Ref. Ares(2024)7483979 - 21/10/2024

multiclimact

D4.2 - DESIGN OF A DIGITAL SOLUTION FOR THE MULTI-PURPOSE MONITORING OF ENVIRONMENTAL AND STRUCTURAL BEHAVIOUR OF BUILDINGS

September 2024 | LIS

MULTICLIMACT

D4.2 - DESIGN OF A DIGITAL SOLUTION FOR THE MULTI-PURPOSE MONITORING OF ENVIRONMENTAL AND STRUCTURAL BEHAVIOUR OF BUILDINGS

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:	Juan Pablo Aguilar-López

Deliverable	D4.2: Design of a digital solution for the multi-purpose monitoring of environmental and structural behaviour of buildings
DoA	T4.2: Design of a digital solution for the multi-purpose monitoring of environmental and structural behaviour of buildings
Lead beneficiary	LIVE INFORMATION SYSTEM SRL (LIS)
Main Autors	Rifat Seferi (LIS), Orazio Colaneri (LIS), Simone Murazzo (LIS), Gloria Cosoli (UNIVPM), Gian Marco Revel (UNIVPM), Alessandro Zona (UNICAM), E. Candigliota (ENEA), V.A.M. Luprano (ENEA), G. Marghella (ENEA), A. Marzo (ENEA), S. Mazzarelli (ENEA), A. Tatì (ENEA), C. Tripepi (ENEA), Ane Ferreiro (CYPE), Marcel Schweiker (UKA), Rania Christoforou (UKA), Mina Moayyedi (UKA), Selene Angelone (ICLEI), Nensi Lalaj (BRC).
Main contributors	Alessandra Mobili (UNIVPM), Francesca Tittarelli (UNIVPM), Andrea Dall'Asta (UNICAM), Graziano Leoni (UNICAM), Michele Morici (UNICAM), Fabio Micozzi (UNICAM), Valeria Leggieri (UNICAM).
Reviewers	Enrico Salvatore (RINA-C), Arianna Verga (RINA-C)
Due date	30.09.2024
Report date	30.09.2024
Version	3.0

Document classification	PU Public

Co-funded by the European Union

REVISION TABLE

Version	Date	What
1.0	05.08.2024	Table of Contents
1.1	05.08.2024	First draft
2.0	28.08.2024	Second draft ready for internal review
2.1	20.09.2024	Third draft ready for quality check by coordinator
3.0	30.09.2024	Final version as submitted

Co-funded by
the European Union

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Abbreviations and Acronyms

ACRONYM	DESCRIPTION
AI	Artificial Intelligence
API	Application programming interface
APK	Android Application Package
BIM	Building Information Modeling
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
HTTP	Hypertext Transfer Protocol
HTTPS	Hypertext Transfer Protocol Secure
IAQ	Indoor Air Quality
IEEE	The Institute of Electrical and Electronics Engineer
IoT	Internet of things
LCA	Life cycle assessment
MCU	Microcontroller unit
MDD	Module Design Document
ML	Machine Learning
MVP	Minimum viable product
NDE	Non-destructive evaluation
NDT	Non-Destructive Testing

Co-funded by
the European Union

NRT	Near Real-Time
O&M	Operations and maintenance
OTA	Over-The-Air
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
SDD	System Design Document
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

Executive Summary

Deliverable 4.2, "Design of a digital solution for the multi-purpose monitoring of environmental and structural behaviour of buildings," 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.

It constitutes the outcome of Task 4.2 aiming at designing and further developing of the LIS BIM-based platform (LIS-Platform), which integrates IoT sensor data to monitor the structural health of buildings and assess environmental conditions and occupants' well-being in near-real-time (NRT).

The LIS-Platform is an advanced digital solution that integrates software, Building Information Modeling (BIM), and IoT devices to create intelligent, self-sensing structures. Developed as part of the MULTICLIMACT project, it leverages the expertise of partners in environmental sciences and engineering to support a multidisciplinary approach. This evolution ensures the platform meets the diverse needs and requirements of all stakeholders, while specifically enhancing resilience and adaptability to climatic and environmental challenges within the construction sector. Furthermore, the platform connects with IoT wearable devices to gather physiological data from occupants, while simultaneously monitoring environmental conditions, offering valuable insights into occupant health and well-being.

The LIS-Platform is a powerful tool designed to benefit each partner within their respective domains, while also delivering significant value to future stakeholders. It would provide real-time decision support, enabling more informed and timely decisions that would lead to better outcomes.

The key results include the completion of the design solution and the successful integration of the BIM model, selected sensors, and data into the LIS-Platform, ensuring full integration and interoperability.

In addition to the key results, several significant achievements were accomplished in T4.2:

- Mobile Application: Released the basic version of the LIS mobile app for Android.
- A survey of the Italian pilot site (Palazzo Fazzini) was conducted, and joint activities were performed. Results from ENEA's NDT campaign were embedded in the digital model.
- LIS-Platform initial release: Supporting multiple user groups, IoT devices, sensors, and biosensors, is now ready for testing. Access is available via email registration.
- Initial findings were presented at the 2024 IEEE International Workshop on Metrology for Living Environment.

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

UNICAM: Recommends sensor types for the seismic monitoring system and provides CAD files and documentation for Palazzo Fazzini.

CYPE: Designs digital models and exports BIM files to the LIS-Platform.

ENEA: Leads non-destructive testing (NDT) at Palazzo Fazzini to assess seismic damage

LIS: Enhances BIM models with data from partners, IoT devices, and sensors, transforming them into dynamic or "live" representations of the building.

UNIVPM: Provides expertise in selecting environmental and physiological sensors.

UKA & ICLEI: Assess environmental and physiological variables related to health and well-being.

BRC: Promotes the LIS-Platform as a flagship solution within the MULTICLIMACT project through the CIW online marketplace and engages with stakeholders.

Certain sections of this document report some simplified contents from previously referenced documents that do not require full chapters to be introduced to describe them. For more detailed information, please refer to the appendix, external links, or request the full documentation. D4.2 focuses on including the most relevant parts, as the original documents may be beyond the scope of this deliverable. The documents referenced are Plan of Approach (PoA), System Requirements

Document (SRD), System Design Document (SDD, to be released in 2025), Module Design Document (MDD, to be released in 2025).

1. INTRODUCTION

Recent decades have seen significant climatic shifts, with an increase in extreme events like floods, earthquakes, and heat waves. These changes necessitate proactive strategies to plan, engineer, and upgrade our built environment to enhance resilience and address both current and future risks. Multiple global megatrends are shaping the future of construction.

Consider just two developments:

- first, buildings are responsible for 30% of global greenhouse gas emissions.
- second, the population of the world's urban areas is increasing by 200,000 people per day, all of whom need affordable housing as well as social, transportation and utility infrastructure.

In the face of such challenges, the industry is almost under a **moral obligation to transform**. Its transformation will have transformative effects elsewhere: on the wider society, by reducing construction costs; on the environment, by improving the use of scarce materials or by making buildings more eco-efficient over time; and on the economy, by narrowing the global infrastructure gap and boosting economic development in general (WEForum 2017). Urbanization has long been a driver of economic growth, human development, and entrepreneurship, but the current scale and speed present unprecedented challenges. By 2030, 43 megacities will exist, most in developing regions, alongside an expanding number of medium-sized cities. Meeting this demand will require rapid, affordable construction while addressing sustainability, resource efficiency, and infrastructure deficits (United Nations and Social Affairs 2019). Despite the critical importance of the engineering and construction (E&C) sector (U.S. Environmental Protection Agency 1989), it has not kept pace with other industries in embracing innovation. Labor productivity in construction has stagnated over the last 50 years, primarily due to fragmentation, outdated processes, and insufficient collaboration. Yet, the industry now has access to transformative technologies—Building Information Modeling (BIM), 3D printing, drones, and augmented reality, among others. These innovations hold the potential to boost efficiency, reduce costs, and improve project safety and outcomes if fully embraced (WEForum 2017). Virtually all other businesses rely on the construction industry to provide and maintain their accommodation, plants and infrastructure, and construction is a determinant of where and how almost everyone lives, works and plays. For nearly the entire population of the world, the built environment heavily influences the quality of life. In the United States, for instance, people on average spend nearly 90% of their time indoors (United Nations and Social Affairs 2019; U.S. Environmental Protection Agency 1989).

Scope

The design and implementation of a digital solution for monitoring environmental and structural behaviour in buildings align with the core requirements of the LIS-Platform. As a standalone application, the LIS-Platform integrates various digital tools and ensures seamless interoperability with other components of the MULTICLIMACT project. This deliverable summarizes the collaborative effort of 8 European partners in designing and further developing the LIS-Platform, which unifies partner requirements into a single solution. It bridges different systems and stakeholders in one portal, enabling smart sensing in the Italian Pilot (Palazzo Fazzini) and improving decision-making. Beneficiaries range from students in residence to civil protection or CEIs personnel. The true value of the LIS-Platform is its ability to enhance collaboration among stakeholders. By providing a single, constantly updated version of the digital model, it consolidates all essential data in one place. This ensures data integrity by maintaining a permanent record of every event, from seismic activities to the findings and reports from testing campaigns.

Requirements

Co-funded by the European Union

- A BIM-based platform with near real-time data collection and visualization.
- Structural Health Monitoring (SHM) and advanced assessments under extreme conditions.
- A data analysis platform to access and study key indicators such as energy efficiency, thermal and seismic SHM, and other metrics from the MULTICLIMACT project.
- The LIS-Platform must facilitate the monitoring of critical situations within the building, including key indicators related to the health and well-being of occupants.

Planning

Like any development or project, we need a basic framework or method to guide us. This helps create a clear plan and ensures all participants stay aligned throughout the different phases. Our goal is to develop a solid Proof of Application (PoA) and track all requirements effectively. For its reliability and structured, document-driven approach, we chose the V-model as our framework. In the following sections, the term "project" will refer to the development of the LiS platform unless otherwise specified.

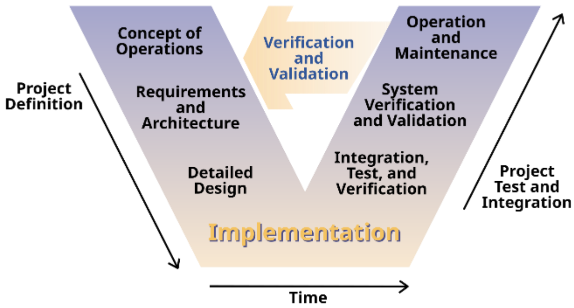


Figure 1. V-model (Leon Osborne, & others)

This approach will be applied across all the Work Packages (WPs) within the MULTICLIMACT project, where LIS is involved in WP4, WP10, and WP11, specifically in tasks T4.2, T10.2, and T11.1.

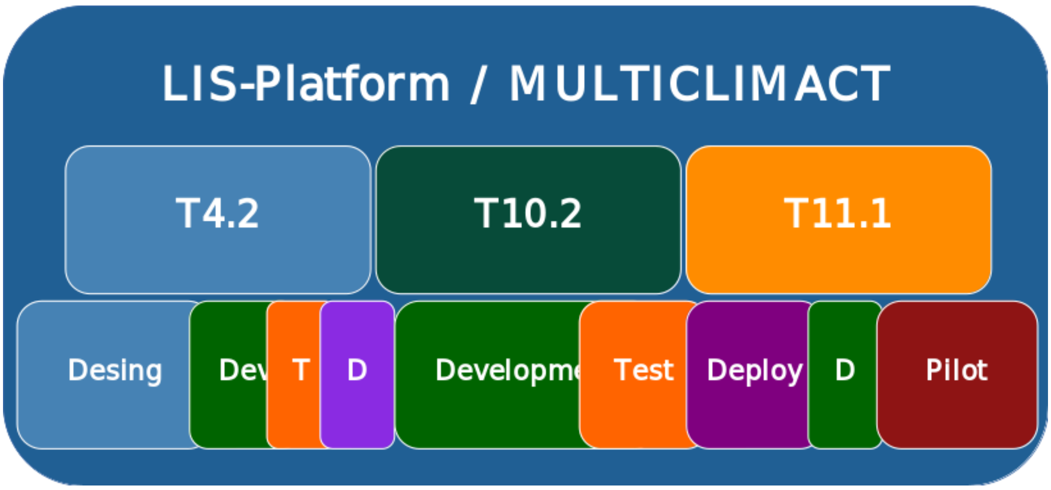


Figure 2. Platform development management

The typical phases of validation in the V-Model are outlined below, organized in terms of documentation. The first two documents will be defined during Task 4.2, with this report serving as a deliverable. The remaining documents will serve as the foundation for Task T10.2 and T11.1, shaping most of the development and deployment phases of the MULTICLIMACT project.

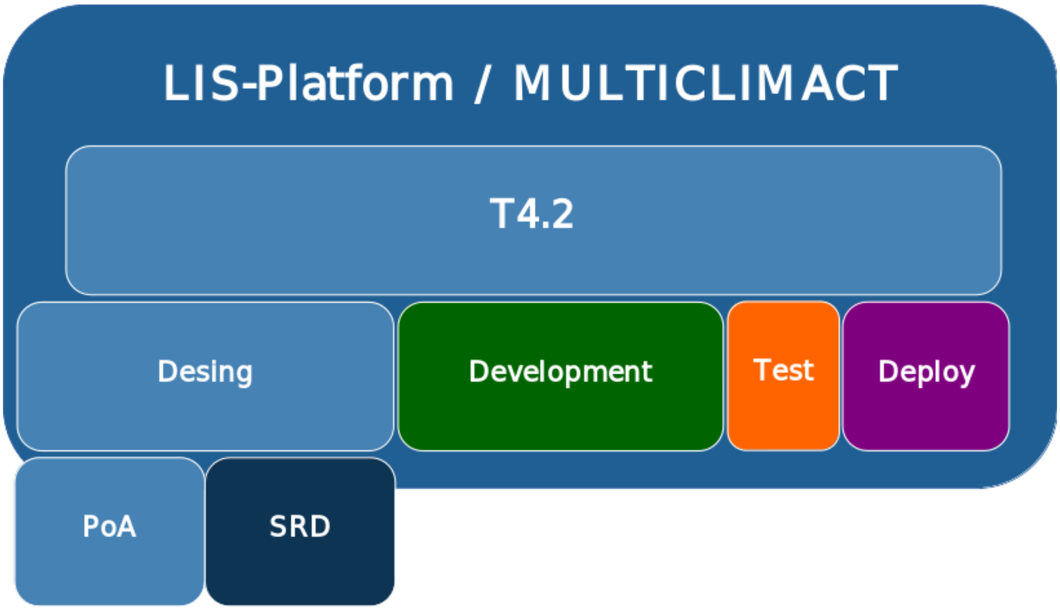


Figure 3. Platform management design phase

- PoA (Plan of Approach)
- SRD (System Requirement Document)
- SDD (System Design Document)
- MDD (Module Design Document)
- Testing Plan
- Final Report

The V-shaped model was chosen due to its well-defined structure in both development lifecycle and project management, making it ideal for projects with clear user requirements. Its document-driven approach ensures that each phase is thoroughly planned, and that accountability is maintained throughout the development stages. To increase flexibility in the V-Shaped approach, some elements are borrowed from the Agile methodology, particularly the creation of the Minimum viable product (MVP).
Although the deliverable was intended to describe the design rather than the development of the digital solution, an MVP of the LIS-Platform was immediately deployed to gather feedback from all partners at an early stage of design.

This adaptive methodology allowed the development team to iteratively refine the design while making incremental progress. Although some adjustments were made dynamically during development, all deviations from the original plan were carefully documented and validated in the more comprehensive testing and validation phase.

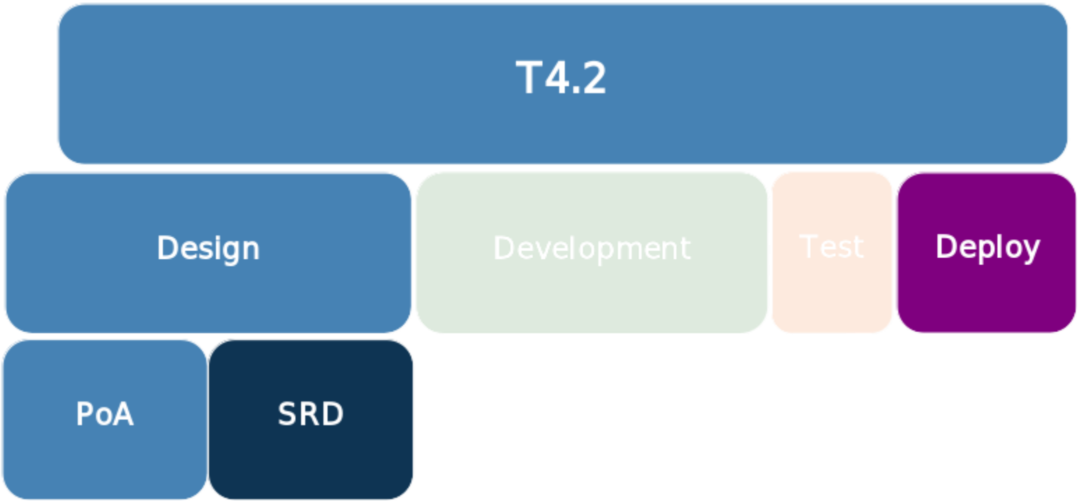


Figure 4. Platform management design phase

The planning phase began collaboratively with all partners, during which activities were outlined and subtasks for T4.2 were distributed. Each partner's contribution will be briefly outlined, focusing on their specific roles and target groups. A Plan of Approach (PoA) was maintained as a live document, continuously updated during meetings until January 2024. With input from all partners, activities were clearly defined, enabling LIS to proceed with the development of the System Requirements Document (SRD) for the LIS-Platform, ensuring all partner contributions were incorporated. An in-depth overview of the management structure, including the approaches and models used, is presented in Figure 1.5. Tasks are broken down into subtasks, ensuring a clear connection to both the overall and specific requirements of the LIS-Platform. A prioritization matrix will guide the development process, ensuring that the most critical features are addressed first. This matrix will also clarify which functionalities and features fall within the platform scope and which elements are outside the boundaries and will not be initiated. The requirements will be transferred from the Plan of Approach to the System Requirements Document. A risk analysis and mitigation strategy are described, and the key components of designing the digital solution, as outlined in deliverable D4.2, are presented here.

Figure 5 Platform management development phase

The presentation of the LIS-Platform, begins with a brief explanation of key paradigms for modelling complex systems, focusing particularly on the concept of a smart building as an intelligent, living entity. We then introduce the mathematical framework used to model this building, with the aim of understanding and analysing its behaviour. This modelling approach also sets the foundation for developing a full Digital Twin of Palazzo Fazzini, utilizing the LIS-Platform.

Co-funded by
the European Union

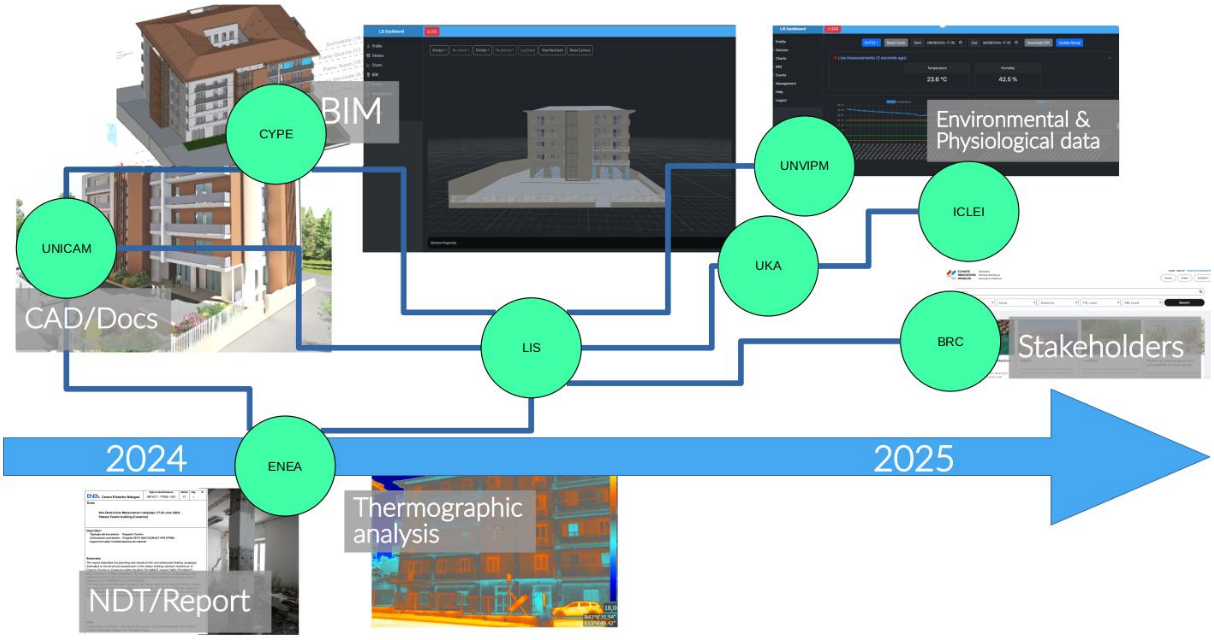


Figure 6. Activities and Connection to the Main Task

1.1. CHALLENGE OF MODELLING A COMPLEX SYSTEM

The building and construction sector is a major resource consumer and environmental polluter, with concrete being the second most used product globally, after water (Taheri 2023). Addressing these challenges requires integrating sustainability and resilience into construction practices, such as using innovative materials, improving energy efficiency, and reducing waste. These efforts create buildings that are both environmentally friendly and capable of withstanding climatic pressures. However, addressing these issues demands more than a qualitative understanding; robust, quantitative models are necessary to accurately simulate and analyse building systems.

Traditional linear design processes, where architectural and engineering decisions are made in isolation, often result in inefficiencies and missed opportunities for energy optimization. In this approach, the architect makes several design decisions with minimal or no regard for their energy impact, then hands the design over to the engineers. The engineers are tasked with making the building functional and comfortable through mechanical systems. The design of these systems often follows a linear process, where components are sometimes specified before all the necessary information is available, limiting the ability to create an efficient system within the constraints set by the architect's design (Lewis 2004). In modern urban development, particularly smart buildings and cities, modelling the built environment as an interconnected system yields significant benefits. Conceptualizing buildings as "living organisms" aligns with systems theory, where components and their interactions work together to achieve specific functions. According to the IEEE-Standard Dictionary, A combination of components that act together to perform a function not possible with any of the individual parts (Cassandras and Lafortune 2010).

```
+--------+        +------------+        +---------+
|  Input  | ----> |   System    | ----> |  Output |
+--------+        +------------+        +---------+
```

Co-funded by
the European Union

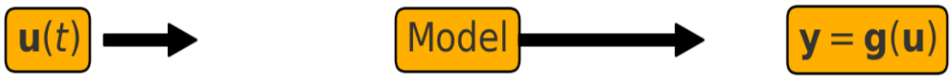


Figure 7. Simple modeling process (Cassandras, C.G. & Lafortune, Stephane. Introduction to DES)

In engineering and science, a fundamental aspect of quantitative analysis lies in developing techniques for designing, controlling, and precisely measuring system performance based on well-defined criteria. Central to this process is the creation of models that duplicate the behaviour of complex systems. Intuitively, we may think of a model as a device that simply duplicates the behaviour of the system itself (Cassandras and Lafortune 2010).

The key question, therefore, is: how can we develop a "device" or, more precisely, a set of interconnected devices that can accurately duplicate the behaviour of a building? By integrating these interconnected devices and creating a mathematical model connected with computational simulations, sensors, and control systems, it becomes feasible to generate a highly accurate digital-to-physical representation of a building. The process of digital replication enables detailed analysis and testing, empowering engineers, researchers, and stakeholders to optimize designs, predict performance with accuracy, and ensure that the building adheres to critical safety, efficiency, and sustainability benchmarks throughout its lifecycle. The development of the LIS-Platform exemplifies a forward-looking initiative to model buildings as complex, dynamic systems, capturing their comprehensive operational behaviour. Although some sections of this document may seem reductionist by deconstructing building networks and systems into their fundamental components, this approach is intentional and grounded in a bottom-up design methodology. However, it is essential to recognize that understanding the behaviour of complex systems cannot be accomplished solely by analysing individual components in isolation; rather, a holistic evaluation of the building as an integrated system is required (Nicolis and Nicolis 2007) The overarching objective of the LIS-Platform is to provide a deep understanding of how various building systems and components interact, with the goal of enhancing occupant comfort, safety, and overall well-being. LIS adopts a data-driven, integrated methodology, utilizing near-real-time operational data to continuously refine and optimize both current operations and future design and decision-making processes.

Despite its advantages, modelling buildings as complex systems presents significant challenges. Complex systems often exhibit emergent behaviour, where interactions between components generate new and sometimes unexpected patterns without centralized control. Traditional analytical methods frequently fail to capture these emergent dynamics. Furthermore, breaking a system down into discrete subsystems may obscure the critical interactions that govern overall performance, especially in areas such as energy consumption and efficiency. Understanding these interactions requires advanced analytical tools, interdisciplinary collaboration, and a systems-level approach that emphasizes the interdependencies within the entire system. The very essence of the system lies in the interaction between parts and the overall behaviour that emerges from the interactions. The system must be analysed as a whole. (Guckenheimer and Ottino 2008)

The MULTICLIMACT approach, much like LIS, emphasizes data-driven design and predictive modelling. Both use real-time data and simulations to forecast building performance under various climate scenarios, allowing for proactive decision-making. This approach is essential for designing resilient, adaptable buildings that can withstand the effects of climate change while optimizing energy efficiency. Treating buildings as integrated systems, rather than a mere collection of isolated parts, offers numerous advantages. One of the most significant benefits is the potential for enhanced energy efficiency. By considering the interactions between a building's various systems such as heating, ventilation, lighting, and structural elements, energy usage can be optimized more effectively than if each system were addressed independently. This integrated systems approach, which models buildings as interconnected components, can unlock significant energy savings by optimizing how these systems interact (Guckenheimer and Ottino 2008; Harvey 2010). Real-time data from buildings in operation can be used to inform and upgrade future designs, creating a feedback loop that drives continuous improvement in building performance.

The LIS-Platform utilizes sensors and IoT technologies for data acquisition, facilitating a comprehensive understanding of building behaviour. Sensors, as one of the most mature data acquisition technologies, are pivotal to the future of the construction industry, both within the EU and globally. As the sector increasingly shifts towards data-driven models, the role of sensors becomes paramount. They serve as the primary source of real-time data, both during the construction phase and post-completion of buildings (European Commission 2021).

However, a notable gap exists between the adoption of sensor technologies in new versus existing buildings. While newer constructions tend to integrate sensors more extensively, most existing buildings remain sensor-deficient due to the high costs of retrofitting. This disparity presents a significant challenge for the widespread deployment of IoT technologies across the construction sector (European Commission 2021).

IoT enables everyday objects, including buildings, to interact with and respond to their environments in advanced, meaningful ways, thereby enhancing our understanding of their behaviour. Through interconnected smart objects (Atzori, Iera, and Morabito 2010), IoT fosters improved environmental awareness and facilitates critical decision-making processes (Zelenkauskaite et al. 2012).This is particularly significant in disaster management scenarios, where LIS is actively developing an early warning system (EWS), push notification systems (PNS), and emergency mode activation, all of which can be directly triggered by platform users.
In the context of disaster management, seamless communication and collaboration between various teams and individuals from geographically dispersed organizations such as medical teams, civil protection units, law enforcement, fire and rescue services, and healthcare providers are essential. This real-time coordination is crucial for effective decision-making and timely action in response to evolving emergencies (Zelenkauskaite et al. 2012). The IoT paradigm is inherently characterized by the interconnection and interdependence of its entities. This interdependence is not limited to the relationships between the objects themselves but also extends to the interconnection of their properties. Conceptually, the IoT can be seen as a complex organism composed of multiple dimensions. One dimension involves the interconnection of physical objects, while another encompasses the interdependence of their attributes. Both dimensions evolve autonomously, driven by the underlying principle of interdependence. This concept mirrors the swarm intelligence seen in nature, where simple organisms such as ants, bees, or bird flocks interact with each other and their environments in a self-organizing manner, without the need for centralized control(Zelenkauskaite et al. 2012). Similarly, IoT systems rely on the collective intelligence of interconnected devices to perform complex tasks. The interdisciplinary nature of IoT is particularly evident in the application of diverse methodologies and tools across various domains. Effective IoT implementations require insights from telecommunications, informatics, electronics, and the social sciences. As IoT operates within the framework of complex systems, comprising heterogeneous, distributed components that function synergistically integration from these fields is essential. This interdisciplinary approach is crucial for addressing the multifaceted challenges of IoT system development and deployment, especially in critical areas such as disaster management (Zelenkauskaite et al. 2012).

A significant portion of the LIS's approach to complex systems is simplified into manageable mathematical models based on dynamic, time-invariant, nonlinear, discrete-state, event-driven systems (DES) (Cassandras and Lafortune 2010). The nonlinearity in DES arises from abrupt, discontinuous state transitions triggered by event occurrences, representing the unpredictable shifts typical of real-world systems (Cassandras and Lafortune 2010).Although a probabiLIStic framework would provide a more comprehensive understanding of building behaviour under variable

Co-funded by the European Union

environmental conditions, such an approach lies beyond the scope of this discussion (Cassandras and Lafortune 2010);(Nicolis and Nicolis 2007);(Guckenheimer and Ottino 2008)).

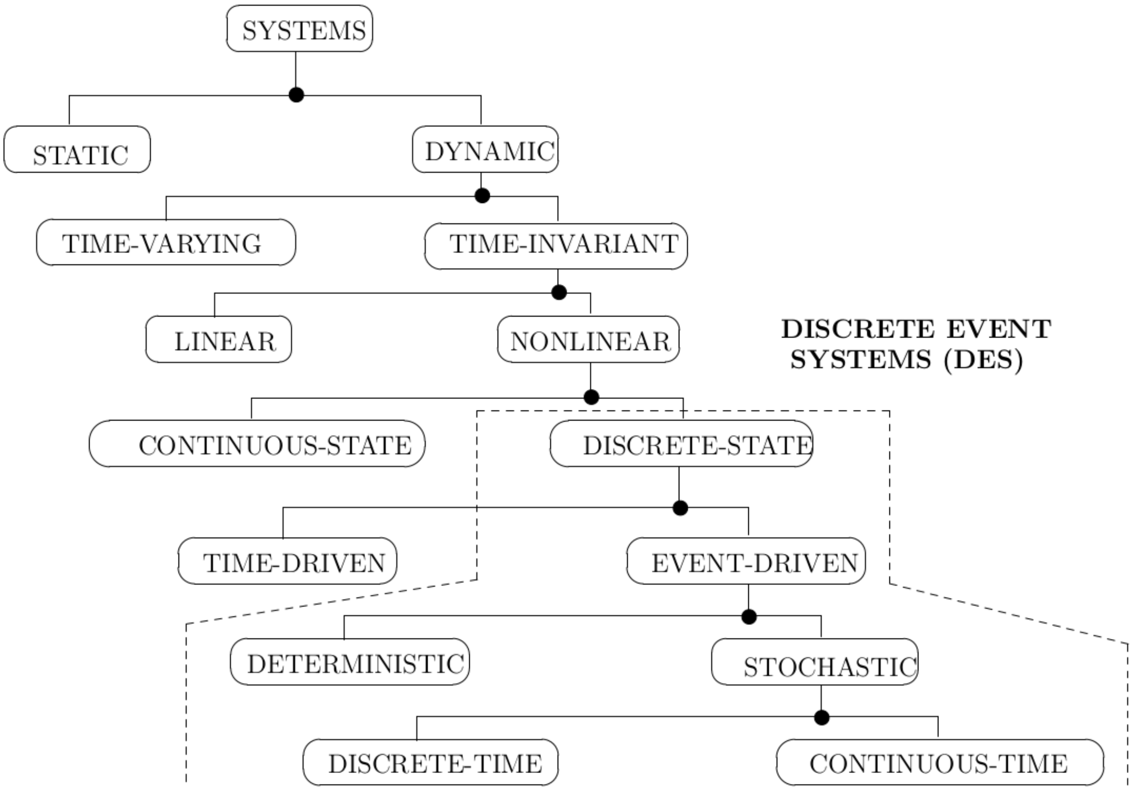


Figure 8. Major system classifications (Cassandras, C.G. & Lafortune, Stephane. Introduction to DES)

Complex systems are often characterized by the dense interconnectivity of their components, where the structure and nature of these connections become more critical than the individual properties of the components themselves. As network connectivity increases, the behavior of the system is primarily defined by "who connects to whom" and the pattern of these connections, rather than by isolated component attributes (A.-L. Barabási 2002). Connectivity has thus become a transformative concept in the study of complex systems, offering valuable insights into their organization and behavior (Turnbull et al. 2018).

Key Components

- LIS-Platform Integration: IoT/CPS with the LIS-Platform, emphasizing secure communication, data integrity, error control, efficient device-to-device communication, and near real-time BIM model visualization.
- Data Engineering: Effective strategies for collecting, processing, analysing, and maintaining data from various sources including sensors, IoT devices, and BIM models. Utilizes advanced algorithms and machine learning techniques for data analysis and prediction.
- The platform pilot will take place at the Palazzo Fazzini in Camerino, Italy, involving researchers, students, engineers, and civil protection personnel.

1.2. PURPOSE AND TARGET GROUP

The purpose of this deliverable is to further advance the development of the LIS-Platform. By integrating contributions from MULTICLIMACT partners, a detailed digital model of a real building will be designed and used to manage and deploy the Italian Pilot. This will enable partners to leverage the LIS-Platform as the primary BIM-based solution for semantically enriched models, incorporating key performance indicators (KPIs) from various domains within the MULTICLIMACT Project, with live sensor measurements providing near real-time responses. Considering the multi-domain solution and the number of partners involved, we have also assigned specific roles to each partner within their respective domains. However, the graph in Figure 9 provides a high-level abstract overview, illustrating all partners across these domains and the degree of their relational dependencies.

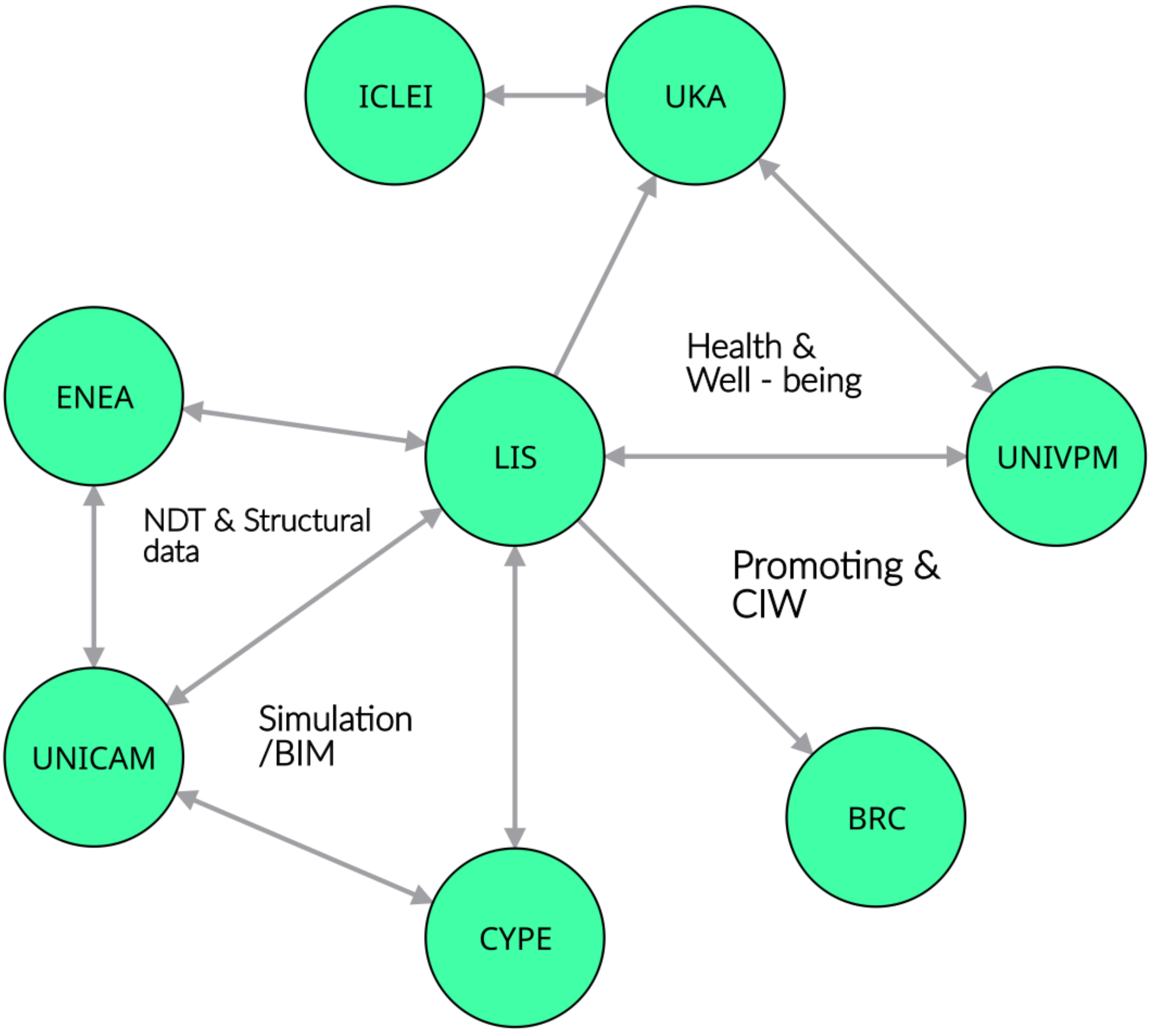


Figure 9. Partner Dependency Graph

2. OBJECTIVES AND EXPECTED IMPACT

Table 1 reports a detailed description of objectives and expected impact for each target group.

PARTNER	OBJ	DESCRIPTION	EXPECTED IMPACT	TARGET GROUP/ STAKEHOLDER
BRC	Promotion and presenting of the earthquake events in an online market	Supporting, dissemination, connection, funding opportunity	Problem owners and innovator agreements	Problem owners, innovators, end-users, entities, municipalities, regions, institutions, universities, research institutions
CYPE	BIM models	Provide free tools for the development of BIM models and development of Fazzini model.	Repository of BIM models for MULTICLIMAT demo cases: Palazzo Fazzini.	Building owners Public Administration
CYPE	Simulation	Earthquake simulation (fire and wind)	Earthquake resilience of the exiting building stock	AEC sector Public Administration
UKA	Contribution to the monitoring of occupants' health and well-being.	Tool for assessing occupant comfort	Comprehensive data and advanced assessment models	Researchers/ Public institutions/ Building managers
ICLEI	Contribution to the monitoring of occupants' health and well-being.	Integration to UKA's work on the comprehensive understanding of multi-domain comfort.	Inclusion of the overall resilience perspective.	Public Administration, Municipalities, Regions
ENEA	Contribution on WP4	built environment to protect people safety	Improve the level of resilience of that system of interest considering the current and expected risk scenarios	Civil Protection, Municipalities, building managers, building owner
UNIVPM	Selecting multi-domain sensors according to their metrological characteristics	Integrate 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)	Evaluation of the status of building and occupants and feedback to control system and BMS with a view of optimizing energy consumption and well-being at the same time	Researchers, public institutions, building managers occupants and caregivers
UNICAM	Structural monitoring system - SHM	Provide indications about the typology of sensors to adopt in an effective seismic monitoring system	Contribution in developing a multidomain monitoring system	Researchers, public institutions, building managers and occupants
LIS	LIS-Platform	D4.2 Design of a digital solution for the multi-purpose monitoring of environmental and structural behaviour of buildings	Complete Design	

Table 1. Detailed description of objectives and expected impact for each target group

Co-funded by the European Union

3. OVERALL APPROACH

3.1. OVERVIEW

A PoA document is a strategic blueprint that delineates the steps and methods for executing a project. It ensures that all participants have a clear understanding of the project's objectives, processes, and expectations. In the context of the MULTICLIMACT Project, the PoA was established at the project's inception, serving as a primary document and a common platform for discussions among all partners involved in Task T4.2. The completion of the PoA marks the transition to collecting system requirements and developing the System Requirement Document (SRD). A brief overview highlighting the most important aspects can be found in the next chapter of this document, while the full PoA will be included in the SharePoint folder.

