconds was applied when merging physiological and environmental samples, ensuring tight temporal correspondence between modalities. This synchronized framework allowed linking each survey entry to the concurrent sensor measurements, forming one unified dataset for subsequent analysis.

6.4. SIGNAL PREPROCESSING

Raw signals underwent systematic cleaning and regularization to produce analysis-ready time series. Key preprocessing steps included:

- Filtering: High-frequency noise above physiological bands was removed. For signals sampled >25 Hz (e.g. accelerometer at 100 Hz), a zero-phase 4th-order Butterworth low-pass filter with 10 Hz cutoff was applied. This preserves relevant dynamics (e.g. body motion) while attenuating artifacts.
- Resampling: All cleaned signals were resampled to a common rate of 25 Hz using the Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) algorithm. The PCHIP method was chosen for its monotonicity-preserving properties and was validated via spectral overlap (>0.95 coherence up to ~4 Hz).
- Missing-data handling: Variables with >20% gaps were excluded from analysis. Short gaps (≤3 consecutive samples) were linearly interpolated, while longer gaps were forward- or back-filled within acceptable windows. Edge segments containing unrecoverable NaNs were trimmed. The final merged dataset contained <0.5% imputed values overall, indicating minimal missingness after cleanup.
- Survey alignment: Survey responses (originally on a 1–5 scale) were mapped to numeric values and forward-filled at 25 Hz between entries, ensuring each comfort rating applied until updated.

All preprocessing was implemented in Python (pandas, NumPy, SciPy) within the LIS containerized environment, ensuring a reproducible pipeline from raw logs to uniformly sampled data ready for analysis. The preprocessing component was also carried out by UNIVPM, with overlapping aspects drawn from Task 8.5, and is included in this section to demonstrate the full flexibility of the LIS-Platform. The emphasis here is not on the data themselves, but rather on showcasing the application

Co-funded by the European Union

of different technologies, AI models, and algorithms that can be executed directly within the LIS-Platform.

6.5. COMFORT MODELLING APPROACH AND FEATURES

The analysis integrated physiological, environmental, and subjective data into a unified feature matrix. In total, 23 derived physiological features (e.g. mean and variability of EDA, heart-rate and HRV metrics from PPG, motion statistics, skin temperature) were combined with 9 environmental metrics (temperature, humidity, CO_2, VOCs, $PM_1/_{2.5}/_{10}$, pressure, illuminance) and 16 raw survey items. Principal component analysis (PCA) was applied to the standardized feature matrix, retaining 10 components that together explained 77.85% of total variance; the per-component contributions were 15.02%, 12.82%, 9.69%, 8.30%, 7.56%, 6.92%, 6.01%, 4.60%, 3.76%, and 3.17% for PC1–PC10, respectively. This exceeds common exploratory thresholds (often targeting 70–80% cumulative variance) and exhibits a smooth scree taper, indicating that dominant structure is captured early while later components contribute diminishing variance. For exploratory analysis, standard K-Means (scikit-learn) was applied to the 10 PCA scores with k=5, using k-means++ initialization, Euclidean distance, Lloyd-style updates, n_init=20, max_iter=300, tol=1e-4, and random_state=0; the choice k=5 was supported by inertia (elbow) and silhouette diagnostics together with domain expertise. K-Means++ selects initial centroids in a distance-aware manner—after one random seed, each subsequent center is chosen with probability proportional to the squared distance from the nearest existing center, so that seeds are well-separated, which typically improves convergence speed and reduces poor local minima relative to purely random starts. Cluster centroids estimated in PCA space were then inverse-transformed through the PCA model and inverse-standardized to recover values in the original feature units, enabling interpretation in terms of the original physiology, environment, and comfort ratings. Subjective survey items were aggregated into four domain scores (visual, acoustic, thermal, air-quality) by averaging relevant questions, and these composites were used post hoc to characterize each cluster's comfort profile. Separately, to predict comfort from the measured signals, an exploratory factor analysis of the 16 survey items identified three latent comfort dimensions: **Acoustic-AirQuality**, **Visual**, and **Thermal** (three factors explaining ~64.3% of variance).

Indoor Comfort Experimental Results

Environmental sensor streams (CO_2, VOC, temperature, humidity, particulate matter) were synchronized and merged with timestamped subjective comfort ratings (Likert 1–5) into a unified, time-aligned dataset. Each environmental measurement was paired to a common clock, and survey entries were forward-filled to 25 Hz so that each rating persisted until updated. Channels exhibiting > 20 % missing data were discarded; dropouts shorter than 0.12 s were linearly interpolated, longer interior gaps were forward- or backward-filled, and edge segments were trimmed, yielding a final dataset with < 0.5 % missing. Four sets of domain-specific environmental features were computed, and Pearson correlation analyses were performed against visual, acoustic, thermal, and air-quality comfort ratings. Visual comfort showed the strongest positive associations with CO_2 ($r \approx +0.16$), VOC ($r \approx +0.17$), temperature ($r \approx +0.15$), and barometric pressure ($r \approx +0.14$). Here, r denotes the Pearson correlation coefficient, a unitless measure ranging from −1 to +1 that quantifies the strength and direction of a linear relationship between two variables. Values close to 0 indicate a weak linear relationship, positive values indicate that both variables increase together, and negative values indicate that one variable increases as the other decreases.

Acoustic comfort increased with higher CO_2 ($r \approx +0.27$), VOC ($r \approx +0.26$), pressure ($r \approx +0.28$) and PM_{10} ($r \approx +0.18$). **Thermal comfort** tracked relative humidity ($r \approx +0.14$) and PM_1 ($r \approx +0.12$), with smaller correlations for temperature and pressure ($|r| < 0.07$). **Air-quality comfort** exhibited only weak links to environmental measures (all $|r| < 0.10$); stronger associations with autonomic markers are addressed in section 4.2.5. As shown in Figure 1, the top ten absolute Pearson correlations for each domain are summarized in bar-chart form.

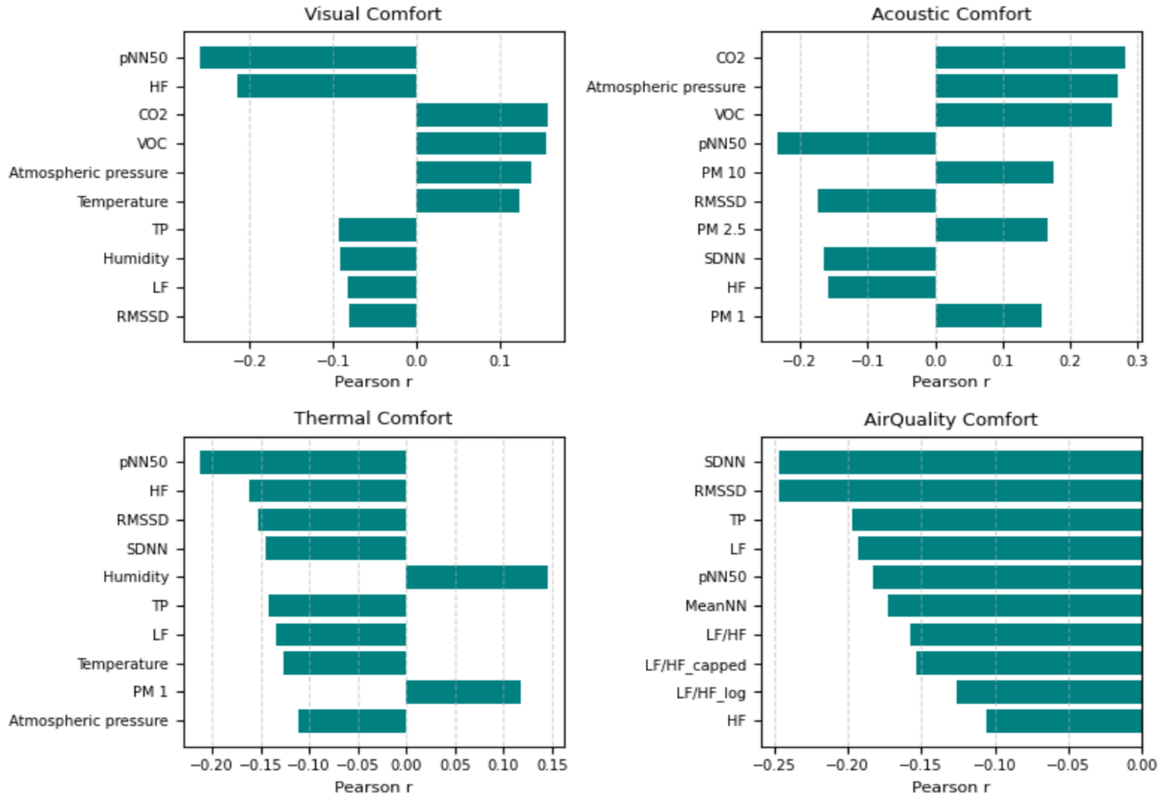

Figure 35. Physiological data within the LIS-Platform (Credits: LIS)

6.6. TEMPORAL COMFORT PATTERN ANALYSIS

The methodology incorporated detailed temporal analysis capabilities to examine comfort evolution patterns throughout monitoring sessions. Individual participant comfort trajectories were analysed to demonstrate the dynamic nature of environmental comfort responses. Subject 11's comfort progression during a 2.5-hour session illustrated how thermal comfort exhibited sharp early-session increases to maximum values (approximately 3.6 units), while visual and air-quality comfort demonstrated more gradual improvements from baseline levels (~2.7) to mid-session peaks (~3.2-3.5). Acoustic comfort maintained relative stability around 2.5 throughout the session, with minor fluctuations occurring primarily during task transitions. Overall comfort tracking revealed steady progression from ~3.4 at session initiation to ~3.75 by mid-morning. This section, adapted from Prof. Gloria Cosoli and colleagues (Cosoli et al., in press), is presented here although most of the work is described in Task 8.5 to illustrate the versatility of the LIS-Platform, drawing on the study A Measurement Approach for the Assessment of Indoor Multidomain Comfort: The MULTICLIMACT Experience.

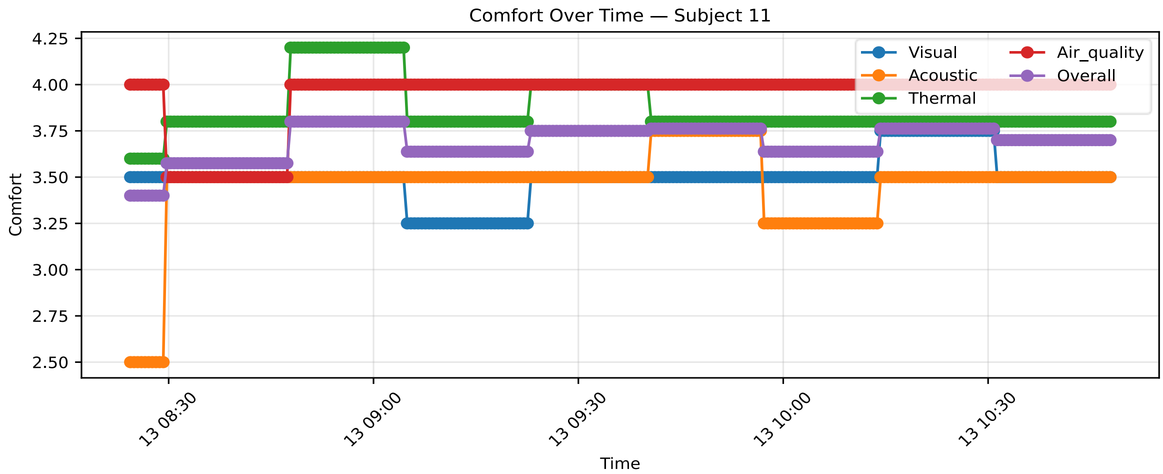

Figure 38. Physiological data within the LIS-Platform (Credits: LIS)