3.2. POA-PROBLEM DEFINITION

Given the notable shifts in climatic conditions, particularly over the past few decades, and the rising occurrence of extreme events like floods, earthquakes, and intense heat waves, it becomes increasingly imperative to proactively strategize, engineer, and upgrade our built environment. This imperative arises from the necessity to enhance resilience and fortify structures against both present and impending risks associated with the evolving climate. The call for action extends beyond mere acknowledgment, urging a comprehensive approach to planning and designing that anticipates and mitigates the challenges posed by these changing environmental dynamics.

3.3. GOAL

Deliverable D4.2 consitutes the outcome of Task 4.2 "Design of a digital solution for the multi-purpose monitoring of environmental and structural behavior of buildings [LIS] (UKA, UNIVPM, UNICAM, CYPE, ICLEI EURO, ENEA, BRC)"within WP4 - Digital solutions for supporting the protective role of the built environment for people safety and quality of living – Plan and Design.

The deliverable aim is to further design a BIM-based software platform called LIS-Platform to monitor various aspects of buildings, providing a comprehensive overview of structural integrity and insights into areas needing intervention. Simultaneously, the platform will integrate functions for evaluating occupants' well-being and include a push notification-based safety feature to alert on emergencies and guide first responders to their location, thereby enhancing the resilience of the entire ecosystem.

PARTNER [TRL, (D) DEPENDENCY, CONTACT]		
ENEA	TRL n.d	Assessment of mechanical properties of building material after extreme actions such as earthquake by correlation of advanced nondestructive testing (ultrasonic tomography and sonic measurements) and destructive testing. Development of a replicable methodology for the assessment that can be applied to similar buildings.
D:CYPE, UNICAM, LIS	Giuseppe Marghella	
UNIVPM	TRL n.d	Recommendations on sensors and data specification for the integration in the LIS-Platform. Contribution to the definition of functions for health and well-being key indicators
D:LIS	Gloria Cosoli	

Co-funded by the European Union

LIS	TRL 5	Further design the LIS-Platform to seamlessly integrate digital tools, standards, and IoT device sensor data from critical building elements/spaces. The platform should feature functions for structural health monitoring and advanced assessment.
D: CYPE(IFC) UNIVPM, UNICAM	Rifat Seferi	
UNICAM	TRL n.d	Indications about the typology of sensors to adopt in seismic monitoring system on a building scale: data deriving from monitoring will be manage within LIS-Platform
D:LIS	Valeria Leggieri	
ICLEI	TRL n.d	Contribute to the design of a digital solution for the multi-purpose monitoring of environmental and structural behavior of buildings by providing inputs on health and well-being key indicators in coordination with UKA.
D: UKA	Selene Angelone	
UKA	TRL n.d	Contribute to the design of a digital solution for the multi-purpose monitoring of environmental and physiological variables related to health and well-being.
D: LIS	MarcelSchweiker	
CYPE	TRL n.d	BIM structural and energy simulation - explore connection with BIMserver.center Open API to retrieve information from the platform (BIM models, site and simulations).
D: UNICAM, LIS	Ane Ferreiro	
BRC	TRL n.d	Promoting and working to add the results of LIS in CIW, finding networks and organizing face to face meetings with other relevant initiatives. project meeting to be attended and 1 capacity building training to be organized “Digital solution for the multi-purpose monitoring of environmental and structural behavior of buildings”. Capacity Developing in terms of innovations and innovative concept as well as market outreach,
D: LIS	Nensi Lalaj	

Table 2. Partner Dependency Contact

3.4. ACTION POINTS

Action points are the specific, measurable steps that need to be taken to achieve the objectives of the task.

3.4.1. GATEWAY NODES

There will be various types of gateways, organized into multiple levels to ensure redundancy, upgradability, service maintenance, and security by design from the outset. The Gateway is designed to collect real-time data from diverse devices (IoT nodes and other gateway nodes) through BLE/Wireless technologies. It is imperative that the Gateway efficiently transmits this data to a dedicated API.

3.4.2. SENSOR NODES

These sensor nodes or external nodes can include external sensors, actuators, or communication devices that interact with the LIS-Platform. They may provide additional data inputs, receive commands, or collaborate with the existing network to expand its functionality and enhance overall system capabilities.

Co-funded by the European Union

3.4.3. IOT SENSOR NODES (LEVEL 2)

The sensor layer will be supported by many IoT devices called leaf nodes. These devices are going to be MCUs equipped with several sensors to measure physical quantities of the environment, such as a room. The storage will be limited to a temporary buffer to hold on data before sending to the next layer of nodes through wireless interfaces like BLE in broadcast.

3.4.4. INTERMEDIATE GATEWAY NODES (LEVEL 1)

These nodes will be installed so that one of them covers at least two rooms of IoT nodes, to provide redundancy in case of faults. Data received from IoT nodes in radio proximity will be stored on persistent storage, serving as a bigger buffer. These nodes will be actual SBCs (single board computers) with TCP/IP connectivity limited to an intranet with the next level of nodes.

3.4.5. CORE GATEWAY NODES (LEVEL 0)

These nodes will form the core of the network, with one node per floor or functional unit of the building. They will manage communication between the local intranet and the wider internet, interfacing with the API on LIS server(s). Optionally, these core nodes can be equipped with software to perform preliminary filtering or analysis of data before transmission. Additionally, core nodes will handle the forwarding and installation of OTA software updates for intermediate and leaf nodes.

3.4.6. WEB APP

The web app must enable user, buildings and device management with a dashboard to visualize data and data analysis. Additionally, it should include a notification system to notify anomalies. There will be the capability of generating reports and exporting selected data in the csv/pdf format. There is the need to implement [owner, technician, researcher] roles. The researcher will have access to all data in an anonymized form, when permitted by law. The technician will have time-limited and scope-limited access to data pertaining to the intervention. The web app should manage different versions and models of devices with different sensors and access data accordingly.

3.4.7. API

A new API will be created allowing read/write operations on the same database of the web app. This must have a strong authentication (MFA or token/key based access) ensuring that only authorized users and partners professionals can access sensor data and insights. This API will receive data from core gateways and write all on the database. This API also serves as the conduit for partners to seamlessly integrate their technologies, transforming raw data into actionable insights.

3.4.8. USER EXPERIENCE (UX) AND USER INTERFACE (UI) DESIGN

The interface should be efficient, intuitive and user-friendly so that users without technical sophistication can benefit from all features with ease. It will have dashboards and charts, and users can select and apply filters based on features and date/time. The UI should support accessibility services.

3.4.9. DATA MANAGEMENT SYSTEM

Based on best practices and partner feedback, we integrated a data analysis module into the software platform. This enhancement enables researchers and partners to fully leverage data through a variety of tools. Users can apply machine learning algorithms, update mathematical models, and conduct studies with the flexibility to make real-time adjustments directly within the platform.

3.4.10. DBMS - DATABASE MANAGEMENT SYSTEM

Design, development and implementation of a relational database (SQL), data redundancy and backup strategies to ensure data integrity and availability.

3.4.11. MOBILE APP

The app will provide a stripped-down version of the web interface giving access to the most important features of the platform. The app will also receive notifications in case of emergency and start a BLE broadcast to infer the user location from the IoT sensors that picked up the signal.

3.4.12. TESTING STRATEGY

Automated and manual tests will be conducted using Unit tests and/or GitHub Workflows on every web page of the web app and every software developed by LIS, before and after the deployment on the server.

3.4.13. KEY PERFORMANCE INDICATORS

Identify specific KPIs for monitoring system performance and stability. This may include metrics related to response times, error rates.

3.4.14. 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.

3.4.15. BENEFITS OF MOSCOW ANALYSIS

PROPERTIES	DESCRIPTION	COMMENTS
Clear Prioritization	It helps in clearly distinguishing critical requirements from less critical ones, ensuring that essential tasks are completed first.	
Resource Management	By prioritizing tasks, teams can allocate resources more effectively, focusing on high-priority items to ensure project success.	
Stakeholder Alignment	It provides a structured way to communicate priorities with stakeholders, ensuring everyone understands what is essential and what can be deferred.	*Stakeholders*
Scope Management	Helps in managing the project scope by clearly identifying what will and won't be included in a specific phase, reducing scope creep.	

Co-funded by the European Union

Flexibility	Allows for adjustments in priorities as project conditions change, helping to keep the project on track even if there are unexpected changes or constraints.	

P/TASK	ACCEPTANCE STATUS	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	In progress
LIS_10	Accepted	Implementation of researcher user roles (read-only access, pseudonymized information).	SHOULD	In progress
LIS_11	Accepted	Support multiple devices as IoT sensor nodes, e.g sensor and actuators, support multiple (*Level 2*)*	SHOULD	In progress
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	In progress
LIS_15	Accepted	Password-less authentication (WebAuthn API) for users.	COULD	In progress
LIS_16	Accepted	Generation of reports in the mobile app and capability to export and send them via email, using external apps.	COULD	starting
LIS_17	Accepted	ML & AI Algorithms	COULD	starting
LIS_18	Accepted	Automatic recall for emergency services (dangerous situations, earthquakes, medical issues, fires, and flooding events) with auto-generated voice.	COULD	starting
LIS_19	Accepted	Automatic basic labeling, and basic pattern recognitions for SHM, and quality of living*	COULD	starting
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 progress T10.2 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
ICLEI_1	Accepted	Revision of the proposed indicators and variables related to human well-being and quality of life at the building scale and provision of inputs based on the work previously done in WP1 for the development of the scorecard and indicators (T1.1 and T1.2).	COULD	done
ENEA_1	Accepted	Type of data and requirements for integration in LIS-Platform	MUST	In progress
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	In progress
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
CYPE_1	Accepted	Integration of BIM models for Fazzini demo case: architecture, sensors and structure simulation.	MUST	done

Table 3. MoSCoW Analysis

3.5. SUB-TASK

Detailed description of overall approach, what has been done / achieved are reported in Table 4.

T4.2	DESCRIPTION	INPUT DATA	PARTNER	OUTPUT DATA	PARTNER
T4.2	Presenting LIS innovation in CIW	Registration	BRC	Form registered	LIS
T4.2	Palazzo Fazzini Documentation	Documentation /CAD	UNICAM	BIM MODEL	CYPE
T4.2	Palazzo Fazzini BIM MODEL	BIM	CYPE	IFC file	LIS
T4.2	Environmental and physiological data from sensors	Sensor type	UNIVPM	Raw data (time series)	UNIVPM, LIS
T4.2	SHM data	Sensor type	UNIVPM	Raw data (time series)	UNIVPM, LIS
T4.2	Sonic and ultrasonic data from measurements	Sonic and ultrasonic Velocity	ENEA	GRAPHs (time series)	UNICAM, LIS
T4.2	Assessments regarding health, well-being & perception of the environment	Form/ physiological variables	ICLE, UKA	Statistical Data and Guidelines	UNIVPM, UNICAM, LIS
T4.2	Data from sensors during seismic events	Sensor type	UNICAM	Time series	UNIVPM
T4.2	Environmental Sensor	Raw data (time series	LIS	GRAPHs (time series)	UNIVPM, UNICAM, ENEA (T 4.6)
T4.2	Physiological data	Raw data (time series	LIS	GRAPHs (time series)	UNIVPM, UNICAM, ENEA (T 4.6)

Table 4. Sub-task and data type

3.6. SRD - SYSTEM REQUIREMENTS DOCUMENT

3.6.1. SRD OVERVIEW

An SRD (System Requirements Document) is a detailed description of the functional and non-functional requirements for a system or software project. It serves as a foundation for designing, developing, and validating a system.

3.6.2. AIM/OBJECTIVES

- Realization of a BIM-based software platform to monitor various aspects of buildings

- Design and develop a BIM-based software platform for monitoring various aspects of building interventions.
- Provide a comprehensive overview of structural integrity and insights into areas that need improvement.
- Near-Real-time (NRT) data visualization.
- Collect data from various sensors across the building.
- Visualization of events relevant to the building.
- Provide real-time notifications about dangerous situations and emergencies (EWS).
- Offer 3D BIM visualization enabling the selection of individual BIM entities.
- Monitor occupants' well-being.
- Enable BIM file (IFC) uploading.
- Enable account management and device management.

3.6.3. 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.

3.6.4. TECHNICAL REQUIREMENTS

P/TASK	ACCEPTANCE 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
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	In progress
LIS_10	Implementation of researcher user roles (read-only access, pseudonymized information).	Researchers can access all data without privacy implications	SHOULD	In progress
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	In progress
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	In progress
LIS_15	Passwordless authentication (WebAuthn API) for users.	Enhance the authentication mechanism	COULD	In progress
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	starting
LIS_17	ML & AI Algorithms	AI can improve the analysis of data	COULD	starting
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	starting
LIS_19	Automatic basic labeling, basic pattern recognitions for SHM, and quality of living.	Auto labeling can reduce times	COULD	starting

Table 5. Technical Requirements

3.6.5. RISK ANALYSIS

	RISK	ORIGIN	POTENTIAL IMPACT	IMPACT (1-10)	CHANCE	CHANCE X IMPACT
R1	Misconfiguration or Architectural (network) Errors	The use of multiple IoT sensor nodes (Level 2) and devices introduces a risk of misconfiguration or architectural errors.	Misconfigurations may compromise the functionality and reliability of the system, leading to data inaccuracies or failures in communication.	10	15%	1.5
R2	Heterogeneous elements causing connection issues may prevent achieving full interoperability	The presence of highly heterogeneous elements in the system may lead to connectivity /interoperability challenges.	Heterogeneity could result in broken connections between devices, disrupting the seamless flow of data and communication.	8	15%	1.2
R3	Problems with	The risk involves	Problems with libraries can lead to	4	60%	2.4

	one or more libraries, frameworks, open sources projects.	encountering issues or problems with one or more libraries used within the system, such as bugs in one or more libraries, deprecated elements, or defunct projects.	system instability, functionality gaps, security vulnerabilities, or performance degradation, affecting the overall reliability and usability of the system.			
R4	Inefficient notification system due to transient network errors, mishandling on the receiving side.	Use wrong tools to implement it, or inefficient implementation.	Inefficient notification systems may cause delays, missed alerts, and increased resource consumption, risking the system's overall effectiveness and responsiveness. The inclusion of irrelevant information heightens the danger of overlooking critical alerts.	8	30%	2,4
R5	Problems with internships	Internships not suitable for this project	Unsuitable internships may lead to inefficiencies, lack of project alignment, and diminished overall project quality.	3	30%	0.9
R6	Problems with access management.	Users can access unauthorized data. Misconfiguration in the enforcement of access rights processes	Misconfigurations in the enforcement of access rights processes may compromise data security and confidentiality.	10	5%	0.5
R7	Data integrity can be compromised	Manipulating databases, insufficient logging, detection, monitoring and active response. Third party integration, Lack of encryption, Vulnerable Application layer,	Data manipulation, unauthorized access, and lack of safeguards may lead to compromised data integrity, posing threats to the reliability and accuracy of stored information.	10	5%	0.5
R8	Failure to ensure data availability, presence of latency and incompatible response times	Misconfiguration of the prevention system and the absence of automatic backups.	Data unavailability, latency, and incompatible response times can impede operations, disrupt services, and hinder the overall performance of the system	10	5%	0.5

Table 6. Risk Analysis

For more information about the risk mitigation strategy, please refer to the Annex 8.2.

3.6.6. RISK IDENTIFICATION

- Regulatory Delays: Potential delays in obtaining necessary approvals.
- Data Privacy Breaches: Risks of unauthorized access to sensitive data.
- Scalability Challenges: Difficulties in scaling technology to meet demand.

3.7. MULTICLIMACT, LIS-SOLUTION

The LIS-Platform is a comprehensive digital solution utilized within MULTICLIMACT as a multidomain monitoring system. It seamlessly manages, visualizes, and analyzes collected data. Designed to integrate with various sensor nodes deployed throughout the building, it captures both environmental and physiological data. This data is transmitted to our web application via robust APIs, ensuring near real-time data transfer and integrity.

The LiS-Network is delineated distinctly . The LiS-Platform, encompassing the LiS-Network, functions similarly to an IoT platform by incorporating all connected IoT devices, rather than focusing solely on the software or interfaces used for device control or sensor monitoring.

Figure 10. Live information System Platform

The LiS-platform includes:

Hardware	Software	Database-Repository (cloud/hybrid/local)
Analytics	End-user Applications	Communication Technologies

This document emphasizes the LIS-Network for clarity and readability. Discussions on Cyber-Physical Systems CPS and their distinctions or overlaps with IoT devices are deliberately excluded, as they fall outside the scope of this project. A clear understanding of the convergence between CPS and IoT concepts can help the IoT stakeholder community effectively leverage CPS research for their initiatives. This insight includes forward-looking perspectives on next-generation technologies that will shape future IoT applications (National Institute of Standards and (NIST) 2020a)

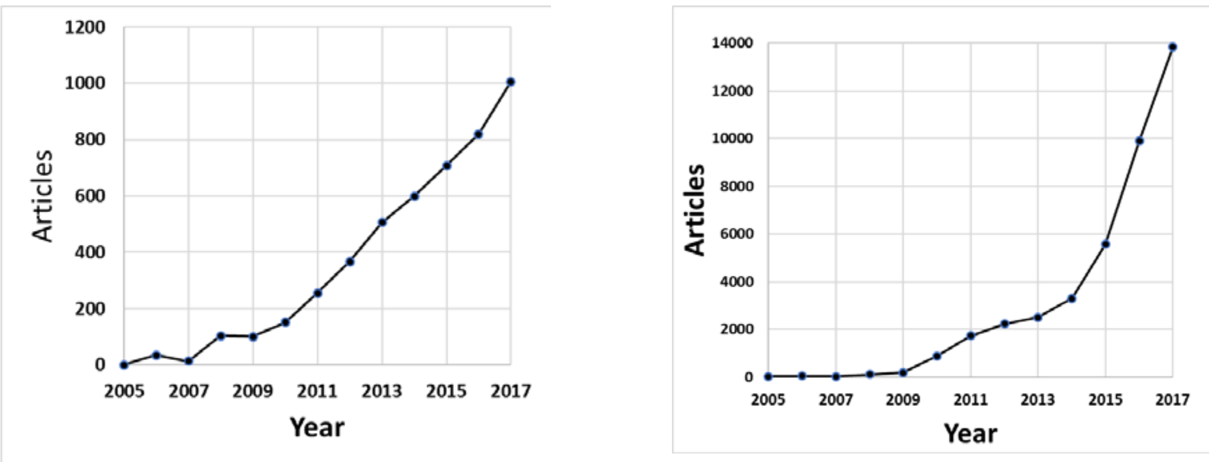


Figure 11. CPS and IoT articles trends (NIST Special Publication 1900-202)

Given that the primary implementation for the Italian Demo site will focus on sensors, with provisions for incorporating actuators at a later stage, it might be tempting to distinguish these systems solely based on the use of sensors. However, academic research suggests that such a distinction is not definitive. Instead, there are varying degrees of overlap, equivalence, subsetting, and supersetting between the definitions and use cases of Cyber-Physical Systems (CPS) and the Internet of Things (IoT).

The integration of the physical and virtual realms is fundamentally mediated by transducers, which include both sensors—devices that collect data from the physical environment and actuators—devices that perform actions based on that data. It is noteworthy that 'sensors' are more frequently referenced than 'actuators' in the literature concerning CPS and IoT (National Institute of Standards and (NIST) 2020a). This prevalence reflects a strong emphasis on information acquisition and transmission from the physical world to the digital domain, often with less consideration given to the feedback loop where actuators implement responses. Thus, the emphasis on sensors alone does not constitute a definitive criterion for distinguishing between CPS and IoT. Both paradigms fundamentally rely on the integrated use of sensor data to achieve seamless interactions between the physical and digital worlds, highlighting that distinctions based solely on the presence of sensors are insufficient without considering the broader system architecture and functional objectives.

LIS-Network Components

The sensors utilized are predominantly Micro-Electro-Mechanical Systems (MEMS), which are typically integrated with a Microcontroller Unit (MCU). The MCU is responsible not only for transmitting raw sensor data but also for performing data processing functions, such as filtering and sampling, to enhance data quality and accuracy.

3.8. LIS-PLATFORM DESIGN & DEVELOPMENT

The LIS-platform, a BIM-based software platform, is being developed to monitor various aspects of buildings. This platform provides a comprehensive overview of structural integrity and insights into areas needing intervention, leveraging a network of IoT devices and sensors. Wireless sensors serve as nodes for autonomous data acquisition, forming a Wireless Sensor Network, which is the foundation of the LIS-Network. For example, embedded sensors in various structures enable the creation of "smart structures," useful in civil and mechanical engineering projects (Caballero and Yen 2003).

The LIS-platform functions as a Smart Building OS, aiding in the creation and management of energy-efficient, sensor-equipped structures protected against natural threats and climatic hazards.

Figure 12. Live information System Platform

Sensor and Data Integration

UNIVPM and UNICAM will manage the integration of sensors and data into the LIS-Platform. UNIVPM will oversee the selection and integration of environmental and physiological sensors, centralizing this process at the Italian demo site of Palazzo Fazzini. UNICAM will handle the selection of sensors for seismic monitoring. Their insights will form the basis for the digital BIM model designed by CYPE and uploaded to the LIS-Platform. ENEA conducted additional in-situ analyses and tests on the Italian pilot (Palazzo Fazzini) and planned joint activities, proposing non-destructive technologies, providing valuable data for building assessments, predictions, simulations, and the creation of a semantically enriched BIM model with near real-time updates.

Occupant Well-being and Safety Features

The LIS-Platform will incorporate features designed to evaluate occupant well-being and provide timely safety alerts via a push notification system PSN. This includes an Early Warning System (EWS) that activates during emergencies, alerting occupants and guiding first responders through an emergency mode enabled on the LIS-Platform. These features significantly enhance the resilience and safety of the entire ecosystem.

Contributions from Partners

Following the design and integration phase, UKA and ICLEI will assess environmental and physiological variables related to health and well-being. This involves integrating psychological and behavioral moderators, assessed via questionnaires on perceived control, PANAS (Positive and Negative Affect Schedule), and clothing levels, alongside environmental conditions such as air temperature, radiant temperature, globe temperature, humidity, and air velocity. The goal is to achieve multi-domain comfort, encompassing both subjective and objective measures like heart rate and skin temperature. ICLEI will leverage their expertise in resilience, integrating work from T1.1 related to the development of the MULTICLIMACT Resilience Scorecard Method. ICLEI will leverage their expertise in resilience, integrating work from T1.1 related to the development of the MULTICLIMACT Resilience Scorecard Method.

3.9. TOOLS WITHIN THE LIS-PLATFORM

In the following sections, the tools developed and deployed as part of the LiS platform are described.

3.9.1. PUSH NOTIFICATION SERVICE (PNS)

Tailored to different user profiles, this service includes early warning systems and emergency alerts to seek help or send warnings to other users. Note that enabling notifications from the browser is necessary for this service to function properly.

Status: Partially deployed.

3.9.2. DEDICATED EMERGENCY MODE PAGE

This page will activate emergency protocols to warn and protect building occupants. It will allow users to send SOS signals and guide first responders to the exact location of those in need.

Status: Partially deployed.

3.9.3. DATA ANALYSIS PLATFORM

Designed to provide access to and analysis of key indicators, this platform has undergone various tests, including monitoring students inside the LIS-Office with their prior consent, in collaboration with UNIVPM and its departments. The platform will monitor indicators such as energy efficiency, thermal and seismic structural health, and other critical metrics derived from the MULTICLIMACT digital tools. These metrics include accessibility, human health, and well-being data.

Status: Deployed.

3.10. INTEROPERABILITY

The LIS-Platform is designed to interoperate with partner solutions, enhancing building resilience. The first example of the successful implementation of the interoperability layer of the LIS-Platform with other platforms within the MULTICLIMACT Project is demonstrated in Task T4.6 and subsequently in D4.6. The ENEA “Smart City Platform” (SCP), based on the SCP specification (SCPS), includes a series of tools being deployed to enhance building resilience. This includes aligning the data model proposed by LIS with the UrbanDataset specification for data exchange within the SCP.

Status: Deployed.

Co-funded by
the European Union

3.11. INTEGRITY LAYER - DLT

As outlined in the Grant agreement (GA), a Proof-of-Concept (PoC) will be developed and deployed to establish the data integrity layer. In this context, a research analysis will be conducted to evaluate the feasibility of leveraging the European Blockchain Services Infrastructure (EBSI) (European Blockchain Services Infrastructure, n.d.), a blockchain network operating across the European Union. However, it is important to note that access to this infrastructure is currently limited to approved partners. Recent communications from EBSI indicate that no new pilot proposals will be considered until Q4 of 2024. In the meantime, we are preparing a proposal for submission to the relevant point of contact, specifically the Ministry of Economic Development in Italy. While the PoC is being finalized, a decision on where to host the solution will be made in consultation with the EBSI committee. It is worth noting that the focus is on hosting the entry and ledger components, allowing for flexibility in selecting a suitable hosting environment. Until then, the necessary transaction schemes for ensuring data integrity can already be tested on the LIS-Platform. For instance, when a user or an authorized individual within a building submits a notification or requests a repair or intervention, the transaction is sent to the administrator, who then determines the appropriate action and acknowledges the transaction’s resolution or closure. This entire process is documented, contributing to the building’s immutable historical records. The same transaction mechanism is also automatically applied to data generated by sensors.

Status: Partially deployed.

3.12. MOBILE APPLICATION DEVELOPMENT

The initial version of the LIS mobile application has been developed and deployed in alpha version using Flutter, leveraging the Bloc pattern for state management. This application features an IFC file viewer and includes capabilities for data visualization from various sensors. At this stage, the application is available exclusively for Android devices.

Status: Partially deployed (via apk).

3.13. RESULTS AND DISSEMINATION

The key public outcomes of this deliverable, including an overview of the LIS-Platform described in Digital Solution S#2, a multipurpose tool for environmental and structural monitoring, will be incorporated by BRC into the CIW. CIW employs a comprehensive, multi-channel approach to ensure broad outreach and meaningful engagement within the climate innovation ecosystem. These channels are strategically designed to enhance access, foster collaboration, and facilitate the dissemination of climate adaptation solutions, effectively connecting innovators, stakeholders, and problem owners across various sectors and levels.

Co-funded by
the European Union

4. LIS-PLATFORM

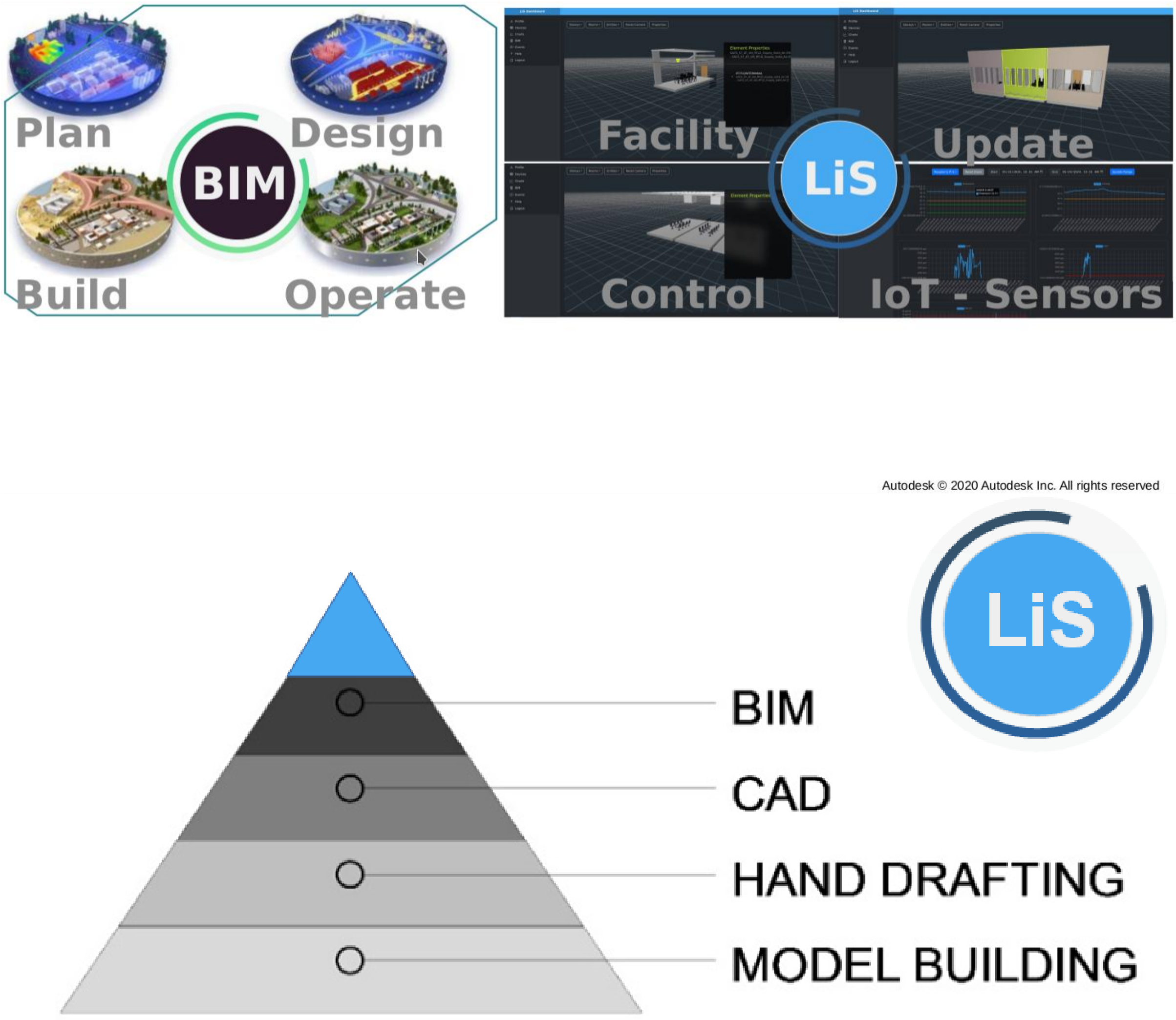


Figure 13. LIS-Platform (Based on Autodesk & Jan Fridrich, Karel Kubečka / Procedia)

4.1. ARCHITECTURE

The integration of Internet of Things (IoT), sensors, Building Information Modeling (BIM) (Albert-Laszlo Barabási 2009; Caballero and Yen 2003; Internet Society (ISOC) 2015), and Artificial Intelligence (AI) into building management offers significant advantages, such as improved efficiency, cost reduction, enhanced security, and greater occupant comfort. These technologies enable real-time data analysis for proactive management, resulting in smarter, more sustainable buildings. IoT allows for continuous monitoring of systems like HVAC, lighting, and structural health, enabling immediate issue detection and reducing downtime. By optimizing energy consumption based on occupancy, weather, and other factors, IoT provides substantial cost savings and environmental benefits. Additionally, predictive maintenance, powered by IoT sensors, mitigates operational risks by forecasting equipment failures and structural issues, allowing for timely interventions that enhance safety and reduce repair costs. IoT transforms everyday objects into intelligent entities capable of interacting with their environment in more advanced ways, deepening our understanding of building systems (Zelenkauskaite et al. 2012).

The IoT paradigm is built on interconnected and interdependent entities, where relationships extend beyond individual objects to the mutual influence of their properties. As connectivity increases, systems evolve from isolated components into dynamic networks, with information flow becoming central to operations (Alderson and Doyle 2010; Albert-Laszlo Barabási 2009). This shift redefines platform functionality, such as that of the LIS-Platform, by extending capabilities beyond physical 3D space. When a system reaches a critical degree of connectivity, it transitions from a collection of discrete parts to a fully connected network, where information flow is the defining characteristic. The true value of IoT lies in this flow, which generates new topologies and enhances operational efficiency through data-driven decision-making. In the LIS-Platform, external nodes (Level 2) mimic biological organisms, adopting decentralized, flexible, and self-organizing behaviors akin to swarm intelligence, effective for solving complex, non-linear problems. SI-based algorithms demonstrate resilience and adaptability, much like the behavior of ant or bee colonies (Zelenkauskaite et al. 2012). At deeper levels (Level 1 and Level 0), the platform incorporates hybrid neural network models, offering greater complexity and adaptability for various algorithms. However, further exploration of these elements exceeds the scope of this document.

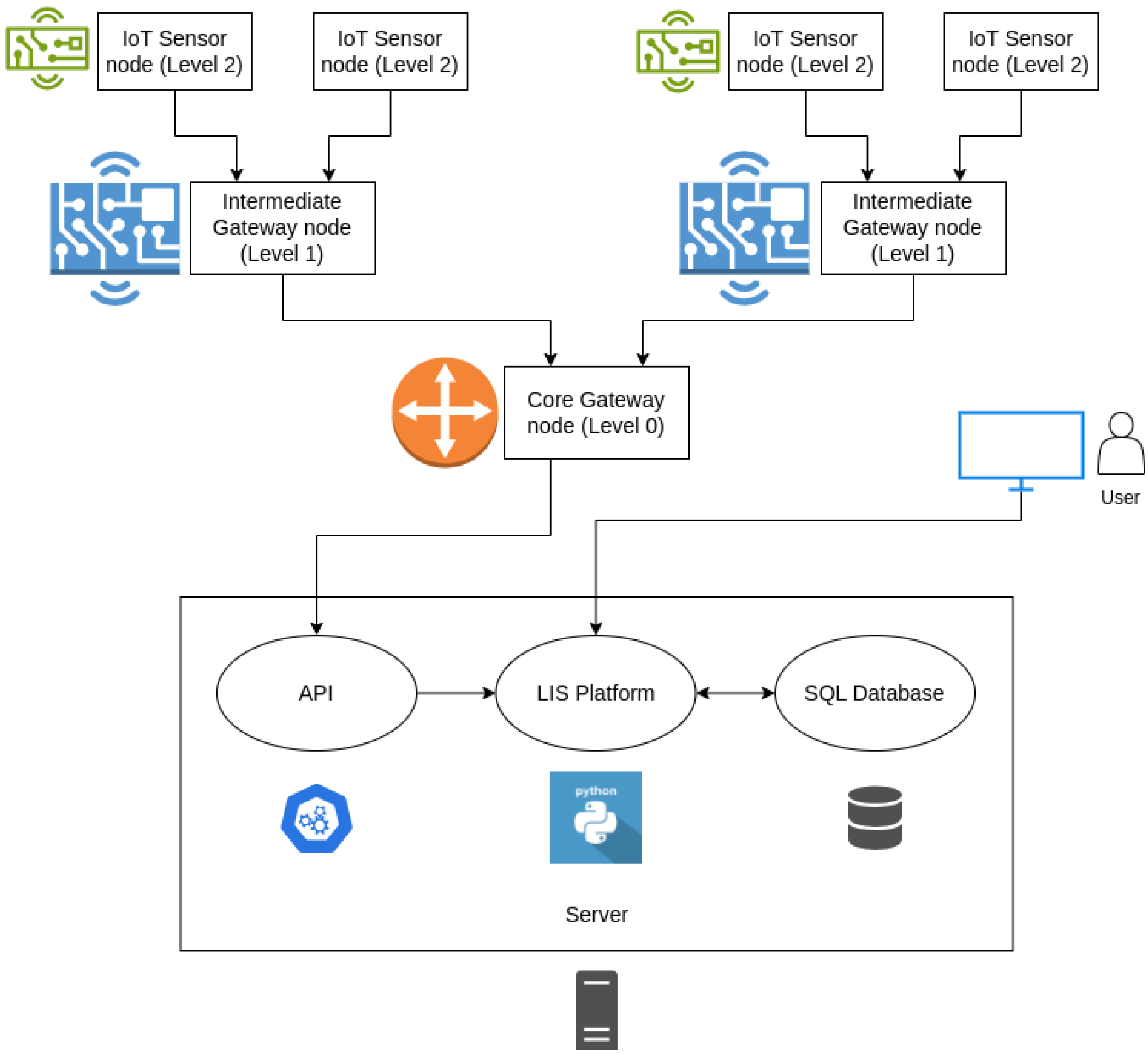


Figure 14. LIS-Platform Architecture Diagram: Comprehensive Overview

Co-funded by the European Union

4.1.1. IOT SENSOR NODES

The sensor layer will be supported by many IoT devices (leaf nodes). These devices are going to be MCUs, or Microcontroller unit equipped with several sensors to measure physical quantities of the environment, such as a room. Storage will be limited to a temporary buffer that holds data before transmitting it to the next layer of nodes via wireless technologies, such as BLE in broadcast mode. This layer will be the first line of a very primitive filtering of data. All the devices in the layer will be configured in such a way that they can only send data. An updated and upgraded version is out of this scope but fundamentally will be present for testing purposes.

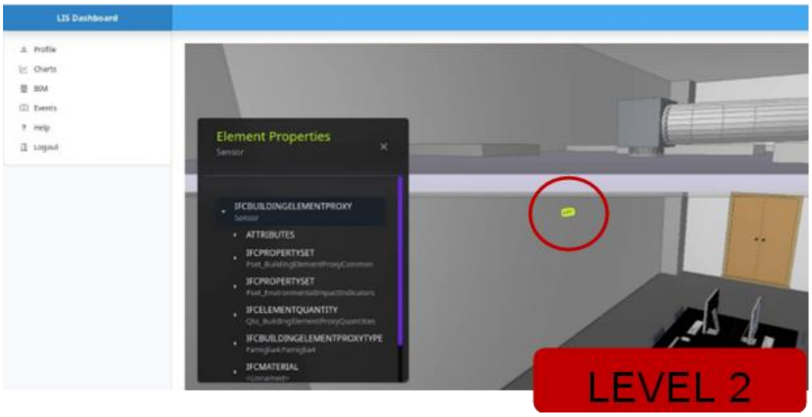


Figure 15. LIS-Platform Architecture Diagram Sensor node

Intermediate Gateway Nodes (Level 1): Installed to cover at least two rooms, these SBC nodes store data from nearby IoT nodes, providing redundancy and acting as buffers. They have TCP/IP connectivity limited to an intranet.

Core Gateway Nodes (Level 0): Serving as the network's core with one per floor, these nodes manage intranet and internet communication, interface with LIS servers, and can perform preliminary data filtering. They also handle OTA updates for other nodes (Optional).

Upon receipt, the data is recorded in a centralized database, where it is processed and stored for further analysis. Our web platform features an intuitive dashboard that allows users to visualize this data through various charts, graphs, and BIM-based representations. This visualization capability is critical for understanding the indoor environment's dynamics and making informed decisions to enhance comfort and well-being. The web app manages users, buildings, and devices, offering a dashboard for data visualization and analysis, anomaly notifications, report generation, and CSV/PDF data export. It supports roles like technician and researcher, with researchers accessing anonymized data and technicians having time-limited access. It also handles different device versions and models.