6.7. CORRELATION ANALYSIS

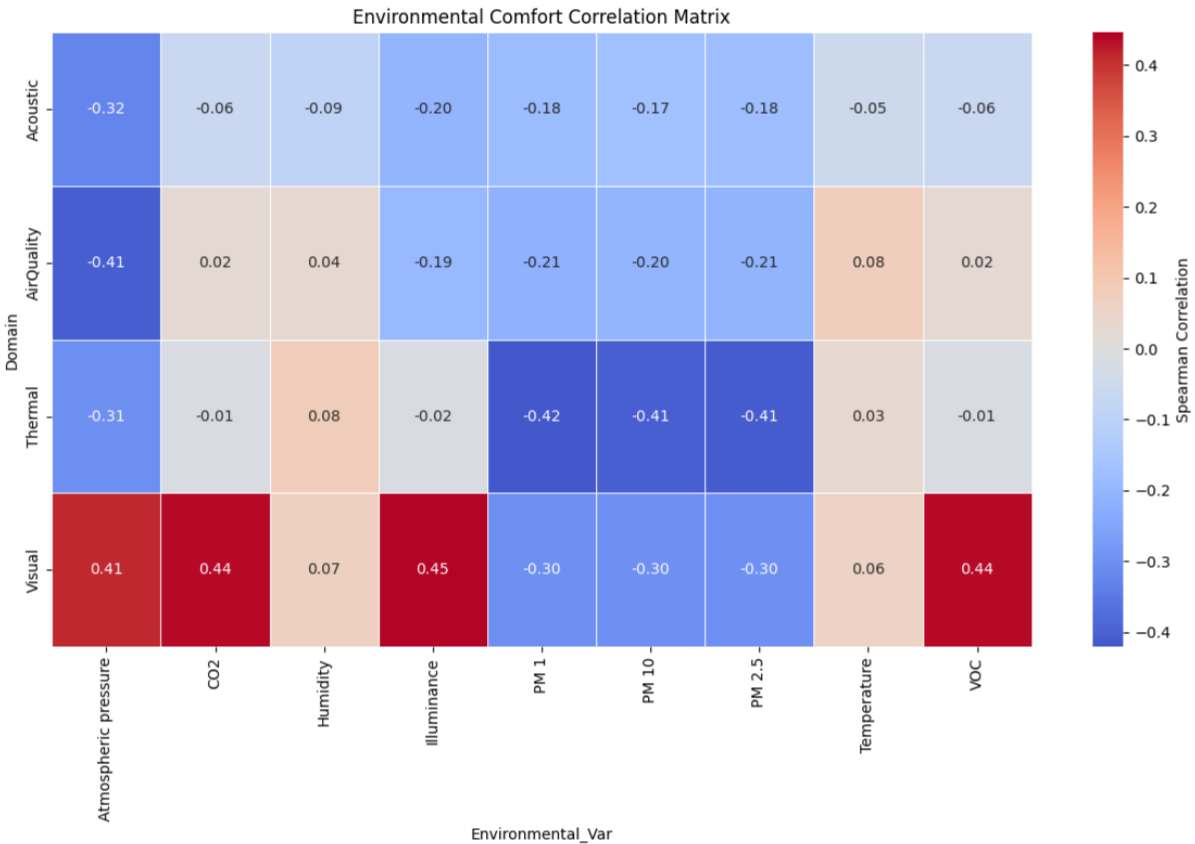

Figure 39. Environmental Correlation Matrix within the LIS-Platform (Credits: LIS)

To quantify pairwise relationships, Spearman correlations were computed between environmental parameters and aggregated comfort domain scores. The key findings were:

- Visual comfort was strongly positively correlated with illuminance (ρ≈+0.45) and, less commonly, with indoor CO_2 and VOC levels (ρ≈+0.44 for each). This indicates that higher light levels were associated with better visual comfort. The CO_2/VOC association may reflect context-specific effects (e.g. window status or ventilation patterns).
- Thermal comfort showed pronounced negative correlations with particulate matter: PM_1 (ρ≈-0.42), $PM_{2.5}$ (ρ≈-0.41), and PM_{10} (ρ≈-0.41). In other words, higher airborne particulate concentrations tended to coincide with lower thermal comfort ratings, consistent with literature on pollution feeling “hotter.”
- Air-quality comfort also correlated negatively with particulates (PM_1, ρ≈-0.19; $PM_{2.5}$, ρ≈-0.21; PM_{10}, ρ≈-0.20) and with atmospheric pressure (ρ≈-0.41), underscoring that poor air conditions degrade perceived air comfort.
- Acoustic comfort exhibited only weak correlations with the measured variables; its strongest link was a moderate negative correlation with pressure (ρ≈-0.32). (This may be an artifact or relate to small pressure-induced hearing effects).

In summary, lighting and air pollution emerged as dominant environmental drivers: better lighting improved visual comfort, while higher particulate matter consistently reduced thermal and air-quality comfort. These heatmap results inform which factors might be most critical to control or monitor in future deployments.

6.8. MODEL PERFORMANCE SUMMARY

The predictive modelling and statistical analyses yielded the following performance outcomes:

- Clustering validation: The k-means clusters were clearly separated in the PCA space, suggesting that the chosen k=5 effectively captured major patterns. The PCA-transformed space showed tight grouping, lending confidence that the clusters are meaningful (no obvious overlap).
- Factor analysis: The three-factor solution explained ~64% of survey variance. The factor structure aligned well with domain groupings (e.g. visual and thermal items loaded on separate factors), supporting their interpretability.

Overall, the unsupervised cluster model performed satisfactorily in revealing structure, whereas the supervised prediction of comfort scores proved challenging on this limited pilot data.

6.9. ANALYTICS ENGINE FOR COMFORT ASSESSMENT AND MODEL UPDATING

The core analytics compute comfort indicators and identify patterns in the data. **Comfort Indicators:** We implement standard thermal comfort indices. The Predicted Mean Vote (PMV) model predicts the average occupant sensation on a 1 (cold) to 5 (hot) scale; PMV=3 is neutral. The system continuously calculates PMV from sensor inputs (air temperature, humidity, occupant activity/clothing if available).

For example, one implemented platform automatically computed PMV from real-time temperature/humidity data and visualized thermal comfort via heatmaps.

Model Updating: The digital twin’s building performance model can be updated in near-real-time as new data arrive. For instance, an energy model or occupant comfort model can be calibrated against sensor measurements, refining parameters for accuracy. Machine learning techniques can learn occupant response patterns. Over time, the system “learns” occupants’ comfort. While specific model-update algorithms are project-dependent, the key idea is that streaming IoT data continually feed back into the simulation or analytical model so the digital twin remains synchronized with reality.

k-means Clustering: To uncover spatial patterns, we apply unsupervised clustering. A common approach is k-means, which groups data points by similarity.

The clustering and factor analyses revealed distinct comfort-related patterns in the data. **Cluster analysis** identified five interpretable "comfort modes" adapted from Prof. Gloria Cosoli and colleagues (Cosoli et al., in press).

Key cluster profiles included:

- "High Comfort" – consistently high comfort ratings in all domains (visual, acoustic, thermal, air-quality) under relatively benign conditions.
- "Medium Comfort / High Arousal" – moderate self-reported comfort paired with elevated physiological arousal (e.g. higher heart-rate variability or EDA).
- "Low Acoustic/Air-Quality, Medium Visual/Thermal" – reduced acoustic and air-quality comfort despite moderate visual and thermal comfort.
- "Medium Visual/Air-Quality, Low Acoustic/Thermal" – a converse pattern with lower visual/air-quality ratings and better acoustic/thermal comfort.
- "Medium Comfort / Relaxed" – generally moderate comfort across domains with lower physiological arousal (more relaxed state).

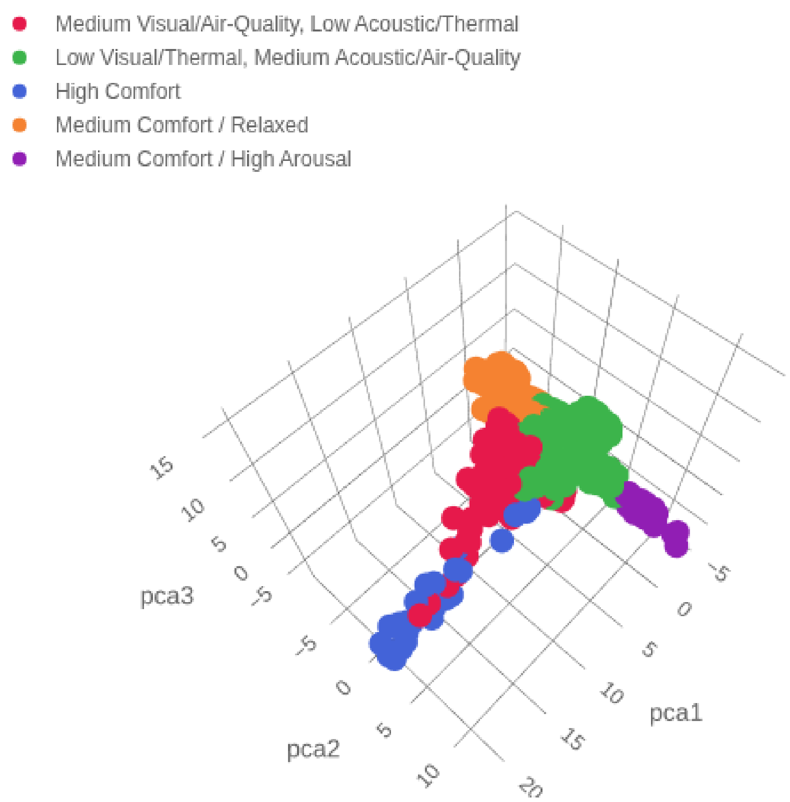

Figure 40. Multi-Domain Analysis and Clustering within the LIS-Platform (Credits: LIS)

These clusters were well-separated in PCA space, confirming distinct multi-domain comfort states. The diversity of profiles (e.g. some clusters showing trade-offs between domains) highlights the complex interplay of environmental factors and individual responses. For example, one cluster's centroid might correspond to a slightly stuffy environment (higher CO_2/VOC levels) eliciting moderate comfort, while another corresponds to ample lighting and low pollution yielding high comfort. Overall, the results demonstrate that even in a controlled office, occupants experienced varying comfort patterns influenced by both the environment and their physiological state.

6.10. VISUALIZATION AND BIM INTEGRATION

This integrated interface shows a 3D floor plan (the BIM model) with color-coded zones, and shows real-time sensor charts (temperature, humidity, etc.). Each sensor is linked to a BIM element, enabling contextual visualization case.rpi.edu. In general, visual integration is achieved by overlaying sensor data on the BIM model: for instance, it can colour zones by current temperature or CO_2 level aps.autodesk.com. Published tools (such as Autodesk Forge Viewers with IoT extensions) already support adding sensor glyphs and heatmaps to a BIM model aps.autodesk.com.

The web application also provides 2D dashboards and charts. Users can select rooms or sensors from the model and view time-series plots of recent data. The example (above) includes dashboards with gauges and line graphs. This visual approach allows stakeholders to "see" data in its spatial context. In our implementation, any BIM object (e.g. a thermostat or window) is mapped to its real-time data. The user can toggle data layers (temperature, humidity, PMV, etc.) on the model. Tools like Plotly.js can render charts, while libraries like IFC.js or three.js render the 3D model. The result is a unified UI where facility managers can rotate the model, click on a room, and immediately inspect its environmental conditions.

6.11. METHODOLOGY LIMITATIONS AND CONSIDERATIONS

The implemented methodology acknowledges several limitations that influenced the analytical outcomes and interpretation of results. The monitoring environment was conducted within controlled laboratory settings, which may not fully represent the complexity and variability of real-world office environments. Additionally, the temporal scope of data collection sessions was relatively brief, precluding comprehensive analysis of longer-term comfort adaptation, fatigue effects, habituation processes, or cumulative exposure impacts from environmental stressors. The coarse resolution of Likert-scale comfort ratings may mask rapid or transient comfort fluctuations that occur at shorter timescales than the survey sampling rate. Furthermore, seasonal variations, diurnal rhythm effects, and adaptive behaviours such as window operation or personal environmental control were not systematically captured within the current methodology framework.

6.12. FUTURE DEVELOPMENT DIRECTIONS

Future methodology refinements should focus on several key enhancement areas to improve predictive capability and real-world applicability. Sensor fusion and artifact correction procedures should be advanced through implementation of accelerometer-driven adaptive filtering for electrodermal activity and photoplethysmography signals, cross-referencing multiple CO_2 and particulate matter sensors, and machine-learning-based denoising of combined physiological and environmental data streams. Deployment scope should be extended to encompass diverse, real-world office environments over extended periods of days or weeks, including open-plan offices, home office settings, and varying HVAC operational strategies. Recruitment of larger, more diverse participant samples with variable demographic and physiological characteristics would enhance model generalizability and robustness. Implementation of finer-grained continuous self-reporting mechanisms, such as ecological momentary assessment via smartphone prompts, alongside higher-resolution environmental monitoring using spatially distributed temperature/humidity sensors and real-time CO_2 flux monitoring, may reveal subtler comfort dynamics not captured by current methodologies. The ultimate goal involves implementing personalized calibration routines incorporating baseline physiological phenotyping and individual occupant preference profiles, integrating these multimodal predictors into live HVAC and lighting control systems to enable truly adaptive, occupant-centered building automation systems.

6.13. STAKEHOLDER USAGE AND ACCESS

Different stakeholders use the system for different purposes.

Facility Managers: They monitor comfort zones and HVAC status. Real-time alerts are generated if conditions deviate from set thresholds. For example, if the temperature drifts above the threshold, the manager is notified to adjust cooling. Studies have shown that providing facility staff with real-time comfort data helps maintain optimal conditions: in one case the system helped managers plan HVAC interventions to keep spaces within comfort targets[6].

Maintenance and Engineers: Structural sensor data feed into asset management. Unusual readings can trigger inspections. Clustering results (from analytics) might also guide sensor deployment or identify under-instrumented areas.

Building Occupants: Through a web/mobile interface, occupants could view summaries of their zone's comfort or submit feedback, which in turn refines the models. Sharing certain data (e.g. indoor temperature, CO_2) can also raise occupant awareness.

Research and Public Partners: All collected data are accessible to project partners via the shared repository. Partners can download datasets for further analysis or apply external algorithms. The platform's open API means partners can integrate the data into their own tools. In sum, the integrated BIM–IoT framework is designed to be multi-user: managers get dashboards and controls, occupants get information, and researchers get raw or processed data.

6.14. RELEVANCE TO LIS OBJECTIVES AND DEPLOYMENT READINESS

This preliminary study exercised the full LIS-Platform pipeline from sensor ingestion through analytics and thus aligns with the project's integration goals. By validating data capture, synchronization, preprocessing, and comfort analytics on real users, the work supports system readiness for the Camerino field trials. The comfort-related findings (e.g. importance of lighting and air quality) will inform experimental design and adaptive control strategies in the main deployment. In short, the results illustrate the LIS-Platform's capability to generate multimodal comfort insights and will guide further refinements as part of the deployment preparation.

6.15. DATA REPOSITORY AND PUBLIC PARTNER ACCESS

The LIS-Platform incorporates a centralized and extensible **data repository** designed to manage multi-source data streams collected from IoT devices deployed across monitored environments. This repository acts as the backbone of the platform, enabling secure, structured, and scalable data management for both environmental and physiological signals. All collected data are funnelled into a centralized data repository. A **time-series database** is used, as it can ingest massive sensor streams and allow real-time querying. Importantly, the repository is accessible to authorized partners. This is achieved via shared dashboards inside the LIS-Platform section. Dashboards include widgets (graphs, charts) that any partner with permissions can view. In our system, each partner organization can log in to the web portal to download repositories for analysis. Security (authentication and encryption) ensures that data access is controlled. Overall, the data repository serves as a common resource where project stakeholders can retrieve data, monitor system status, and collaboratively analyze building performance.

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[6] mdpi.com

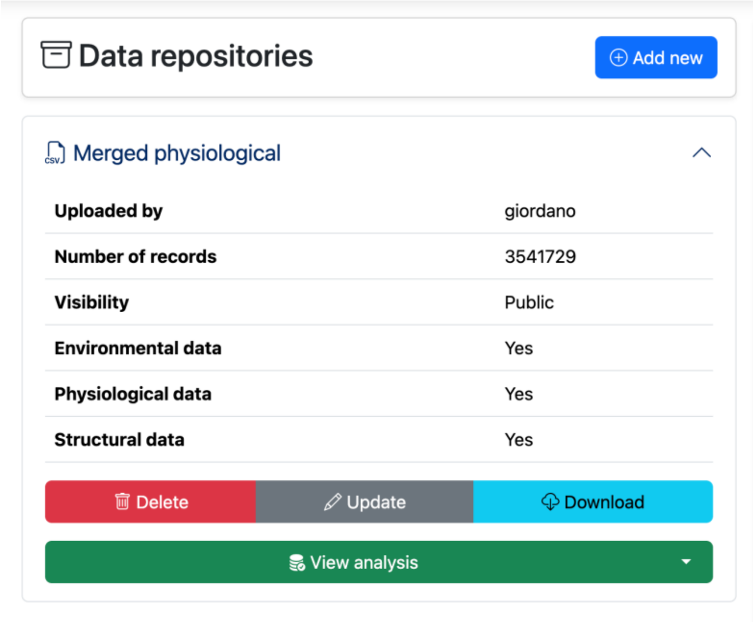

Figure 41. Data Repository and Public Partner Access LIS-Platform (Credits: LIS)

In accordance with **GDPR (General Data Protection Regulation)**, all data collection from human subjects (physiological signals, survey responses) is performed with explicit informed consent. Personally identifiable information is never stored in raw form within the repository. Data are pseudonymized and encrypted both in transit and at rest. Access is logged and traceable, with configurable audit mechanisms. The LIS data repository is also structured to be compliant with **FAIR principles** (Findable, Accessible, Interoperable, Reusable), supporting reproducibility, data reusability, and machine-readability. Metadata schemas are used to describe each dataset's origin, modality, unit of measurement, and semantic linkage to BIM entities. In the future, alignment with **Open Science Cloud** or similar federated repositories will enable selective publication of open datasets derived from the platform's test campaigns, supporting the broader scientific community.

In summary, the LIS-Platform's repository not only supports robust, secure, and scalable data storage but also promotes ethical and transparent collaboration among all partners involved in the MULTICLIMACT project and beyond.

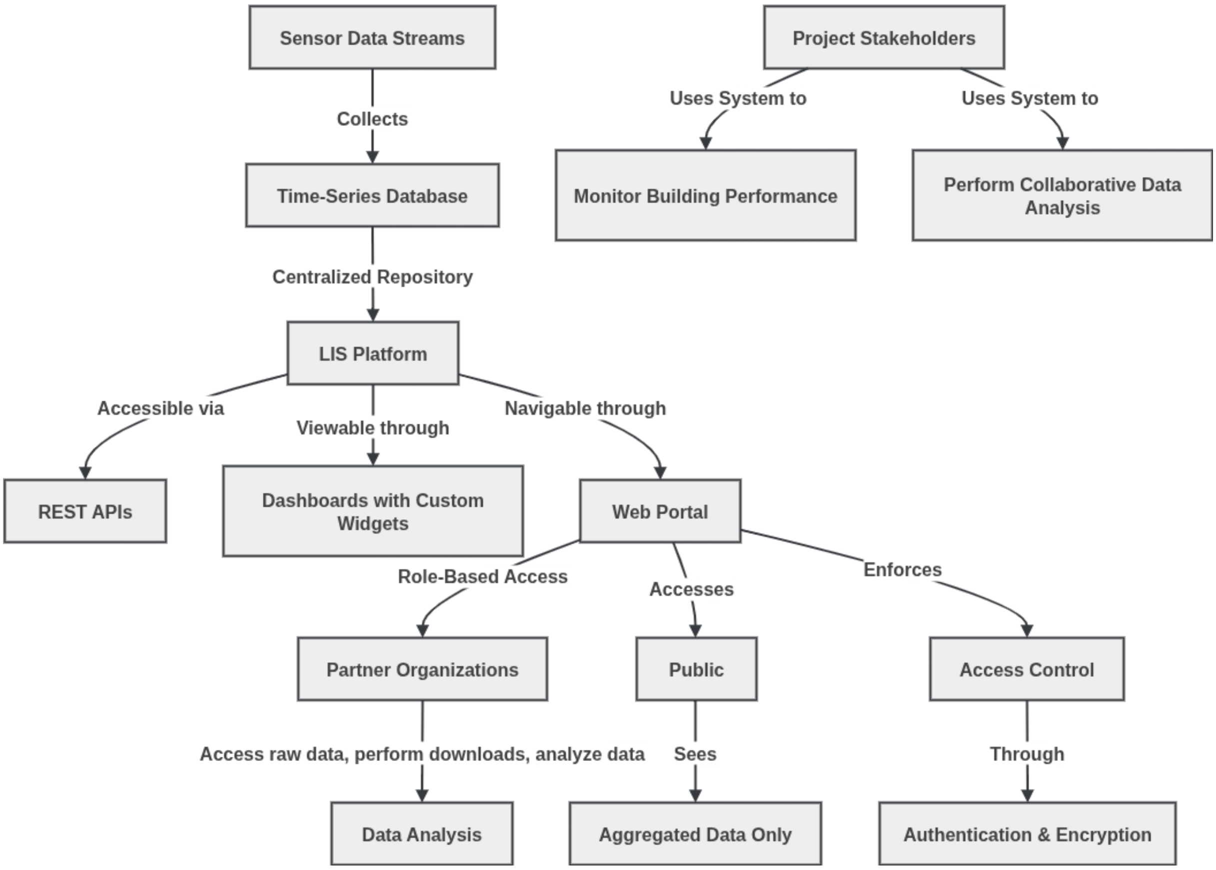

Figure 42. Overview of the LIS-Platform: From Data Repository to Stakeholder Integration (Credits: LIS)

7. LIS MOBILE COMPANION APP

The integration of mobile companion applications with Building Information Modeling (BIM) platforms has become a central theme in the development of real-time monitoring and safety systems across the built environment. This shift reflects the growing need for continuous, on-site access to digital building models and sensor data, enabling immediate response to dynamic conditions. Recent European research has established that mobile devices, particularly Android-based systems can serve as reliable clients in cloud-connected BIM/IoT frameworks, leveraging persistent communication protocols such as WebSockets[7] to receive real-time data updates and emergency alerts (Vittori et al., 2023). These communication channels support bi-directional messaging, enabling not only passive monitoring but also active interaction with BIM-integrated services. Several EU-led projects have adopted microservice-based backends and semantic data models (e.g., BRICK ontology, RDF graphs) to facilitate interoperability between BIM platforms and mobile clients (Pauwels et al., 2022). Mobile applications within these architectures provide access to sensor telemetry, geolocation services, and event-triggered notifications, functioning as front-line tools in digital twin ecosystems (Quinn et al., 2022). However, platform-specific constraints remain significant. Android allows background services to maintain socket-based connections reliably, whereas iOS restricts persistent background execution,

[7] WebSocket is a communication protocol that provides a full-duplex (two-way), persistent connection between a client (like a web browser) and a server.

necessitating fallback mechanisms such as polling or silent push notifications. Consequently, many real-time systems prioritize native Android clients while employing progressive web applications (PWAs) or hybrid approaches for cross-platform support. Mobile applications are also increasingly designed with awareness of hardware limitations and environmental conditions, such as battery constraints, sensor availability, and network reliability, to ensure continuity of service in safety-critical contexts (Tanga et al., 2022). Beyond data delivery, mobile apps are now expected to offer advanced capabilities including SOS alerts, man-down detection via motion sensors, and integration with live BIM models for location-based risk assessment (Everbridge, 2023). This evolution signals a broader convergence of BIM, IoT, and mobile computing toward an integrated, context-aware safety infrastructure one that empowers on-site personnel with immediate, spatially relevant insights drawn from continuously updated digital models.

Methodology:

The development methodology for the LIS mobile app leveraged a hybrid approach: combining a WebView-based interface with selective native Android components to enhance performance and access device capabilities. The rationale was to reuse the existing LIS-Platform's web application (for consistency and rapid development) while overcoming the limitations of a pure web app by integrating native features where necessary. This approach is reminiscent of the Progressive Web App strategy adopted in the LIS-Platform (Candigliota et al.2025) but goes a step further by embedding the web app in a native container. In practice, the Android app loads the LIS-Platform's web pages in a WebView[8], presenting the familiar BIM dashboard and data views. Wherever the web interface needs functionality that a web view alone cannot provide reliably (or where a native implementation is superior), the app replaces or augments it with native modules. For example, file uploads, BIM model viewing, or chart interactions could remain in the web domain, but critical features like persistent connectivity, background geolocation, and notifications are handled natively.