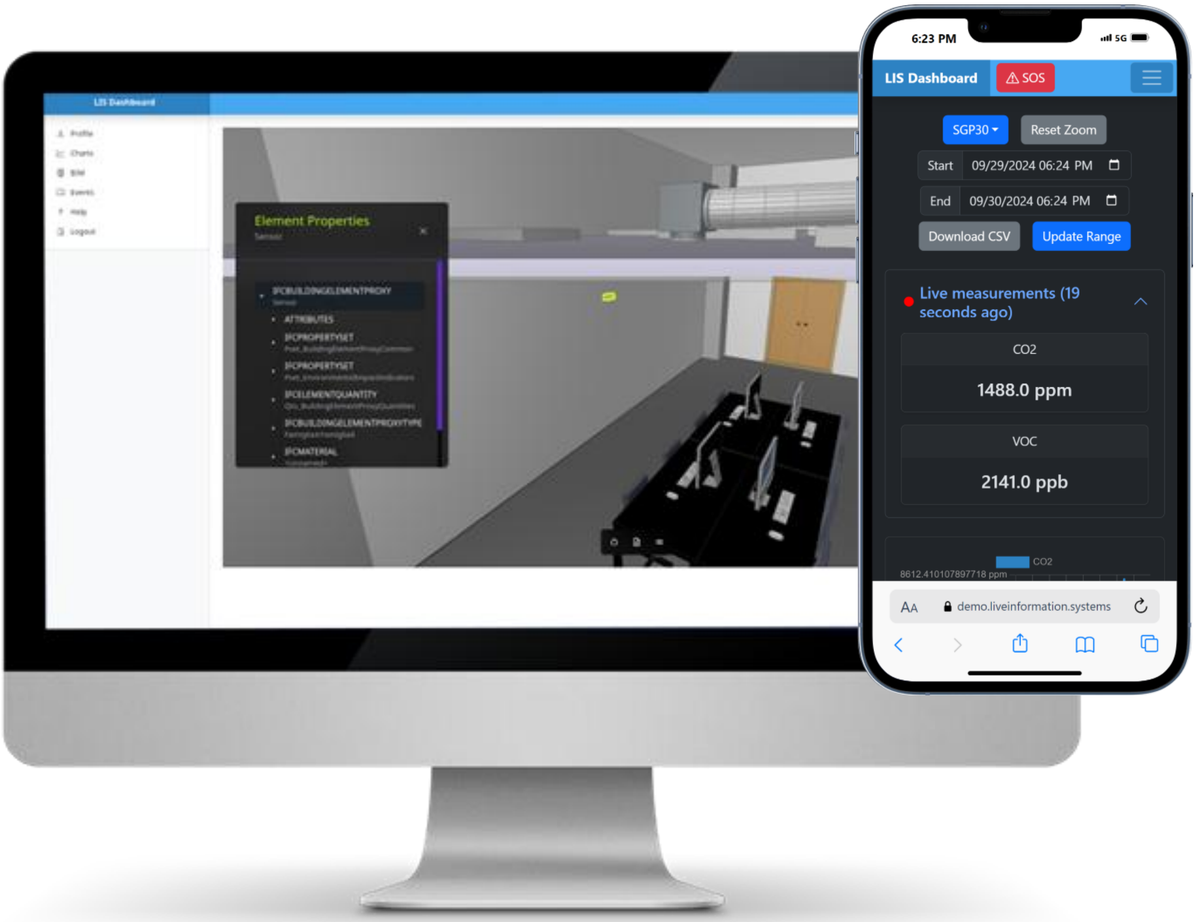


Figure 16. Web and Mobile View, testing live measurements

This image demonstrates the selection of a sensor (external node) and the retrieval of data from the main IFC file. It shows how this data is enriched with new live updates from changing environmental or structural conditions and displayed directly in the LIS-platform. This core functionality of the LIS-Platform enables the integration of various IoT devices with the digital model, facilitating the creation of a smart building, smart structure, or digital twin.

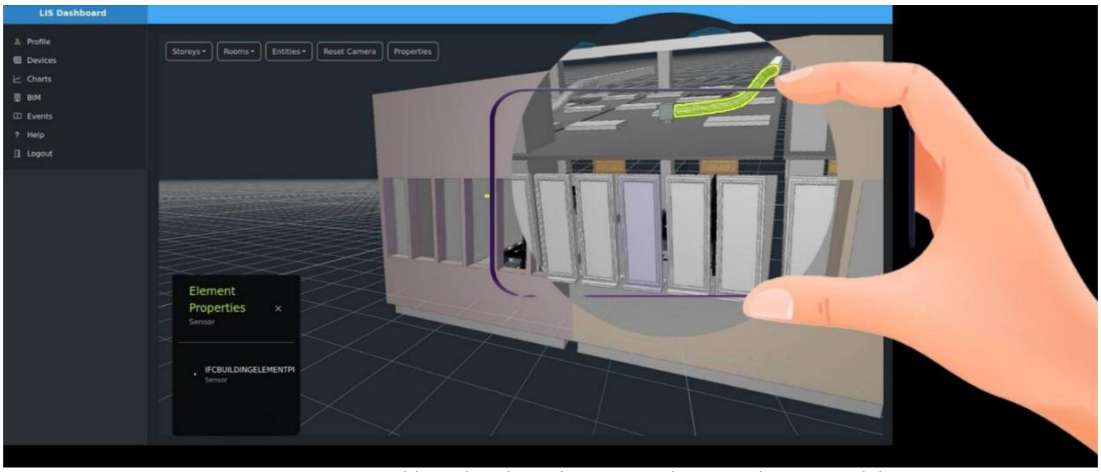


Figure 17. Main Dashboard with Real-Time Insights into the BIM Model

As shown in this image, you can select different layers or objects, often referred to as assets, within the building. By making the outer layers vanish, you can access assets located inside the walls or in other inner sections of the building. To view details, select the asset and click the "Properties" button, which will display the Element Properties box.

4.2. LIS – UI/UX

The user interface (UI) is designed to be straightforward, providing essential information about the type of building. Users with owner or admin privileges can edit building details, manage users, control various sessions, and open new sessions. Additional features include password change functionality and the option to enable a dark mode theme.

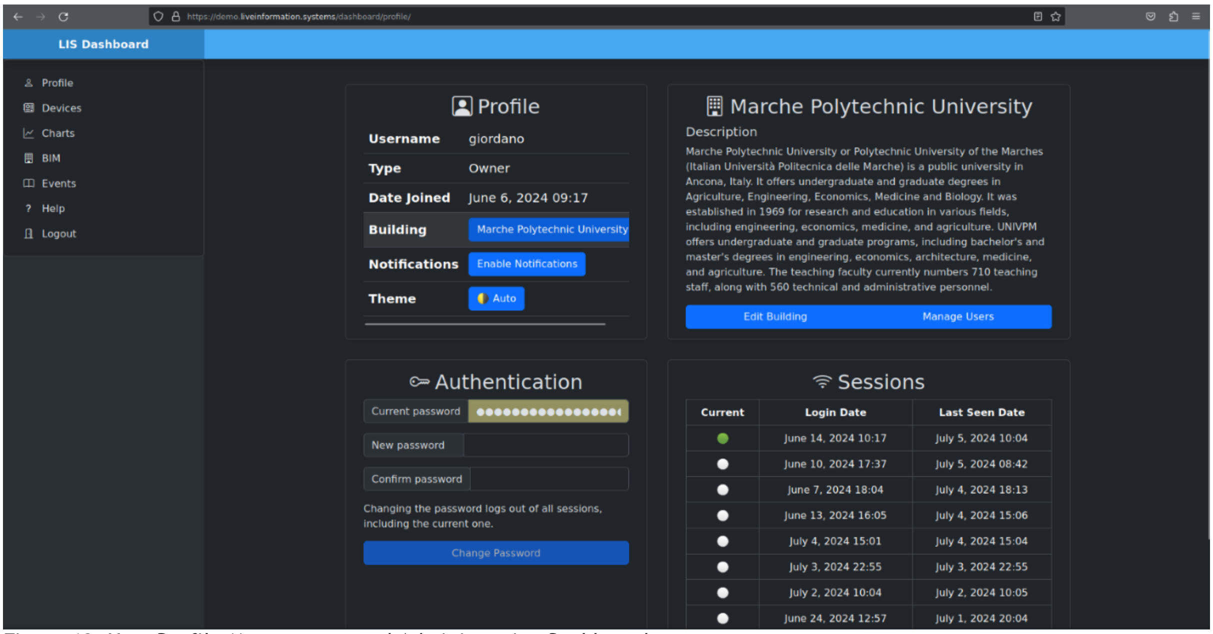


Figure 18. User Profile Management and Administration Dashboard

Figure 19 illustrates the process for adding, inviting, or removing an owner. The owner can manage user privileges within the system. These privileges can be added or removed based on the user's profile. Owners can grant or revoke access to various features and functionalities, ensuring that each user has appropriate permissions according to their role. This includes the ability to edit building details, manage users, control sessions, handle IoT devices, and more. By customizing these privileges, the owner can maintain security and efficiency within the system.

Co-funded by the European Union

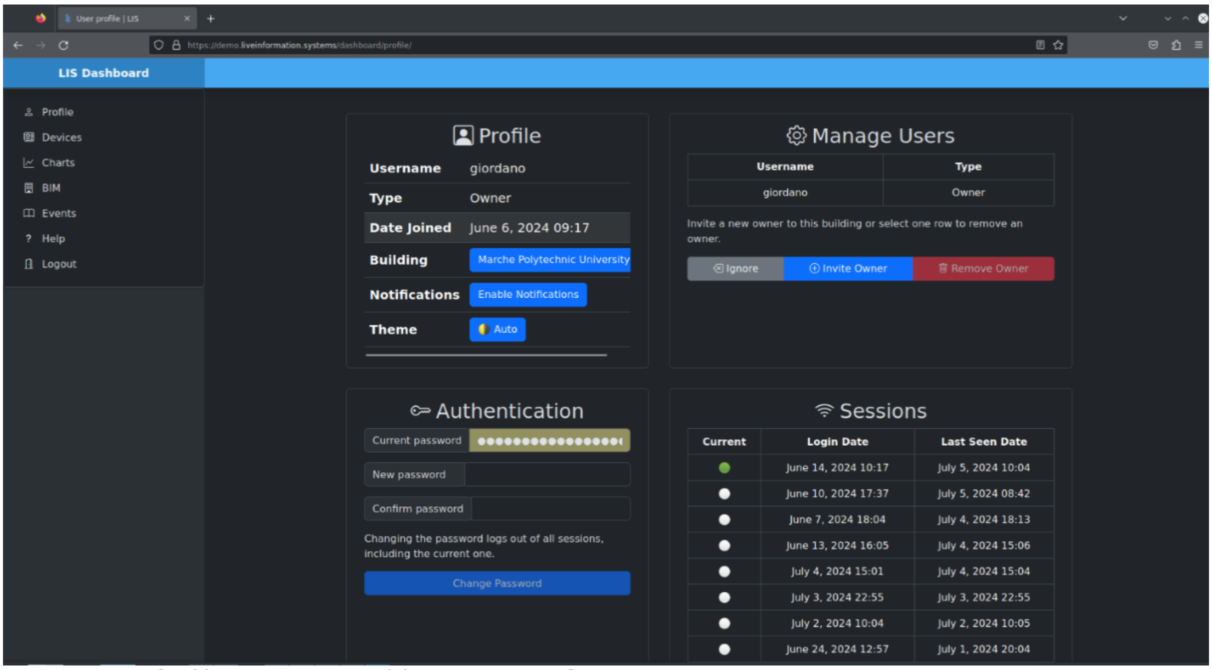


Figure 19. User Profile Management and Owner Invitation Process

The owner can manage user privileges within the system. These privileges can be added or removed based on the user's profile. Owners can grant or revoke access to various features and functionalities, ensuring that each user has appropriate permissions according to their role. This includes the ability to edit building details, manage users, control sessions, handle IoT devices, and more. By customizing these privileges, the owner can maintain security and efficiency within the system.

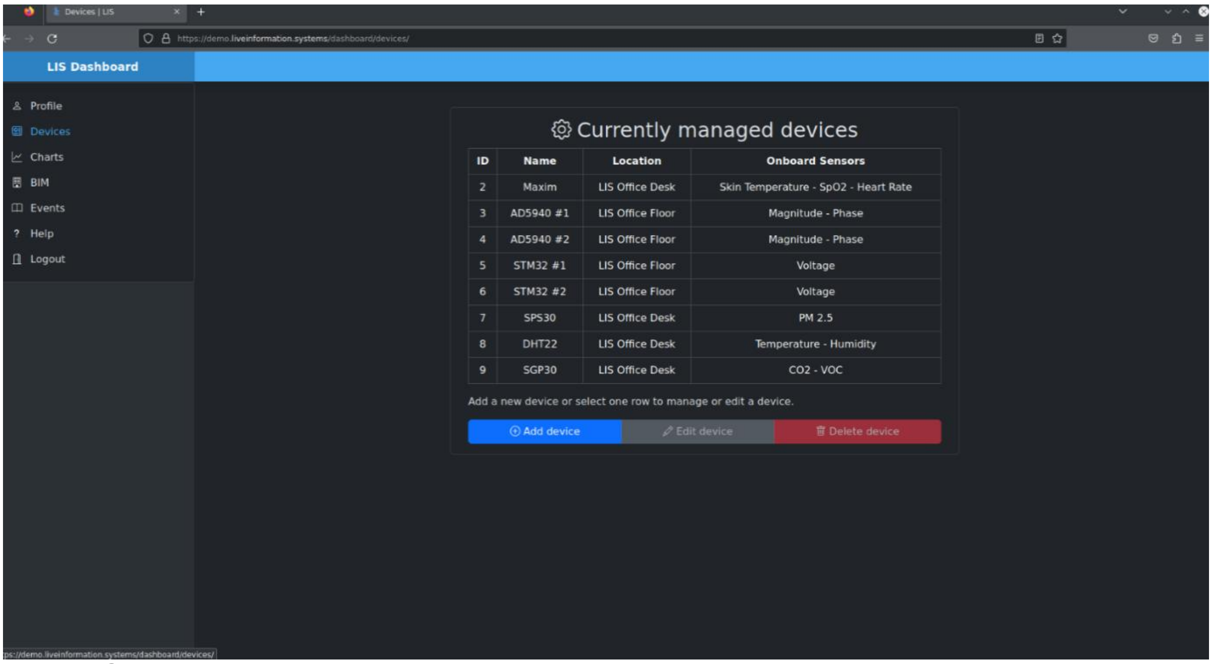


Figure 20. Device Management

Co-funded by
the European Union

In addition to managing users, buildings, and internal assets, you can also control external nodes or sensors, including IoT devices. This includes adding, editing, and deleting these devices to ensure comprehensive monitoring and management.

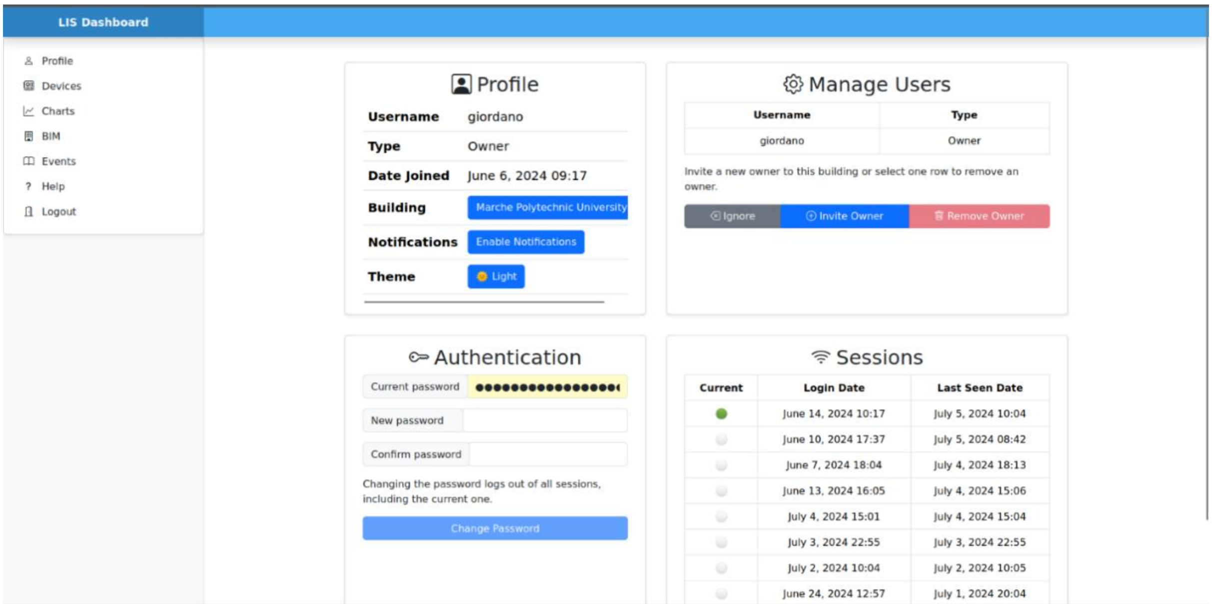


Figure 21. Notification Settings

To enable notifications on mobile or desktop via the browser, click on the "Enable Notification" button as shown in Figure 21. A pop-up will appear, prompting you to allow notifications. Once permitted, notifications will be activated. We are currently developing a forced mode for notifications during critical events, which will be included as a special use case in an emergency protocol. The LIS-Platform is designed to create a comprehensive indoor environment monitoring system that dynamically optimizes building operations, enhancing both comfort and energy efficiency. By tracking key indoor air quality (IAQ) parameters—such as CO2 levels, volatile organic compounds (VOCs), and particulate matter (PM2.5)—the platform ensures a healthy indoor environment. Additionally, thermal comfort data is used to fine-tune heating and cooling systems, maintaining ideal conditions for occupants.

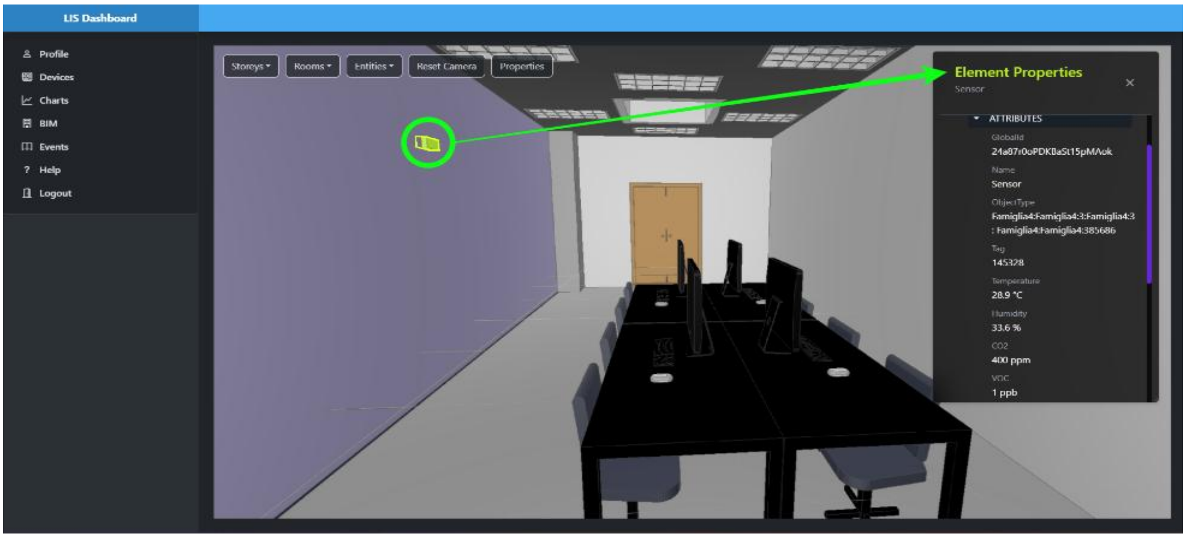


Figure 22. Sensor Node

Moreover, by incorporating wearable sensors to track physiological parameters such as heart rate and skin temperature, the system can provide personalized comfort adjustments, ensuring the indoor environment meets each occupant's specific needs. This personalized approach is particularly beneficial in diverse environments like offices, schools, and healthcare facilities, where occupants' needs can vary significantly.

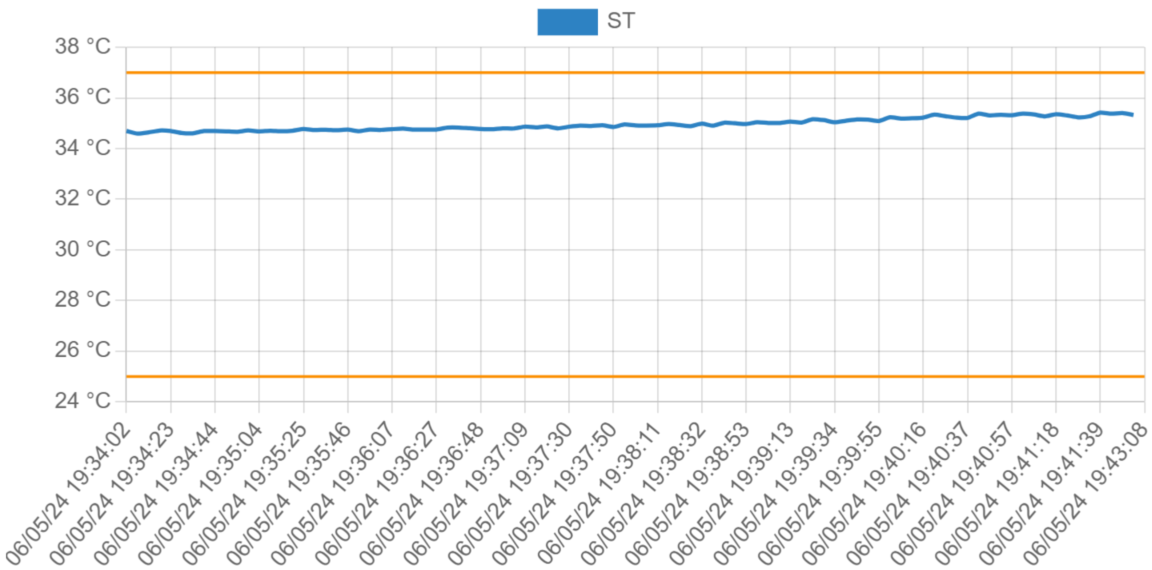


Figure 23. Comprehensive Analysis of Physiological Data Collected from Biosensors

Upon receipt, the data is recorded in a centralized database, where it is processed and stored for further analysis. Our web platform features an intuitive dashboard that allows users to visualize this data through various charts, graphs, and BIM-based representations. This visualization capability is critical for understanding the indoor environment's dynamics and making informed decisions to enhance comfort and well-being.

Device Event ▾

Event Timestamp	Event Text	Event Device
May 31, 2024 10:44	Humidity Is Now Outside The Intended Interval	Raspberry Pi 5
May 30, 2024 17:29	VOC Is Now Over The Intended Limit	Raspberry Pi 5
May 30, 2024 16:56	VOC Is Now Over The Intended Limit	Raspberry Pi 5
May 30, 2024 16:49	VOC Is Now Over The Intended Limit	Raspberry Pi 5
May 30, 2024 16:42	VOC Is Now Over The Intended Limit	Raspberry Pi 5
May 30, 2024 16:40	VOC Is Now Over The Intended Limit	Raspberry Pi 5
May 30, 2024 16:34	VOC Is Now Over The Intended Limit	Raspberry Pi 5

Figure 24. Event Visualization

Additionally, our platform offers BIM visualization, which integrates sensor data directly into the building's digital twin (Figure 22). This feature allows for spatially contextualized monitoring, where users can see sensor readings mapped onto the BIM model. This spatial integration aids in identifying problem areas and understanding how different parts of the building are performing relative to each other.

Co-funded by the European Union

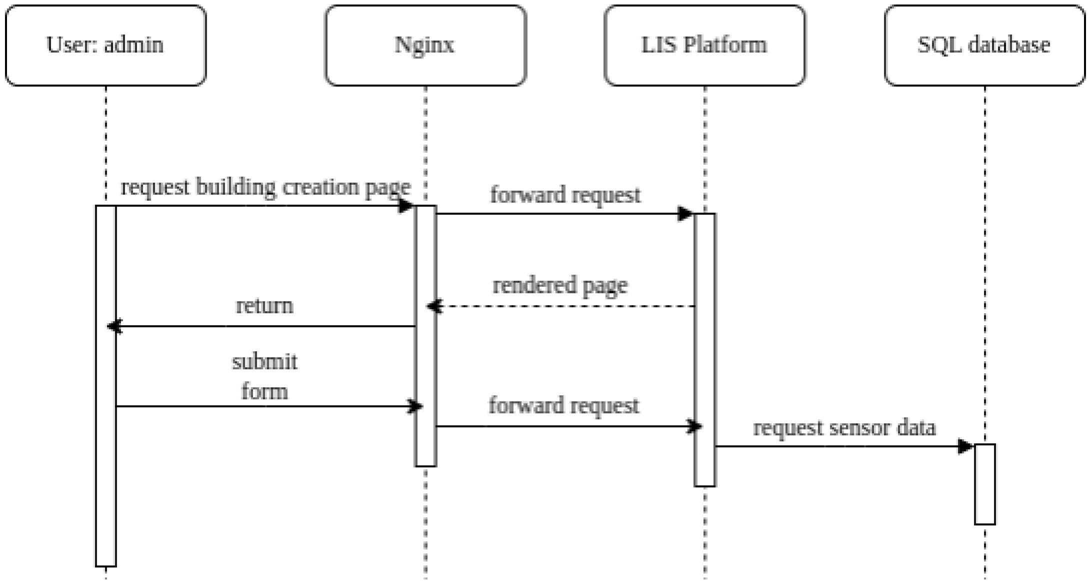


Figure 25. Building creation diagram

This digital solution enhances monitoring and management of indoor environments and provides actionable insights that can improve occupant well-being and energy efficiency. By leveraging advanced technologies in data collection, transmission, storage, and visualization, our platform ensures a comprehensive approach to indoor environment management, aligning with the goals of the EU project Multiclimact and the monitoring initiatives at Palazzo Fazzini.

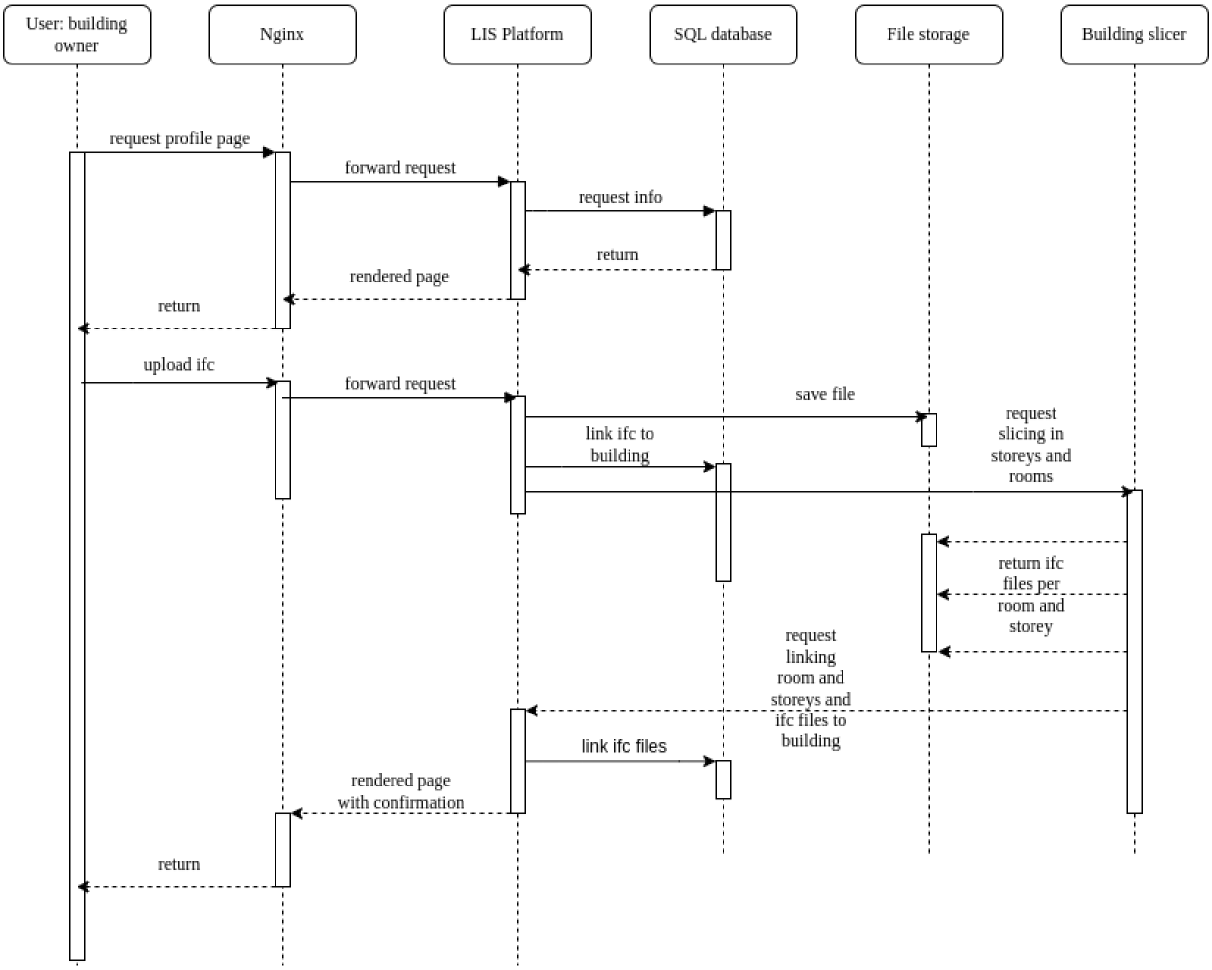


Figure 26. IFC File Submission Diagram

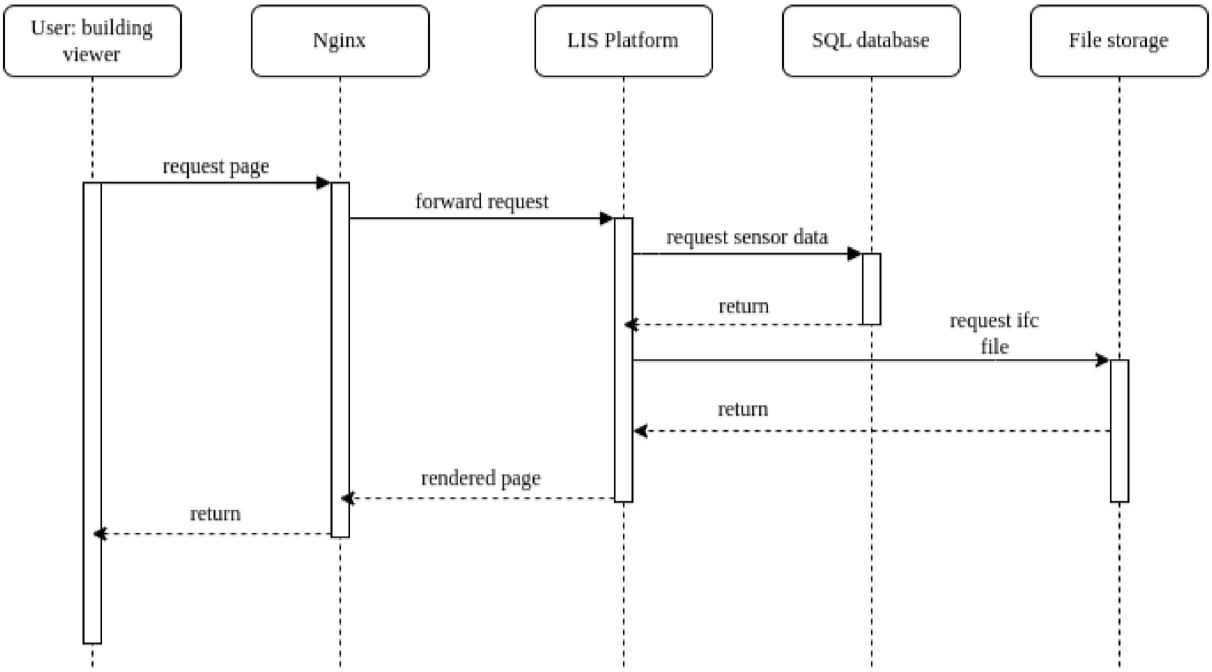


Figure 27. BIM File Viewer Diagram

4.3. LIS-DATA VISUALIZATION

To analyse the time series data of devices or sensors, start by selecting the desired device from the dropdown list. Next, choose the time interval by either zooming in on the graph or manually setting the desired range. This approach enables a detailed examination of the selected device's performance across the specified period, providing valuable insights into its operational behaviour and trends.

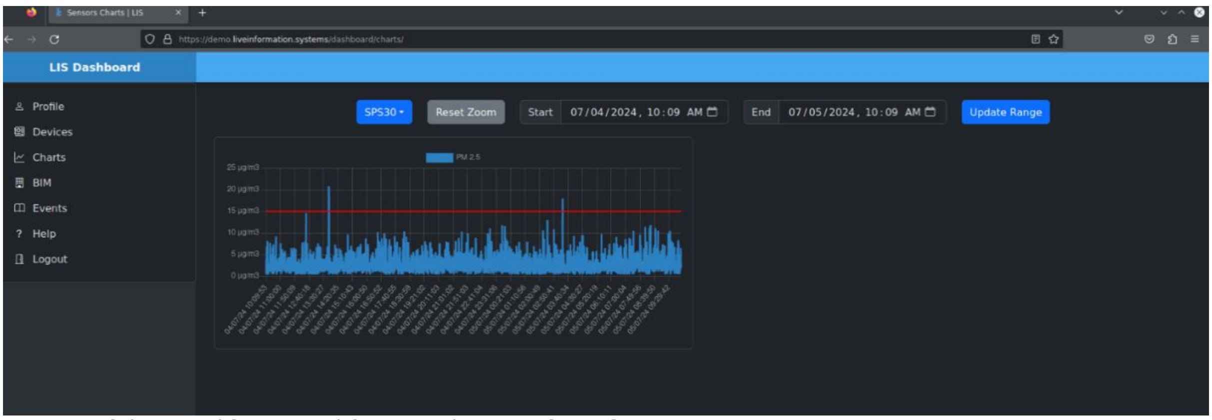


Figure 28. Selection of Sensors and Corresponding Time Series Data

Co-funded by
the European Union

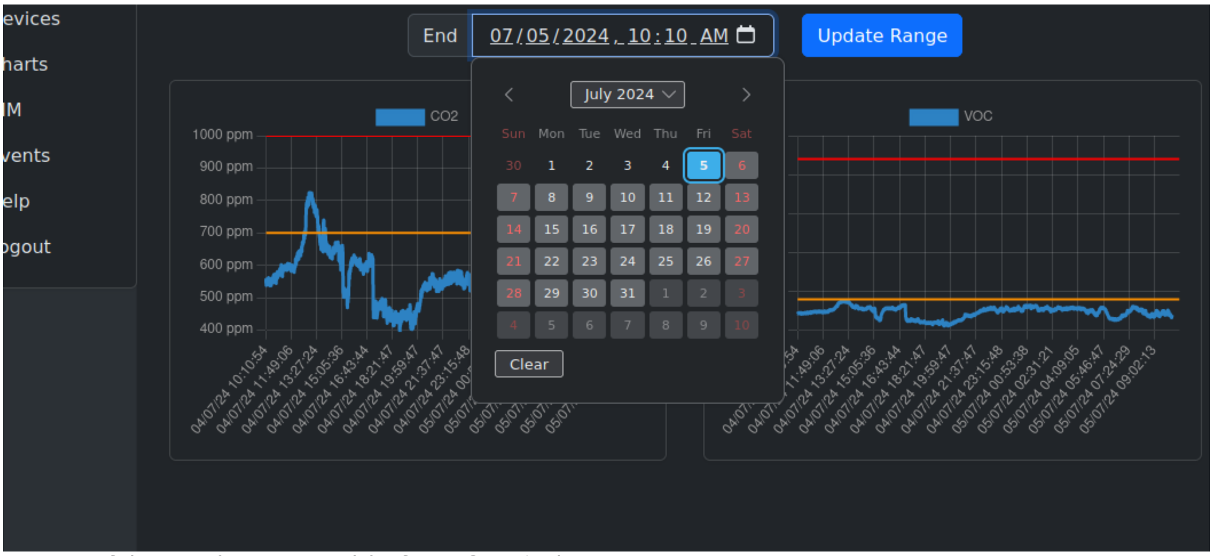


Figure 29. Selection of Time Interval for Sensor Data Analysis

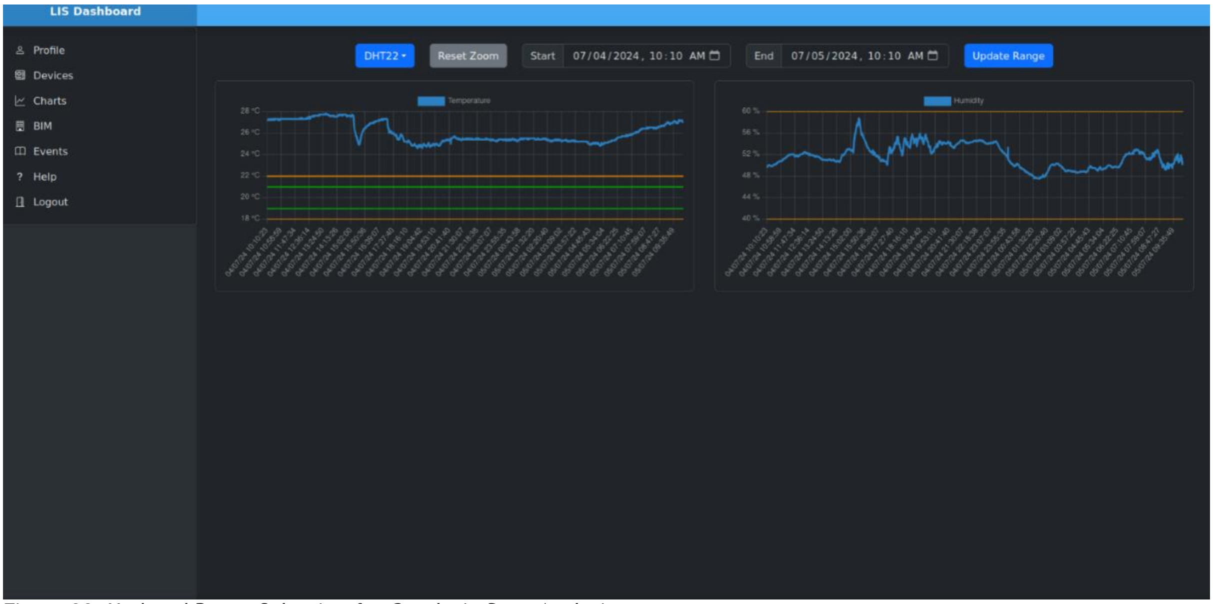


Figure 30. Updated Range Selection for Graphs in Data Analysis

4.4. LIS-FACILITY MANAGEMENT

Another main functionality related to objects or assets inside the building is the management of an online updated Facility Management System, referred to as LIS-Facility. Users can select an object that requires attention, such as a faulty HVAC component, a leaking pipe, a broken table, or a facility inspection. Responsibilities can be checked and registered. After selecting an object and using the event button, users can choose between statuses such as "broken," "repair request," "repaired," and document how the object has changed.