Continuous server connection:

The app establishes a persistent WebSocket connection (using Ktor's [9]client library in Kotlin) to the LIS server. Upon login, a secure WebSocket channel is opened and kept alive as long as the app (or its background service) runs. The choice of WebSockets ensures low-latency, bidirectional communication – the server can push urgent messages (e.g. an evacuation order or sensor alarm) immediately, and the app can send heartbeat signals or SOS messages without HTTP overhead. Implementing this with Ktor allows using Kotlin coroutines for efficient asynchronous handling of the socket. The *WebSocket client component* listens for connection events and messages in the background. To run continuously, the app utilizes Android foreground service capabilities (showing a persistent notification to stay alive) – a necessary design since Android's modern battery optimizations (Doze mode) could otherwise pause background network activity. We carefully manage thread usage and reconnection logic: if the socket drops (due to network loss or server issues), the app automatically attempts to reconnect, and it triggers a local notification to inform the user of the connectivity loss. Emergency SOS and geolocation: A cornerstone of the methodology is the integration of *native geolocation services* for accurate position tracking during an SOS event.

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[8] A WebView is a component that lets you display web content inside a mobile or desktop application.

[9] Ktor is a framework for building asynchronous server-side and client-side, https://ktor.io

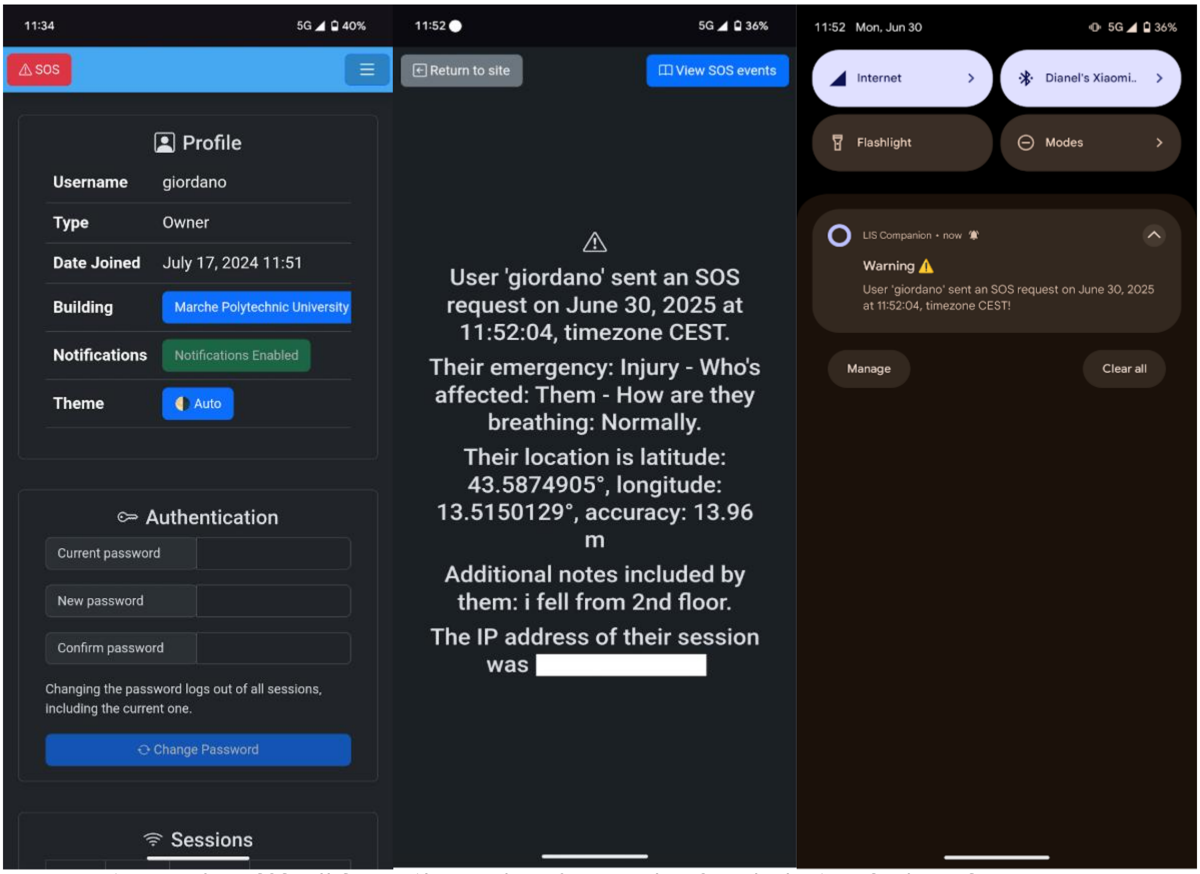

Figure 43. App Interface, SOS Full-Screen Alert, and Notification When Outside the App (Credits: LIS)

When a user presses the SOS button (in the app's interface), the app fetches the device's current GPS coordinates via Android's fused location provider (which combines GPS, Wi-Fi, and cell data for best accuracy as shown above.

These coordinates, along with user identity and a timestamp, are immediately sent through the WebSocket to the server as an SOS message. The decision to use native location APIs (as opposed to relying on the web view or manual user input) was to leverage the phone's sensors for high accuracy and timeliness. As noted in research, getting a reliable GPS fix may require multiple satellite signals and validation steps. By using the native API, the app can ensure it has a fresh and precise location (potentially even using Android's location callbacks to wait for an accurate fix) before sending the SOS. The server, upon receiving the SOS packet, can log the incident, plot the user on the BIM model or map, and initiate further emergency workflows (e.g., notify supervisors). Simultaneously, the app shows the user a confirmation that help is called. This real-time loop – from button press to server alert – is made possible by the persistent WebSocket channel and native sensor access. Connectivity loss alerts: A unique methodological feature is handling unexpected disconnections. Because the app is meant to function as a lifeline, if that lifeline breaks, we treat it as an event.

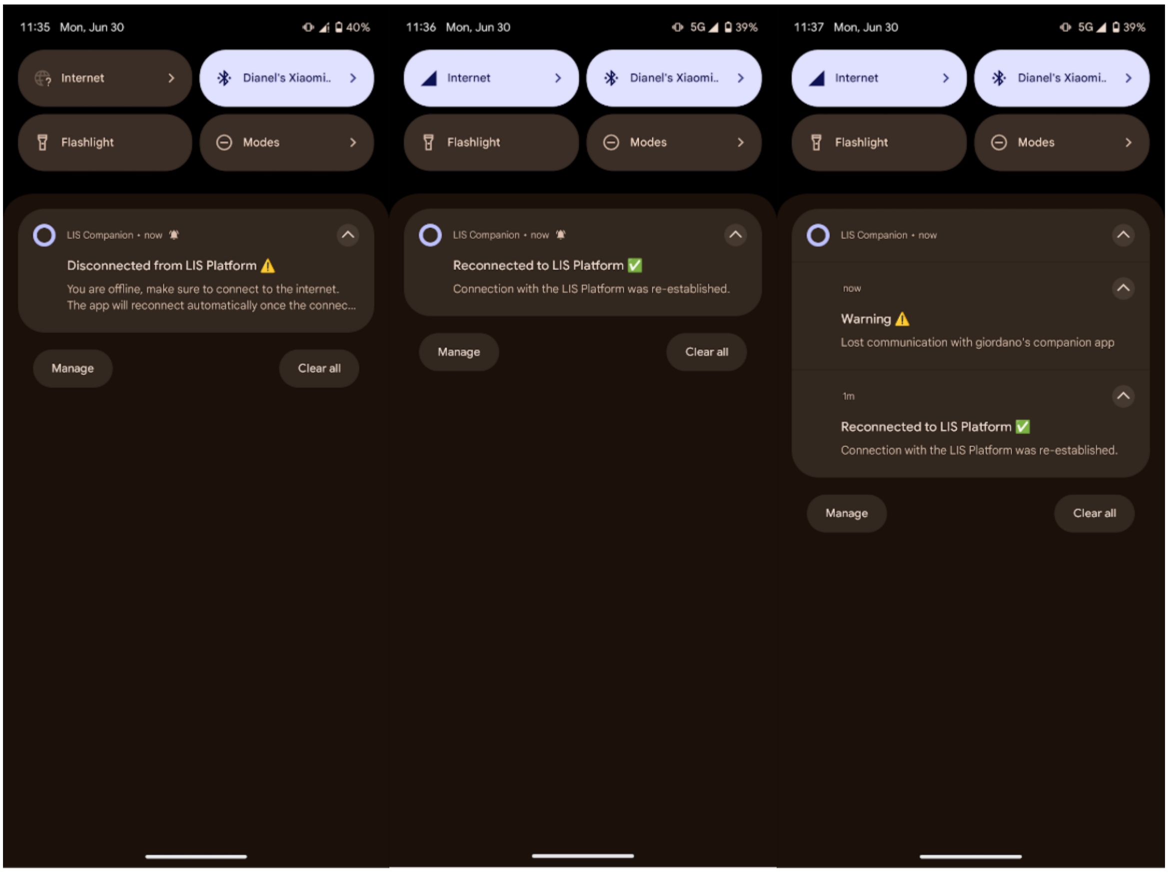

Figure 44. Showing real-time notification of network events between the app and the LIS-Platform (Credits: LIS)

The app's WebSocket listener continuously monitors the connection state. If the socket closes or an error occurs, the app immediately triggers two actions: (1) it displays a native notification on the device, warning the user that the connection to the platform has been lost, and (2) it logs the event to the LIS Platform (either via an alternate API call or upon reconnection). On the server side, the LIS Platform registers a disconnection alert for that user/device, similar to a dead-man's switch. This methodology ensures that if a device goes offline unexpectedly (e.g., the phone battery dies or the user is incapacitated and the app crashes), the system does not fail silently. Instead, it raises awareness so that supervisors can follow up. Many commercial safety systems rely on periodic check-ins or heartbeat timeouts for similar purposes, but our implementation with a live WebSocket and immediate native callback is more responsive. For example, while some apps use timed sessions that trigger an alert only if the user fails to check in, our app actively notifies as soon as the connection drops. This strategy was informed by the limitation that iOS devices cannot maintain such a live link in the background. WebSocket listener monitors the connection state continuously. If the socket is closed or an error occurs, the app instantly triggers two actions: (1) display a native notification on the device warning the user that the connection to the platform is lost, and (2) log this event to the LIS-Platform (e.g., via an alternate API call or when reconnecting). On the server side, the LIS-Platform registers a "disconnection alert" for that user/device – analogous to a dead-man's switch. This methodology ensures that if a device goes offline unexpectedly (e.g., phone battery dies, or the user is incapacitated and the app crashes), the system does not silently fail. Instead, it raises awareness so that supervisors can follow up. Many commercial safety systems rely on periodic check-ins or heartbeat timeouts for similar purposes, but our implementation with a live WebSocket and immediate native callback is more instantaneous. (For example, some apps use a timed session that triggers an alert if the user doesn't check in, whereas our app actively notifies as soon as the connection drops.) This strategy was informed by the understanding that iOS devices cannot maintain such a live link in background. By focusing on Android, we could implement a true always-on connection that *instantly detects drop-offs*, rather than simulating it with delayed mechanisms. Native Android integration: In addition to connectivity and location, the app uses other native Android features to enhance functionality:

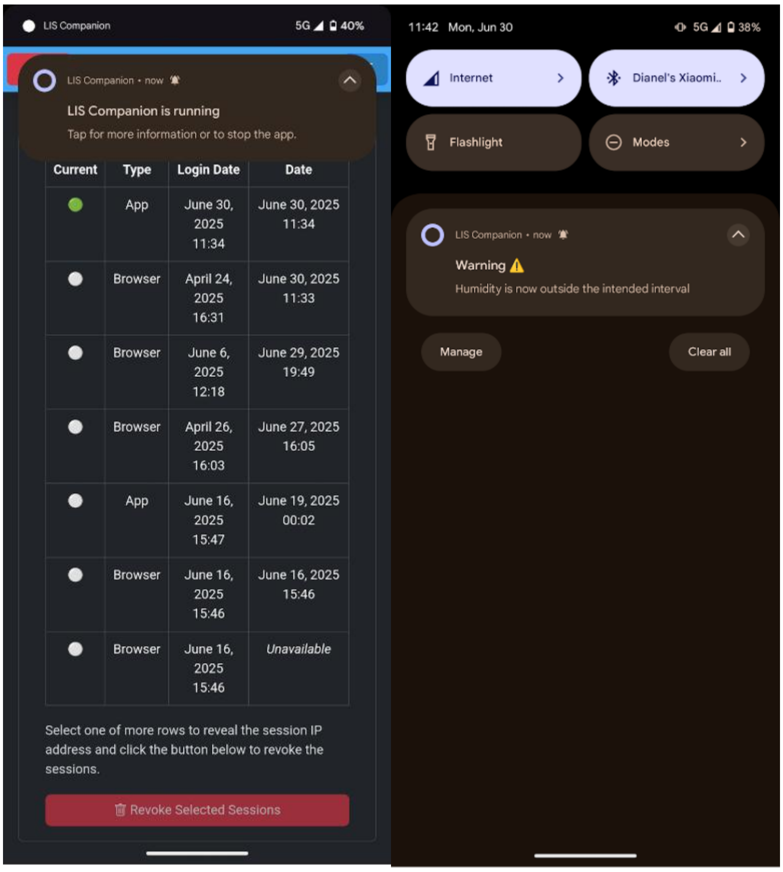

Figure 45. Showing LIS-Platform sessions and device sensors notifications (Credits: LIS)

Notifications: The app uses Android's Notification Manager to push alerts for various events (SOS sent confirmation, connection lost warning, new message from server, etc.). Native notifications are visible system-wide (even on the lock screen) and can leverage sounds/vibration for urgency. This improves reliability because, unlike a web alert or in-app message, a native notification will grab attention immediately. It also allows the app to alert the user even if the web view portion is not active (e.g., user is on home screen or another app). This design choice aligns with best practices for critical alerts in mobile apps – leveraging the OS notification system for any important, asynchronous event.

QR code login: The app simplifies authentication by using a QR code scan for login credentials. We integrated Google's ML Kit vision API to handle barcode scanning on-device. ML Kit's barcode-scanning library can quickly decode QR codes using the phone's camera, entirely offline.

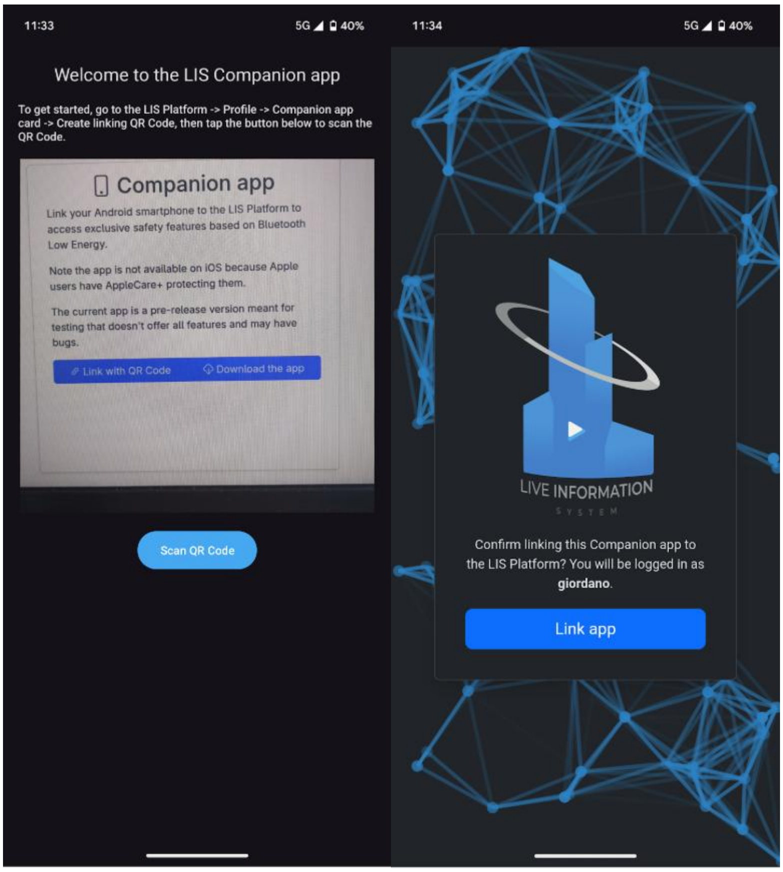

Figure 46. Showing first run UI and linking confirmation dialog (Credits: LIS)

The workflow is that the user can generate a QR code (likely via the LIS web platform on a desktop) that encodes their session token or login info; the mobile app's camera scanner (launched via a native interface) reads this and logs the user in without manual typing. This method was chosen for user convenience and security (QR codes are single-use and avoid entering passwords on mobile). ML Kit's on-device processing means the camera frames are analysed locally, and no video feed is sent externally, addressing privacy. Implementing this in the native layer was crucial – while a web app could use JavaScript to access a camera, it's far less efficient and cannot leverage ML Kit easily. By using ML Kit, the login process is fast and robust, showcasing how native tech enhances the overall integration.

WebView bridging: Throughout development, we established communication between the WebView and native code (through JavaScript interfaces). For instance, when the user taps the SOS button in the web interface, under the hood it calls a JavaScript handler that invokes the Android native function to get location and send the WebSocket message. Similarly, if the native code receives an incoming alert, it can inject a JavaScript event into the WebView to display a message or prompt the user within the web UI. This two-way bridge ensured that the *user experience remains seamless* — the user sees one unified app, even though behind the scenes the heavy lifting (network, GPS, scanning) is done natively. The development process also considered power management and reliability. Continuous GPS and network use can strain battery life. We mitigated this by requesting location updates only when needed (on SOS or periodically at modest intervals) rather than continuous high-frequency tracking. The WebSocket connection is maintained through a foreground service to prevent Android from terminating it. We tested multiple scenarios, including network changes, app closure via swipe, and device sleep, to refine the reconnection logic. The app was built and tested on modern Android devices, ensuring it meets the latest API requirements for background work and notifications (e.g., using Notification Channels for Android 8+). In summary, our methodology combined the flexibility of a web-based UI with the power of native Android services, resulting in an application that maintains a continuous, reliable link to the BIM platform and fully exploits smartphone capabilities for emergency and alert use-cases.

Differences with Existing Apps

The LIS mobile app stands out from other solutions in both the BIM and safety/emergency domains. The following sections highlight its key differences and innovations, supported by comparisons with existing applications. Integration of BIM data with Safety Alerts: Unlike generic lone-worker safety apps which are standalone, our app is tightly integrated with a BIM/IoT platform. Traditional safety apps (e.g. SHEQSY, StaySafe, SolusGuard) focus on tracking worker location and sending panic alarms to a monitoring center.[10] They do not incorporate BIM models or sensor data from a site's digital twin. By contrast, the LIS app allows any SOS or alert to be viewed in context – for example, on the BIM model of the building or infrastructure being monitored. This provides additional situational awareness (e.g., knowing which BIM model is linked). Our app brings that research concept into practice within an existing platform. Continuous Real-Time Connection vs. Polling/Push: Many existing mobile solutions cannot maintain a truly continuous socket connection, especially on iOS. They rely on techniques like periodic server polling, scheduled check-ins, or push notifications to update status. For instance, if an iOS-based app wants to detect a lost connection or emergency, it might send a silent push notification every few minutes to prompt a response (a known workaround since iOS will suspend background sockets). Our Android-native app avoids this stop-gap approach by using a persistent WebSocket, giving instantaneous communication. This means if a worker hits SOS, the alert is sent immediately (no waiting for the next poll), and if the connection drops, the app and server know within a fraction of a second. The difference is akin to having a live phone line versus a radio check-in schedule. In safety terms, those seconds or minutes gained by real-time connectivity can be critical. Furthermore, the LIS companion app proactively notifies on disconnection, which is not a standard feature in most apps. For example, typical lone-worker apps like Ok Alone or StaySafe might trigger an alarm if a check-in is missed after a set interval, but they don't explicitly generate an instant alert the moment the phone goes offline. Our system's design, treating connectivity loss as an alert, is a differentiator that adds a layer of fail-safe monitoring.

Native Android Features for Accuracy and Reliability: Because we built specifically for Android, we leveraged capabilities that cross-platform or web-based apps often don't. Accurate location and sensor use is one area: our app can utilize high-accuracy GPS mode. Competing apps which are web-based (PWAs) or built with cross-platform frameworks might be limited by the lowest-common-denominator of features. The LIS app's use of ML Kit for QR scanning[11] is another subtle difference – many enterprises apps use QR codes, but they often require a network call to decode (or use less optimized libraries). Ours does it on-device instantly.

This focus on native performance means a smoother user experience in critical moments (fast login, quick location fix, etc.). Additionally, by being Android-specific, we ensure that even if the device is in power-saving mode, our foreground service keeps running. Cross-platform apps might not handle this as gracefully. In short, the decision to go *native Android* yields a reliability advantage in

[10] Safety APP

[11] Developers Google

continuous operation, whereas apps that must also support iOS or run in a web context have to compromise (due to iOS background restrictions or browser limitations).

Use of WebView Hybrid Architecture: Compared to other BIM mobile solutions, our approach was unique. Big BIM software vendors like Autodesk or Bentley provide mobile apps (for example, Autodesk BIM 360 Field or PlanGrid) which are fully native apps oriented toward project data, issue tracking, and model viewing. Those apps typically sync data periodically and use push notifications for assigned tasks or issues, but they are not maintaining a live two-way connection for emergency alerts. On the other end, the LIS team's own initial mobile strategy was a PWA (to "develop once and deploy everywhere"). However, pure PWAs cannot utilize certain native-only capabilities easily (such as continuous background execution and certain sensors). Our hybrid WebView approach allowed rapid development (reusing the existing LIS web interface) similar to a PWA, but with injection of native functions where needed. This means we achieved a balance of portability and functionality that pure native BIM apps or pure web apps lack. For example, if the LIS web platform updates its UI, the mobile app reflects that immediately (since it's essentially loading the web content), reducing duplicate development. Yet, unlike a plain WebView app, we have tight integration with device hardware. Many existing apps choose one path (native or web) and miss out on benefits of the other; our app is differentiated by successfully combining them. Emergency-focus in a BIM platform context: The inclusion of an SOS emergency feature in a BIM platform's mobile app is itself a distinguishing factor. Typical BIM or facility management platforms emphasize data sharing, modelling, and maybe issue tracking, but not emergency response. Conversely, emergency apps (like Everbridge's Safety Connection or dedicated lone-worker tools) are standalone and not aware of BIM data. Everbridge's solution[12], for instance, excels at corporate emergency notification and can *locate employees and send them alerts* (with an SOS button feature), but it is a general system not tied to a BIM or building maintenance database. Our app is different because an SOS alert from a user isn't just a message to a security team; it's also an event within the BIM-centric system (LIS) that could cross-link with sensor readings or asset information (what equipment is in that area?). This integrated context is a novel capability. In practical terms, it means a project using LIS could have one unified tool where both facility data and safety monitoring coexist, rather than deploying one app for BIM and another for safety.

Platform-specific optimization vs. cross-platform reach: Many existing apps prioritize being available on both iOS and Android (and sometimes as web apps) to capture all users. Our solution deliberately prioritizes Android to achieve a technical edge (continuous connectivity and background operation). The downside is iOS users cannot use this native app, but the trade-off is improved functionality on the chosen platform. Some might compare this to apps that attempted cross-platform and had to limit features on iOS. By focusing on Android, we avoid the lowest-common-denominator problem. In environments where issuing rugged Android devices to workers is feasible, this is a smart choice. It's a different philosophy from most commercial apps which try to support everything even if it means no one gets the absolute best performance. In our case, for critical safety usage, reliability was more important than universal device coverage.