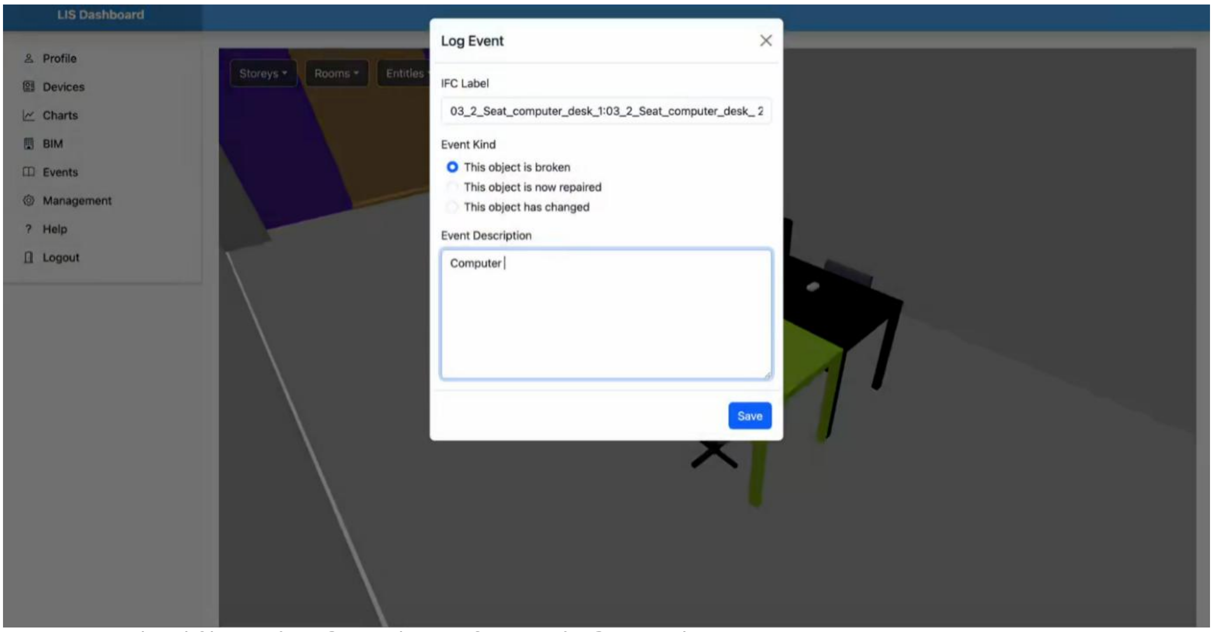


Figure 31. Updated Objects from BIM and Event Creation for Personnel

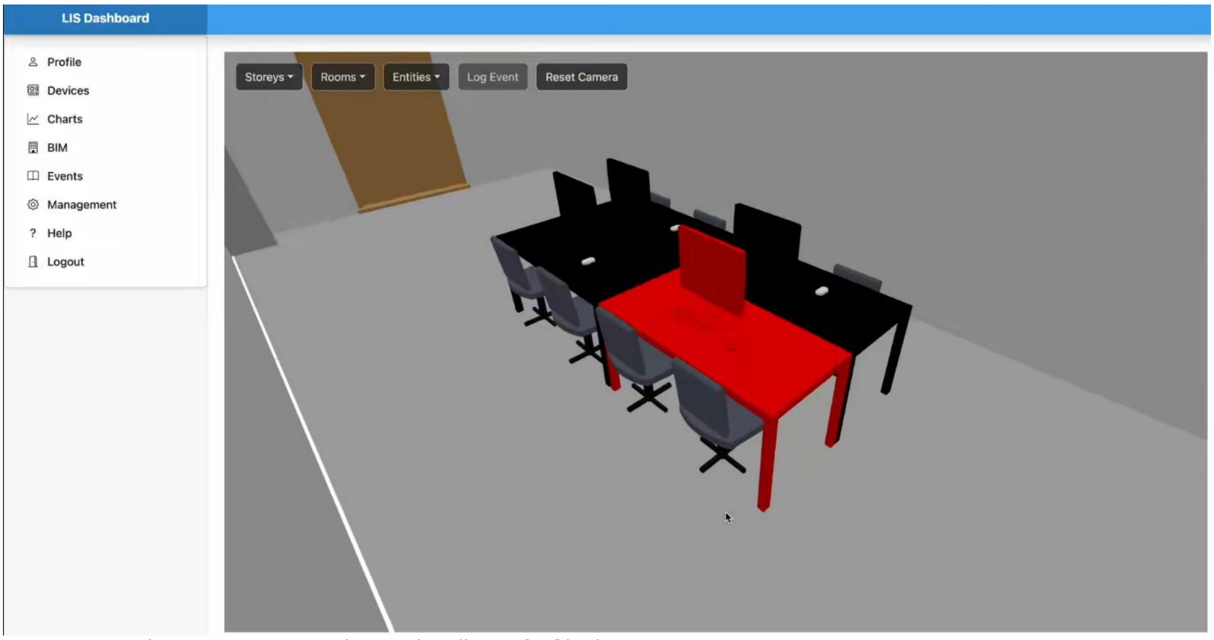


Figure 32. Facility Management and event handling LIS – Platform

This action will trigger a notification based on your profile, typically alerting both the owner and the profile most closely linked to the responsibility for the repair or intervention. With the development of the event log and event indices, we can now fully integrate data from both structural health monitoring and structural assessment processes. This integrated visualization is crucial for understanding the building's structural behaviour and the dynamics of the indoor environment, utilizing version control of the digital model. The goal is to deliver valuable insights to stakeholders, enhancing decision-making.

4.5. LIS-EMERGENCY MODE AND PUSH NOTIFICATION

i) A Push Notification Service (PNS) tailored to different user profiles, which incorporates early warning systems and emergency notifications. This allows users to seek help or send alerts to others in critical situations.

ii) A dedicated emergency mode page that activates the emergency protocol, aimed at alerting and safeguarding building occupants. This feature enables users to send SOS signals and provides first responders with precise locations of individuals in need. At the top of every page, a red SOS button is prominently displayed for quick access to emergency mode. The user is prompted to share their location, after which simple questions are asked to assess the situation and provide optional notes to assist first responders. While the user answers the questionnaire, their device's location is continuously updated to ensure the most accurate information. Upon completion, the user's location (if permission is granted), along with their answers, notes, and metadata from the session, is sent to the LIS Platform. Additionally, every other member’s web browser window in the building is replaced with a full-screen message informing them about the emergency, along with a link to view other SOS events. The SOS can also be optionally relayed via SMS, email, or messaging platforms.

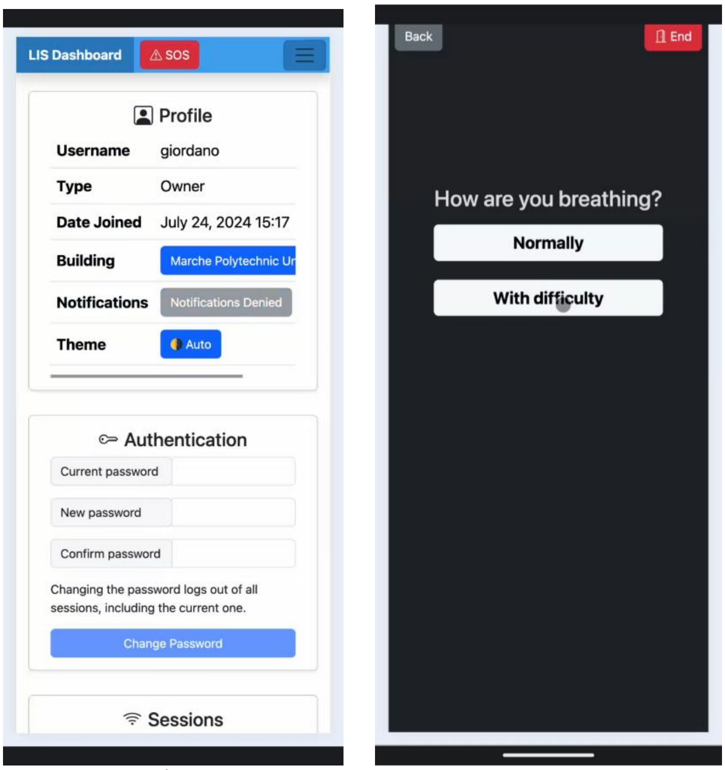


Figure 33. First Test Emergency Mode

4.6. LIS-SECURITY LAYER

As we increasingly connect devices to the Internet, new opportunities to exploit potential security vulnerabilities grow. Poorly secured IoT devices could serve as entry points for cyberattack by allowing malicious individuals to re-program a device or cause it to malfunction (Internet Society (ISOC) 2015).

The construction industry must also confront emerging threats, such as cybersecurity risks, which have often been overlooked in the past. This is particularly critical when considering the evolution of the smart city concept, as illustrated in Figure 34. Smart cities encompass a wide range of elements, from software systems to critical life-saving devices and machinery embedded within the urban infrastructure. Addressing these cybersecurity vulnerabilities is essential to ensuring the safety, reliability, and resilience of these interconnected systems. While the convergence of web, cloud, and mobile platforms, along with the Internet of Things (IoT), promises numerous significant benefits, it also introduces increased vulnerabilities—especially in a decentralized industry like construction, which involves a wide array of stakeholders (WEForum 2014) (WEForum 2017). As demonstrated by (Seferi, Giangiacomi, and Berberi 2019), smart buildings or their components can be susceptible to availability-based attacks, such as Distributed Denial of Service (DDoS) attacks. In the cited study, a simulated DDoS attack rendered all communication and notification systems within an ideal smart building non-operational. This attack utilized Bluetooth and wireless technology, which are commonly found in most smartphones (Seferi and others 2019).

More recently, as cities and communities have become more connected, networked and technologically sophisticated, new challenges and opportunities have arisen that demand a rethinking of traditional approaches to sustainability, resilience, public safety and social services, information and communications, and the human relationship to technology (National Institute of Standards and (NIST) 2020b).Therefore, to fully realize the potential of smart buildings and the broader implementation of digital twin paradigms, including their application at the city level in creating smart cities, it is crucial to prioritize cybersecurity and address cyber threats from the outset. Security measures must be treated as fundamental requirements, not merely as afterthoughts, in the design and deployment of systems within smart buildings. The extended attack surface from known attacks includes IoT devices in smart buildings, which create a larger and extended attack surface. Attacks considered only harmful to digital systems can also cause significant physical damage.

Figure 34. Evolution of the smart city concept and dimensions (GCTC Strategic Plan 2024-2026)

Within the Palazzo Fazzini or the LIS-Network, each connected device serves as a potential entry point for cyber threats. Despite the system being built on cyber resilience (the ability of an organization to withstand and recover from cyberattacks while maintaining operations) and the implementation of all known security best practices, attacks targeting availability can still result in the complete shutdown of an area, a section of the smart building, or the entire system. To mitigate these risks, best practices should encompass control over the firmware, security by design, and other well-established frameworks.

This strategy should be applied to each IoT device, as every node consists of one or more sensors or actuators. It is crucial to ensure regular updates and monitor all security patches from vendors, who may release patches to address vulnerabilities. Many IoT devices are intentionally designed without any ability to be upgraded, or the upgrade process is cumbersome or impractical. For example, consider the 2015 Fiat Chrysler recall of 1.4 million vehicles to fix a vulnerability that allowed an attacker to wirelessly hack into the vehicle (“Fiat Chrysler Recall Jeep Hacking” 2015).

The LIS Team has developed a robust system that automatically updates all nodes simultaneously, significantly enhancing security and minimizing vulnerabilities. While this system is designed to prevent a wide range of attacks, it does not cover physical attacks involving signal jammers (e.g., illegal Wi-Fi jammers), which fall outside the scope of this document. Moreover, it is essential to develop resilient buildings that can withstand not only physical but also cyber threats(European Commission 2021).To achieve this, within the MULTICLIMACT project, LIS will utilize NIST frameworks for cybersecurity and implement best practices to ensure robust cybersecurity measures are in place for its pilot initiatives (National Institute of Standards and Technology 2024; O'Reilly and Rigopoulos 2024).

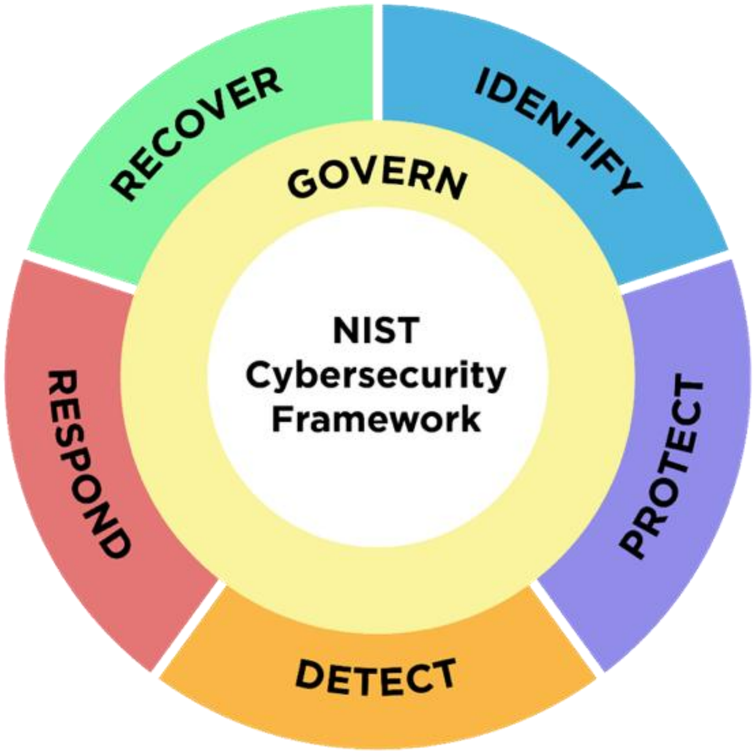


Figure 35. NIST CSF Core Functions (NIST)

Figure 36. NIST CSF Core Functions (NIST)

The components, some of which can be represented by both random variables are put into a stochastic model (a statistical tool to estimate probability distribution, which has one or more random variables over a period). The statistical process will yield a probability distribution. Companies that can analyse the dependencies between components (see Figure 37) can help various risk models estimate risk exposure.
For example, the number of attacks a company or institution will experience depends on the assets and general trends or pattern in the attacker community (WEForum 2014).

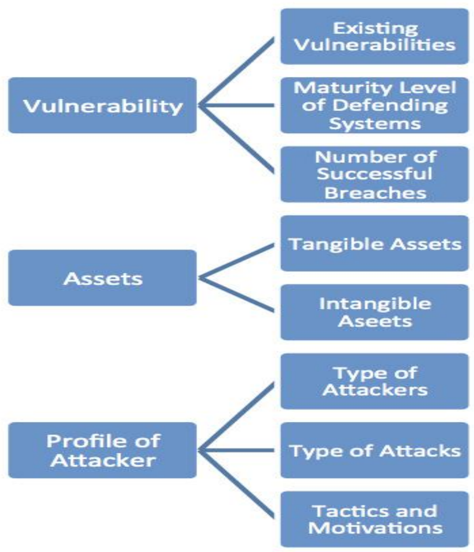


Figure 37. Cyber value-at-risk components (WEForum 2014 - Partnering for Cyber Resilience)

Whether it's the forward-collision prevention system in a car, a medical device's ability to adapt in real-time, or the latest Internet of Things (IoT) innovation, cyber-physical systems are a key source of competitive advantage in today's innovation-driven economy.

The Department of Homeland Security (DHS) identifies CPS in areas such as automobiles, medical devices, building controls, and the smart grid. These systems integrate smart, networked technologies with embedded sensors, processors, and actuators that interact with the physical world while ensuring real-time, reliable performance in safety-critical applications. DHS also emphasizes the growing role of CPS in critical infrastructure, government operations, and everyday life.

Research from the Harvard Business Review highlights the transformative potential of combining software (cyber) and hardware (physical) to revolutionize technology. It defines "smart, connected products" as consisting of three essential elements: physical components, smart components, and connectivity.

4.7. LIS-PLATFORM SECURITY OVERVIEW

The Live Information System (LIS) Platform adopts a comprehensive and multi-layered approach to security, ensuring robust protection at every level of its architecture. Built on the reliable Django web framework, the platform inherits a strong foundation for security while extending it with additional measures tailored to our needs.

4.7.1. CORE SECURITY MEASURES:

Django Framework Security: the LIS-Platform leverages the inherent security features of Django, including safeguards against common web vulnerabilities such as cross-site scripting (XSS), cross-site request forgery (CSRF), SQL injection, and clickjacking. These protections are activated and meticulously configured to ensure maximum effectiveness. Additionally, Django's secure password storage mechanisms and complex requirements are fully utilized to protect user credentials.

Transition to Passkeys: to enhance login security and combat phishing, we are transitioning from traditional passwords to passkeys. This approach uses authenticators like mobile devices and security keys, offering a more secure and user-friendly authentication process.

4.7.2. BEST SECURITY PRACTICES:

In this section, we will evaluate some of the best security practices that can be implemented in this project, using a table to keep track and ensure transparency. This section is intentionally brief to avoid overwhelming the reader.

SP1	Input Validation	We validate all user inputs, as well as non-user inputs such as cookies and HTTP headers, to ensure that no data is trusted without verification. This prevents potentially harmful data from compromising the system.
SP2	Encrypted Communications	All communications with the LIS-Platform are encrypted using HTTPS with a secure configuration. Additionally, we have mechanisms in place to revoke device credentials if they are transmitted insecurely via HTTP.
SP3	Content Security Policy (CSP)	We strictly avoid the inclusion of third-party content and enforce this policy through a comprehensive CSP. This not only enhances security but also protects user privacy.
SP4	Referrer Information Management	To safeguard user privacy, we remove referrer information when users navigate away from the LIS-Platform, preventing external sites from knowing where users originated from.
SP5	Isolated File Processing	User-uploaded IFC files are processed within a highly isolated instance, which has no access to the LIS-Platform's database or network. This isolation ensures that even if a file is compromised, the core system remains secure.

Co-funded by the European Union

SP6	Web API Security	We leverage standard web APIs, such as Content Security Policy and Trusted Types, to enforce strong protections against XSS and other injection attacks. These APIs provide an additional layer of defense by restricting the types of content that can be executed or included.
SP7	Platform Isolation	The LIS-Platform itself operates within an isolated environment with minimal access to the underlying operating system. This isolation helps protect both the platform from external software and the operating system from potential threats posed by the platform.

Table 1. Security Practices

4.8. DIGITAL TWINNING SYSTEM

Digital Twin (DT) technology can have significant applications in buildings due to its ability to serve as a bridge between the physical and digital worlds. Unlike CAD, which focuses solely on digital design, and IoT, which mainly monitors and collects data from the physical world, DT enables two-way interaction between the two realms. This characteristic of DT allows buildings to become more 'intelligent' by dynamically adjusting their near real-time behaviour based on insights and recommendations from their digital counterparts. For example, a Digital Twin of a building can continuously analyse data from various sensors (like temperature, occupancy, and energy usage) and suggest adjustments to optimize comfort, safety, and efficiency. It can also predict maintenance needs, detect potential issues before they become critical, and improve overall building management. This integration of near real-time monitoring and data-driven decision-making makes DT highly applicable for enhancing the performance, sustainability, and safety of modern buildings (Glaessgen and Stargel 2012).

4.8.1. PROCESS OF BUILDING A FUNCTIONAL DIGITAL TWIN

In this section, we are focusing on the methodologies for Digital Twin (DT) system modelling. It's useful to conceptualize the building, along with all its connections, as a single integrated product—a "smart building." This abstraction allows us to apply modelling techniques and frameworks commonly used in product design to the development of a Digital Twin for buildings. By viewing a building as a unified product, we can leverage established product design methodologies to create a Digital Twin that effectively represents and interacts with the physical environment. This approach is particularly beneficial because it brings structure and clarity to the complex task of modelling various building systems and their interactions.

Developing a fully functional Digital Twin for an existing physical product typically involves six essential steps. These steps can be tailored and applied to the context of smart buildings, enabling us to construct a comprehensive digital model that accurately reflects the behaviour, performance, and lifecycle of the building. This approach not only increases the efficiency and effectiveness of building management but also enhances our capability to monitor, predict, and optimize building operations in real-time (Tao et al. 2018).

- Step(1): Build the virtual representation of the physical product
- Step(2): Process data to facilitate design decision-making
- Step(3): Simulate product behaviours in the virtual environment
- Step(4): Command the physical product to perform recommended behaviours
- Step(5): Establish real-time, two-way, and secure connections between physical and virtual product Step(6): Collect all kinds of product-related data from different sources.

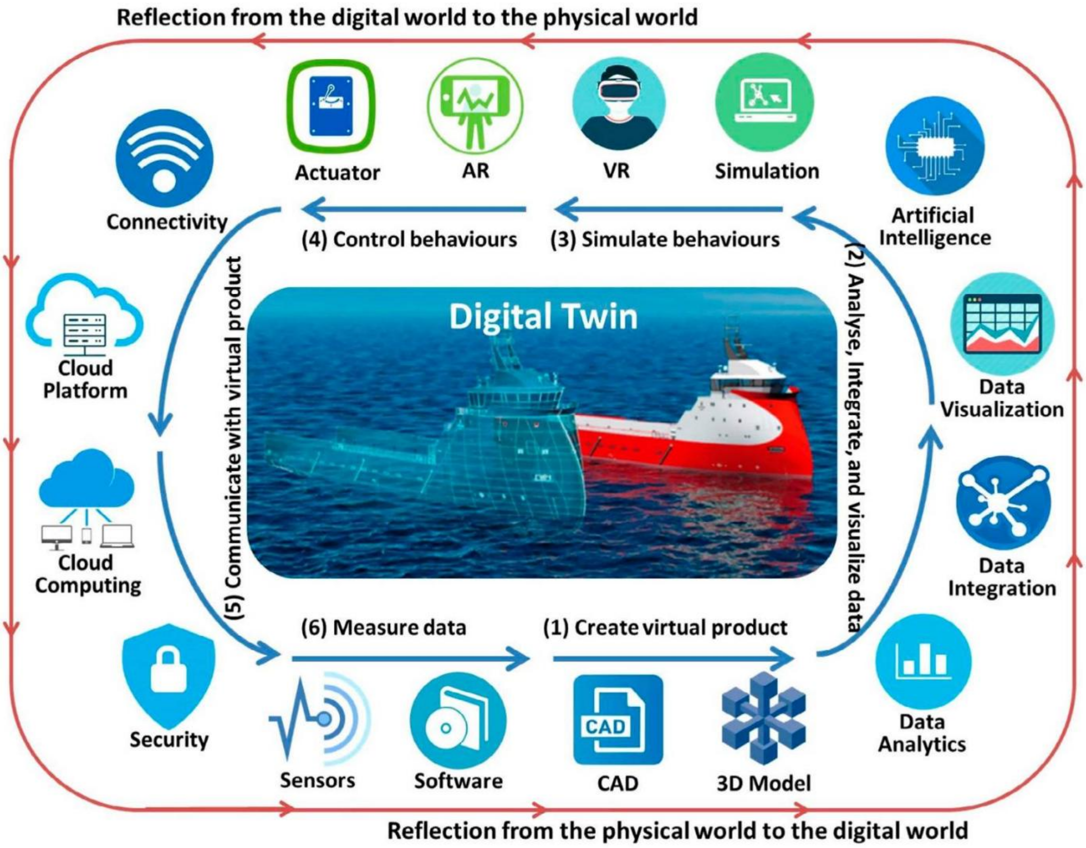


Figure 38. Enabling technology of DT. (Tao, Fei, 2018. Digital Twin-Driven Product Design Framework)

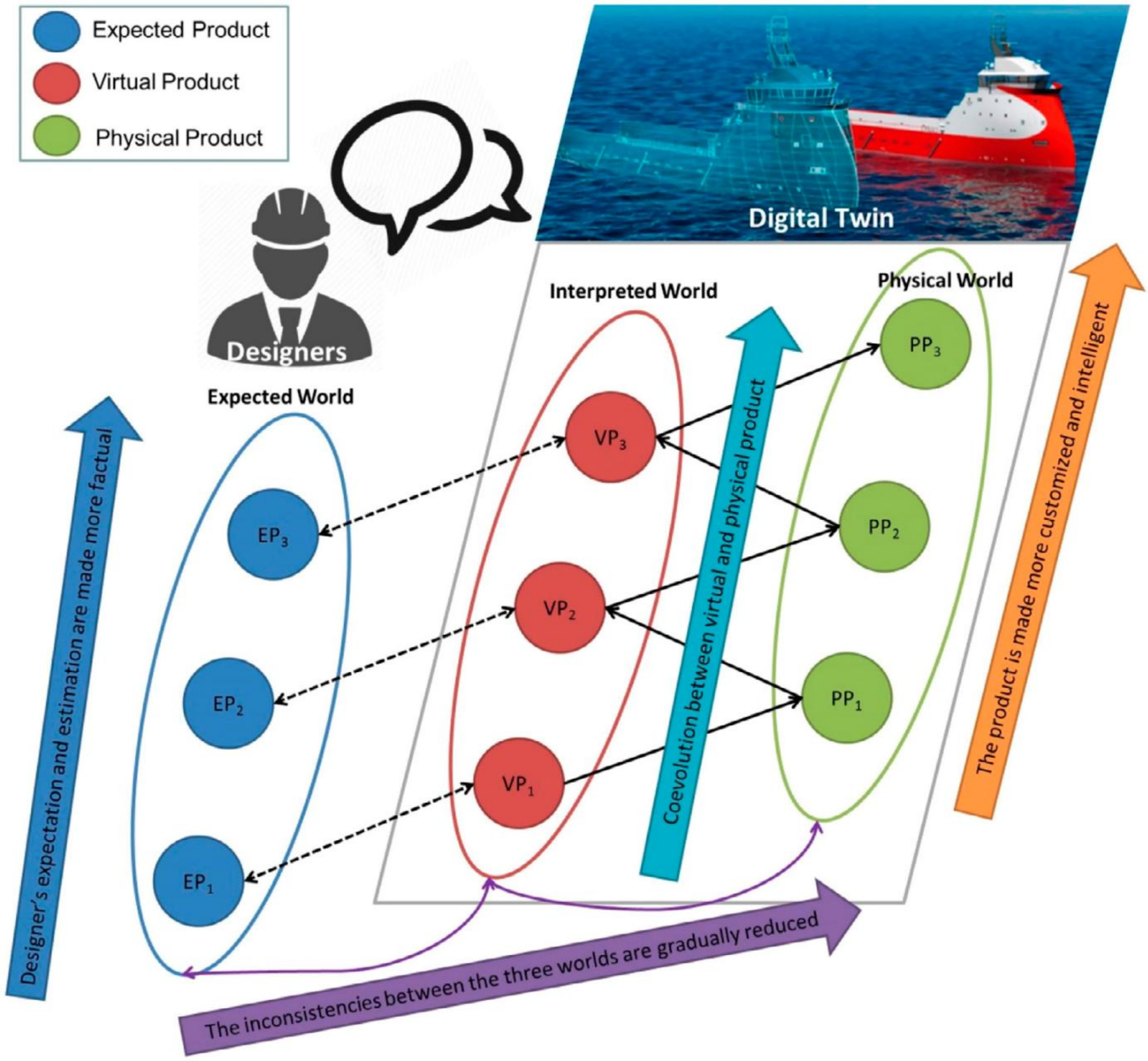


Figure 39. Enabling technology of DT. (Tao, Fei, 2018 Digital Twin-Driven Product Design Framework)

Designers are encouraged to adjust their expectations based on 'facts' that have been cross-examined in both the virtual and physical worlds, allowing them to make more informed design decisions. This process gradually minimizes inconsistencies among the expected product, the virtual model, and the physical product concerning their function, behaviour, and structure. Additionally, the physical product becomes more personalized and intelligent by incorporating various insights and 'lessons' learned from the virtual model. Ultimately, the dynamic interactions between the virtual and physical products drive a coevolution, enhancing the effectiveness of the digital twin (Glaessgen and Stargel 2012; Tao et al. 2018).

4.8.2. LIVE INFORMATION SYSTEM AND DT_FAZZINI

As part of the MULTICLIMACT project, a preliminary study will be conducted before the deployment of the Italian pilot, utilizing the existing infrastructure at UNIVPM. A prototype system, currently operational in the LIS Office, includes various environmental and seismic sensors. Initial in-situ testing on the Palazzo Fazzini (CAMERINO) and data collection were completed with ENEA.

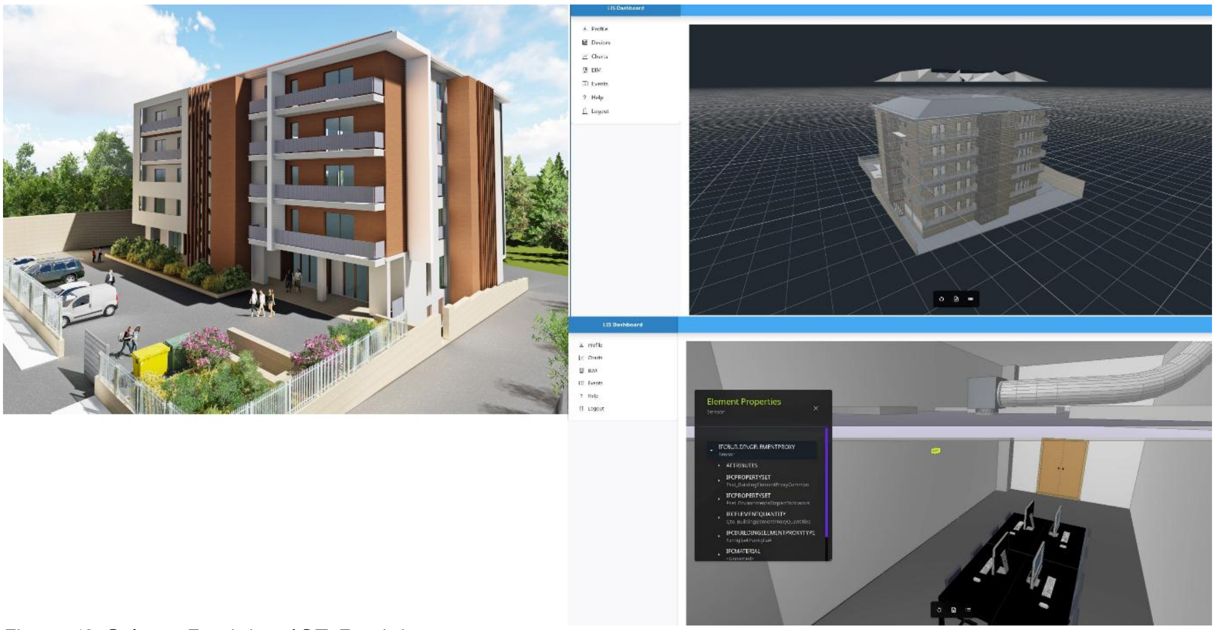


Figure 40. Palazzo Fazzini and DT_Fazzini

The pilot study will conduct a series of experiments and measurements in different settings to explore the following key relationships:

- Re_1: Environmental – Structural
- Re_2: Environmental - Physiological
- Re_3: Comfort - Health/Well-being
- Re_4: Psychological - Physiological

While initial benchmarks and variables will rely on traditional methods, such as factors-of-safety (FoS) (Glaessgen and Stargel 2012), this study aims to transcend these conventional approaches. Traditional structural health monitoring techniques often depend on similitude and heuristic interpretations of operational and anomalous conditions. As NASA has emphasized, these FoS stem from a heuristic legacy, where values like 1.5 or 2.0 have historically been considered sufficient to account for certain 'unknown unknowns' (e.g., loads, material properties), despite a lack of clear empirical justification. By adopting a digital twin approach, in alignment with NASA's guidelines, the project recognizes the limitations of probabilistic and reliability-based methods. These methods frequently assume a direct correlation between historical data and current operational environments—an assumption deeply ingrained in engineering practice but rarely scrutinized. For instance, engineering design and analysis often rely on computer codes for failure prediction, but these codes are primarily effective in scenarios they have previously encountered, which constrains their predictive power in unfamiliar contexts. We recognize that true system observability goes beyond basic software observability, which only measures how well a system’s state can be inferred from available metrics. In a broader context, digital twin systems require continuous and comprehensive monitoring to ensure accurate observation and analysis.

To address these challenges, the Italian Pilot will implement advanced correlation analyses to develop innovative algorithms and Key Performance Indicators (KPIs). The initial focus will be on ensuring that these KPIs are both useful and actionable, designed to accurately capture the dynamic behaviour of the system. The iterative nature of the LIS-Platform will enable continuous model updates and refinements, leading to increasingly robust and predictive tools that improve the effectiveness and accuracy of the pilot's outcomes. The LIS digital solution will be tested within the MULTICLIMACT project, with particular emphasis on initiatives such as providing open access to structural monitoring data, energy data, and derived KPIs. These efforts aim to raise public awareness and foster a more informed community. The interoperability challenge, partially demonstrated in the ENEA TASK 4.6

Co-funded by the European Union

case study, will be addressed through digital solutions like providing the Camerino municipality with the ENEA SCP (Smart City Platform) for collecting and monitoring harmonized datasets produced by digital tools such as CIPCast and the LIS. Additionally, other iterations of the system can be integrated or aligned with larger frameworks at the city level, such as the H-KPI Framework from NIST (Serrano et al. 2022).

To address relationships, like Re_1, which focus on the interaction between the environment and structural health monitoring (SHM) or damage, ENEA will conduct specific experiments and tests. The results will be integrated into the digital model of the Pilot Building stored on the LIS-Platform. A similar approach will be used for other types of relationships as well. A complete report is provided in the annex.

This paragraph outlines the digital twinning process for the Building and Construction sector, which is based on a classic approach combined with an iterative process. It also provides a step-by-step breakdown of the LIS-Platform to facilitate the digital twinning process.

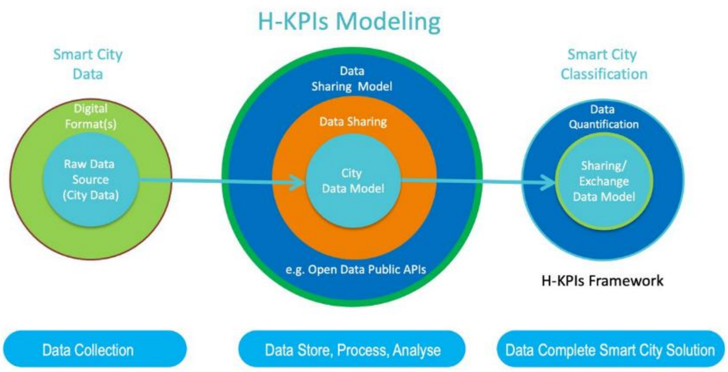


Figure 41. Smart City Data and Information Flow (Adapted from Multiple Frameworks)

4.9. PARTNERS

The following Table 7 depicts the main contributions from project partners in the development of this deliverable.

PARTNER SHORT NAME	CONTRIBUTIONS
BRC	Section 7.2.1
CYPE	Section 7.2.2
ENEA	Section 7.2.6 and Annex 7.3.
ICLEI	Section 7.2.4
LIS	Overall content
UKA	Section 7.2.3
UNICAM	Section 7.2.5
UNIVPM	General feedback on the document and section 7.2.7

Table 7. Contributions of Partners

Table 8 highlights the key contributions of project partners, along with potential stakeholders and interested groups who could benefit from the positive outcomes.

PARTNER	GROUP	STAKEHOLDERS
BRC, ENEA	Problem Owners, Innovators, End-Users	Municipalities, Regions, Institutions, Universities, Research Institutions.
CYPE	Building Owners	
CYPE, ICLEI	Public Administration	Municipalities, Regions
CYPE	AEC Sector	(Architecture, Engineering, and Construction) professionals
UKA, UNICAM	Researchers and Public Institutions:	
UKA, ENEA, UNIVPM, UNICAM	Building Managers	
ENEA	Civil Protection	
UKA, UNIVPM, UNICAM	Occupants	Occupants and Caregivers

Table 8. Contributions of Partners and Stakeholders

Co-funded by the European Union

4.9.1. SUPPORT INNOVATION SOLUTION FOR A SECURE MARKET OUTREACH

Climate Innovation Windows (CIW) was developed as part of the BRIGAID project, 'Bridging the Gap for Innovations in Disaster Resilience,' funded by the EU from 2016 to 2020. It is an online marketplace for innovative climate resilience solutions, dedicated to addressing challenges posed by climate hazards, such as floods, extreme weather events, and droughts. The platform can also expand its scope to include solutions for seismic risks, such as earthquakes. Serving as a central repository for solutions developed under the MULTICLIMACT project, it ensures broad accessibility and promotes the widespread dissemination of these critical innovations.

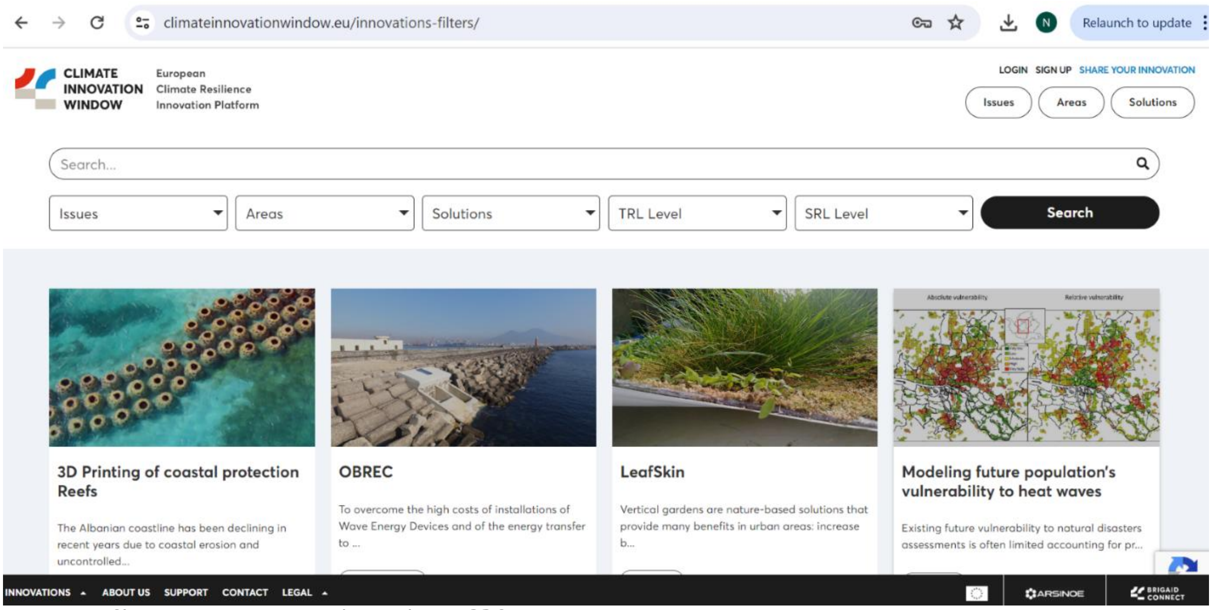


Figure 42. Climate Innovation Window website (BRC)

Among the solutions to be featured on the marketplace is the LIS-Platform, a flagship solution developed as part of Task 4.2 within the MULTICLIMACT project. As this solution undergoes testing, it will be added to the marketplace, ensuring that key stakeholders—such as urban planners, policymakers, municipalities, and private sector entities—can easily access and implement it. The marketplace is designed to foster collaboration and knowledge-sharing, enabling stakeholders to adopt proven strategies that enhance climate resilience across diverse regions. The CIW utilizes a multifaceted approach to channels, ensuring broad reach and impactful engagement within the climate innovation ecosystem. These channels are strategically designed to facilitate access, collaboration, and dissemination of climate adaptation solutions, connecting innovators, stakeholders, and problem owners across various levels. At the heart of CIW's channels lies its digital platform, serving as the primary interface for interaction, information exchange, and service delivery. This platform is engineered to be user-friendly, comprehensive, and accessible, making it the central hub for climate innovators to showcase their solutions, for problem owners to find innovative technologies, and for stakeholders to engage in meaningful collaborations. It features a range of tools and resources, including a centralized repository of innovations, funding opportunities, and a community space for networking and collaboration. CIW extends its reach and enhances its impact through strategic partnerships with EU-funded projects, regional and city authorities, and other relevant stakeholders. These partnerships are crucial for integrating CIW into broader climate action frameworks, ensuring that the platform's offerings are aligned with current needs and opportunities. By collaborating with these entities, CIW facilitates the direct engagement of innovators with potential implementers and beneficiaries of their solutions, thereby accelerating the adoption and scaling of climate adaptation innovations.

Recognizing the value of collaboration and synergy, CIW actively engages with other platforms dedicated to climate action and innovation. This engagement allows for the exchange of knowledge, resources, and best practices, amplifying the collective impact on climate adaptation efforts. Through this network of platforms, CIW leverages complementary strengths and capabilities, fostering a cohesive and robust climate innovation ecosystem.

4.9.1.1. Purpose and Target Group

Climate Innovators: solution providers developing innovative technologies and approaches for climate adaptation. They seek funding, collaboration opportunities, and visibility to bring their solutions to market.

EU-funded Projects: initiatives focused on the EU Mission on Adaptation to Climate Change, looking for innovative solutions to enhance project sustainability and impact.

Problem Owners: regions, cities, and entities facing climate adaptation challenges and in need of effective, innovative solutions to address these issues directly.

4.9.2. BIM Models and Simulations

A core aspect to the task 4.2 is the use of BIM models (architecture, sensor and structural models) in the LIS-Platform. In MUTICLIMACT project BIM will serve as a shared knowledge resource, constituting a reliable basis for decision making during buildings lifecycle. As climate conditions evolve, BIM will deploy key technologies that offer an approach for the design and adaptation of building to climate hazards through its capabilities for energy simulation, structural simulation and integrated planning.