In conclusion, the LIS mobile app sets itself apart through its real-time, always-on design and its fusion of emergency response features with BIM-based contextual data. While there are apps that do real-time safety tracking and others that provide mobile BIM access, the LIS app marries the two domains. Its use of continuous WebSocket connectivity (vs the typical reliance on intermittent sync or push) and Android-native optimizations gives it an edge in responsiveness and reliability. These differences

[12] Everbridge

make the app particularly suited for scenarios requiring high safety standards on project sites providing capabilities that existing BIM viewers or safety apps alone do not offer. Each design choice, from the hybrid architecture to the focus on Android, was driven by the goal of a continuous, dependable link between the field and the BIM platform, something that is not found in conventional apps today.

FEATURES	OTHER APPS	LIS MOBILE
Connectivity	Sync or Push	Always connected
Platform	Android or iOs	Android only
Dedicated Emergency Protocol	No	Present
Access to sensors in real-time	Limited	Full
Access to BIM models	Limited	Full (incl. different models)

Table 6. LIS Mobile App: A Comparative Analysis.

7.1. CONCLUSION

Task 10.2 delivers a comprehensive digital twin system that merges BIM with IoT sensing for enhanced building monitoring. The end-to-end framework, from sensor installation through analytics to visualization, ensures that all stakeholders have actionable data. Comfort metrics and clustering analytics provide deeper insights into building performance, while the BIM interface ties everything back to the spatial model. Crucially, the data repository and dashboards offer open access to partners, fostering collaboration. Overall, this approach supports smarter facility management and progress toward energy-efficient, occupant-centric buildings.

8. RESULTS

This section presents the core results of the digital twin development for the Ex-Carmelitane building the Italian demonstration pilot in MULTICLIMACT. These results showcase the integration of BIM models with energy and structural simulations, the deployment of sensors, and data clustering processes. The outcomes illustrate the project's capacity to generate a dynamic, data-rich environment that brings together various digital layers—architecture, energy, structure, and IoT within a unified platform. This is a key milestone for MULTICLIMACT's ambition to promote climate-resilient, occupant-aware, and performance-oriented building management systems.

8.1. BIM MODELS AND LIS-PLATFORM INTEGRATION

The architectural and simulation models were shared through the BIMserver.center platform, which served as the central Common Data Environment (CDE). This federated model approach enabled multiple layers of information (architecture, structure, energy, etc.) to coexist, update dynamically, and interact within the same virtual space. The integration allowed each partner to contribute to the project using their domain tools—Revit for architecture, CYPECAD for structure, and CYPETHERM EPlus for energy, while maintaining synchronisation through IFC-based exchanges. These models were then fully linked to the LIS-Platform, which enables real-time data ingestion, spatial querying, and comfort/structural monitoring.

8.1.1. BIM MODEL

The BIM model of the Ex-Carmelitane building was created collaboratively by UNICAM and CYPE using Autodesk Revit, based on surveys and documentation provided by UNICAM. The Revit interface (Figure 11) shows the developed 3D view, which captures the geometry and internal distribution of the building across all levels.

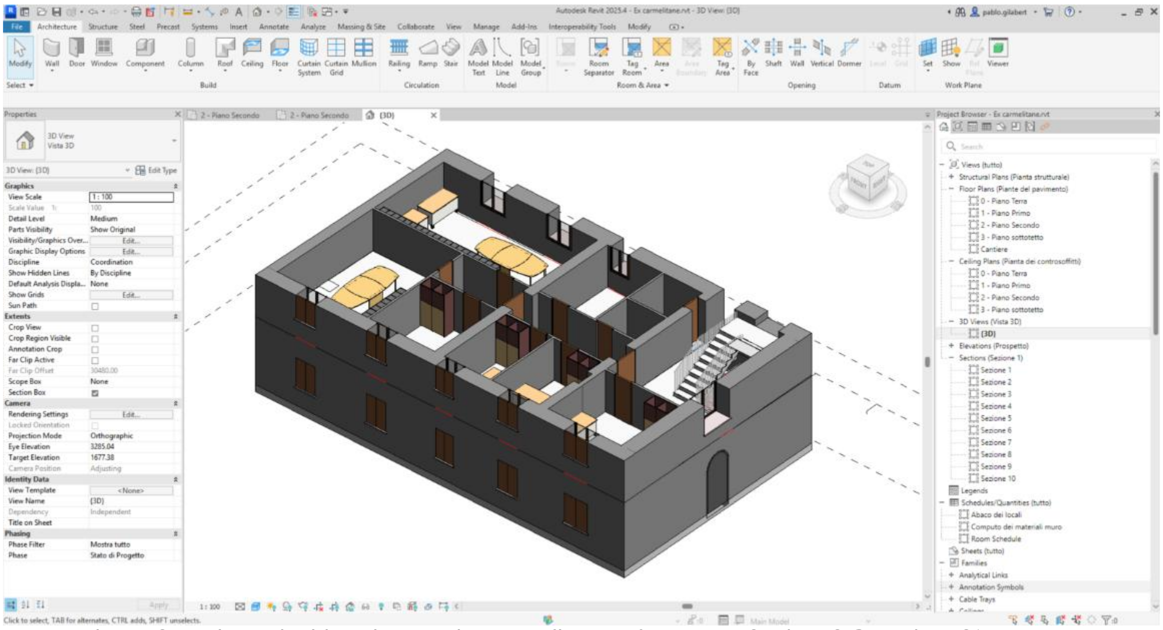

Figure 47. The Ex-Carmelitane building showing the upper floor configuration (Credits: CYPE and UNICAM)

This model was used as the architectural base for all subsequent simulations and analysis. Each building element was modelled to allow proper mapping of thermal zones, structural components, and sensor locations. The model was exported in IFC format and uploaded to BIMserver.center.

Once on the platform, this architectural model became the central reference in a federated model, where other contributions such as the analytical model, structural simulation, and energy analysis were layered. This structure (Figure 48. *BIMserver.center federated model view - architectural, structural & analytical layers (Credits: CYPE)*) enables a true digital twin experience, where all data contributions converge.

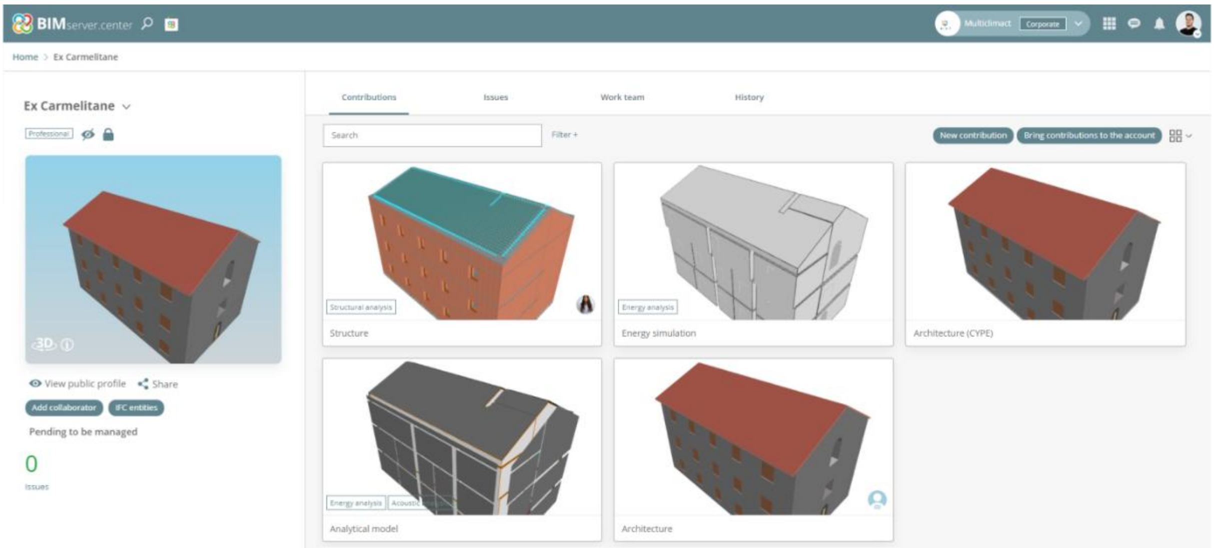

Figure 48. BIMserver.center federated model view - architectural, structural & analytical layers (Credits: CYPE)

8.1.2. ENERGY ANALYSIS

An energy simulation was carried out using CYPETHERM EPlus. Although the information provided for the building regarding consumptions was not provided, the model gave out key insights into thermal behaviour under real climate conditions. Figure 49 shows the energy balance of the building for each month, taking into account the energy lost or gained due to thermal transmission via opaque and light elements (Q_{op} and Q_w, respectively), the energy interchange due to ventilation and infiltrations (Q_{ve+inf}), the gain in heat due to occupancy (Q_{ocup}), lighting (Q_{light}) and internal equipment (Q_{equip}) as well as the necessary heating (Q_H) and cooling (Q_C) inputs.

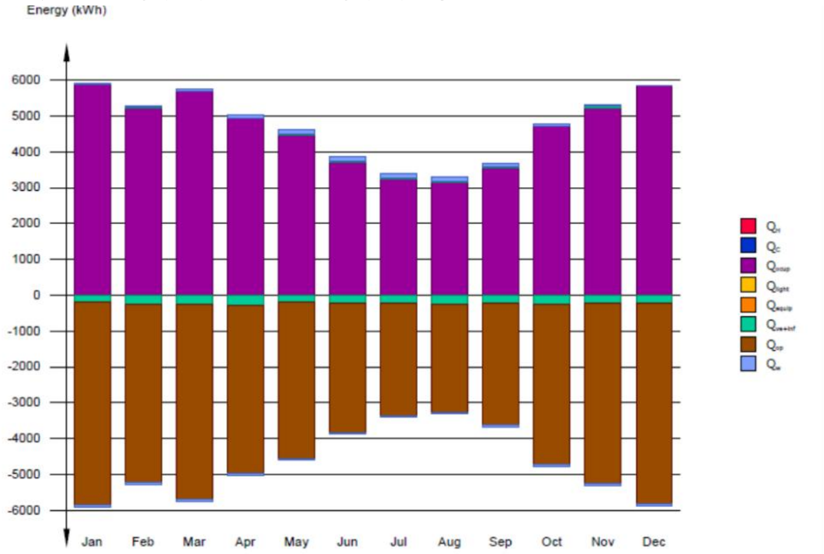

Figure 49. Monthly energy balance of the Ex-Carmelitane building under current conditions (Credits: CYPE)

The results showed high transmission losses through opaque elements during winter (Q_{op}), negligible cooling and heating demands due to the lack of HVAC systems information (as stated in previous sections), and peak internal gains in warmer months from simulated occupancy and lighting. The following table displays the numerical values of the preceding bar chart, the energy balance of the whole building, as the sum of the energy involved in the energy balance of each thermal zone of the building calculation model. The sign criteria adopted consists of using positive values for energy contributed to the zone and negative values for energy that is extract.

	Jan (kWh)	Feb (kWh)	Mar (kWh)	Apr (kWh)	May (kWh)	Jun (kWh)	Jul (kWh)	Aug (kWh)	Sep (kWh)	Oct (kWh)	Nov (kWh)	Dec (kWh)	Year (kWh/year)
Q_{op}	-5660.4	-4978.0	-5452.1	-4706.4	-4346.6	-3610.5	-3135.6	-3019.9	-3407.6	-4492.9	-5020.8	-5610.9	-53441.70
Q_w	22.9	32.7	63.4	94.0	126.2	131.3	141.2	120.5	85.8	50.3	34.4	19.8	383.54
	-41.4	-42.8	-43.2	-47.5	-37.7	-39.2	-41.5	-42.1	-46.8	-53.5	-51.5	-51.3	
Q_{ve+inf}	20.2	29.7	26.1	27.9	24.8	26.9	26.4	32.4	30.7	11.9	43.3	2.8	-2476.74
	-201.9	-252.5	-253.0	-280.3	-204.5	-222.7	-219.3	-237.5	-220.0	-239.4	-236.2	-212.6	
Q_{occup}	5867.0	5213.0	5678.1	4923.2	4461.9	3724.8	3232.4	3142.8	3549.6	4706.8	5225.5	5841.6	5556.67

Table 7. Monthly energy balance values of the Ex-Carmelitane building.