The objective of CYPE for Task 4.2 is: providing the BIM tools (CYPE Architecture, Open BIM SATO and CYPECAD); developing the BIM models of Fazzini demo case (architecture, structure, sensors) and assisting LIS with the integration of those models in the platform.

Therefore, BIM capabilities align with MULTICLIMAT's mission of enhancing resilience of Europe's build environment. Within the project BIM addresses to critical aspects of climate resilience:

- Architectural BIM models: allow owners and public administrations to have a 3D model and data repository of the building, this information can be extremely valuable in case of emergency (fire/folding) for the correct action of emergency services in case of rescue or evacuation. It can be of a great value to facilitate refurbishment after a natural disaster.
- Structural simulation based on BIM models: allows owners and public administrations to predict the behaviour of the building in case of earthquake conditions and promote measures and adapt those buildings that doesn't reach the earthquake standards.
- Sensor allocation in BIM models: allows owners to access building data from sensors in a more user-friendly way.

Beyond these specific applications above described, BIM can contribute to the overall resilience of the building by integrating diverse expertise from architecture, engineering, socioeconomics, and climate science into a unified model. BIM's detailed 3D visualizations transform complex data into accessible insights, aiding informed decision-making and stakeholder engagement. Its support for the entire lifecycle of a building ensuring that resilience measures remain adaptable and responsive to evolving conditions. Additionally, BIM facilitates cost-effective planning by enabling precise analysis and comparison of resilience strategies, ensuring reliability and robustness in addressing the challenges posed by natural and climatic hazards.

4.9.2.1. Purpose and Target Group

The MULTICLIMACT project provides advanced tools to enhance structural resilience and energy efficiency in Europe's built environment. Each of these tools plays a role for the different stakeholders: building owners, professionals in the Architecture, Engineering, and Construction (AEC) sector, and public administrators. Meanwhile the tools are oriented and meant to be used by building

Co-funded by the European Union

designers (architects/engineers) the outcome of the tools is of special relevance for the stakeholders above mentioned.

- Building Owners: MULTICLIMAT BIM tools are crucial for owners looking to future-proof their properties. BIM tools provide a robust platform for creating detailed 3D models, allowing owners to visualize and plan renovations or new builds that are resilient to natural hazards.
- AEC Sector: For architects, engineers, and construction professionals, BIM tools simplify the design and construction process. fostering better collaboration and integration of various design elements. This is crucial for developing resilient and compliant building designs.
- Public Administration: Public administrators responsible for urban planning and regulatory oversight benefit greatly from BIM tools, ensuring new developments are in line with community resilience objectives, providing precise assessments of a building’s energy performance and environmental impact, facilitating the enforcement of energy efficiency regulations and supporting the approval of construction projects that meet stringent earthquake safety standards.

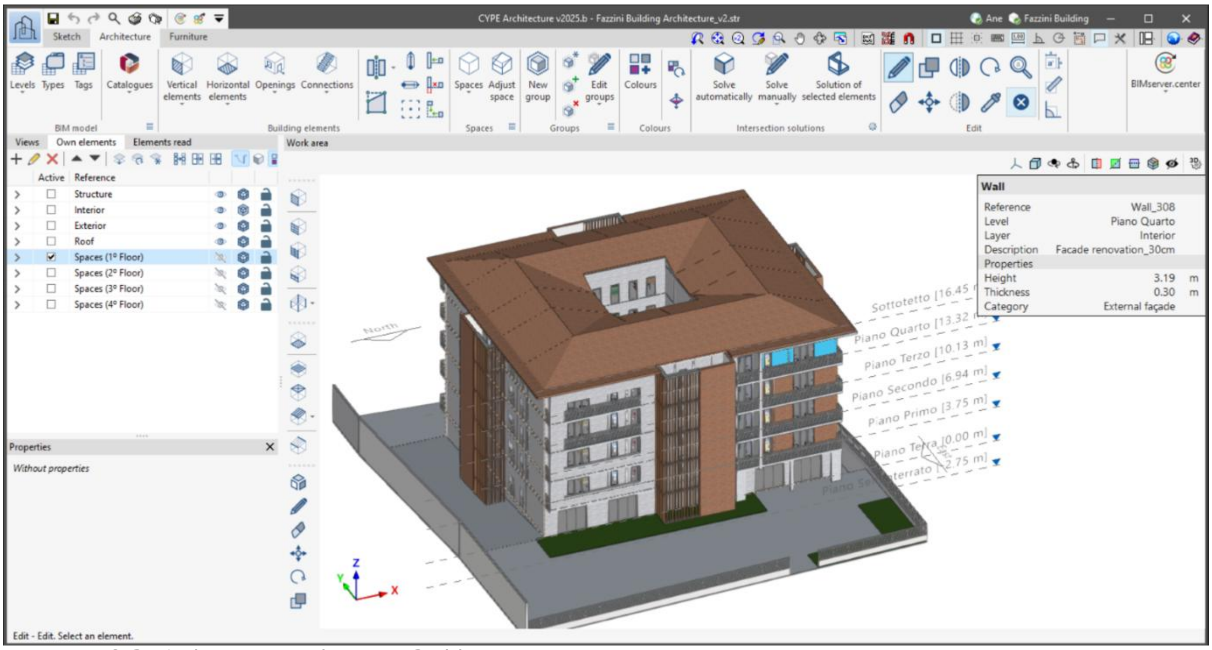


Figure 43. CYPE Architecture with Fazzini Building

4.9.2.2. Solutions for Design:

CYPE Architecture is a free of use BIM tool for the architectural modelling of buildings. Its design was based on two fundamental phases in the digital development of a project: the architectural design phase and the 3D/BIM modelling phase. Thus, it was designed to adopt both traditional modelling tools (surface areas, edges, intersections, extrusions, curves, etc.) and the new BIM modelling tools (walls, floor slabs, roofs, columns, etc.), which when combined allow users to move from sketches to architecture effortlessly. In MULTICLIMACT project, CYPE Architecture has been used as tool for the development of BIM models.

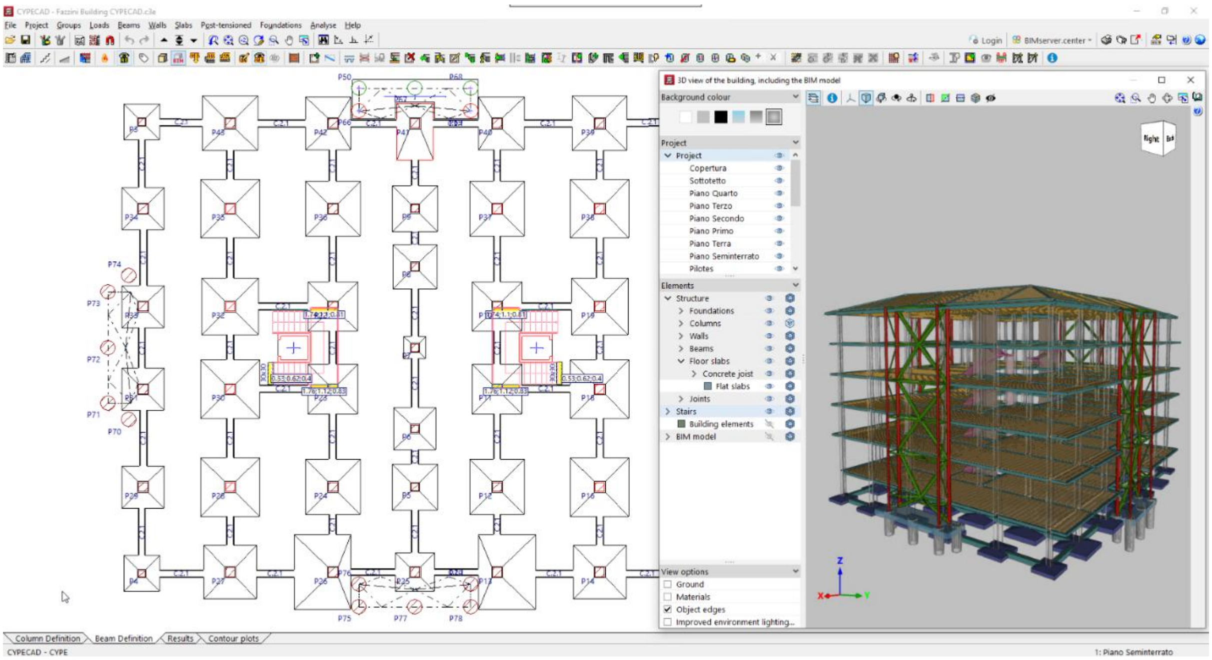


Figure 44. CYPE CAD with the Fazzini Building

Open BIM SATO: a software that collects energy data from a building and allows it to be represented in a three-dimensional model using BIM technology. In this case the software has been used to create a provision of sensors that later had been linked with output information from the sensors in the LIS platform.

Solutions for Simulation:

CYPECAD: is a software designed for the analysis and design of reinforced concrete and steel structures, catering to both building and civil engineering projects. CYPECAD integrates with Building Information Modeling (BIM) workflows. It offers comprehensive design capabilities for various structural elements and supports advanced analysis, including seismic and wind load assessments. In MULTICLIMACT project CYPECAD will be use to simulate structural behaviour in case of earthquake. CYPECAD is a tool of extrema importance to be applied to the old building stock giving owners the possibility to prevent structure deformation applaying measures to improve the structure resilience in case of earthquake.

4.9.3. A COMPREHENSIVE UNDERSTANDING OF MULTI-DOMAIN INTEGRATION

The UKA's contribution to task 4.2 aims to achieve comfort, combining both subjective and objective measures. This approach could be beneficial in gaining deeper insights into the interactions between buildings and their occupants. By understanding how different environmental factors influence human comfort and behaviour, the project can contribute to the development of a human-centric design for the built environment which promotes healthier and more productive environments. This task aims to contribute to the design of a comprehensive digital solution for multi-purpose monitoring of environmental variables and building occupant behaviour, which is part of the LIS BIM-based platform. The platform will support structural health monitoring and advanced assessment, as well as monitoring and providing key indicators related to occupant health and well-being (Betley et al. 2023).

An important aspect of this task as a part of the MULTICLIMACT project is the integration of functions for monitoring occupant comfort, which is currently mainly assessed by environmental sensors. Within the project, a field study will be conducted at the Palazzo Fazzini located in Italy to integrate real-time data from different sensors into a BIM platform. Different models will be optimized by incorporating different types of signals to provide a comprehensive overview of the subject's status and responses to environmental stimuli including temperature, relative humidity, air velocity, lighting, and noise. The UKA's contribution to this project focuses on assessing environmental and physiological variables related to health and well-being (Christoforou, Lange, and Schweiker 2024). This involves integrating potential psychological and behavioural moderators, which will be assessed via questionnaires, assessing perceived control, PANAS (Positive and Negative Affect Schedule) (Crawford and Henry 2004), and clothing level, along with environmental conditions like air temperature, radiant temperature, globe temperature, humidity, and air velocity. The goal is to achieve multi-domain comfort, encompassing both subjective and objective measures, such as heart rate, skin temperature, etc.

4.9.3.1. Purpose and Target Group

The primary purpose of this project is to develop a digital platform that can monitor and assess both the environmental aspects and the well-being of the occupants. This focus ensures that buildings are designed to ensure the health and well-being of their occupants.

The target groups include a diverse range of stakeholders. Researchers can use the platform to gather and analyse data for academic and practical insights. Public institutions can use the platform to ensure that buildings meet health and safety standards. Building managers can use the platform to monitor and maintain building performance, while occupants can benefit from a more comfortable and healthy living or working environment.

4.9.4. IMPACT

The UKA's contribution to task 4.2 aims to achieve a comprehensive understanding of multi-domain comfort, combining both subjective and objective measures. This approach could be beneficial in gaining deeper insights into the interactions between buildings and their occupants. By understanding how different environmental factors influence human comfort and behaviour, the project can contribute to the development of a human-centric design for the built environment which promotes healthier and more productive environments. Incorporating psychological and behavioural moderators, such as presence questionnaires, perceived control and PANAS, along with environmental conditions, will help the LIS-Platform achieve a holistic understanding of multi-domain comfort.

4.9.5. INCLUDING HUMAN HEALTH AND WELLBEING

Include human health and wellbeing perspective in multi-purpose monitoring of environmental and structural behaviour of buildings.

In the context of task 4.2 which aims at further developing the LIS BIM-based platform for structural health monitoring and advanced assessment of buildings, ICLEI provides support with the assessment of environmental and physiological variables related to health and well-being. In close collaboration with UKA as the academic institution in the consortium holding expertise on social and human health and well-being aspects, ICLEI provides insights for the monitoring of the overall resilience of buildings occupants.

4.9.5.1. Purpose and Target Group

The purpose is to leverage ICLEI's expertise in the theme of resilience and to integrate the work already conducted in T1.1 in relation to the development of the MULTICLIMACT Resilience Scorecard Method (Angelone, Palmieri, and Rama 2024).

4.9.5.2. Impact

In task 1.1 the MULTICLIMACT Resilience Scorecard was developed as a method to assess resilience of an asset. The Scorecard can be applied at different scales (i.e., building, urban, and territorial) and consists of a set of 134 questions spanning across different thematic areas aiming at serving local administrators, building and infrastructure managers among others, to assess the “as is” resilience of an asset against a spectrum of natural and climatic hazards, supply-chain disruptions, and socio-economic stressors. This multi-faceted approach ensures a holistic understanding of vulnerabilities and potential areas for improvement, recognizing moreover the intrinsic link between built environment resilience and human well-being and integrating insights from various disciplines.

Based on this work, for T4.2 ICLEI conducts a further screening of the scorecard to highlight which health and well-being aspects can be important to test in the demonstrator site, contributing in this way to UKA’s work in achieving a comprehensive understanding of multi-domain comfort.

4.9.6. SELECTION OF SENSORS FOR BUILDING-SCALE SEISMIC MONITORING: DATA MANAGEMENT VIA LIS-PLATFORM

In the framework of EU project Multiclimact, the pilot project will take place in the Palazzo Fazzini in Camerino (Italy), owned by UNICAM, which is a public building located in a high-risk seismic area and subject to public funding for the seismic retrofit and energy efficiency interventions. The building was severely damaged following the seismic events of Central Italy 2016 and for this reason it was subject to a seismic retrofitting improving the seismic capacity with innovative dissipation system (Gioiella et al. 2023; 2024; 2018; 2019). In this context, it is crucial to monitor structural response of the building equipped with innovative earthquake system protection in case of seismic events. With this aim different types of sensors can be employed such as accelerometers, displacement transducer, strain gauge, inclinometers properly located in a building allowing a real-time monitoring of time-series of measurable physical indicator parameters (e.g., accelerations, displacements) and collection of huge amounts of data for further processing to derive and understand dynamic properties and, consequently, actual structural behaviour.

4.9.6.1. PURPOSE AND TARGET GROUP

Provide indications about an effective seismic monitoring system composed by different typology of sensors able to collect and process data about structural and dynamic behaviour of a building during seismic events.

Target groups: researchers, public institutions, building managers and occupants.

4.9.6.2. IMPACT

The monitoring system involves the installation of different types of sensors (accelerometers, linear transducers, inclinometers, strain gauge) that provide during the seismic events the dynamic response of the structure and their interaction with the dissipation system inserted. The monitoring system will include the installation of accelerometer sensors at the base of the building to evaluate the free field seismic, at second level and attic floors. Displacement transducers will also be inserted at the level of the connections between the floors and the externals towers near the dissipator to control the differential displacements between the systems. To evaluate the deformation of the tower, inclinometers are added at different levels. In addition, to control the level of the stress in the tower, strain gauges are installed at the base of the vertical element.

The sensors will be connected to a DAQ which will manage the acquisition of signals during seismic events. The acquired time histories will be stored in a server accessible from the LIS-Platform to post-process the acquired data.

4.9.7. CREATION OF DIGITAL TWINS TO MANAGE RESILIENT

In recent years, innovative Non-Destructive Testing (NDT) techniques, applicable for the assessment of existing civil structures, have become available for in-situ analysis on Reinforced Concrete (RC) and masonry structures, but they are still not established for regular inspections, especially after seismic events. The damage assessment of RC buildings after seismic events is a very relevant issue in Italy, where most of the constructions built in the last 50 years are RC structures. Furthermore, there is also a growing interest in being able to monitor structural health aspects by storing them on the building's digital twin. For these reasons, it is necessary to develop an affordable and ready-to-use NDT procedure that provides more accurate indications on the real state of damage of reinforced concrete buildings also after seismic events.

For the structural assessment of existing concrete structures, it is important to know the strength of different elements. Assessment of the compressive strength of structures can be done by (i) destructive coring tests in varying amounts and (ii) calibrated indirect methods, combining destructive coring with non- or semi-destructive techniques. It is worth noting that the RILEM TC 249-ISC (D Breysse et al. 2019; Denys Breysse et al. 2021a) has recently published some Recommendations on NDT in situ strength assessment of concrete introducing a new methodology to reduce the errors in the technical assessment following the UNI EN 13791:2019 standard ("UNI EN 13791:2019." 2019). The RILEM methodology is easy to apply and can give results (mean strength estimates, local strength estimates) equivalent or more accurate than those provided by previous approaches; mostly can save a significant number of destructive testing (which are mandatory anyway), through the conditional coring option, without any additional cost. Furthermore, it is important also to formulate a feasible procedure for inspection on-field to check and monitor buildings subjected to seismic events.

Starting from the NDT methodology for damage assessment of reinforced concrete buildings after seismic events tested on shaking table (Polimeno et al. 2018), in the project MULTICLIMACT, ENEA is investigating the damage induced by the seismic actions on Palazzo Fazzini, Italian Demo site, by means of an experimental NDT campaign (based on ultrasonic tomography and sonic techniques) to demonstrate the capability of these techniques to detect structural damage and provide an estimation of the state of the building's health, information that can be integrated into BIM.

Another aim of this task is to monitor building material behaviour over time by means of NDT. In particular, the thermo-hygrometric behaviour of two different walls after the renovation of Palazzo Fazzini, one of which will be upgraded with innovative surface finishes with multifunctional mortar developed in task 3.3, will be detected by sensors and the entire system will be managed by the control unit for remote data acquisition and supplied with an enabling license.

4.9.7.1. Purpose and Target Group

The purpose of the activities is the integration of the LIS-Platform monitoring system with structural and thermo-hygrometric data. Upon receipt, the data is recorded in a centralized database, where it is processed and stored for further analysis. The web platform allows users to visualize data through BIM-based representations at the level of single column and single wall. This visualization capability is critical for understanding building structural behaviour and indoor environment's dynamics. The goal is to provide useful information to the stakeholders, generally the public entities devoted to guarantee the safety condition of the territory against natural risks and enhance comfort and well-being (e.g. Civil Protection, Municipalities, building managers).

4.9.7.2. Impact

Structural data related to the actual state of Palazzo Fazzini are collected through two different steps: documental analysis and non-destructive tests. The first one is based on data collected and summarized by UNICAM in the mechanical characterization of building materials ("Relazione Delle Indagini e Sulla Caratterizzazione Meccanica Dei Materiali" 2021) and the subsequent seismic vulnerability assessment ("Relazione Di Calcolo, Vulnerabilità, Miglioramento Relazione Geotecnica" 2023). The columns to be tested are selected based on the following criteria: the level of solicitation, accessibility, and comparisons with existing destructive and non-destructive test data. The specific locations of the tests are shown in the image below Figure 45.

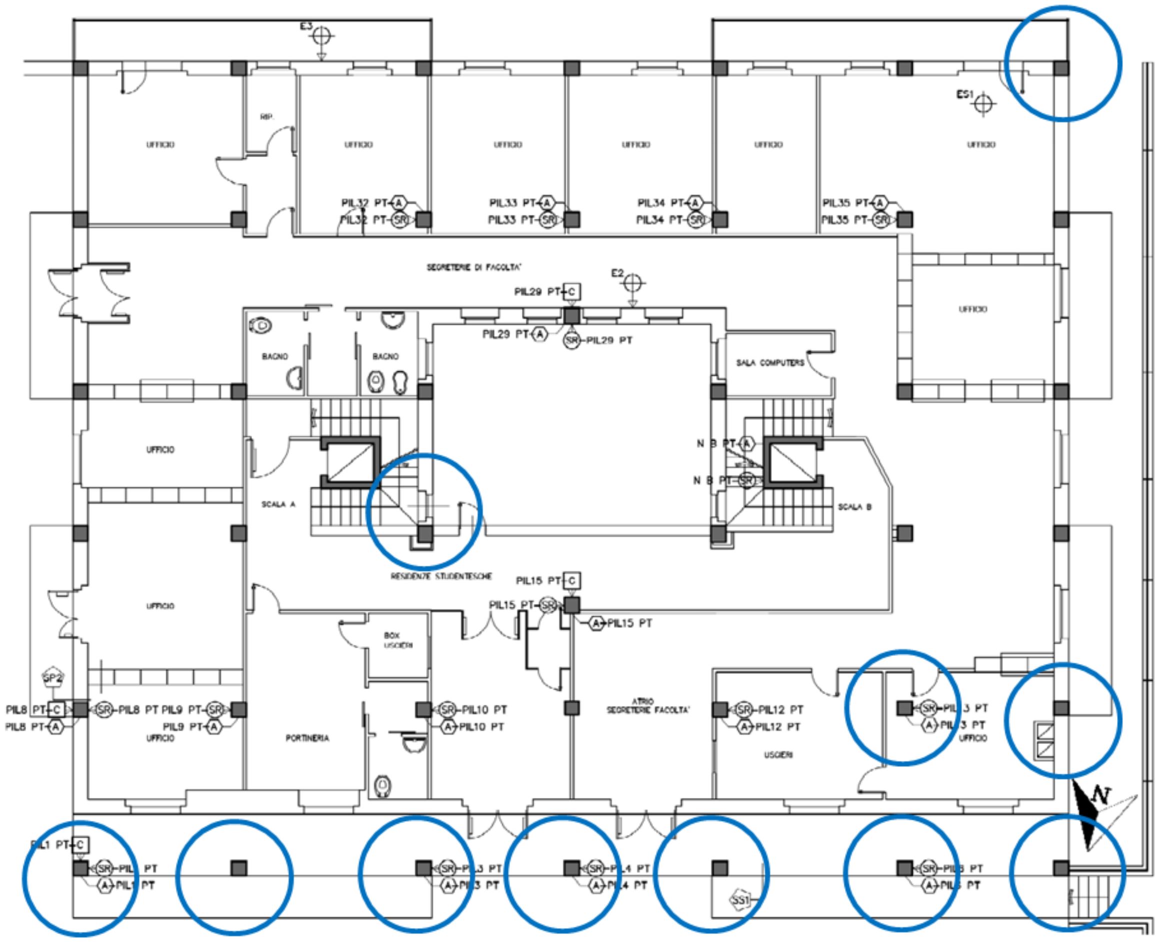


Figure 45. Location of NDT at ground floor of Palazzo Fazzini

On the selected columns ultrasonic tests, ultrasonic tomography and sonic tests are carried out. As for the thermo-hygrometric behaviour of the retrofitted building, the following devices will be installed: sensors to measure in real time the temperature and relative humidity both inside the wall and on its external and internal surfaces. All the collected data are integrated in the LIS-Platform monitoring system; structural data as a static time-placed reference, thermo-hygrometric data in real time during acquisition as dynamic information.

4.9.8. SENSORS AND DATA SPECIFICATIONS

UNIVPM gives recommendations on sensors and data specification for the integration in the LIS-Platform; also, it contributes to the functions for health and well-being key indicators.

In the context of built environment, it is fundamental to assess the comfort and well-being of the occupants. This is a complex theme, given that multidisciplinary competences and multidomain spheres are required/involved (Altomonte et al. 2024). What is more, different types of comfort should be considered, such as thermal, acoustic, and visual ones. In last decades, it has been highlighted that not only environmental quantities determine comfort, but also psychological and physiological parameters influence our own perception of the surrounding environment (Gloria Cosoli et al. 2023). Hence, a continuous measurement of the different parameters could be useful to properly quantify a subject's well-being, also to have feedback towards the living environment and to potentially be able to exploit that information for control purposes in a feed-forward loop that could optimize not only well-being but also the building energy consumption (Cho et al. 2023). Data-fusion techniques play a pivotal role in this field as well as Artificial Intelligence (AI) and Machine

Learning (ML) algorithms (Boutahri and Tilioua 2024), which can be exploited to determine synthetic indices efficiently describing a subject's health status and well-being.

In the European project MULTICLIMACT, environmental and physiological parameters will be measured and smoothly collected thanks to the integration of all the sensors in a unique BIM-based platform de eloped by the project partner LIS. This enables to enrich the BIM with real-time information concerning not only the building itself, but also its occupants, with a holistic perspective focused on a human-centric design of the built environment. For sure, this can be useful to enhance the resilience of the whole ecosystem (building + dwellers) towards natural and climate-related hazards.

4.9.8.1. Purpose and Target Group

The aim of UNIVPM within T4.2 is to propose and agree on a list of environmental and physiological sensors to be integrated in the LIS-Platform, which will be the centralized acquisition hub in the Italian demo site, i.e., Palazzo Fazzini. The stakeholders can be identified in buildings managers and also to caregivers that could be interested in monitoring a subject from remote.

4.9.8.2. Impact

UNIVPM has identified structural, environmental, and physiological sensors to be employed in the Italian demo site that should be integrated in the LIS-Platform; in particular, the DomX IAQ sensor (DomX Private Company, Greece) has been selected (and purchased) for its ability to acquire parameters related to thermal, visual, and Indoor Air Quality (IAQ) domains. Its technical specifications are reported hereafter:

- Temperature Room temperature (°C)
- Relative Humidity (%)
- Atmospheric Pressure (Pa)
- CO2 Concentration (PPM)
- Breath VOCs Volatile organic compounds (VOCs) (exhaled breath)
- Particulate Matter concentration (PM0.5, PM1.0, PM2.5, PM4, PM10 sizes)
- Illuminance (LUX)
- IAQ indicator
- Static IAQ index based on recent sensor history

Regarding physiological sensors, particular attention has been paid to wearable multidomain devices for their ability to simultaneously collect data related to different domains without influencing the normal activities of daily living. However, possible movement artifacts and also limited signal quality due to particular operating conditions should be considered when interpreting the results. In a first phase of the project, the MAXREFDES104 (Analog Devices, Massachusetts, US) has been employed; it can collect, among the others, data from a photoplethysmographic (PPG) sensor and from a temperature sensor (measuring the skin temperature). The preliminary results from test carried out in LIS offices during the first months of 2024 have been inserted in a conference paper to be presented by UNIVPM in June 2024 (G Cosoli and others 2024).

Then, when the test protocol for the experimental campaign in Palazzo Fazzini has been better discussed, other options come out, such as EmotiBit and MUSE (InteraXon Inc., Toronto, Canada). The final choice is strictly linked to the budget availability and also to the sensors already owned by the partners involved in the Second Phase of the MULTICLIMACT project (in particular, in WP8 and WP11).

4.10. PARTNER INTEGRATION WITH THE LIS PLATFORM

4.10.1. INTEGRATION WITH UNIVPM

The first one is the health and well-being integration with UNIVPM, series of customizations were made to fit this monitoring solution with the selected biosensors, wirelessly connected to the LIS-Platform. The initial test was conducted in coordination with UNIVPM, based on the framework provided by UKA and ICLEI, check Annex *Annex_UNIVPM* for more.

The first results are published in the 2024 IEEE International Workshop on Metrology for Living Environment (G Cosoli and others 2024).

Sensor type	Model	Measured quantity
PPG	MAX86176	PPG signal (from which Heart Rate, HR, and oxygen saturation, SpO_2, can be derived)
Temperature	MAX30208	Skin temperature (ST)

Figure 46. First integration with UNIVPM

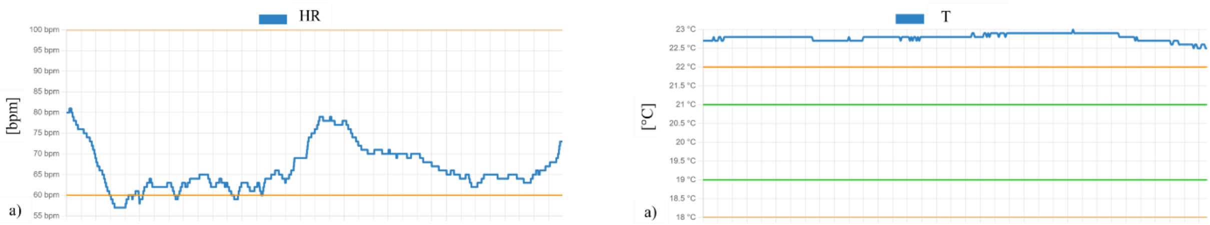


Figure 47. First integration with UNIVPM, Example Graphs HR, T

4.10.2. INTEGRATION WITH UNIVPM II

The second integration with UNIVPM is based on SHM and environmental variables, where IoT devices were used based on previous research from UNIVPM and hardware from Analog.

Sensor type	Model
Air temperature (T) sensor	DHT22
Relative humidity (RH) sensor	DHT22
CO_2 sensor	SGP30
PM2.5 sensor	SPS30
VOC sensor	SGP30

Figure 48. Second integration with UNIVPM

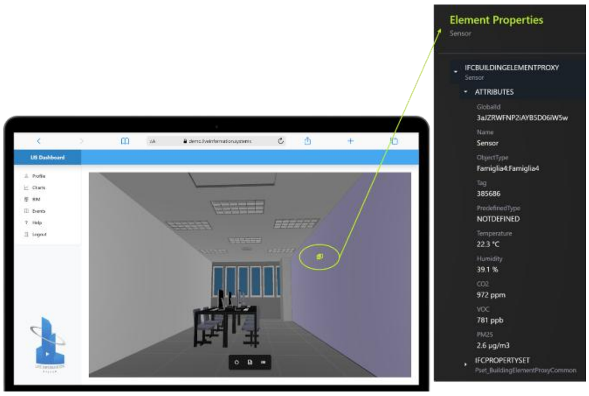


Figure 49. Full integration with UNIVPM

4.10.3. INTEGRATION WITH CYPE

The third integration involved the digital model, designed using BIM methodologies from CYPE, based on requirements from UNICAM and LIS. The digital model of Palazzo Fazzini was completely redesigned by CYPE in BIM format, incorporating inputs from both UNICAM and LIS. Using CYPE's software suite, the model was developed and subsequently exported as an IFC file, the industry-standard format for ensuring interoperability. This IFC file was then uploaded to the LIS Platform, where it is continuously enriched with additional data from project partners, along with real-time data from IoT devices installed in the building. This followed two prior integrations with UNIVPM. As Palazzo Fazzini is still undergoing renovation, an initial test was conducted at the with UNIVPM. The IoT devices, equipped with customized sensor modules, were selected based on specifications provided by both UNICAM and UNIVPM, ensuring alignment with the project's technical requirements.

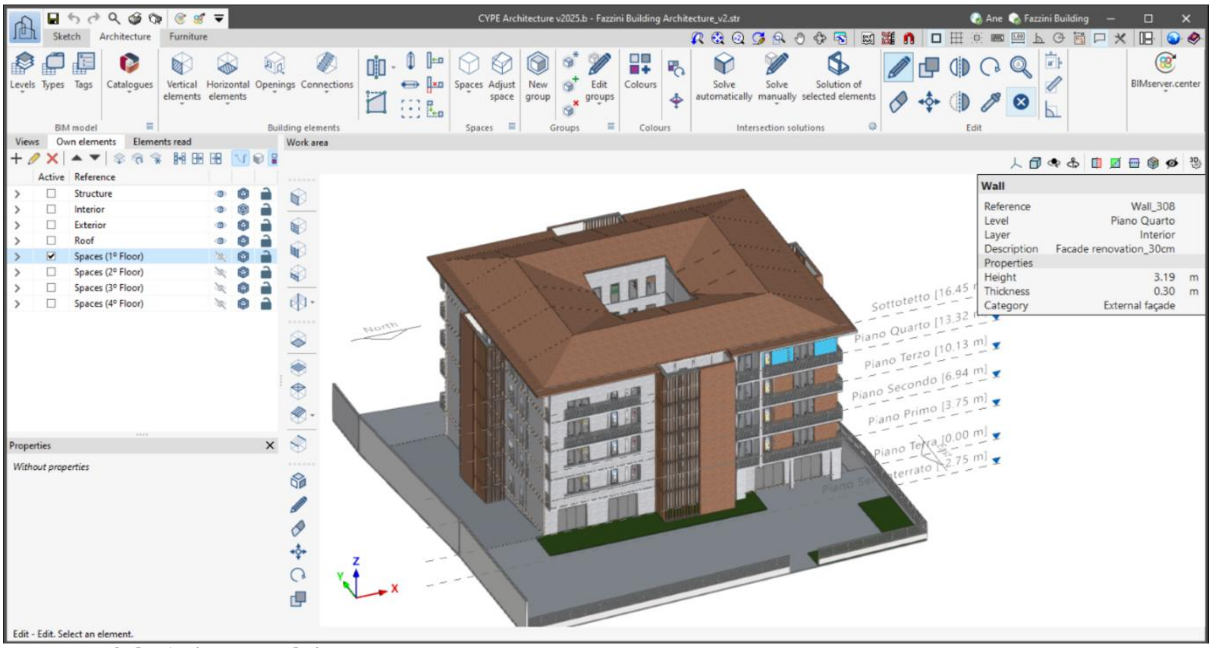


Figure 50. CYPE Architecture Palazzo Fazzini

Figure 51. Device and BIM Model Integration

Depending on user type, individuals can select the specific data they need from the building, such as information on various building elements and chronological events relevant to facility management.

Particular attention has been paid to security and safety features within the platform. Users can trigger an SOS alert, which will prompt an emergency page and allow immediate location tracking through their terminal or mobile phone signal. In cases where users wear devices compatible with the LIS-Platform, physiological data will be visible to caregivers or emergency teams, enhancing response efforts. The emergency alert functionality is further explained in 3.9.2, which details the LIS-Platform's features. Another critical function is the Early Warning System (EWS) developed within the LIS-Platform. This system automatically sends alerts to all users within or near the building in case of emergencies. A dedicated alert is also sent to emergency responders, and non-critical activities on the platform are suspended to ensure that only vital data is transmitted, preserving resources. During evacuation or catastrophic events, first responders will be guided to the exact locations of individuals who may be injured or trapped.

4.10.4. INTEGRATION WITH ENEA

The fourth integration was carried out with ENEA after their structural assessment of Palazzo Fazzini.

(a)

(b)

(c)

Figure 52. Images by Street View: (a) June 2022, (b) and (c) June 2019

Starting from the NDT methodology for damage assessment of reinforced concrete buildings after seismic events, tested on a shaking table (Denys Breysse et al. 2021b) , in the MULTICLIMACT project, ENEA is investigating the damage induced by seismic actions on Palazzo Fazzini, the Italian demo site, through an experimental NDT campaign (based on ultrasonic tomography and sonic techniques). The goal is to demonstrate the capability of these techniques to detect structural damage and provide an estimate of the building's health status, which can be integrated into BIM. The aim of these activities is to integrate the LIS-Platform monitoring system with structural and thermo-hygrometric data. Once received, the data is recorded in a centralized database, where it is processed and stored for further analysis. The web platform allows users to visualize data through BIM-based models.

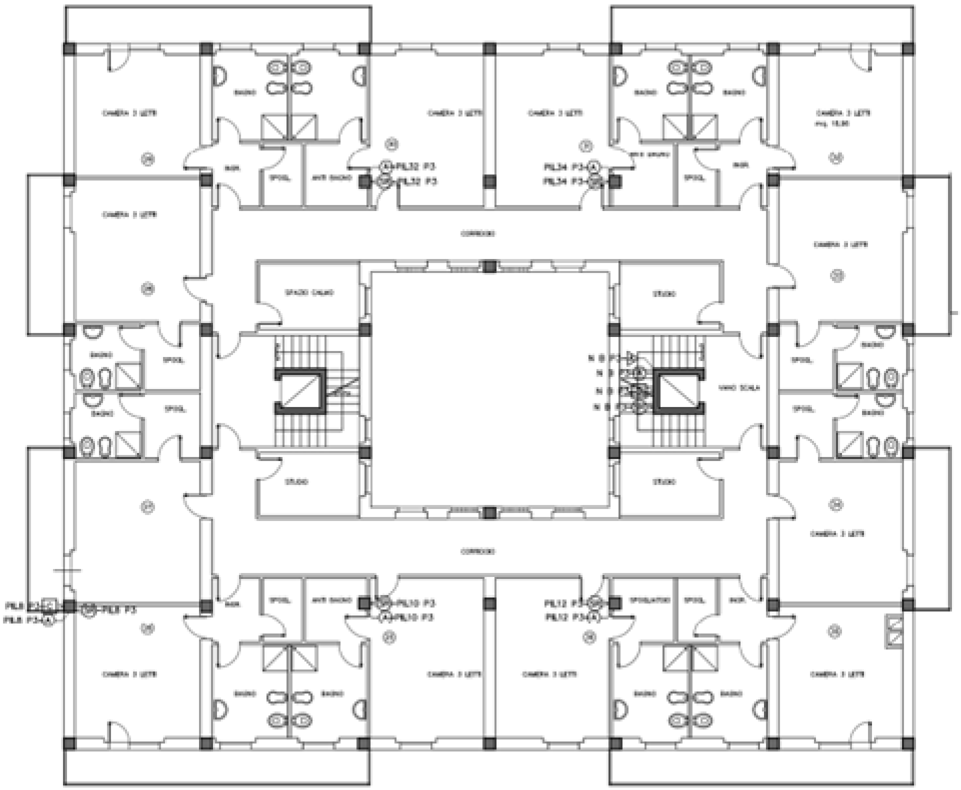


Figure 53. Floor type, condition of things

Figure 54. Ultrasonic test

The monitor displays the ultrasonic signal where at time 0 the transmitting probe generates the pulse that propagates inside the abutment and after a certain interval the probe on the opposite side receives the wave. The first part of the signal is null and is called propagation time then the signal increases in intensity the green vertical line determines the arrival time of the wave. The measurement is carried out continuously, usually once per second (Figure 55).