Co-funded by the European Union

Where:

- Qop: Energy transfer corresponding to the thermal transmission across opaque elements of the envelope, kWh/m²·year.
- Qw: Energy transfer corresponding to the thermal transmission across light elements of the envelope, kWh/m²·year.
- Qve+inf: Energy transfer corresponding to the thermal transmission due to ventilation, kWh/m²·year.
- Qocup: Energy transfer corresponding to the internal heat gain due to internal occupancy, kWh/m²·year.

The evolution of the internal operative temperature is shown in *Figure 50. Temperature (°C) evolution graphs for Ex-Carmelitane Building (Credits: CYPE)*, which displays the evolution of the minimum, maximum and average temperatures of each day. Temperature evolution graphs confirm that internal comfort thresholds are not met, particularly in colder months. This supports MULTICLIMACT's interest in thermal resilience, showing how historical buildings behave without conditioning and where passive strategies might be needed.

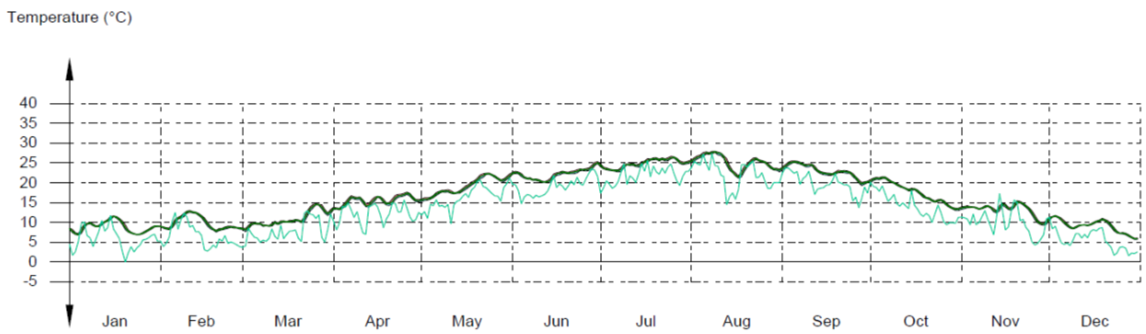

Figure 50. Temperature (°C) evolution graphs for Ex-Carmelitane Building (Credits: CYPE)

In line with Task 10.2 objectives, these simulations were not only visualised independently but also mapped back onto the IFC model, allowing room-by-room comparison and future correlation with sensor data.

8.1.3. STRUCTURAL ANALYSIS

The structural simulation of the building was performed in CYPECAD, based on the architectural BIM model. Load-bearing elements including columns, beams, walls, and slabs were modelled according to Eurocode standards. Once the structural geometry was set, an analytical model was generated, comprising an interconnected mesh of line and surface elements representing the actual building behaviour. This analytical representation, displayed in Figure 51. *Analytical model in CYPECAD showing structural mesh and vertical supports (Credits: CYPE)*, provides a detailed visual of the internal structural logic, including the connections between floors, vertical supports, and the pitched roof system. The model accurately reflects the multi-storey configuration of the building and served as the basis for all simulations and verification checks.

Reports were generated for ultimate limit states (ULS), member checks, reinforcement plans and seismic justification (modal participation, eccentricities, seismic shear). All structural simulations considered both global performance and local reinforcement adequacy, which later supported the mapping of structural indicators in LIS.

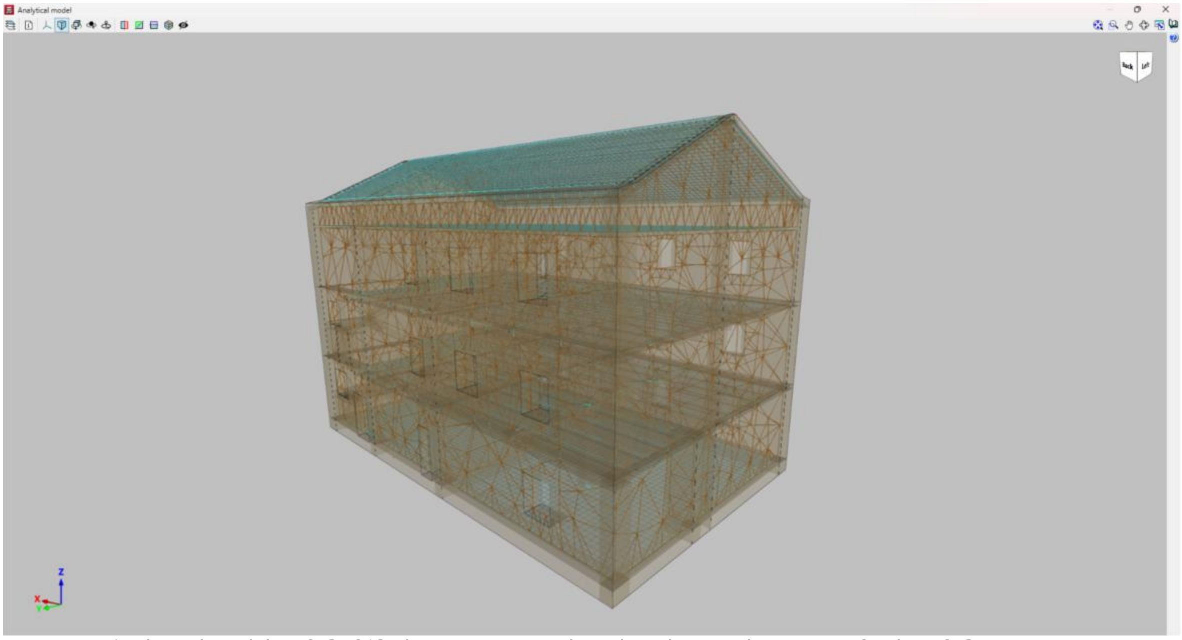

Figure 51. Analytical model in CYPECAD showing structural mesh and vertical supports (Credits: CYPE)

A first set of results involved the displacement analysis under self-weight and permanent loads. Vertical displacement values were calculated for each floor slab and graphically represented as colour gradients across the ground floor in *Figure 52. Vertical displacement results for ground floor slab (mm) (Credits: CYPE)*. The maximum displacement observed was 0.54 mm, located near the slab's central spans. All measured deformations were minor and within acceptable serviceability thresholds, indicating good structural stiffness and load distribution across the bearing system.

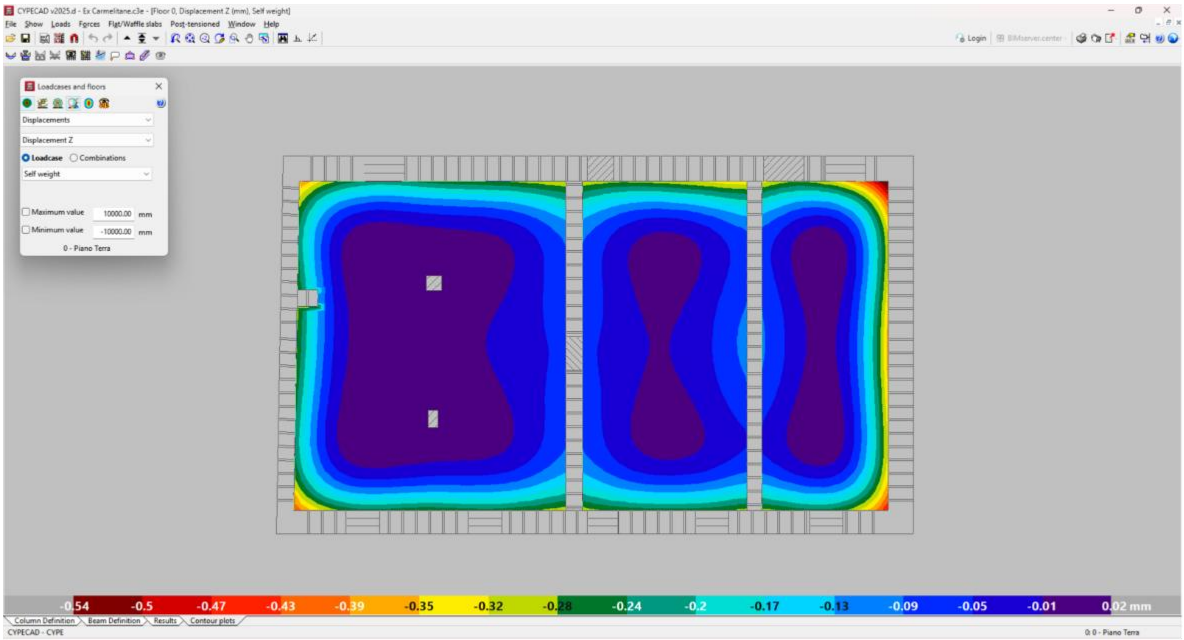

Figure 52. Vertical displacement results for ground floor slab (mm) (Credits: CYPE)

The model also underwent compliance checks under Eurocode 2 (EN 1992-1-1). These checks are essential for historical or retrofitted buildings, where excessive cracking could compromise long-term durability. The results for beams, summarised in Figure 53, confirmed that all beams met the verification criteria. Notably, beams such as P8–P7 and B5–P8 were explicitly checked on multiple faces, with maximum calculated crack widths below the regulatory limits. All analysed components were marked as "VERIFIED", confirming structural integrity under service loads.

Beams	CHECK FOR CRACKING (EUROCODE 2 EN 1992-1-1:2004/AC:2008)						Status
	$W_{k,F,top}$	$W_{k,F,Rgt.side}$	$W_{k,F,bot.}$	$W_{k,F,Lft.side}$	σ_{sr}	V_{crack}	
B0 - B1	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	Verified	**VERIFIED**
B2 - B3	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	Verified	**VERIFIED**
B2 - B4	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	Verified	**VERIFIED**
B5 - P8	x: 2.477 m Verified	D.N.P.(1)	D.N.P.(1)	D.N.P.(1)	x: 2.477 m Verified	Verified	**VERIFIED**
P8 - P7	x: 3.565 m Verified	D.N.P.(2)	x: 1.871 m Verified	D.N.P.(2)	x: 1.381 m Verified	Verified	**VERIFIED**
P7 - B6	x: 0 m Verified	D.N.P.(2)	D.N.P.(2)	D.N.P.(2)	x: 0 m Verified	Verified	**VERIFIED**

Notes:
$W_{k,F,top}$: Calculation of crack width: Top face
$W_{k,F,Rgt.side}$: Calculation of crack width: Right side face
$W_{k,F,bot.}$: Calculation of crack width: Bottom face
$W_{k,F,Lft.side}$: Calculation of crack width: Left side face
σ_{sr}: Minimum reinforcement area
V_{crack}: Cracking due to tangential shear stresses
x: Distance to the origin of the bar
η: Demand capacity ratio (%)
D.N.P.: Not applicable

Checks that do not proceed (D.N.P.):
(1) The check does not proceed, as the maximum tensile stress in the concrete does not exceed its tensile resistance.
(2) The check does not proceed, as there is no stressed reinforcement.

Figure 53. Crack width checks on structural beams (Credits: CYPE)

In addition to these serviceability and ultimate limit verifications, the structure was subjected to seismic assessment in accordance with Eurocode 8 (EN 1998-1). A modal spectral analysis was performed in both the X and Y directions, using a behaviour factor (q) of 3.60 for each. The design parameters reflected the local seismicity of Camerino, with a design ground acceleration (agR) of 0.16 g and soil type C. The design spectrum and modal participation plots are included in Figure 7.1.3.d, where the key contributing modes are identified.