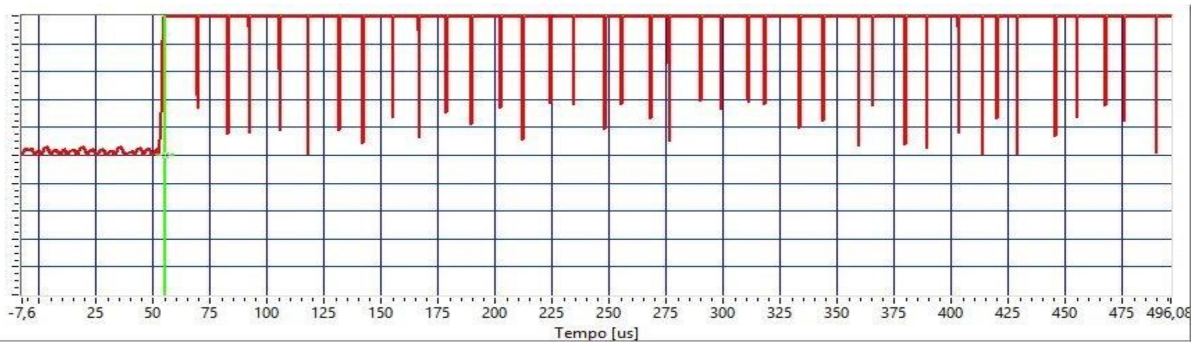


Figure 55. Digitalised ultrasonic signal

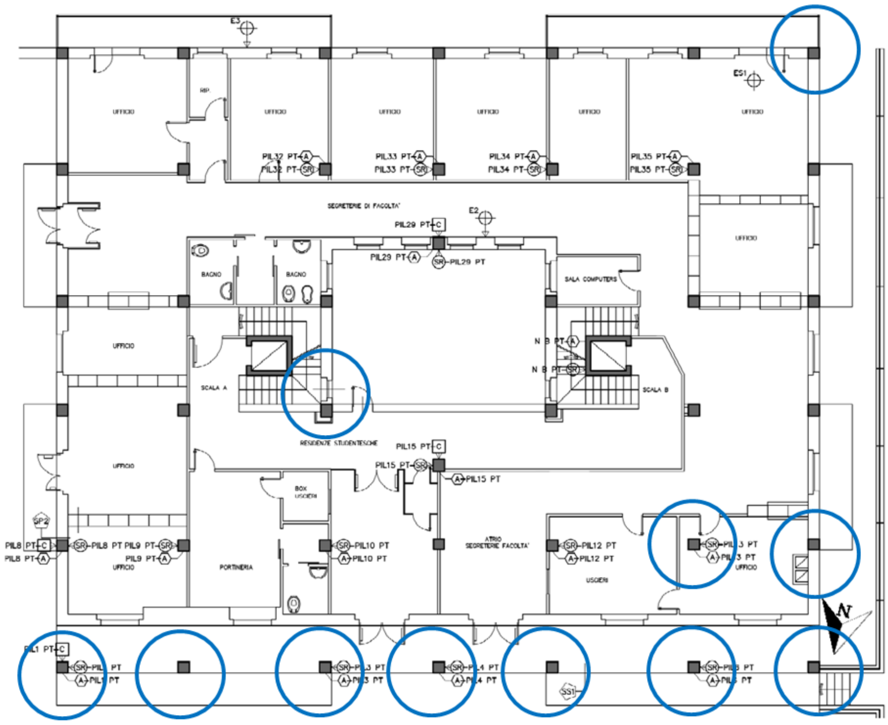


Figure 56. Location of columns that were tested

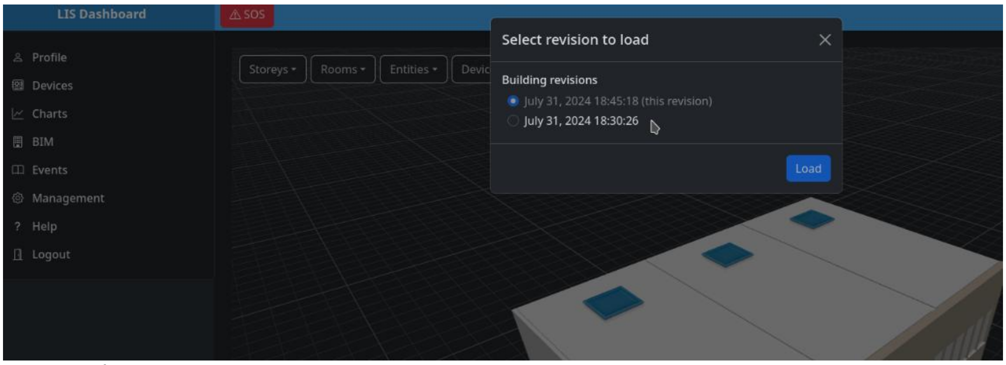


Figure 57. Version selection

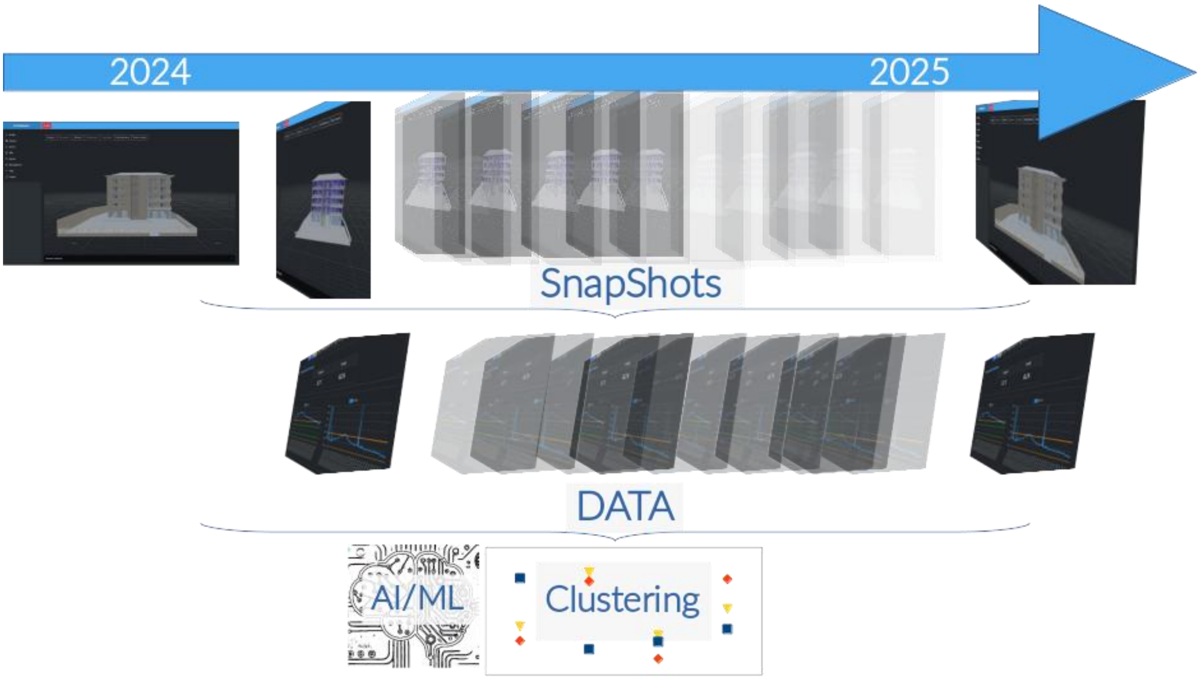


Figure 58. Historical Snapshots and Functionalities of the LIS

To enhance the visualization of these results, the LIS team implemented a specialized fork of the version for the building, enabling users to view the outcomes of the testing campaign directly within the web browser. These data are permanently embedded in the digital model uploaded to the LIS-Platform and remain accessible, even when downloaded and opened using standard BIM tools or IFC viewers.

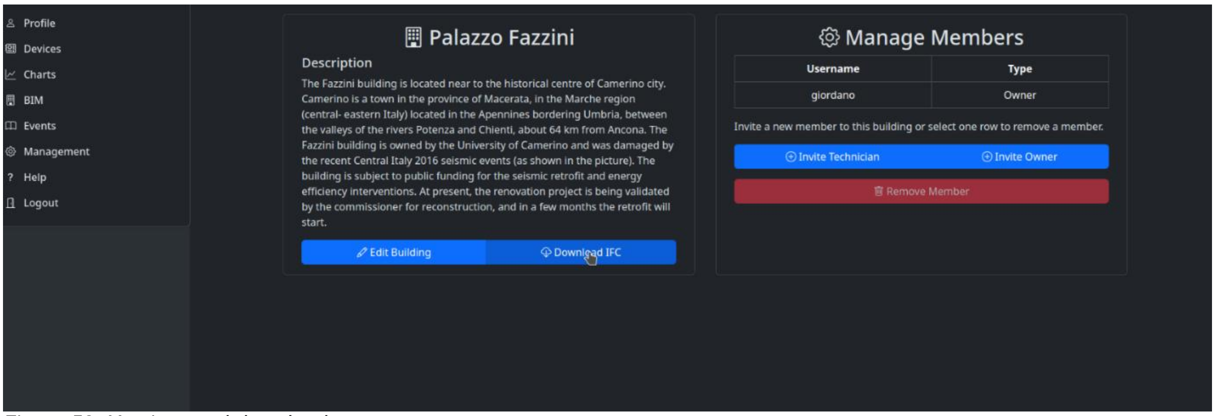


Figure 59. Versions and downloads

As shown in Figure 59, users can seamlessly navigate between different versions of the building, enabling them to examine results both before and after retrofitting. This dynamic functionality allows users and administrators to switch between versions, facilitating chronological evaluations of changes or selecting a specific version of interest. Additionally, users can explore various events within the LIS-Platform, which document changes in the physical structure. These events are generated either by users or through data collected from devices and sensors integrated into the building.

Figure 60. Column n. 13

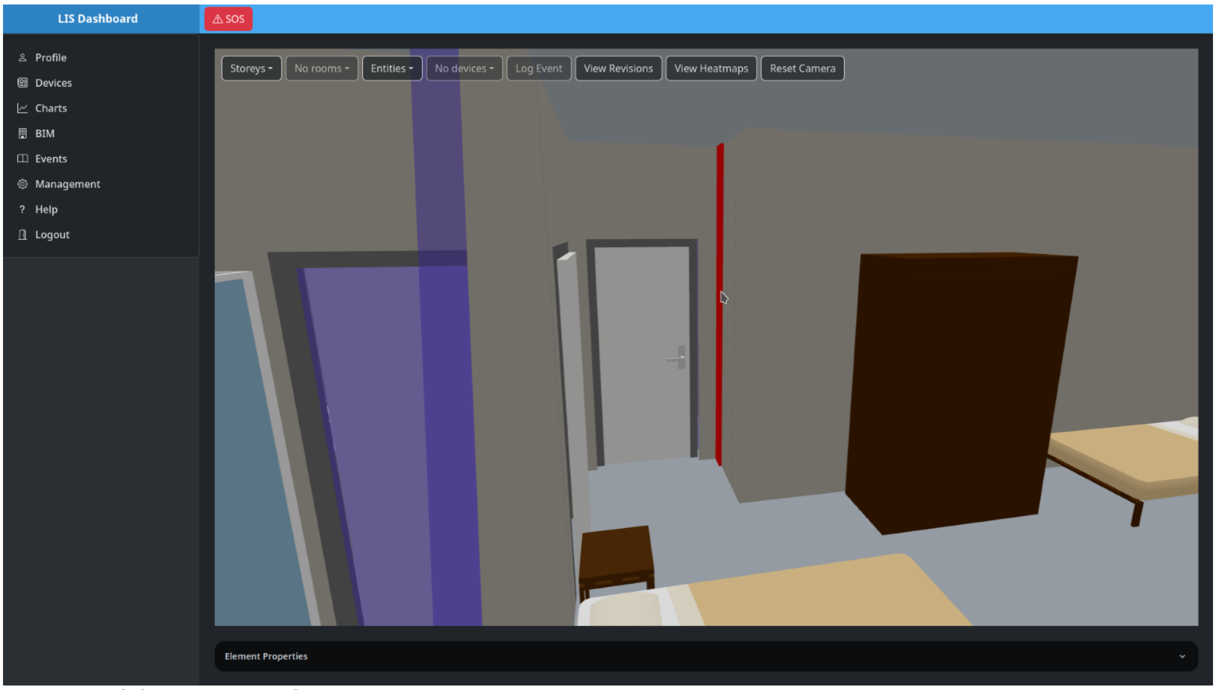


Figure 61. Column n. 13 in LIS

As destructive test and NDT data are uploaded to the LIS platform, the content will be permanently linked to the test object, ensuring that the data remains associated with the digital model indefinitely, even after downloading the IFC file. Column 13 is already selected, and the colour scheme indicates that there is data linked to the 3D representation

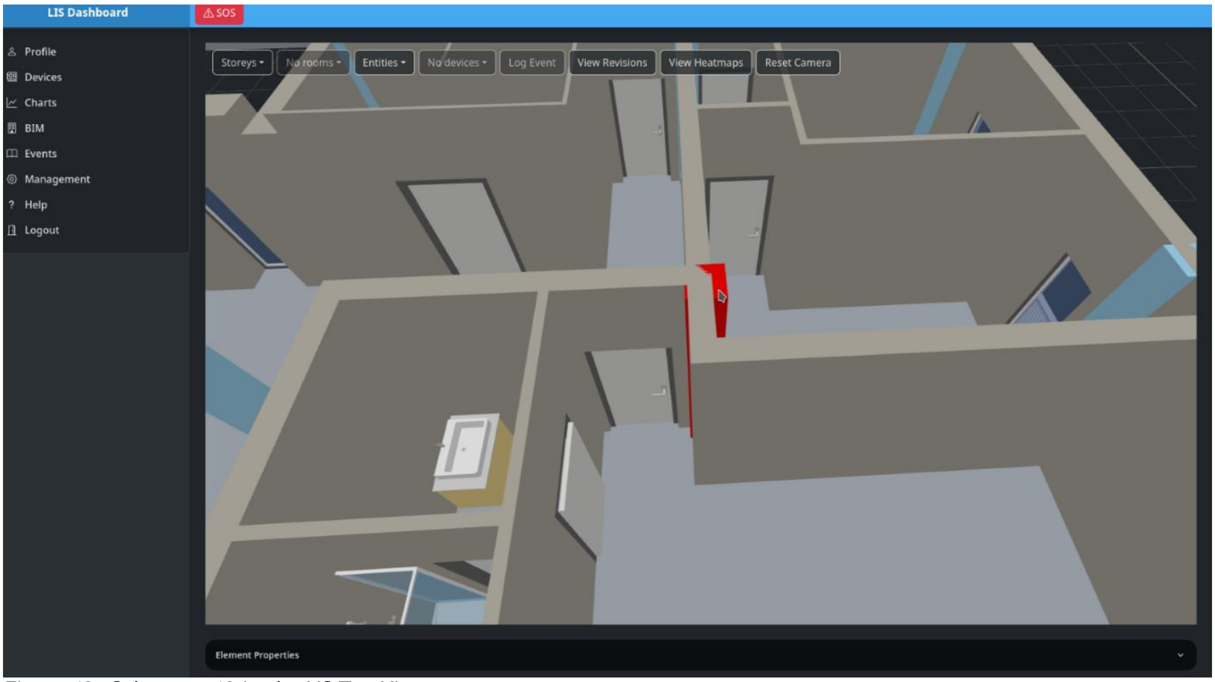


Figure 62. Column n. 13 in the LIS Top View

You can navigate within the 3D model (BIM) and hide objects near the object of interest, in this case, Column n. 13, to focus on the relevant data more clearly.

Figure 63. Column n. 13 in LIS selected

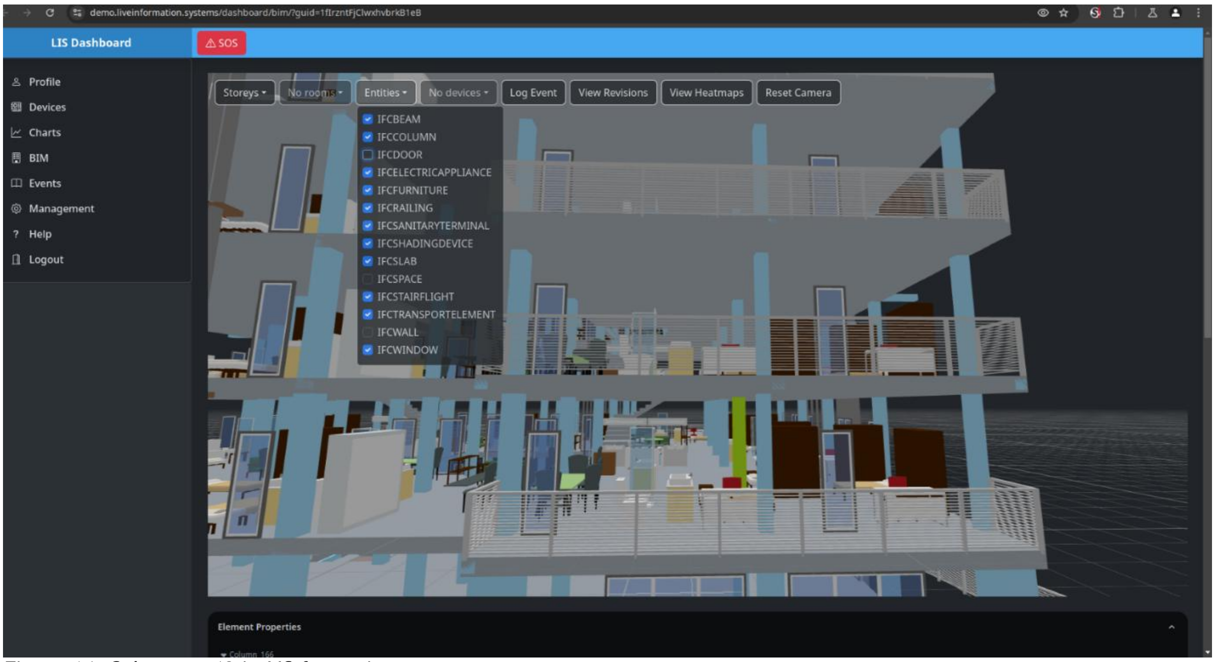


Figure 64. Column n. 13 in LIS front view

This image demonstrates how you can 'switch off' various elements in the digital model within the LIS platform, allowing you to focus specifically on the object of interest.

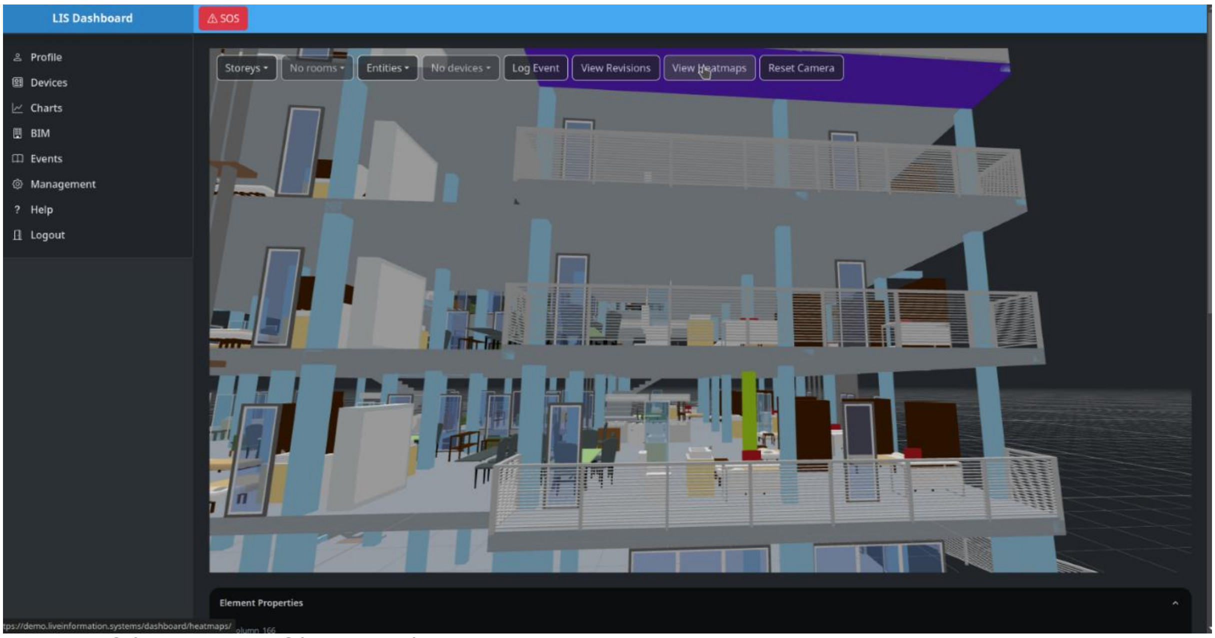


Figure 65. Column n. 13 in LIS heatmap selection

Different objects can have various methods applied to them. In this case, the object of interest, Column n. 13, has a specific method called 'view heatmaps.' As a result, we can expect to see a matrix or table format, enabling us to evaluate a heatmap of the associated values.

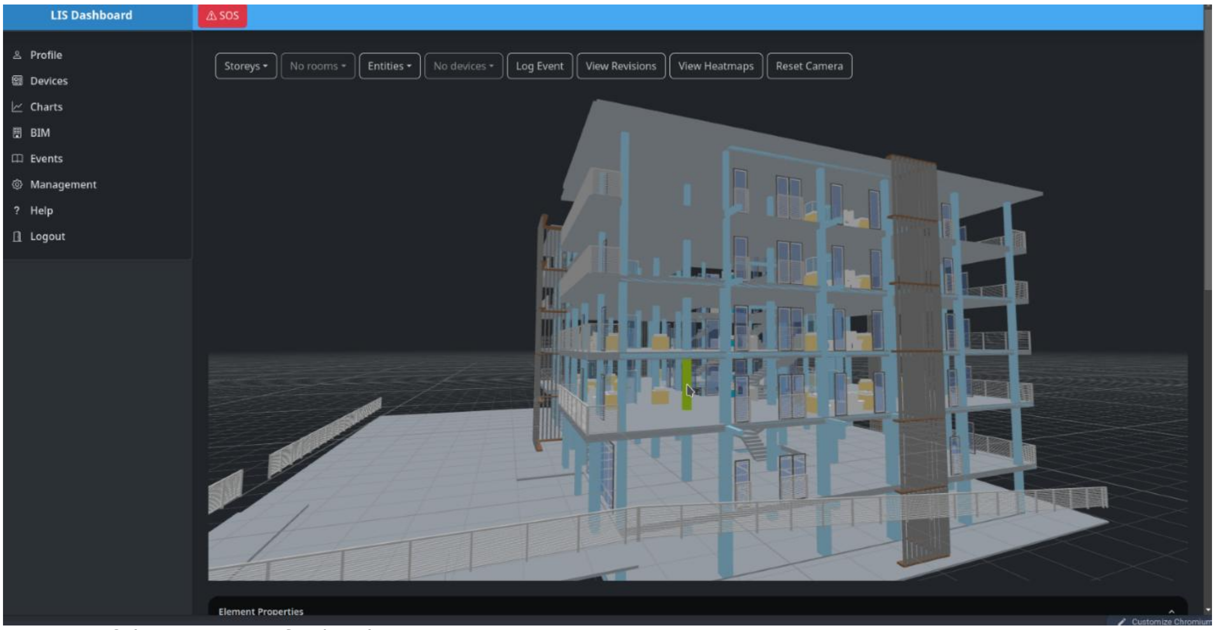
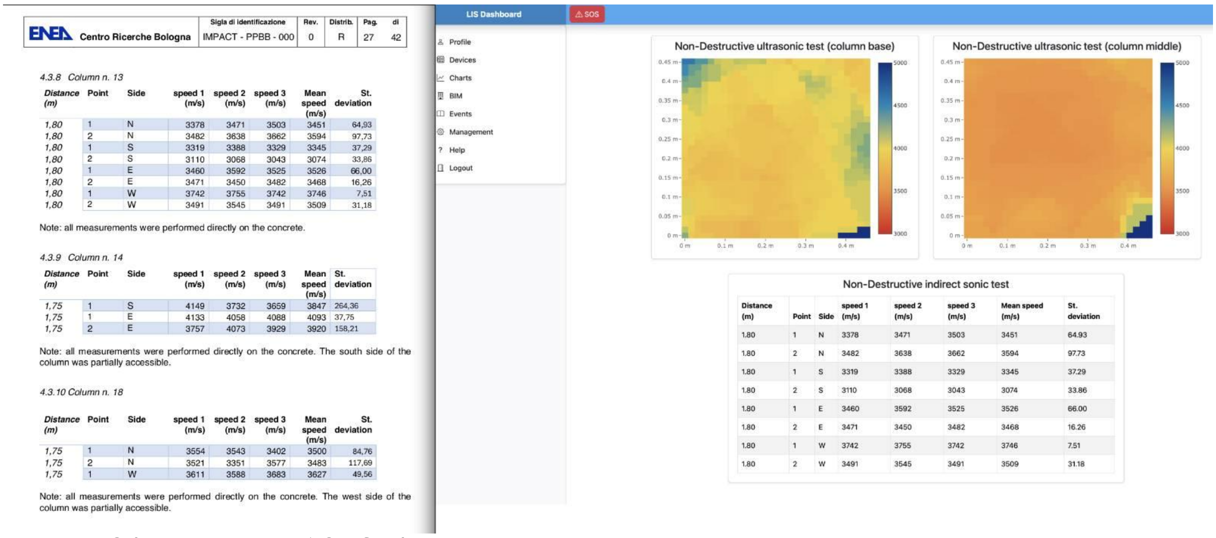


Figure 66. Column n. 13 in LIS side-selection



ENEA Centro Ricerche Bologna	Sigla di identificazione	Rev.	Distrib.	Pag.	di
	IMPACT - PPBB - 000	0	R	27	42

4.3.8 Column n. 13

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
1,80	1	N	3378	3471	3503	3451	64,93
1,80	2	N	3482	3638	3662	3594	97,73
1,80	1	S	3319	3388	3329	3345	37,29
1,80	2	S	3110	3068	3043	3074	33,86
1,80	1	E	3460	3592	3525	3526	66,00
1,80	2	E	3471	3450	3482	3468	16,26
1,80	1	W	3742	3755	3742	3746	7,51
1,80	2	W	3491	3545	3491	3509	31,18

Note: all measurements were performed directly on the concrete.

4.3.9 Column n. 14

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
1,75	1	S	4149	3732	3659	3847	264,36
1,75	1	E	4133	4058	4088	4093	37,75
1,75	2	E	3757	4073	3929	3920	158,21

Note: all measurements were performed directly on the concrete. The south side of the column was partially accessible.

4.3.10 Column n. 18

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
1,75	1	N	3554	3543	3402	3500	84,76
1,75	2	N	3521	3351	3577	3483	117,69
1,75	1	W	3611	3588	3683	3627	49,56

Note: all measurements were performed directly on the concrete. The west side of the column was partially accessible.

Non-Destructive indirect sonic test

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
1.80	1	N	3378	3471	3503	3451	64.93
1.80	2	N	3482	3638	3662	3594	97.73
1.80	1	S	3319	3388	3329	3345	37.29
1.80	2	S	3110	3068	3043	3074	33.86
1.80	1	E	3460	3592	3525	3526	66.00
1.80	2	E	3471	3450	3482	3468	16.26
1.80	1	W	3742	3755	3742	3746	7.51
1.80	2	W	3491	3545	3491	3509	31.18

Figure 67. Column n. 13 in ENEA & LIS values

Here, we can see a side-by-side comparison of the original data from the ENEA report and the heatmaps we created, which are linked to the specific object under study.

Thermographic analysis

The thermographic technique is a typically non-destructive investigation, due to its characteristic of analysing the thermal behaviour of the subjects under examination without using contact probes.

Through the analysis of thermograms it is possible to trace the state of degradation of the building structure and materials, highlighting the thermal differences between parts. Moreover, the thermal images allow the identification of the different building materials that constitute the structure (stones, bricks, mortar) and highlight the presence of beams, metal bodies, pipes, plugging. From these investigations, qualitative information is obtained about the analysed area and the extents of degradation (Figure 68, Figure 69).

Figure 68. North side - Via le mosse - Entrance

Co-funded by the European Union

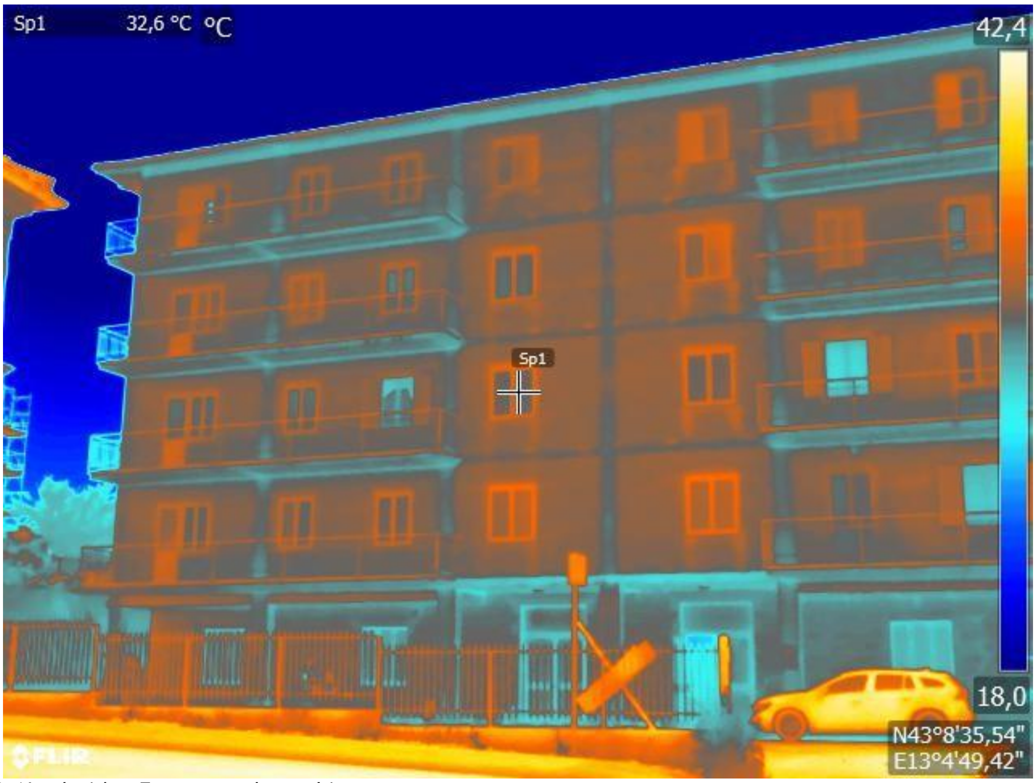


Figure 69. North side - Entrance - thermal images

Conclusion of the NDT campaign

This approach is particularly important in cases such as Palazzo Fazzini, where the NDT data and earlier reports correspond to the building's previous physical state, enabling users to make informed comparisons across different stages of the assessment. The main structural information related to the actual state of the building have been taken from reports released by University of Camerino (UNICAM). They consist of an experimental test campaign, including a complete geometric survey and the mechanical characterization of materials, as well as on the structural analyses and on the seismic retrofitting of the building. Based on these evaluations, in situ non-destructive tests were planned and carried out also by ENEA. They consisted of pacometric, direct ultrasonic, tomographic reconstruction and sound tests aimed at testing the effectiveness and feasibility of implementing the methodology for damage assessment of reinforced concrete buildings, after seismic events, already experimented through shaking table in ENEA Lab.

Data integrity and version control

To ensure the integrity of version control, we recommend clearly labelling different versions rather than overwriting existing ones. As will be discussed in future chapters, we have also implemented an integrity layer, and a proof of concept (PoC) for Distributed Ledger Technology (DLT) has been evaluated to ensure that changes and "transactions" within the building and between stakeholders are permanent and immutable.

Promoting at CIW

Following the deployment of the LIS-Platform with these features, the next phase focuses on stakeholder engagement. A preliminary list of stakeholders was drafted by LIS for BRC, and from this point, BRC will work to upload the MULTICLIMACT digital solutions, including LIS, onto the CIW platform. The engagement plan, tailored specifically for the MULTICLIMACT project by BRC, outlines how feedback from stakeholders will be integrated during subsequent project phases, ensuring continuous improvement and relevance.

Co-funded by the European Union

5. DEVIATIONS TO THE PLAN

No deviations from the plan occurred.

6. OUTPUTS FOR OTHER TASKS IN WP4 AND OTHER WPS

6.1. INTERDEPENDENCIES WITH OTHER WP4 TASKS

WP4	DESCRIPTION	INPUT DATA	PARTNER	OUTPUT DATA	PARTNER
T4.3	Design of a digital solution for climate-proof characterization of thermal and energy solutions	Plans for development of BIM models	COMSA, REA	Energy simulation	CYPE
T4.6	Design of a common, high-level standardized architecture for MULTICLIMAT digital solutions.	UrbanDataset	ENEA	UrbanDataset	CYPE
T4.6	Design of a common, high-level standardized architecture for MULTICLIMAT digital solutions.	UrbanDataset: Microclimate Monitoring &Health Monitoring	LIS	UrbanDataset	ENEA

6.2. INTERDEPENDENCIES WITH OTHER WPS AND TASKS:

WPX	DESCRIPTION	INPUT DATA	PARTNER (SRC)	OUTPUT DATA	PARTNER (DST)
T1.1	MULTICLIMACT resilience scorecard method	Scorecard	ICLEI	Human/ well-being resilience aspects in buildings	UKA
T1.2	MULTICLIMAT Toolkit assessment framework.	n.d	CYPE	n.d	n.d
T3.3	Multifunctional mortars development	innovative nature-based material	UNIVPM	Palazzo Fazzini Room renovation	UNICAM
T2.4	Description of CIW-Innovators	CIW Information	BRC	excising Innovators	BRC
T2.5	Description and expertise for extreme weathers events definitions	Information of extreme weathers	BRC	CIW	BRC

T8.5	Environmental data from sensors + Subjective data from questionnaires	Sensor type + survey	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	ENEA	GRAPHs (time series)	UNIVPM
T10.2	Subjective and objective measures	Sensor type + survey	LIS	Data analysis platform	UKA
T11.1	Environmental and physiological data from sensors	Sensor type, data type	UNIVPM	Raw data (time series) to be processed to enrich BIM	UNIVPM, LIS
T11.1 UKA	Test of the MULTICLIMACT solutions, exploiting the monitoring protocol and systems	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

Co-funded by the European Union

7. LITERATURE /REFERENCES

Alderson, David, and John Doyle. 2010. “Contrasting Views of Complexity and Their Implications For Network-Centric Infrastructures.” *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans* 40 (4): 793–803. https://doi.org/10.1109/TSMCA.2010.2048027.

Altomonte, S, S Kaçel, P W Martinez, and D Licina. 2024. “What Is NExT? A New Conceptual Model for Comfort, Satisfaction, Health, and Well-Being in Buildings.” *Building and Environment*.

Angelone, S, E Palmieri, and B Rama. 2024. “MULTICLIMACT Resilience Scorecard Method.”

Atzori, Luigi, Antonio Iera, and Giacomo Morabito. 2010. “The Internet of Things: A Survey.” *Computer Networks* 54 (15): 2787–2805. https://doi.org/10.1016/j.comnet.2010.05.010.

Barabási, A.-L. 2002. *Linked: The New Science of Networks*. Cambridge, MA: Perseus Publishing.

Barabási, Albert-Laszlo. 2009. “Scale-Free Networks: A Decade and Beyond.” *Science* 325 (5939): 412–13. https://doi.org/10.1126/science.1173299.

Betley, E C, A Sigouin, P Pascua, S H Cheng, K I MacDonald, F Arengo, Y Aumeeruddy-Thomas, S Caillon, M E Isaac, and S D Jupiter. 2023. “Assessing Human Well-Being Constructs with Environmental and Equity Aspects: A Review of the Landscape.” *People and Nature* 5:1756–73.

Boutahri, Y, and A Tilioua. 2024. “Machine Learning-Based Predictive Model for Thermal Comfort and Energy Optimization in Smart Buildings.” *Results in Engineering* 22:102148.

Breysse, D, J.-P. Balayssac, S Biondi, D Corbett, A Goncalves, M Grantham, V A M Luprano, A Masi, A V Monteiro, and Z M Sbartai. 2019. “Recommendation of RILEM TC249-ISC on Non-Destructive in Situ Strength Assessment of Concrete.” *Materials and Structures/Materiaux et Constructions* 52.

Breysse, Denys, Jean-Paul Balayssac, Maitham Alwash, Samuele Biondi, Leonardo Chiauzzi, David Corbett, Vincent Garnier, et al. 2021a. “In-Situ Strength Assessment of Concrete: Detailed Guidelines.” In *Non-Destructive In Situ Strength Assessment of Concrete, Practical Application of the RILEM TC 249-ISC Recommendations*, 3–56. https://doi.org/10.1007/978-3-030-64900-5_1.

Caballero, Amaury, and Kang Yen. 2003. “The Use of Micro-Electro-Mechanical Systems (MEMS) in the Construction Industry.” In *Proceedings of the 20th International Symposium on Automation and Robotics in Construction (ISARC 2003)*, 73–78. https://doi.org/10.22260/ISARC2003/0030.

Cassandras, C G, and Stephane Lafortune. 2010. *Introduction to Discrete Event Systems*. 2nd ed. New York: Springer. https://doi.org/10.1007/978-0-387-68612-7.

Cho, S, H J Nam, C Shi, C Y Kim, S H Byun, K C Agno, and J W Jeong. 2023. “Wireless, AI-Enabled Wearable Thermal Comfort Sensor for Energy-Efficient, Human-in-the-Loop Control of Indoor Temperature.” *Biosensors and Bioelectronics* 223:115018.

Christoforou, R, S Lange, and M Schweiker. 2024. “Individual Differences in the Definitions of Health and Well-Being and the Underlying Promotional Effect of the Built Environment.” *Journal of Building Engineering* 84:108560. https://doi.org/10.1016/J.JOBE.2024.108560.

Cosoli, G, and others. 2024. “Measuring the Occupants’ Well-Being in the Built Environment: Towards the Integration of Physiological and Environmental Parameters in a Multidomain BIM-Based Platform.” In *2024 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv)*, 454–59. Chania, Greece. https://doi.org/10.1109/MetroLivEnv60384.2024.10615597.

Cosoli, Gloria, Silvia Angela Mansi, Ilaria Pigliautile, Anna Laura Pisello, Gian Marco Revel, and Marco Arnesano. 2023. “Enhancing Personal Comfort: A Machine Learning Approach Using Physiological and Environmental Signals Measurements.” *Measurement* 217 (August):113047. https://doi.org/10.1016/j.measurement.2023.113047.

Crawford, J R, and J D Henry. 2004. “The Positive and Negative Affect Schedule (PANAS): Construct Validity, Measurement Properties and Normative Data in a Large Non-Clinical Sample.” *British Journal of Clinical Psychology* 43:245–65. https://doi.org/10.1348/0144665031752934.

European Blockchain Services Infrastructure. n.d. “Digital Building Blocks Project.” https://ec.europa.eu/digital-building-blocks/sites/display/EBSI/Home.

European Commission. 2021. “Digitalisation in the Construction Sector.” Brussels. https://ec.europa.eu/infocentre/digital-building-blocks/en.

“Fiat Chrysler Recall Jeep Hacking.” 2015. *The Guardian*. https://www.theguardian.com/business/2015/jul/24/fiat-chrysler-recall-jeep-hacking.

Gioiella, L, F Micozzi, L Ragni, and A Dall’Asta. 2023. “Building Back Better: The Case Study of the Fazzini College.” In *COMPDYN 2023 9th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering*. Athens, Greece.

Gioiella, L, F Micozzi, L Ragni, L Graziano, and A Dall’Asta. 2024. “A 3 Element Model for the Damage Controlled Design: The Case Study of the Fazzini College.” In *18th World Conference on Earthquake Engineering*. Milan, Italy.

Gioiella, L, E Tubaldi, F Gara, L Dezi, and A Dall’Asta. 2018. “Stochastic Seismic Analysis and Comparison of Alternative External Dissipative Systems.” *Shock and Vibration* 2018. https://doi.org/10.1155/2018/5403737.

Gioiella, L, E Tubaldi, L Ragni, F Gara, and A Dall’Asta. 2019. “The Seismic Retrofit by External Dissipative Systems: A Case Study.” In *Proceedings of the 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN2019)*. Crete, Greece. https://doi.org/10.7712/120119.7154.19270.

Glaessgen, Edward H, and Doane Stargel. 2012. “The Digital Twin Paradigm for Future NASA and U.S. Air Force Vehicles.” In *Proceedings of the 53rd AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference*. https://doi.org/10.2514/6.2012-1818.

Guckenheimer, J, and J Ottino. 2008. “Foundations for Complex Systems Research in the Physical Sciences and Engineering.” https://www.nsf.gov/pubs/reports/complexsystems.pdf.

Harvey, Danny. 2010. *Energy and the New Reality 1*. New York: Routledge. https://doi.org/10.4324/9781849774918.

Internet Society (ISOC). 2015. “The Internet of Things: An Overview.” Reston, VA. *https://www.internetsociety.org/resources/doc/2015/iot-overview*.

Lewis, M. 2004. “Integrated Design for Sustainable Buildings.” *Building for the Future, A Supplement to ASHRAE Journals* 46 (9): 22–30.

Mancini, Adriano, Gloria Cosoli, Alessandra Mobili, Luca Violini, Giuseppe Pandarese, Alessandro Galdelli, Gagan Narang, Elisa Blasi, Francesca Tittarelli, and Gian Marco Revel. 2024. “A Monitoring Platform Based on Electrical Impedance and AI Techniques to Enhance the Resilience of the Built Environment.” Acta IMEKO 13 (3): 1–12. https://doi.org/10.21014/actaimeko.v13i3.1722.

National Institute of Standards and Technology. 2024. “The NIST Cybersecurity Framework (CSF) 2.0.” https://doi.org/10.6028/NIST.CSWP.29.

National Institute of Standards, and Technology (NIST). 2020a. “Special Publication 1900-202: Global Community Technology Challenge (GCTC).” Gaithersburg, MD. https://doi.org/10.6028/NIST.SP.1900-202.

National Institute of Standards, and Technology (NIST). 2020b. “Special Publication 1900-207: Global Community Technology Challenge (GCTC).” Gaithersburg, MD. https://doi.org/10.6028/NIST.SP.1900-207.

Nicolis, Gregoire, and Catherine Nicolis. 2007. *Foundations of Complex Systems: Nonlinear Dynamics, Statistical Physics, Information and Prediction*. 1st ed. Berlin: Springer. https://doi.org/10.1007/978-3-540-33929-2.

O’Reilly, Patrick, and Kristina Rigopoulos. 2024. “Fiscal Year 2023 Cybersecurity and Privacy Annual Report.” https://doi.org/10.6028/NIST.SP.800-229.

Polimeno, M R, I Roselli, V A M Luprano, M Mongelli, A Tatì, and G De Canio. 2018. “A Non-Destructive Testing Methodology for Damage Assessment of Reinforced Concrete Buildings after Seismic Events.” *Engineering Structures*. https://doi.org/10.1016/j.engstruct.2018.02.053.

“Relazione Delle Indagini e Sulla Caratterizzazione Meccanica Dei Materiali.” 2021.

"Relazione Di Calcolo, Vulnerabilità, Miglioramento Relazione Geotecnica." 2023.

Seferi, and others. 2019. "Vulnerabilities and Attacks in a Smart Buildings Scenario." In *2019 IEEE 23rd International Symposium on Consumer Technologies (ISCT)*, 296–98. IEEE. https://doi.org/10.1109/ISCE.2019.8901044.

Serrano, M, E Griffor, D Wollman, M Dunaway, M Burns, S Rhee, and C Greer. 2022. "Smart Cities and Communities: A Key Performance Indicators Framework." Gaithersburg, MD. https://doi.org/10.6028/NIST.SP.1900-206.

Taheri, Shima. 2023. "A Review on Five Key Sensors for Monitoring of Concrete Structures." *Journal of Sensors*. https://doi.org/10.3390/s230101011.

Tao, Fei, Fangyuan Sui, Ang Liu, Qinglin Qi, Meng Zhang, Boyang Song, Zirong Guo, Stephen Lu, and Andrew Nee. 2018. "Digital Twin-Driven Product Design Framework." *International Journal of Production Research* 57 (12): 1–19. https://doi.org/10.1080/00207543.2018.1443229.

Turnbull, L, M T Hütt, A A Ioannides, and others. 2018. "Connectivity and Complex Systems: Learning from a Multi-Disciplinary Perspective." *Applied Network Science* 3 (11). https://doi.org/10.1007/s41109-018-0067-2.

United Nations, Department of Economic, and Population Division Social Affairs. 2019. *World Urbanization Prospects: The 2018 Revision*. New York: United Nations. https://population.un.org/wup/Publications/.

U.S. Environmental Protection Agency. 1989. "Report to Congress on Indoor Air Quality: Volume 2." Washington, DC. https://nepis.epa.gov/Exe/ZyPDF.cgi/9100TO51.PDF?Dockey=9100TO51.PDF.

Zelenkauskaite, A, N Bessis, S Sotiriadis, and E Asimakopoulou. 2012. "Interconnectedness of Complex Systems of Internet of Things through Social Network Analysis for Disaster Management." In *2012 Fourth International Conference on Intelligent Networking and Collaborative Systems*, 503–8. Bucharest, Romania. https://doi.org/10.1109/iNCoS.2012.25.

8. ANNEX

8.1. ANNEX LIS-PLATFORM

The LIS-Platform delivers advanced structural health monitoring (SHM) and offers critical insights into occupants' well-being through both physiological and environmental measurements. The platform also includes emergency management features, such as a Push Notification Service (PNS) for early warnings, an emergency protocol system, and a data analysis platform for monitoring energy efficiency and structural integrity. A Proof-of-Concept (PoC) is underway to explore the use of blockchain technology (DLT) to ensure data integrity, and a mobile app is being developed using the Flutter framework. The IoT infrastructure, referred to as LIS-Network, operates similarly to a Wireless Sensor Network (WSN) in the context of edge computing. While incorporating AI-on-the-edge capabilities, the primary focus is not on advancing specific AI paradigms or edge computing technologies but rather on the practical objective of creating a "live" building—a dynamic, self-monitoring system that adapts, responds in real-time, and demonstrates resilience for the future.

8.2. ANNEX – RISK MITIGATION STRATEGY

	Risk	Origin	Mitigation strategy
M1	Misconfiguration or Architectural (network) Errors	The use of multiple sensor nodes and devices introduces a risk of misconfiguration or architectural errors.	Select hardware including the Gateway capable of multi connections. Documentation: Maintain detailed documentation of network configurations. Regular Audits: Conduct frequent audits to identify and rectify errors. Automation: using automated tools (like Ansible) to provision and configure infrastructure reduces the risk of human error and simplifies management.
M2	Heterogeneous elements causing connection issues may prevent achieving full interoperability	The presence of highly heterogeneous elements in the system may lead to connectivity /interoperability challenges.	Change the affected libraries. Interoperability Protocols: Establish standardized communication protocols. Communication Standards: Implement standardized communication protocols.
M3	Problems with one or more libraries	The risk involves encountering issues or problems with one or more libraries used within the system, such as bugs in one or more libraries, deprecated elements, or defunct projects.	Make the implementation more efficient or change libraries Regular Audits: Conduct frequent library audits. Update Management: Systematic approach to update and patch management. Thorough Testing: Develop comprehensive testing protocols. Write down the SBOM (software bill of materials) and take steps to reduce the number of dependencies
M4	Inefficient notification system due to transient network errors, mishandling on the receiving side.	Use of wrong tools to implement it, or inefficient implementation	Sticking to well-maintained implementation leveraging operating system capabilities as much as possible.
M5	Problems with internships	Internships not suitable for this project	Ensuring best practices for secure access management and tailoring your approach to the specific needs and risks of your web app and IoT platform. Maintaining robust security.
M6	Problems with access management.	Users can access unauthorized data. Misconfiguration in the enforcement of access rights	Fail-closed authorization where unclear/invalid roles are forbidden to access data. Comprehensive audit.

Co-funded by the European Union

		processes	
M7	Data integrity can be compromised	Manipulating databases, insufficient logging, detection, monitoring and active response. Third party integration, Lack of encryption, Vulnerable Application layer.	Ensure up-to-date, encrypted and verifiable backups, test restore capabilities, implement redundancy, and maintain continuous monitoring to safeguard data accessibility. Prevent unauthorized tampering or corruption of data. Ensure a secure and tamper-resistant way to store data that cannot be altered once recorded. (alt DLT).
M8	Failed to ensure data availability, presence of latency and incompatible response times	Misconfiguration of the prevention system and the absence of automatic failover.	Prefer use of servers geographically closer to the nodes infrastructure and use load balancers to distribute load and provide failover.

Table 9. Risk Mitigation Strategy

8.3. ANNEX UNIVPM

Detailed data were collected from students who wear wearable biosensors that monitor health indicators like heart rate, oxygen level SpO2, skin temperature and movement/acceleration. At the same time, we were using indoor environmental sensors to gather information on factors such as temperature, humidity, air quality, and lighting within the building. The ethics committee has thoroughly reviewed and approved the process of testing and monitoring the students' biometric data and the environmental data within the LIS office. This approval ensures that all ethical standards and privacy concerns are properly addressed during the data collection and analysis.

8.4. ANNEX - ENEA

In recent years, innovative Non-Destructive Testing (NDT) techniques, applicable for the assessment of existing civil structures, have become available for in-situ analysis on Reinforced Concrete (RC) and masonry structures, but they are still not established for regular inspections, especially after seismic events. The damage assessment of RC buildings after seismic events is a very relevant issue in Italy, where most of the constructions built in the last 50 years are RC structures. Furthermore, there is also a growing interest in being able to monitor structural health aspects by storing them on the building's digital twin. For these reasons it is necessary to develop an affordable and ready-to-use NDT procedure that is able to provide more accurate indications on the real state of damage of reinforced concrete buildings also after seismic events.

For the structural assessment of existing concrete structures, it is important to know the strength of different elements. Assessment of the compressive strength of structures can be done by (i) destructive coring tests in varying amounts and (ii) calibrated indirect methods, combining destructive coring with non- or semi-destructive techniques. It is worth noting that the RILEM TC 249-ISC [1,2] has recently published some Recommendations on NDT in situ strength assessment of concrete introducing a new methodology to reduce the errors in the technical assessment following the UNI EN 13791:2019 standard [3]. The RILEM methodology is easy to apply and can give results (mean strength estimates, local strength estimates) equivalent or more accurate than those provided by previous approaches; mostly can save a significant number of destructive testing (which are mandatory anyway), through the conditional coring option, without any additional cost. Furthermore, it is important also to formulate a feasible procedure for inspection on-field to check and monitoring buildings subjected to seismic events.

Starting from the NDT methodology for damage assessment of reinforced concrete buildings after seismic events tested on shaking table [4], in the project MULTICLIMACT, ENEA is investigating the damage induced by the seismic actions on Palazzo Fazzini, Italian Demo site, by means of an experimental NDT campaign (based on ultrasonic tomography and sonic techniques) to demonstrate the capability of these techniques to detect structural damage and provide an estimation of the state of the building's health, information that can be integrated into BIM.

The purpose of the activities is the integration of the LIS Platform monitoring system with structural and thermo-hygrometric data. Upon receipt, the data is recorded in a centralized database, where it is processed and stored for further analysis. The web platform allows users to visualize data through BIM-based representations at the level of single column and single wall. This visualization capability is critical for

understanding building structural behavior and indoor environment's dynamics. The goal is to provide useful information to the stakeholders, generally the public entities devoted to guarantee the safety condition of the territory against natural risks and enhance comfort and well-being (e.g. Civil Protection, Municipalities, building managers).

2 Non-destructive investigations plan

The “Palazzo Fazzini” is in Camerino, along Le Mosse Street. It was built between 1970 and 1975 and its original intended use was as residential building or hotel. Later, it has been home to the ERSU housing and to the Civil Protection territorial presence until October 2016 when, due to the well-known seismic events of 26th and 30th, it was damaged and declared unusable. In Figure 1 some recent images of the building by Street View.

(a)

(b)

Street View: (a) June 2022, (b) and (c) June 2019

Since the original project documentation is not available, the main structural information related to the actual state of the building, summarised in this paragraph, have been taken from reports released by University of Camerino (UNICAM). These reports contain the activities commissioned by UNICAM. They consist on an experimental test campaign, including a complete geometric survey and the mechanical characterization of materials, as well as on the structural analyses and on the seismic retrofitting of the building [1-2]. The building has a rectangular plan with sides of 30.18mx25m and an internal courtyard of 8.35mx8.35m (Figure 2). There is an underground floor, five floors above ground and an attic room for maintenance. The total height of the building is 21m, from the base to the peak of the pavilion covering.

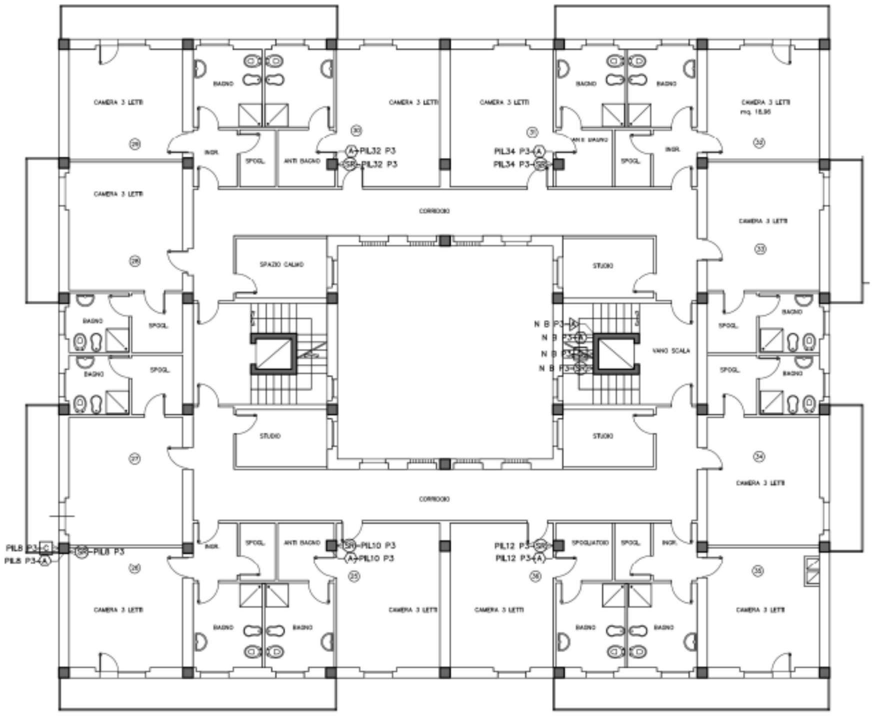
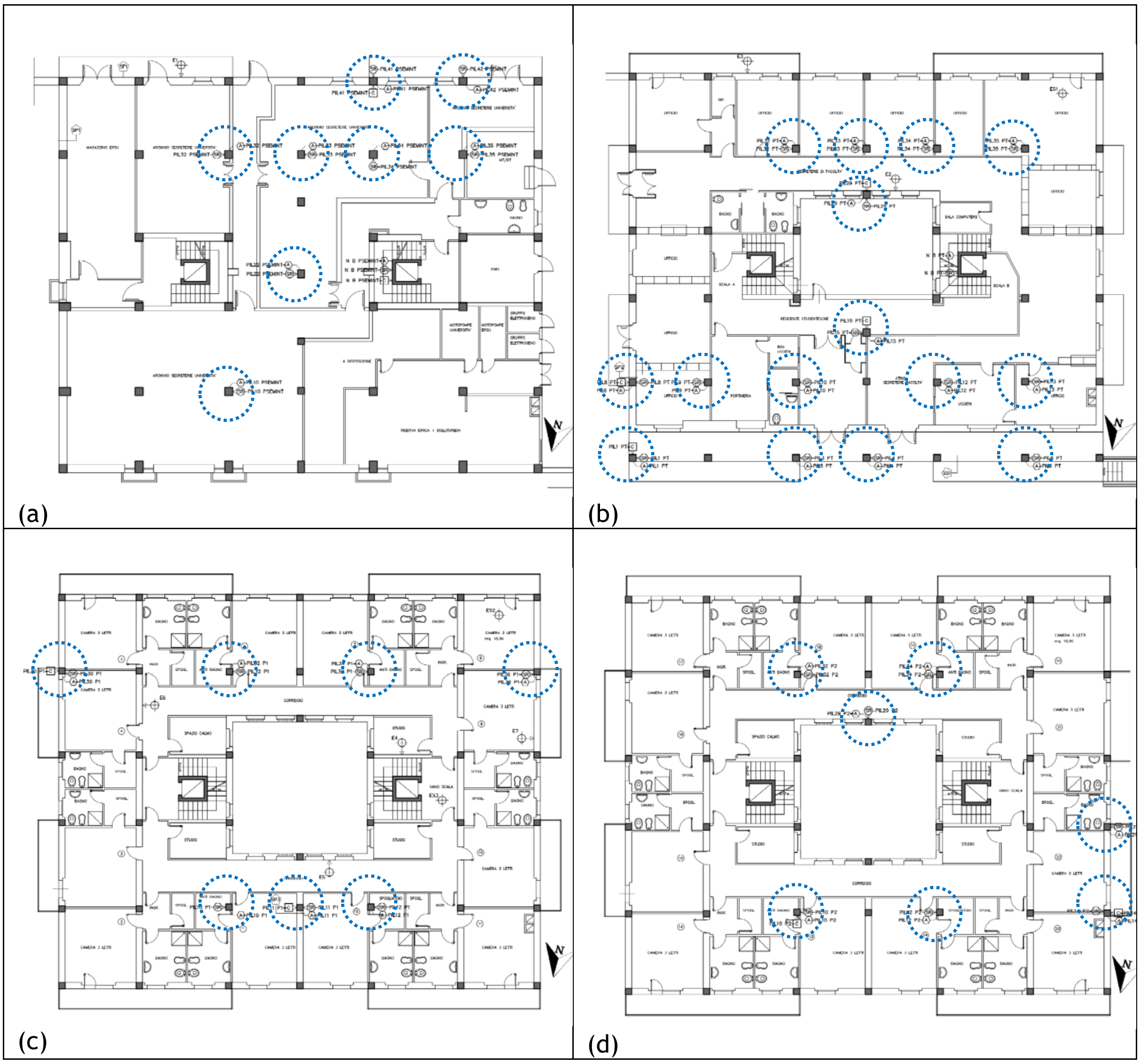


Figure 70: Floor type, condition of things

The structure is made of reinforced concrete, with columns cast-in-place and REP type (partially prefabricated) beams only directed in the direction orthogonal respect to the main façade. Floors are cement type with unreinforced slab. Two stairwells are symmetrically positioned, with respect to a line orthogonal to the main façade, and they are positioned next to the sides that surround the internal courtyard. Stairs reinforced concrete slabs are cast in place directly on the external infill walls and no structural connections act between them and the two corresponding elevator cores. Superficial foundations are made of plinths, connected each other only along frames direction, and of rafts below each of the elevator cores.

For the mechanical characterization of concrete, the experimental test campaign commissioned by UNICAM integrated Destructive Tests (DT) on 14 samples with Non-Destructive ones (NDT), sclerometric and ultrasonic type, homogeneously diffused in the building as shown in Figure 71, where columns tested (at their mid-height) are highlighted with a dotted circle. Please refer to the Report on the survey and on the mechanical characterization of the materials [1] for details.



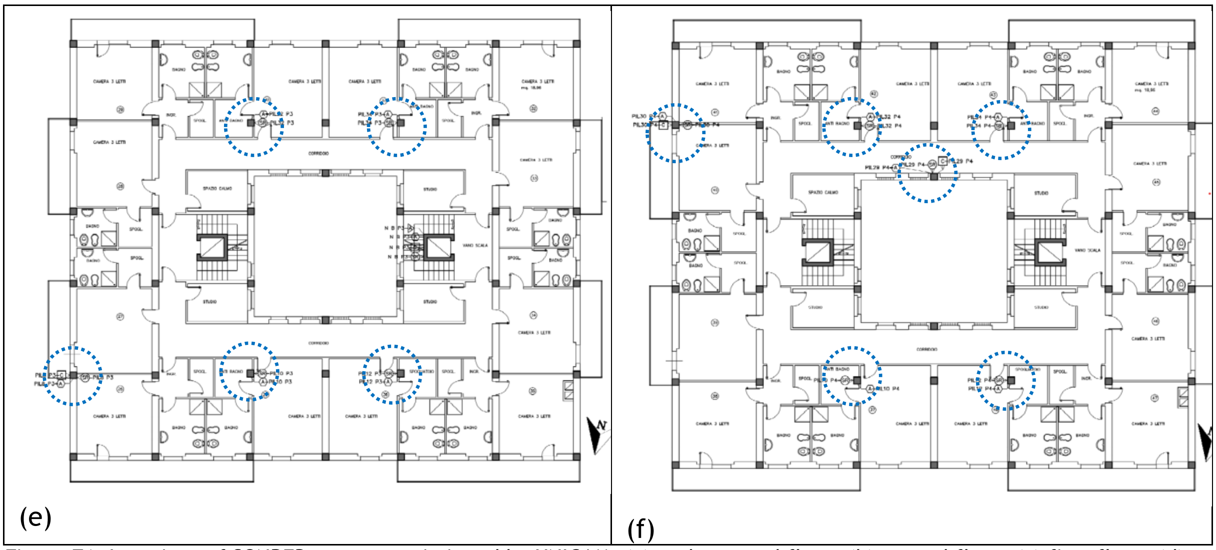


Figure 71: Locations of SONREB tests commissioned by UNICAM: (a) underground floor; (b) ground floor; (c) first floor; (d) second floor; (e) third floor; (f) fourth floor.

With the aim of demonstrating the capability of NDT tests to detect structural damage of a building after a seismic event, two sub-activities are currently underway by ENEA. The first sub-activity consists on carrying out pacometric, ultrasonic and sonic tests on some columns of the building in order to explore the possibility and the effectiveness of implementing the new methodology developed within RILEM TC 249-ISC [3-4]. This methodology aims at reducing the errors in the technical assessment of concrete strength through NDT following the UNI EN 13791:2019 standard [5]. The second sub-activity consists on carrying out tomographic ultrasound analysis to verify the applicability of Non-destructive testing methods, experimented through shaking table [6], for damage assessment of reinforced concrete buildings after seismic events. Since the building is damaged and declared unusable, ENEA selected the columns to test, first of all, on the basis of their accessibility. Among those of easy access, the choice was based on the possibility of comparison with the destructive and non-destructive tests already available by UNICAM [1] and on the level of solicitation [2]. Finally, the choice fell on the columns highlighted with solid circles (blue and green lines) in Figure 72. In the same figure, blue circles (dotted and solid lines) indicate the columns already tested at the mid-height by UNICAM. As useful reference for campaign of test performed by ENEA, and described in the next paragraphs, the values of ultrasonic velocities obtained by UNICAM are summarised in **Error! Reference source not found.** 7.

Co-funded by the European Union

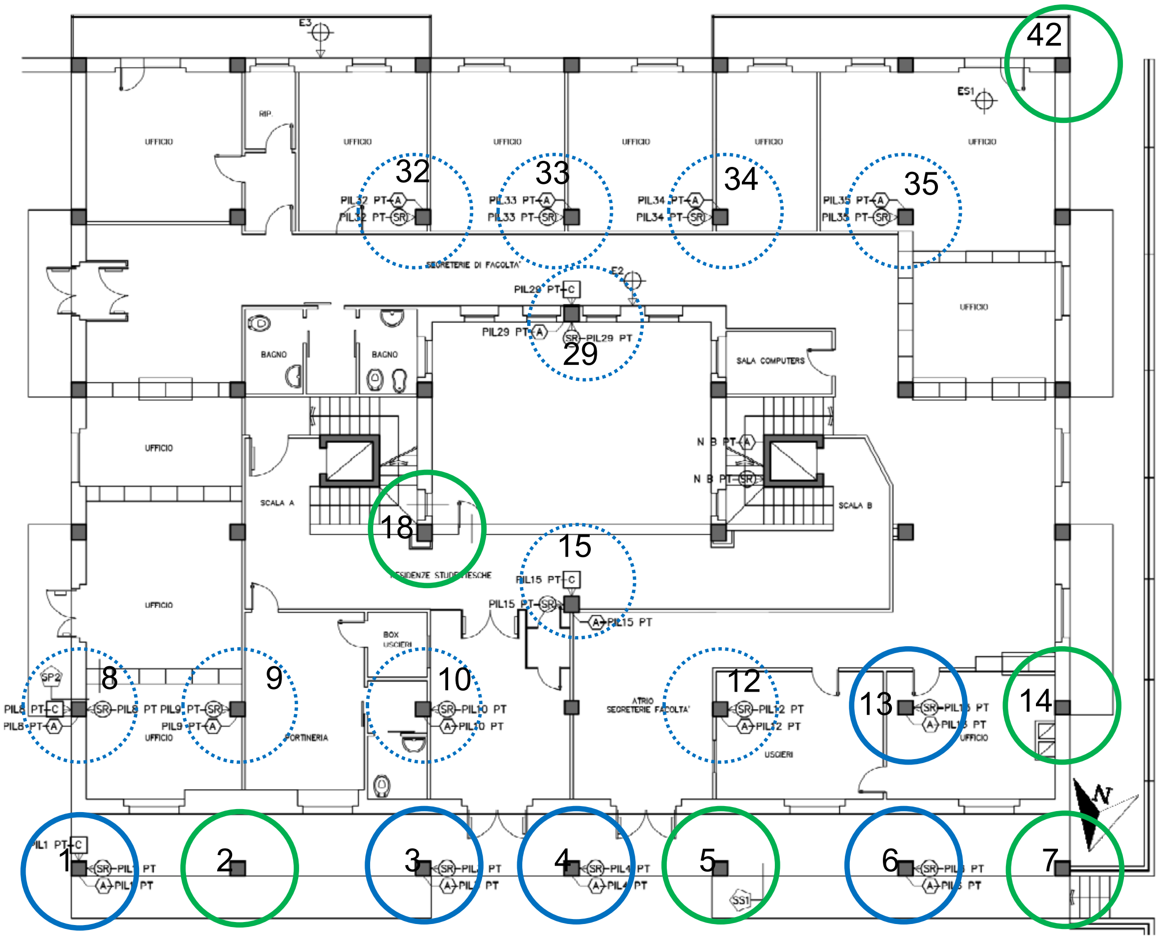


Figure 72: With solid circles (blue and green lines) the columns selected by ENEA for testing through NDT; with blue circles (dotted and solid lines) the columns already tested by UNICAM.

	Col 1	Col 3	Col 4	Col 6	Col 8
Direction	Y	Y	Y	Y	X
L (m)	0,35	0,455	0,455	0,45	0,455
V (m/s)	3845	3893	3813	3828	3970
	Col 9	Col 10	Col 12	Col 13	Col 15
Direction	Y	Y	Y	Y	X
L (m)	0,45	0,43	0,45	0,445	0,35
V (m/s)	3634	3384	3833	3318	3821
	Col 29	Col 32	Col 33	Col 34	Col 35
Direction	X	Y	Y	Y	X
L (m)	0,35	0,45	0,40	0,45	0,45
V (m/s)	4029	3763	3991	3388	3821

Table 7 – Values of ultrasonic Velocities on columns already tested at the mid-height by UNICAM [1]

Experimental set-up

The experimental NDT campaign was based on pacometric, ultrasonic, sonic and thermographic techniques to demonstrate their capability to detect structural damage and provide an estimation of the state of the building's health.

Ultrasonic measurements

Ultrasonic tests are performed as part of the non-destructive testing for the determination of elastic and mechanical properties. The operation of the equipment is based on the effects of the propagation of vibrational pulses applied to a solid medium according to the following principles.

The speed at which the applied pulses propagate is a function of the elastic characteristics of the medium used and of its density.

Inhomogeneity (due to cracks, cavities, degraded areas, etc.) alters the propagation speed and attenuates the modulus of the vibration wave.

The impulse is generated by means of an electrodynamic sonic transmitter (using a piezoelectric ceramic tablet) and signal detection is ensured by a receiver consisting of a piezoelectric probe of the same type as the transmitter [Figure 73]. By means of a pre-amplification, an amplification and a filtering system, the received signal is transmitted to the processing system in optimal condition, and the system provides the display on the computer monitor. The entire process is carried out via the computer of the equipment supported by the appropriate software. A low-frequency ultrasound instrument 'IMG5000CSD' was used, which uses 50 KHz probes of 2" diameter [Figure 74].

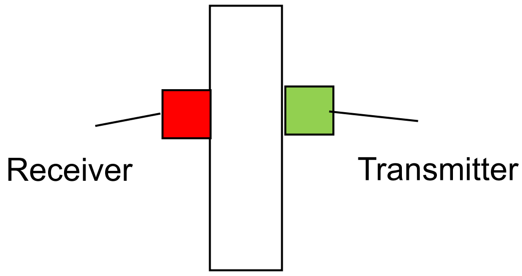


Figure 73: Diagram of direct ultrasonic measurements: Green Transmitting Probe, Red Receiving Probe.

Figure 74: 50Khz ultrasonic probe.

After the pacometric tests to search for iron under the concrete cover [Figure 75], three ultrasonic measurements were taken for each point, the value of which is expressed in microseconds. The value read represents the time it takes for the sound emitted by the transmitting probe to reach the opposite end of the element where the receiving probe is positioned (Figure 76). The three time measurements are averaged and through the length in metres the speed of sound expressed in metres per second is calculated. The higher the average velocity value, the higher the quality of the material.

Figure 75: Pacometric test

Figure 76: Ultrasonic test

The monitor displays the ultrasonic signal where at time 0 the transmitting probe generates the pulse that propagates inside the abutment and after a certain interval the probe on the opposite side receives the wave. The first part of the signal is null and is called propagation time then the signal increases in intensity the green vertical line determines the arrival time of the wave. The measurement is carried out continuously, usually once per second (Figure 77).

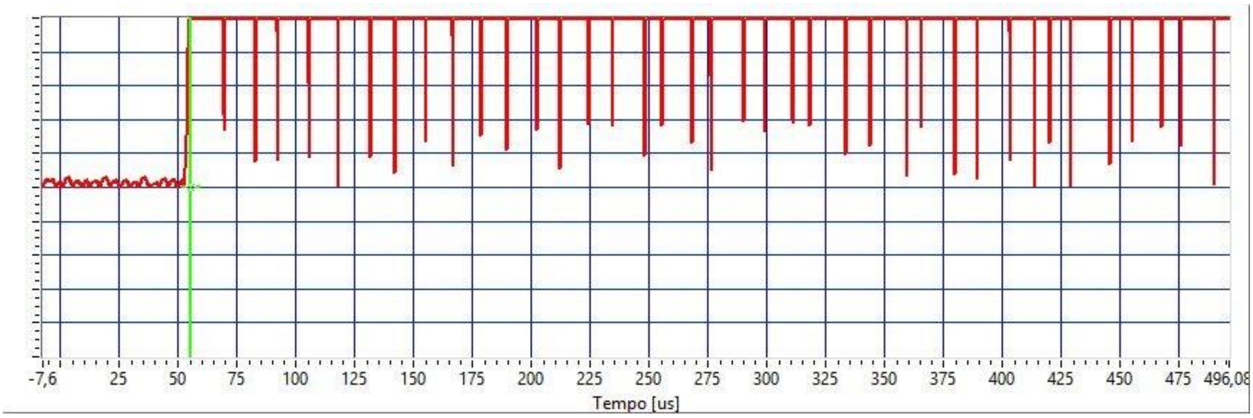


Figure 77: Digitalised ultrasonic signal.

Sonic measurements

The sonic velocity test technique is based on the generation of mechanical impulses with frequencies in the sound field. The sound wave is generated on the element, the column in the specific case of this measurement campaign, by impacting with an instrumented hammer, and is received by a sensor (piezoelectric accelerator) placed at a different point on the element. To calculate sonic velocity, it is necessary to measure the travel time of a sonic signal through a surface. In our case indirect measurements were carried out placing the impact point of the instrumented hammer and the receiving accelerator on the same face of the column as reported in Figure 78, at a distance of about 1,80 m.

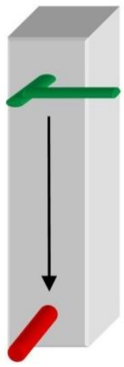


Figure 78: scheme of indirect measures.

Measurements were carried out by Level 3 personnel trained according to UNI/PdR 56:2019 [2]. The signal processing and the measurement acquisition were handled with the IMG 5200 CSD instrument (Figure 79), which is a digital low-frequency equipment for the control of inhomogeneous materials, equipped with a touchscreen, with multiple functions such as the storage of oscillograms (A-Scan) and relative calibration parameters. An instrumented hammer with an accelerometer sensor (Figure 80) for measuring sonic velocities was connected to the IMG 5200 CSD.

Figure 79: IMG 5200 CSD device.

Figure 80: sonic velocity instrumentation (instrumented hammer for measuring sonic velocity).

Co-funded by the European Union

Both devices are connected to a signal amplifier and an analogue-to-digital converter for visualisation and data recording on a laptop computer.

The processing of the data consists of determining the flight times (expressed in microseconds): the read values represent the time the sound emitted by the hammer takes to reach the end of the element in which the accelerometer sensor is positioned. The crossing velocity of the investigated element, generally expressed in m/s, is obtained from these values, knowing the distance between the point of impact of the hammer and the position of the receiver, as well as the dimensions – cross section - of the column.

For each measurement setting on the column, at least three distinct measurements are generally carried out and their signals recorded: the velocity at the column is the average value of the three measurement values.

Thermographic measurements

The thermographic analyses were conducted with the T560 thermal imaging camera (Figure 81): it is a camera with a microbolometer detector with 640 x 480 pixels resolution that is sensitive to infrared with a wavelength between 7.5-14 mm, a range that limits interference from the atmosphere. The detected flux is converted into an electrical signal by the detector. This signal is filtered and amplified by the electro-optical system, thus producing images that can be displayed in grey tones or false colours, depending on the different thermal levels associated with each other by a conventional scale. The acquired images, or thermograms, represent the surface heat map (to a depth of approximately 3-4 cm) of the analysed objects. The data are collected in real time, recorded on a memory card and a sound commentary can be associated with them. A built-in 4" LCD monitor allows direct viewing of the images. See Table 2 for full features.

Figure 81: Thermal Imaging camera T560

Imaging and optical data	
Infrared resolution	640 × 480 pixels
UltraMax (super-resolution)[1]	Yes
NETD	<40 mK @ 30°C (86°F)
Field of view	24° × 18°
Minimum focus distance	• 0.15 m (0.49 ft) • Macro mode 50 µm as option
Minimum focus distance with MSX	0.5 m (1.64 ft)
Focal length	17 mm (0.67 in)
Spatial resolution (IFOV)	0.66 mrad/pixel
Available extra lenses	• 14° (AutoCal) • 42° (AutoCal) • Dual FOV 24°/14° (service calibration required) • 6° (service calibration required) • 80° (service calibration required) • Macro lens 2.0x (service calibration required)
Lens identification	Automatic
f number	1.3
Image frequency	30 Hz
Focus	• Continuous LDM • One-shot LDM • One-shot contrast • Manual
Field of view match	Yes
Digital zoom	1–8x continuous

Table 2 – Thermal imaging camera features

Measurement	
Camera temperature range	• –20 to 120°C (–4 to 248°F) • 0 to 650°C (32 to 1202°F) • 300 to 1500°C (572 to 2732°F)

Object temperature range and accuracy (for ambient temp. 15 to 35°C (59 to 95°F)	• Range –20 to 120°C (–4 to 248°F):
	  ◦ –20 to 100°C (–4 to 212°F): ±2°C (±3.6°F)
	  ◦ 100 to 120°C (212 to 248°F): ±2%
	• Range 0 to 650°C (32 to 1202°F):
	  ◦ 0 to 100°C (32 to 212°F): ±2°C (±3.6°F)
	  ◦ 100 to 650°C (212 to 1202°F): ±2%
	• Range 300 to 1500°C (572 to 2732°F): ±2%

Measurement campaign

First of all, a preliminary inspection was carried out to get in touch with the building and confirm the effectiveness of the location of the tests. Visual inspection, thermographic study of the building and a photographic campaign helped to identify structural elements, possible degradation processes of concrete and corrosion of reinforcements and to verify the accessibility of the selected columns. Then the positions of the bars, both longitudinal (vertical) and transversal, or stirrups, were inspected using the pacometer and marked with chalk. Figure 82 shows a plan of the building, highlighting the columns that were the subject of ultrasonic or sonic velocity measurements.

Co-funded by the European Union

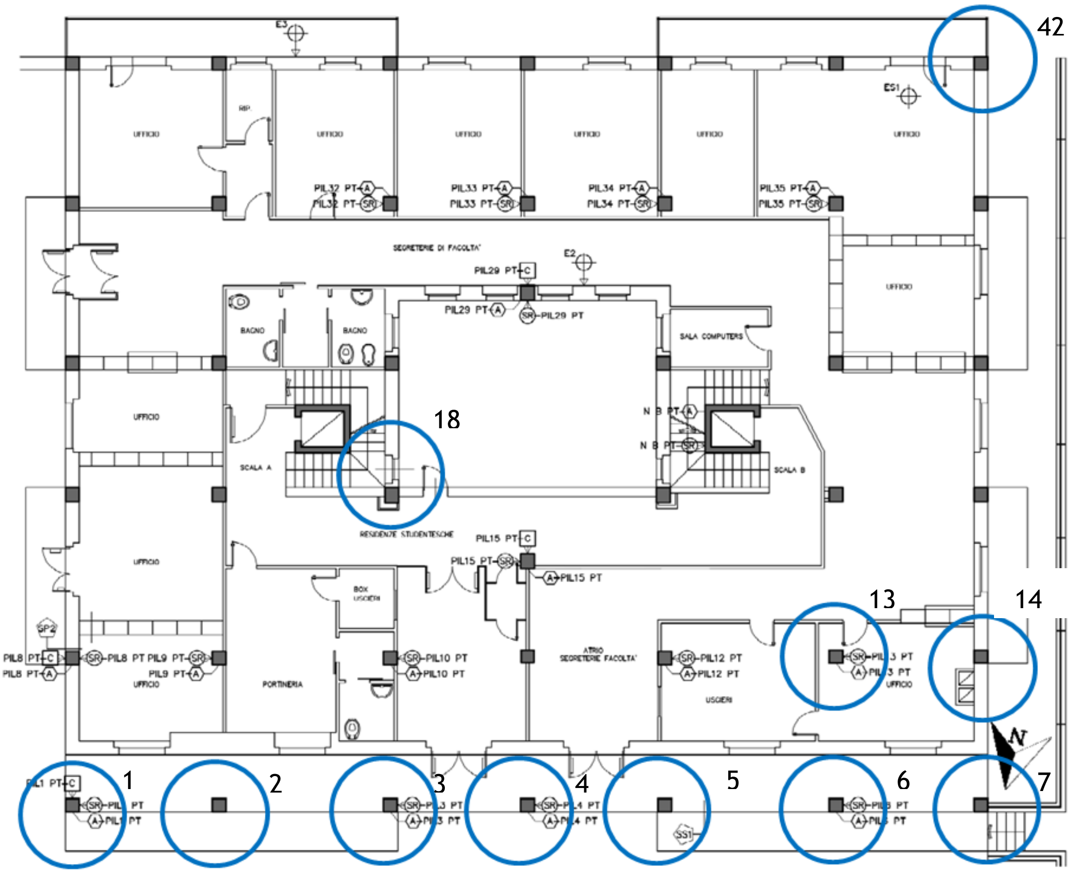


Figure 82: location of columns that were tested

Ultrasonic Test campaign results

Ultrasonic tests were carried out on columns number 1, 6 and 13 at ground floor. For a more precise measurement, both from a statistical and a structural point of view, two measurement points (1 and 2) were identified for each face of the columns (N, E, S, and W), as showed in Figure 83.

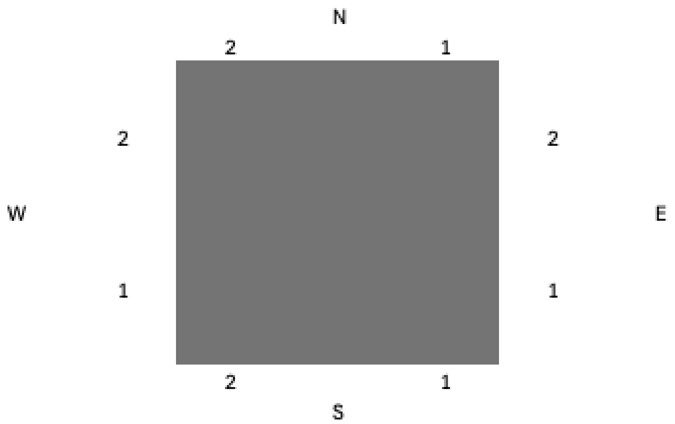


Figure 83: scheme of the Ultrasonic measurements

A total of 8 direct measurements (two on each side: from north to south, from south to north, from east to west and from west to east) were performed at the foot, at the middle span and at the top of the columns. The distance between the points on the opposite faces is constant, given that the columns have a square shape. The achieved data are reported for each pillar in following sections.