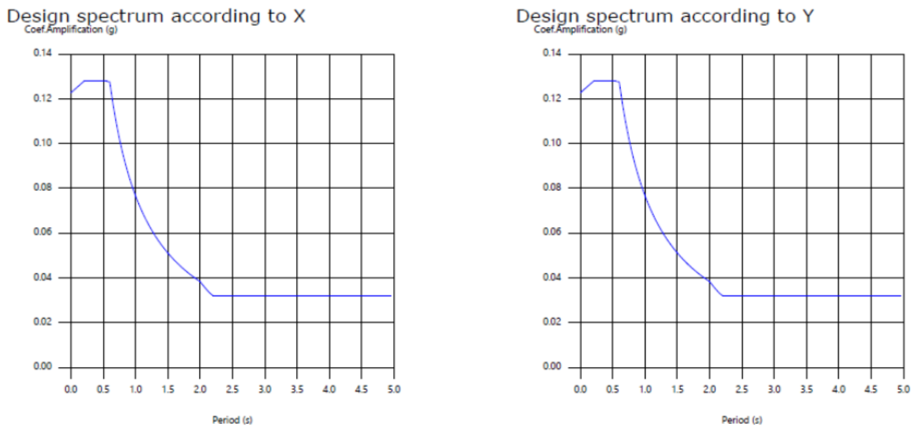

Figure 54. Seismic design spectrum and modal participation (Credits: CYPE)

The results of this dynamic analysis revealed that the highest participation in the X direction occurred in Mode 8, with 75% of the mass displaced. In the Y direction, Modes 4 and 6 contributed the most, reflecting the building's asymmetric stiffness and mass distribution. The modal displacements reached up to 67 mm in the softest mode, as detailed in the seismic report.

Further insight was obtained through the evaluation of eccentricities between the centres of mass and centres of stiffness at each floor level. These metrics, essential for assessing torsional effects during earthquakes, are shown in Table 8. Centre of mass, centre of stiffness and eccentricities of each floor. At the second floor, for instance, an eccentricity of 0.85 metres was recorded along the X-axis, indicating potential torsional rotation that must be considered in seismic resilience strategies.

Floor	c.o.m (m)	c.o.s (m)	e_x (m)	e_y (m)
Ridge Line	(9.97, 5.73)	(9.86, 5.78)	0.11	-0.05
3 – Attic Floor	(10.10, 5.70)	(10.17, 5.83)	-0.07	-0.13
2 – Second Floor	(10.27, 5.68)	(11.12, 5.87)	-0.85	-0.19
1 – First Floor	(10.27, 5.90)	(10.98, 5.70)	-0.70	0.20

Table 8. Centre of mass, centre of stiffness and eccentricities of each floor

Where:

- c.o.m.: Coordinates of the centre of mass of the floor (X,Y)
- c.o.s.: Coordinates of the centre of stiffness of the floor (X,Y)
- eX: Eccentricity of the centre of mass with respect to the centre of stiffness (X)
- eY: Eccentricity of the centre of mass with respect to the centre of stiffness (Y)

Finally, the distribution of seismic shear forces among structural elements was studied. The analysis showed that walls and shear walls resist the overwhelming majority of seismic forces, particularly in the upper floors. According to the results Table 9. Seismic shear resistance per element floor, over 99% of the horizontal shear is absorbed by walls, with columns playing a marginal role. This finding confirms the dominant structural role of the masonry enclosure and reinforces the importance of maintaining the continuity and condition of vertical wall systems in seismic events.

Earthquake load case	$\%Q_x$		$\%Q_y$	
	Columns	Walls	Columns	Walls
Seismic X1	0.38	99.62	5.56	94.44
Seismic Y1	0.62	99.38	3.41	96.59

Table 9. Seismic shear resistance per element floor

These results collectively support the integration of structural indicators within the LIS-Platform, contributing to the overarching MULTICLIMACT goal of unifying environmental and structural monitoring within a digital twin. The structural model, along with its simulations and verification checks, establishes a reliable baseline for comparing future data collected from sensors installed in the building.

9. STAKEHOLDER ENGAGEMENT PLAN

A stakeholder engagement plan was proposed by BRC, and a comprehensive list of contacts was provided, filtered by domain and relevance. However, no further action was taken, as we believe that our work is better represented within the broader context of the MULTICLIMACT project. Additionally, many external stakeholders may not be interested in engaging with a single solution still at TRL 6–7. Therefore, a more targeted filtering of these contacts could be handled by the project leader. Since our primary goal remains to adapt the LIS-Platform to the needs of as many stakeholders as possible, a more focused and market-driven strategy may be essential moving forward.

10. DEVIATIONS TO THE PLAN

The transition from the original pilot site to a new one triggered a chain of dependencies that significantly impacted the project timeline. This change led to several months of delay and rendered certain previously developed software modules and testing campaigns unusable. To mitigate these effects and preserve valuable work already completed, the team decided to retain the original site, Palazzo Fazzini, as a *pre-pilot* focused on future capabilities. As a result, both the Carmelitane Building and Palazzo Fazzini are now integrated and hosted within the LIS-Platform. Recognizing the risk of further delays affecting other developments, the LIS Office was transformed into a living lab to test sensor modules and validate platform functionalities in parallel. This approach enabled continued progress and ensured readiness of key components.

Additionally, work by UNIVPM and UKA on the correlation between environmental quality and the physiological well-being of occupants continued as planned. In this context, UNIVPM obtained ethical clearance to process physiological data.

In summary, two complete *pre-pilot* setups were implemented, including sensor deployments and BIM-based digital models, to address delays caused by the pilot change. Despite the challenges, project partners remained cooperative and committed, ensuring continued momentum and alignment with long-term objectives.

11. OUTPUTS FOR OTHER WPS

Deliverable 10.2 outlines interdependencies between tasks across different work packages, including those with the same deadline or with deadlines extending beyond the submission of this deliverable. A proactive approach was therefore essential, initiating early communication with partners to ensure synchronization and foster open discussions for improved collaboration.

11.1. WORK PACKAGE WP8 - DESIGN PRACTICES AND METHODS

Work Package 8 focused on the development of planning and design methods, with particular attention to their application and validation in real-world contexts. Each method was further refined to ensure its suitability for testing in the MULTICLIMACT demonstration sites under Work Package 11.

Task 8.5, led by UKA, translated the developed guidelines into concrete requirements, criteria, and tools for assessing defined Key Performance Indicators (KPIs). UKA also designed a study framework for implementation using the LIS Platform, incorporating both subjective and objective measures. This supported a holistic evaluation of the short- and long-term effects of the interventions.

11.2. WORK PACKAGE WP11 MULTICLIMACT DEMONSTRATION – TEST

WP11 is dedicated to testing and demonstrating the MULTICLIMACT framework in real-world conditions across four large demonstration sites. These sites are in diverse geographical and social contexts and address a wide range of natural hazards and disasters across various scales of the built environment. Task 11.1 specifically focuses on the Italian demonstration site, primarily targeting the building scale. However, some solutions from the MULTICLIMACT toolkit also extend to urban and territorial assessments, enabling a multi-scale approach.

The demonstration activities will include:

- Testing the CREMA tool to evaluate both the current ("as-is") conditions and the impact of the MULTICLIMACT toolkit on the resilience of the analysed assets.

- Testing all relevant MULTICLIMACT toolkit components developed for the Italian demo site, including those from Tasks 8.4, 8.5, 9.3, 10.1, and 10.2.

The **LIS-Platform** will act as the main BIM-based, multidomain platform supporting the demonstration, providing data integration, visualization, and decision-support capabilities.

11.3. WORK PACKAGE WP15

Work Package 15 focuses on the continued in-field demonstration of the MULTICLIMACT framework across the four major demonstration sites. This work package is dedicated to monitoring and evaluating the impact of the implemented MULTICLIMACT toolkit interventions within each site's local context. Task 15.1 Deployment of the MULTICLIMACT framework at the building scale.

The **LIS-Platform** will serve as the primary BIM-based, multidomain tool supporting this phase, enabling data integration, visualization, and decision-making through its advanced analytics and interoperability features.

12. CONCLUSION

LIS-Platform, the digital solution for the multi-purpose monitoring of environmental and structural behaviour of buildings, developed for application to a real demo, is a key output of the MULTICLIMACT project. It is now fully operational and accessible online. Project partners have been onboarded and have begun using its features and functionalities, with the platform ready for deployment in the Italian Pilot. Therefore, Task 10.2 can be considered fully completed. This achievement was made possible largely thanks to the valuable feedback provided by CYPE, UNIVPM, UKA, ENEA, RINA, and UNICAM. Their input on platform features and UI/UX allowed us to implement timely improvements and complete development within the project timeline. All partners were ready to make extra efforts and put in additional work to maintain the project schedule and ensure timely completion of every aspect of this deliverable. For the MULTICLIMACT project, Deliverable D10.2 represents a cornerstone, as it can be used for the integration of other demo cases within the same platform, ensuring coherence and uniformity across all pilot sites.

Further development also took place beyond the Grant Agreement, as an improvement to the overall concept and usability of the platform. Examples include:

- Maintaining the previous pilot and continuing the development already started in Task T4.2. This enabled partners such as CYPE, ENEA, and UNICAM, who could not transfer their earlier work into the new pilot to continue their research and maintain access to the Palazzo Fazzini building and all correlated data within the LIS-Platform.
- Creating a digital version of surveys that can be prompted directly from the platform. Data can now be timestamped with the actual condition of the building and enriched with real measurements, including physiological data from occupants. This reduced data fragmentation, errors, and delays by replacing paper-based processes, legacy software, or ad hoc solutions with a unified, centralized platform that aggregates and permanently links questionnaire responses with real-time data. The LIS Team developed this solution in a robust way, making it an additional tool within the LIS-Platform. This advancement would not have been possible without the open-mindedness of partners UKA and UNIVPM, who positively engaged with testing in the *pre-pilot* setup. Following successful evaluation, the solution was deemed robust enough to be included in the pilot phase as well.
- Revisiting the LIS Mobile App. The app is now fully functional and can be downloaded once access is granted through the LIS-Platform. It serves as a companion application, providing the same functionalities as the LIS-Platform while maintaining coherence in overall UI/UX and features. Additional functionalities were adapted specifically to mobile use cases, ensuring flexibility and accessibility for users in the field.

13. LITERATURE /REFERENCES

[FROM RIFAT: Please ensure compliance with the required format. References will be added at the end, after the pilot setup is completed]

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14. ANNEX SHM-SENSORS

Recommend sensor types for the SHM

Dewesoft IOLITEi 3xMEMS-ACC-S, a compact data acquisition device equipped with a built-in triaxial MEMS accelerometer.

It integrates the accelerometer, analog-to-digital conversion, and an EtherCAT interface, making it suitable for precise and synchronized vibration and seismic measurements. By performing the signal conversion internally, the device avoids noise pickup from analog cables. Data is transmitted via EtherCAT directly to DewesoftX software or any EtherCAT master system.

Key Features:

- High sensitivity: noise density of 0.7 µg/√Hz
- Measurement range: ±15 g
- Wide bandwidth: up to 460 Hz
- Sampling rate: 1 kS/s
- Temperature monitoring: internal sensor reports MEMS sensor temperature
- Typical Applications:
- Ground vibration monitoring
- Seismic studies
- Mining operations
- General Specifications:
- Interface: EtherCAT with RJ45 connectors
- Power consumption: ~1.5 W, powered via passive PoE
- Operating temperature: -40 to +65 °C
- Enclosures: available in IP20 (standard) or IP67 (outdoor version with waterproof housing and pressure equalization)
- Weight: 105 g, aluminium housing

Software Integration:

Fully supported by DewesoftX (automatic recognition, simple configuration, real-time display, recording, and analysis). Compatible with other EtherCAT masters such as Beckhoff TwinCAT, NI LabVIEW, Simulink RT, and Acontis.

Location:

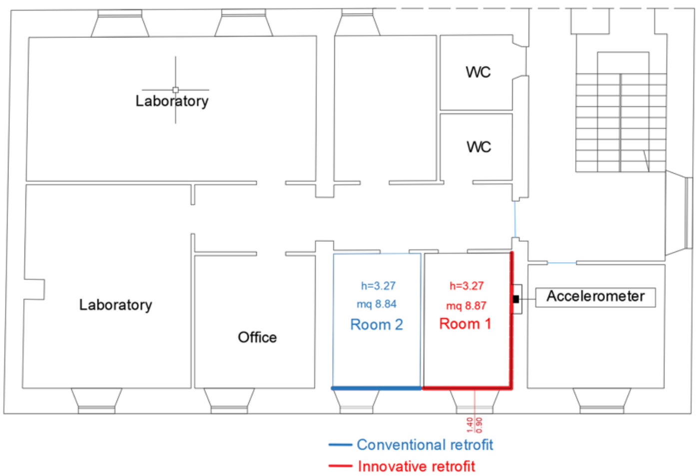

Figure 55. Deployment of Sensors for the Italian Demosite (Credits: UNICAM)