Figure 84: column n. 1

Location	side (m)	height (m)	Point	Direction	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
Foot	0,35	0,34	1	NS	4135	4169	4208	4171	29,83
			1	SN	4240	4239	4216	4232	11,09
			2	NS	4206	4194	4207	4202	5,91
			2	SN	4108	4118	4133	4120	10,27
			1	EW	4128	4130	4160	4139	14,64
			1	WE	4116	4120	4142	4126	11,43
			2	EW	4045	4090	4083	4073	19,77
			2	WE	4059	4097	4106	4087	20,37
Middle	0,35	1,54	1	NS	3579	3596	3582	3586	7,41
			1	SN	3586	3575	3642	3601	29,34
			2	NS	3487	3463	3509	3486	18,79
			2	SN	3458	3470	3456	3461	6,18
			1	EW	3737	3716	3753	3735	15,15
			1	WE	3715	3724	3769	3736	23,62
			2	EW	3564	3560	3562	3562	1,63
			2	WE	3541	3554	3550	3548	5,44
Top	0,35	2,95	1	NS	3626	3636	3628	3630	4,32
			1	SN	3606	3605	3581	3597	11,56

		2	NS	3693	3686	3704	3694	7,41
		2	SN	3647	3646	3651	3648	2,16
		1	EW	3617	3627	3608	3617	7,76
		1	WE	3625	3635	3601	3620	14,27
		2	EW	3615	3588	3576	3593	16,31
		2	WE	3548	3560	3528	3545	13,20

Figure 85: column n. 6

Location	side (m)	height (m)	Point	Direction	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
Foot	0,455	0,60	1	NS	4068	4056	4067	4064	18,67
			1	SN	4045	4056	4057	4053	10,66
			2	NS	4080	4072	4043	4065	8,73
			2	SN	4049	4066	4100	4072	4,11
			1	EW	4106	4125	4129	4120	18,35
			1	WE	4054	4084	4093	4077	13,72
			2	EW	4009	4026	4085	4040	12,71
			2	WE	4096	4103	4146	4115	5,79
Middle	0,455	1,90	1	NS	4084	4063	4065	4071	9,46
			1	SN	4094	4099	4097	4097	2,05
			2	NS	4113	4102	4104	4106	4,78
			2	SN	4087	4081	4096	4088	6,16
			1	EW	4039	4051	4030	4040	8,60
			1	WE	4040	4026	4058	4041	13,10
			2	EW	3950	3941	3937	3943	5,44
			2	WE	3956	3984	3979	3973	12,19

Top	0,455	2,80	1	NS	3733	3734	3725	3731	4,03
			1	SN	3724	3729	3690	3714	17,33
			2	NS	3715	3718	3724	3719	3,74
			2	SN	3693	3710	3697	3700	7,26
			1	EW	3607	3606	3601	3605	2,62
			1	WE	3620	3625	3620	3622	2,36
			2	EW	3738	3731	3712	3727	10,98
			2	WE	3738	3737	3722	3732	7,32

Figure 86: column n. 13

Location	**side (m)**	**height (m)**	**Point**	**Direction**	**speed 1 (m/s)**	**speed 2 (m/s)**	**speed 3 (m/s)**	**Mean speed (m/s)**	**St. deviation**
Foot	0,452	0,33	1	NS	3984	3961	3967	3971	9,74
			1	SN	3941	3931	3929	3934	5,25
			2	NS	4035	4023	4044	4034	8,60
			2	SN	4039	4042	4062	4048	10,21
			1	EW	3867	3873	3867	3869	2,83
			1	WE	3862	3862	3869	3864	3,30
			2	EW	3808	3806	3821	3812	6,65
			2	WE	3807	3802	3806	3805	2,16
Middle	0,452	1,72	1	NS	3566	3543	3560	3556	9,74
			1	SN	3527	3542	3516	3528	10,66
			2	NS	3575	3578	3579	3577	1,70
			2	SN	3581	3562	3560	3568	9,46
			1	EW	3469	3469	3458	3465	5,19
			1	WE	3476	3465	3473	3471	4,64

			2	EW	3507	3502	3499	3503	3,30
			2	WE	3511	3515	3504	3510	4,55
Top	0,452	3,11	1	NS	3517	3519	3500	3512	8,52
			1	SN	3530	3525	3539	3531	5,79
			2	NS	3588	3606	3589	3594	8,26
			2	SN	3515	3549	3551	3538	16,52
			1	EW	3495	3500	3516	3504	8,96
			1	WE	3496	3480	3488	3488	6,53
			2	EW	3495	3503	3509	3502	5,73
			2	WE	3464	3462	3472	3466	4,32

Summary

The average values of the velocities measured on the three investigated columns are reported in the following table for comparison:

Speed (m/s)	Foot	Middle	Top
Column 1	4144	3590	3618
Column 6	4076	4045	3694
Column 13	3917	3522	3517

Ultrasonic tomographies results

The ultrasonic tomography was carried out on column n. 13 at three different heights: foot, middle span, top. To carry on these tests the measurement points were identified from 1 to 8 and their x and y coordinates were accurately measured, identifying the NW corner as the point with coordinates 0;0 (

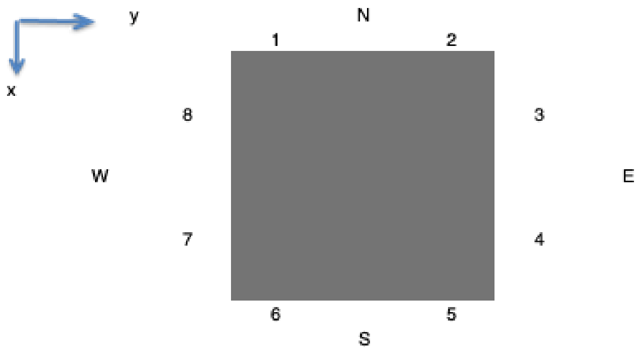


Figure 87).

Figure 87: scheme of the ultrasonic tomography measurements

The measurement was carried out putting the transmitter on each point and the receiver in the remaining seven points, on a rotation basis.

Point 1 transmits; points 2, 3, 4, 5, 6, 7 and 8 receive.

Point 2 transmits; points 1, 3, 4, 5, 6, 7 and 8 receive.

Co-funded by
the European Union

Point 8 transmits; points 1, 2, 3, 4, 5, 6 and 7 receive.

The measurement points coordinates are fundamental in order to define the distance between transmitter and receiver for each measure and, thus, to calculate the velocity of the signal.

Column 13, foot

The following tables report the times measured between each pair of points and the coordinates of the measurement points. The test was performed at a height of 330mm from the floor.

Time (ms)	1	2	3	4	5	6	7	8
1	0,0	63,8	93,0	112,6	131,3	112,3	79,3	45,4
2	61,0	0,0	39,1	71,8	115,0	137,0	120,2	97,7
3	89,4	39,9	0,0	36,4	84,8	122,7	125,1	117,8
4	112,7	77,1	38,8	0,0	48,9	99,5	118,6	125,7
5	130,2	114,6	83,2	47,6	0,0	63,3	92,3	115,5
6	112,3	135,2	120,3	97,3	62,1	0,0	45,4	81,4
7	76,6	122,7	123,4	116,9	93,3	45,7	0,0	42,3
8	45,9	99,9	118,4	122,9	115,2	81,8	46,7	0,0

Coordinates (m)	X	Y
1	0,135	0,000
2	0,370	0,000
3	0,465	0,145
4	0,465	0,275
5	0,380	0,455
6	0,120	0,455
7	0,000	0,320
8	0,000	0,180

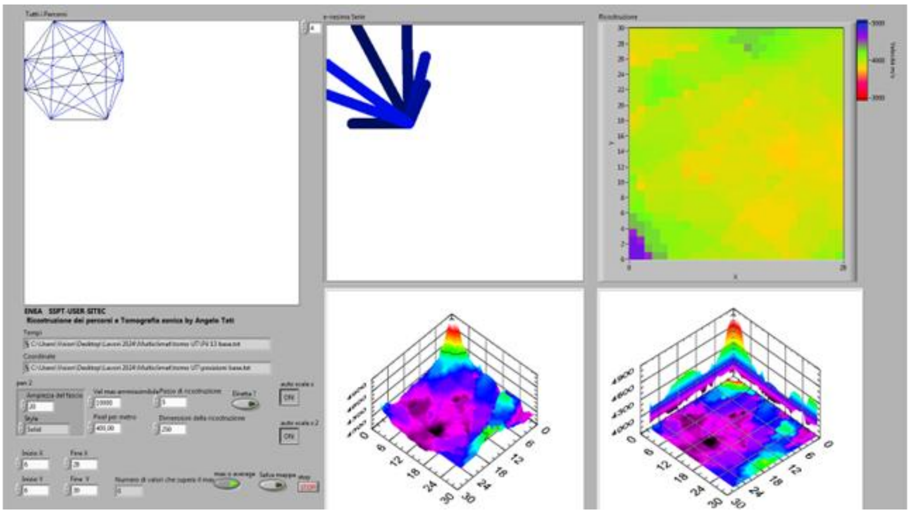


Figure 88: software elaboration

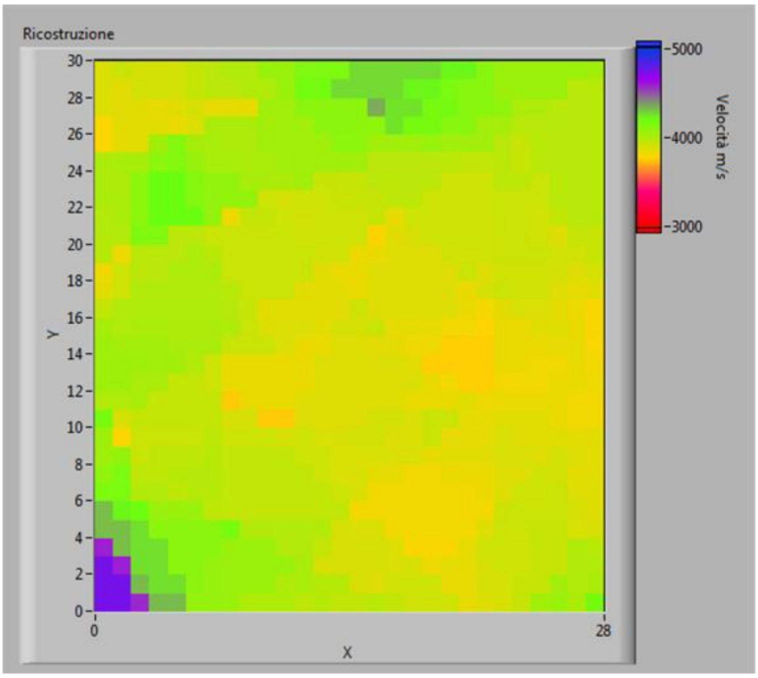


Figure 89: Tomographic test

The green colour indicates a 4000 m/s speed. The geometric distribution of the velocities is homogeneous, indicating a good structural integrity. No apparent damages were detected.

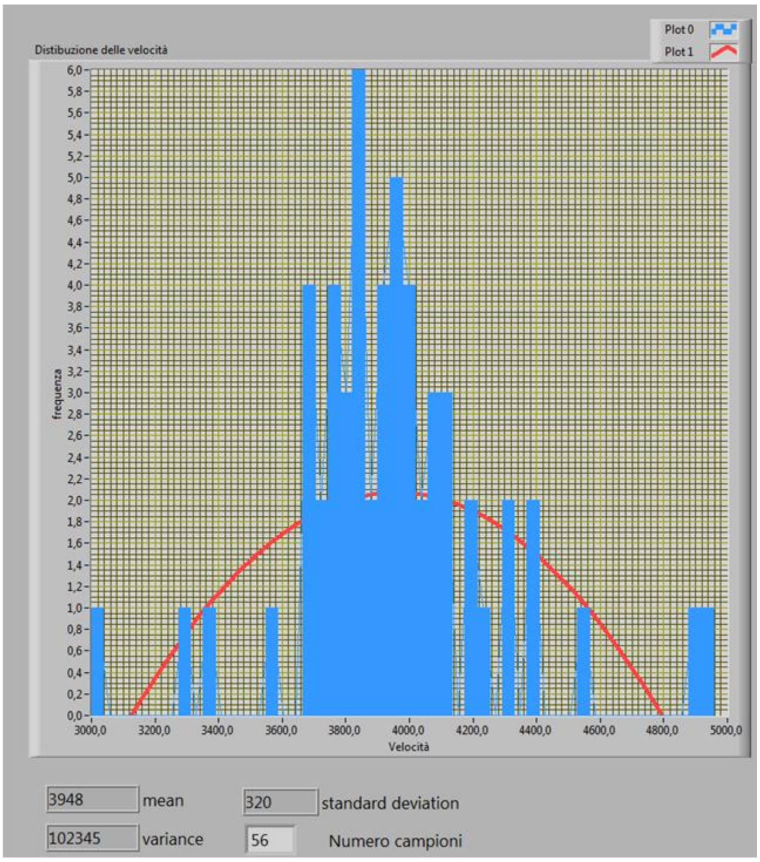


Figure 90: speed distribution. The main value is comparable with the map.

Column 13, middle span

The following tables report the times measured between each pair of points and the coordinates of the measurement points. The test was performed at a height of 1720mm from the floor.

Time (ms)	1	2	3	4	5	6	7	8
1	0,0	67,4	97,4	139,9	145,0	127,1	95,0	37,8
2	66,2	0,0	33,6	97,2	126,7	146,5	135,5	100,4
3	96,7	33,6	0,0	72,7	104,9	144,3	147,1	127,1
4	138,1	99,0	69,8	0,0	39,9	101,9	129,4	146,9
5	144,8	127,8	102,4	39,0	0,0	64,7	95,1	134,7
6	127,1	147,8	143,0	100,2	63,5	0,0	37,6	97,0
7	95,8	136,3	148,2	129,8	97,7	36,8	0,0	62,5
8	40,2	98,2	128,1	146,6	135,3	95,9	61,9	0,0

Coordinates (m)	X	Y
1	0,110	0,000
2	0,348	0,000
3	0,452	0,900
4	0,452	0,345
5	0,330	0,452
6	0,100	0,452
7	0,000	0,330
8	0,000	0,110

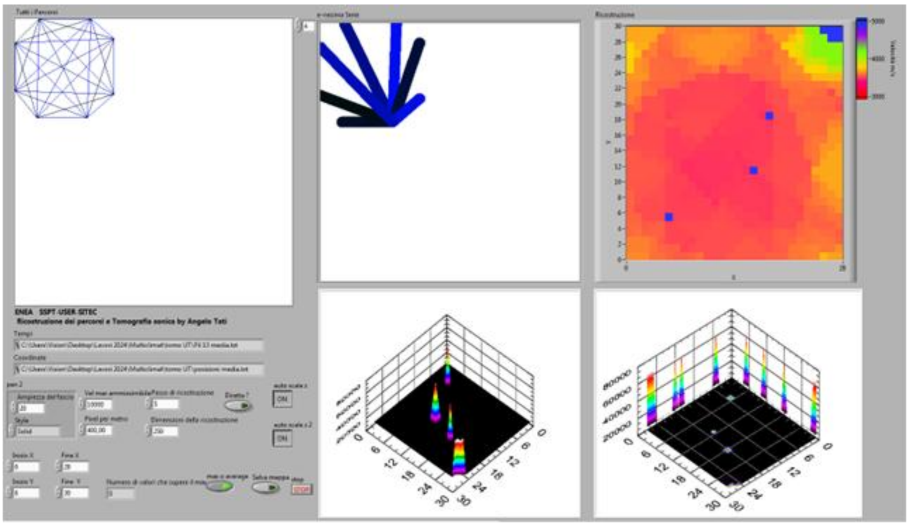


Figure 91: software elaboration

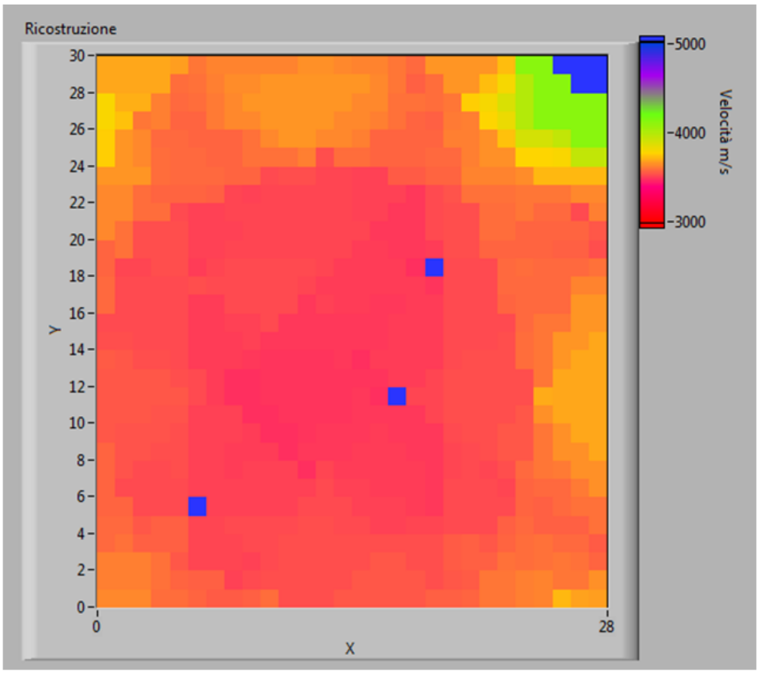


Figure 92: tomographic test.

The results obtained at middle span indicate a lower velocity: in Figure 92 the colour scale is the same of Figure 89, but the red colour indicates a speed around 3000 m/s.

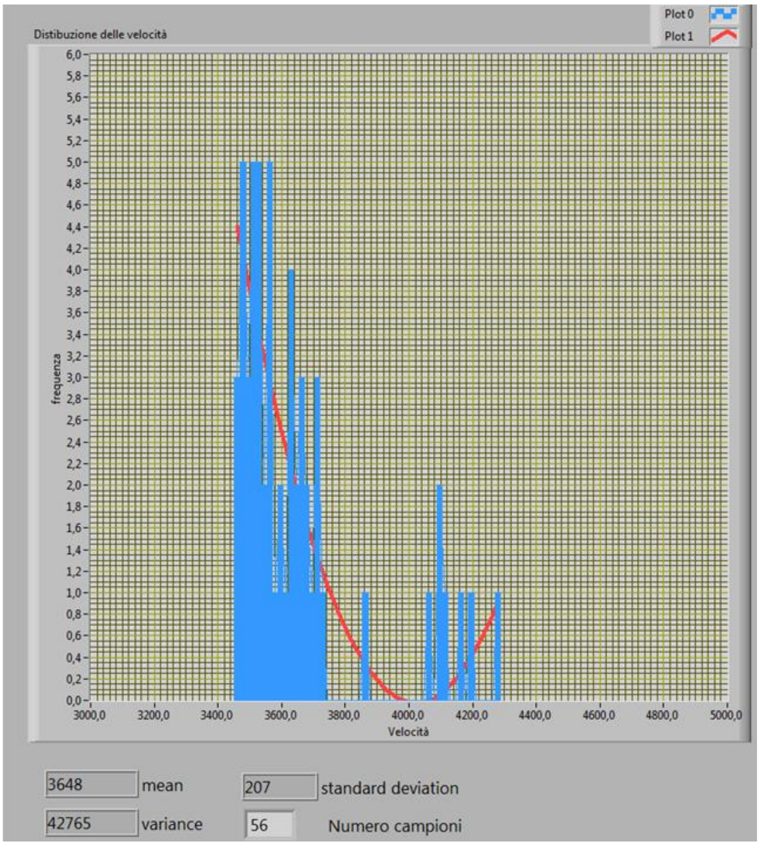


Figure 93: speed distribution. The main value is comparable with the map but lower in comparison with the value measured at column foot

Indirect Sonic Tests Campaign results

The sonic tests were carried out both on the columns already investigated with ultrasonic tests, in order to compare the data obtained with the two techniques, and on eight other columns with the aim of widen the knowledge of the structure. Tests on the latter were carried out only on two sides of the column, taking into account the two main directions.

The tests on the columns already tested were carried out by placing both the hammer and the receiver directly on the concrete surface. In the other columns hammer and receiver were positioned sometimes on the concrete and other times on the plaster, as specifically indicated for each test, preliminarily checking that the plaster was not detached from the column. Where possible a distance between the hammer and the receiver of 1.80 m was maintained, but in some cases this distance was varied to be able to carry out the test.

It is worth remembering that for correct execution of sonic tests it is necessary to have both a free column surface and a sufficiently large space in front of it so that the instrumented hammer can have the correct excursion to impact the column with energy suitable for the propagation of the sonic impulse.

Measurement points on the four sides of the columns were named as specified in Figure 94.

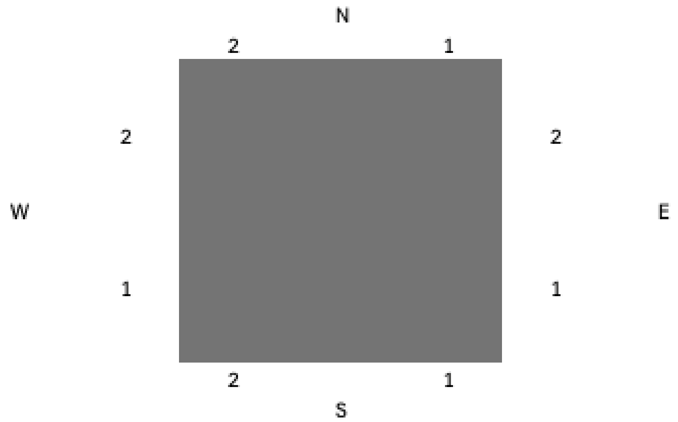


Figure 94: scheme of the Sonic measurements

Column n.1

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
1,36	1	N	3614	3484	3629	3576	79,74
1,36	2	N	3483	3401	3540	3475	69,87
1,36	1	S	3483	3525	3428	3479	48,64
1,36	2	S	3569	3483	3497	3516	46,14
1,36	1	E	3613	3659	3722	3665	54,72
1,36	2	E	3336	3584	3362	3427	136,30
1,36	1	W	3787	3738	3771	3765	24,99
1,36	2	W	3598	3613	3722	3644	67,68

Note: all measurements were performed directly on the concrete.

Co-funded by the European Union

Column n. 2

Distance (m)	**Point**	**Side**	**speed 1 (m/s)**	**speed 2 (m/s)**	**speed 3 (m/s)**	**Mean speed (m/s)**	**St. deviation**
1,75	1	S	4309	4360	4326	4332	25,97
1,75	2	S	3916	3889	4058	3954	90,79
1,75	1	W	4244	4276	4326	4282	41,33
1,75	2	W	4260	4228	4212	4233	24,44

Note: all measurements were carried out on a plastered surface.

Column n. 3

Distance (m)	**Point**	**Side**	**speed 1 (m/s)**	**speed 2 (m/s)**	**speed 3 (m/s)**	**Mean speed (m/s)**	**St. deviation**
1,75	1	S	4133	3916	4134	4061	125,57
1,75	2	S	4088	3861	4000	3983	114,45
1,75	1	W	3902	3902	4014	3939	64,66
1,75	2	W	4000	4044	4015	4020	22,37

Note: the point of measure at the top of the column was located directly on the concrete, while at the foot the column was covered with plaster.

Column n. 4

Distance (m)	**Point**	**Side**	**speed 1 (m/s)**	**speed 2 (m/s)**	**speed 3 (m/s)**	**Mean speed (m/s)**	**St. deviation**
1,75	1	S	3720	3758	3822	3767	51,55
1,75	2	S	4482	4428	4411	4440	37,07
1,75	1	E	4326	4015	4464	4268	229,99
1,75	2	E	4260	3972	4073	4102	146,12

Note: the point of measure at the top of the column was located directly on the concrete, while at the foot the column was covered with plaster.

Column n. 5

Distance (m)	**Point**	**Side**	**speed 1 (m/s)**	**speed 2 (m/s)**	**speed 3 (m/s)**	**Mean speed (m/s)**	**St. deviation**
1,50	1	S	3937	4214	4196	4116	154,99
1,50	2	S	4309	4196	4196	4234	65,24
1,75	1	W	4088	4118	4118	4108	17,32
1,75	2	W	4377	4442	4292	4370	75,22

Note: all measurements were carried out on a plastered surface.

Co-funded by the European Union

Column n. 6

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
1,75	1	N	3758	3875	3757	3797	67,84
1,75	2	N	3520	3707	3623	3617	93,66
1,75	1	S	3695	3757	3875	3776	91,44
1,75	2	S	3623	3732	3647	3667	57,27
1,75	1	E	3543	3647	3659	3616	63,79
1,75	2	E	3455	3720	3745	3640	160,70
1,75	1	W	3875	3600	3848	3774	151,58
1,75	2	W	3720	3600	3848	3723	124,02

Note: all measurements were performed directly on the concrete.

Column n. 7

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
1,75	1	N	3197	3100	3321	3206	110,77
0,9	2	N	3801	3826	4099	3909	165,31
1,75	1	S	4326	4394	4149	4290	126,48
1,75	2	S	4073	4044	4228	4115	98,93

Note: all measurements were carried out on a plastered surface, preliminarily checking that the plaster was not detached from the column. East and west sides were not accessible, then measures take into account only one direction.

Column n. 13

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation
1,80	1	N	3378	3471	3503	3451	64,93
1,80	2	N	3482	3638	3662	3594	97,73
1,80	1	S	3319	3388	3329	3345	37,29
1,80	2	S	3110	3068	3043	3074	33,86
1,80	1	E	3460	3592	3525	3526	66,00
1,80	2	E	3471	3450	3482	3468	16,26
1,80	1	W	3742	3755	3742	3746	7,51
1,80	2	W	3491	3545	3491	3509	31,18

Note: all measurements were performed directly on the concrete.

Column n. 14

Distance (m)	Point	Side	speed 1 (m/s)	speed 2 (m/s)	speed 3 (m/s)	Mean speed (m/s)	St. deviation

Co-funded by the European Union

1,75	1	S	4149	3732	3659	3847	264,36
1,75	1	E	4133	4058	4088	4093	37,75
1,75	2	E	3757	4073	3929	3920	158,21

Note: all measurements were performed directly on the concrete. The south side of the column was partially accessible.

Column n. 18

Distance (m)	**Point**	**Side**	**speed 1 (m/s)**	**speed 2 (m/s)**	**speed 3 (m/s)**	**Mean speed (m/s)**	**St. deviation**
1,75	1	N	3554	3543	3402	3500	84,76
1,75	2	N	3521	3351	3577	3483	117,69
1,75	1	W	3611	3588	3683	3627	49,56

Note: all measurements were performed directly on the concrete. The west side of the column was partially accessible.

Column n. 42

Distance (m)	**Point**	**Side**	**speed 1 (m/s)**	**speed 2 (m/s)**	**speed 3 (m/s)**	**Mean speed (m/s)**	**St. deviation**
1,80	1	S	3565	3521	3554	3547	22,90
1,80	2	S	3543	3554	3437	3511	64,61

Note: the point of measure at the foot of the column was located directly on the concrete, while at the top the column was covered with plaster. Only the south side of the column was accessible.

Summary

The average values of velocities measured on the investigated columns are reported in the following table for comparison:

Location	**Speed (m/s)**
Column 1	3568
Column 2	4200
Column 3	4001
Column 4	4144
Column 5	4207
Column 6	3701
Column 7	3880
Column 13	3464
Column 14	3953
Column 18	3537
Column 42	3529

Comparison between Ultrasonic and Sonic tests results

Location	Ultrasonic test foot (m/s)	Ultrasonic test middle (m/s)	Ultrasonic test top (m/s)	Sonic test (m/s)
Column 1	4144	3590	3618	3568
Column 6	4076	4045	3694	3701
Column 13	3917	3522	3517	3464

Thermographic analysis

The thermographic technique is a typically non-destructive investigation, due to its characteristic of analysing the thermal behaviour of the subjects under examination without using contact probes.

Through the analysis of thermograms it is possible to trace the state of degradation of the building structure and materials, highlighting the thermal differences between parts. Moreover, the thermal images allow the identification of the different building materials that constitute the structure (stones, bricks, mortar) and highlight the presence of beams, metal bodies, pipes, plugging. From these investigations, qualitative information is obtained about the analysed area and the extents of degradation (Figure 95-Figure 98).

North side - Via le mosse - Entrance

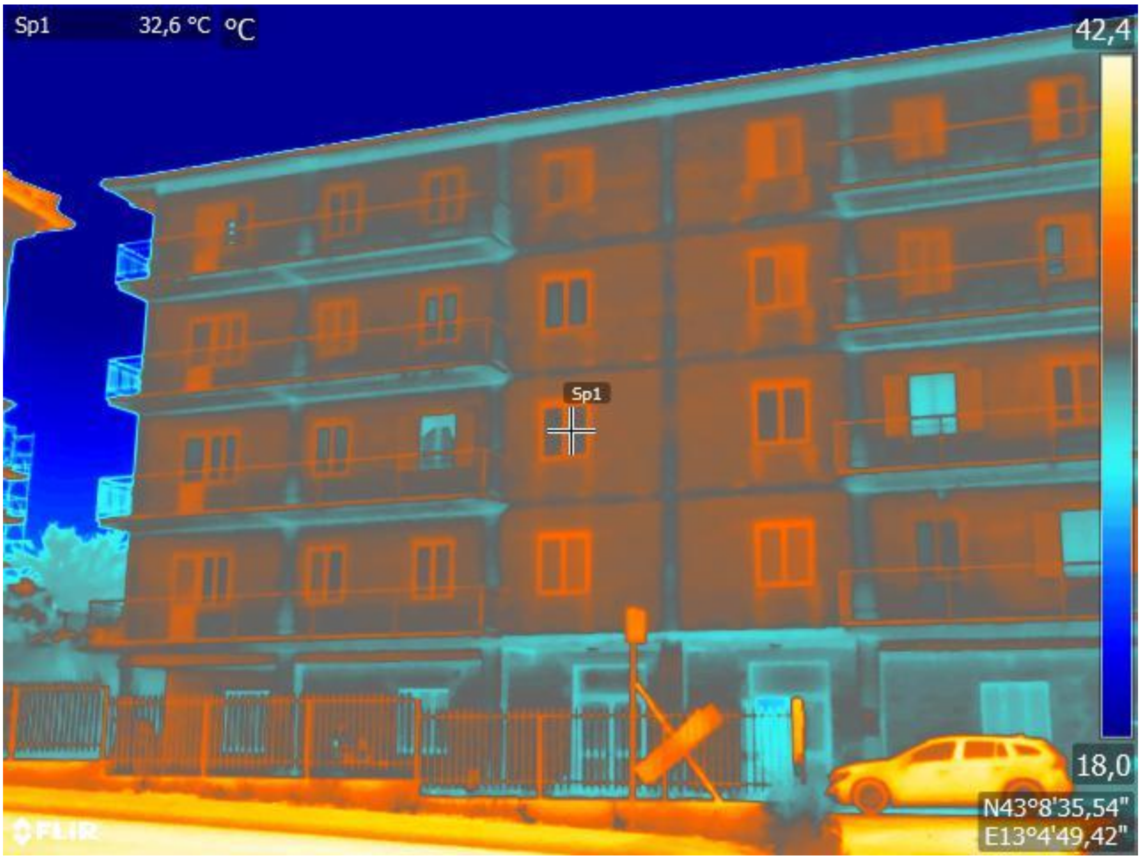


Figure 95: visual and thermal images of the façade; West side - Via Le Mosse – Side view

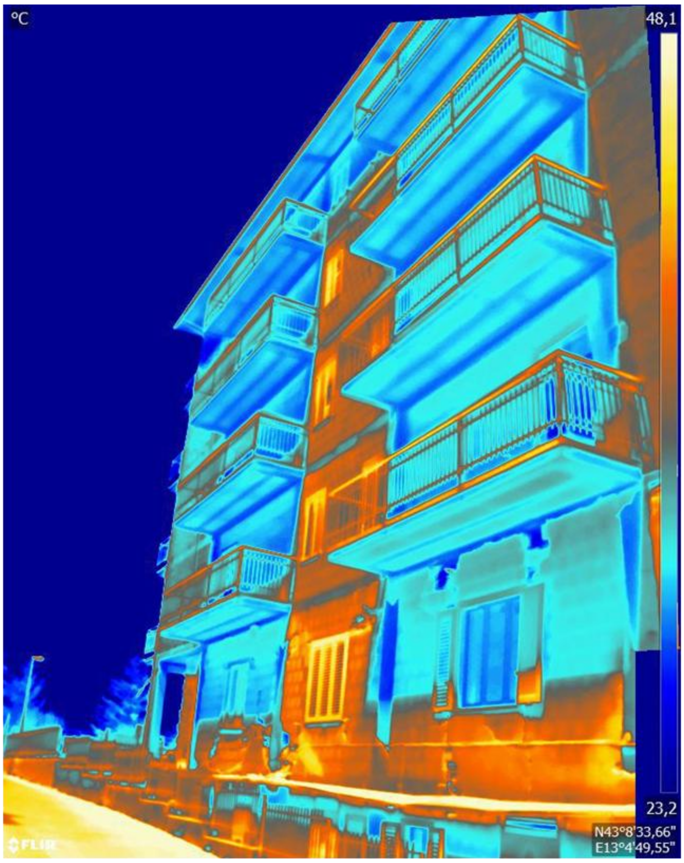


Figure 96: visual and thermal images of the façade; East side - Embankment

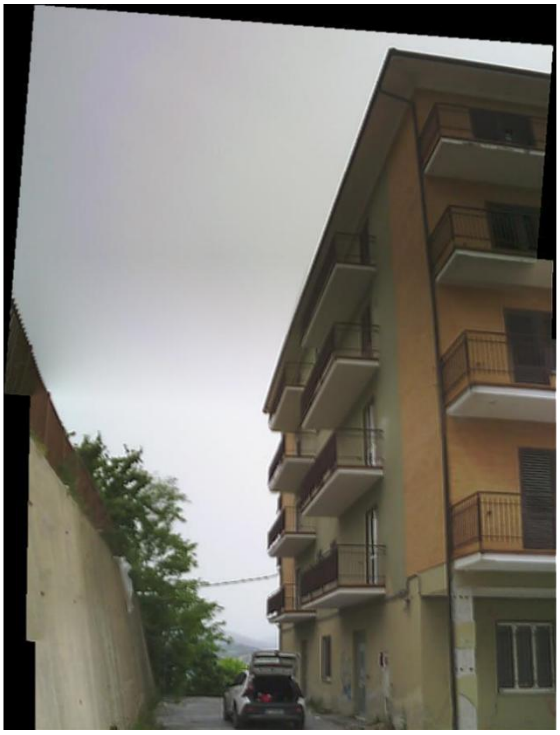


Figure 97: visual and thermal images of the façade, South side

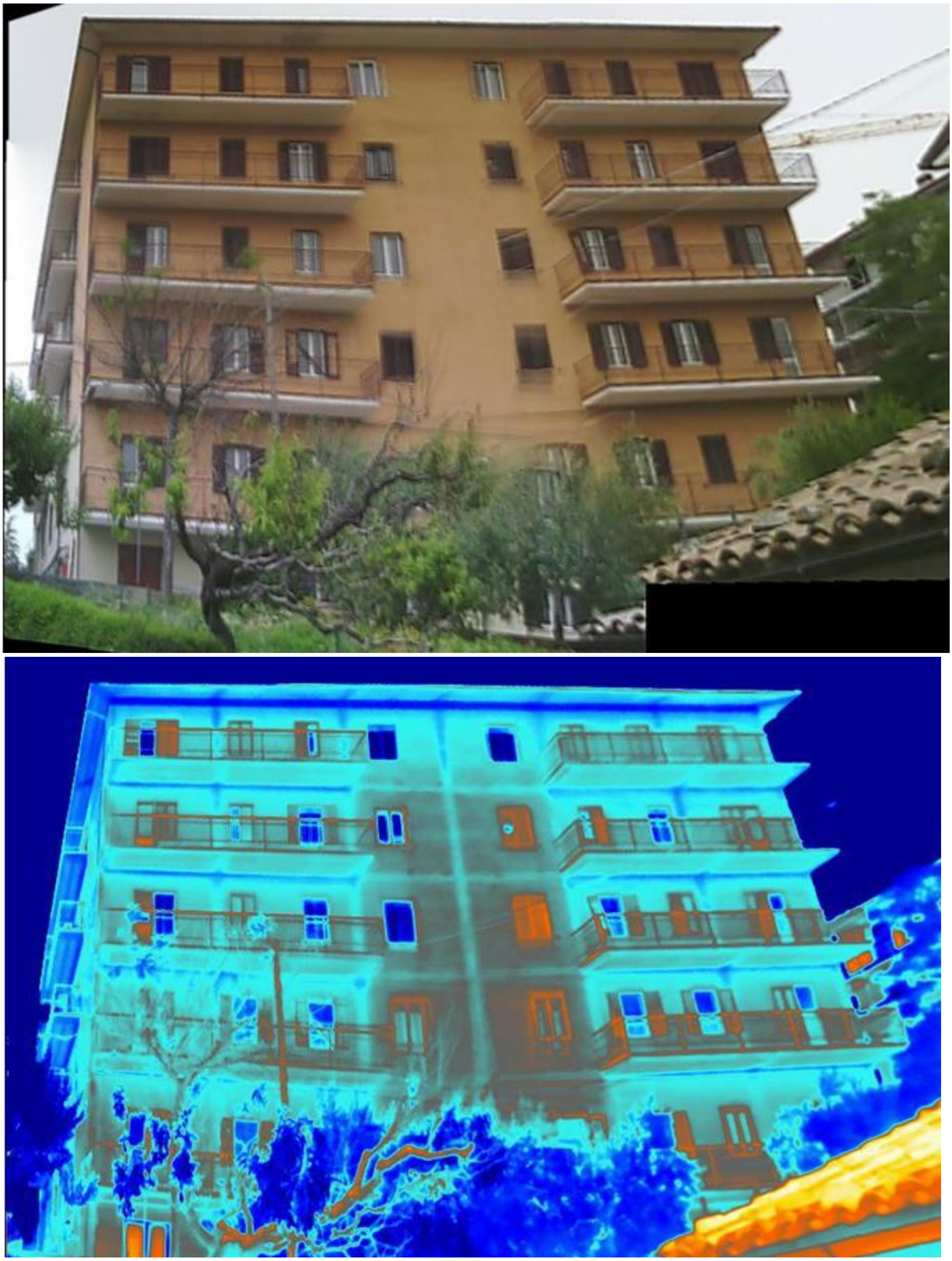


Figure 98: visual and thermal images of the façade

Co-funded by
the European Union

Cost, time and personnel

At the conclusion of the experimental campaign with both sound and ultrasound tests, some considerations can be made. They are summarized below.

Ultrasonic Testing

Direct UT ultrasonic tests are valid on rough structures, where it is easier to position the probes and align them on opposite faces of the investigated element.

They offer greater accuracy in transit time measurement and subsequent calculation of sound velocity in the element under investigation because of their higher oscillation frequency (50 KHz with the instrumentation used).

On the other hand, the need of plaster removal from the surface of the element on both faces and the use of a coupling medium (between probe and surface) result in a damage needing for subsequent restoration works.

Ultrasound tomography

The full tomography provides more information on whole section of the investigated element, but it is time consuming since many measures and a following data elaboration are required.

On the other hand, a partial tomography gives less data than the full tomography but in a short time, although providing comparable information. Then, it can be suggested for homogeneous elements, such as concrete columns.

Indirect Sound Test

Indirect sound test finds more widespread application because there is no need to remove plaster, no need for a coupling medium, and it requires access to only one side of the element. On the base of some previous experiences, it is important to set the distance between hammer and accelerometer sensor at about 1,85 m.

Obtained data are comparable with those achieved by ultrasonic tests. On the contrary, they have lower transit time accuracy (greater standard deviation than Ultrasonic measurements).

These aspects affect the time required to perform the tests. Vantages and drawbacks of each test method are briefly reported below.

In the case of direct tests, the need to operate on two opposite sides of the element requires a careful preliminary work to allow for proper alignment of the measurement points. This operation can be complicated by the presence of curtain walls, doors, as well as furniture elements. Generally, the execution of a direct test requires up to over 1 hour to be done.

In the case of ultrasonic tests the surfaces must be smoothed for a proper coupling of the sensors, making the test even longer.

Indirect sound tests are faster but less precise than direct tests.

For the above reasons, the costs of direct ultrasonic testing are higher while indirect sound testing has minimal impact in terms of “damage” to the analyzed structure, cost and duration.

The best personnel number to optimize the execution of the tests is 3 people:

1-2 people to identify the element, to define the measurement points and to prepare the surface.

2 people to hold the sensors;

1-2 people in charge of signal reading and reporting.