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Abstract

This deliverable outlines the foundational groundwork of the DIGITMAN project and establishes a strategic framework for an occupant-centric approach within digital building management. The document begins by delineating the scope of the research project, focusing on occupancy-based management strategies and identifying pertinent areas of interest. It then outlines a framework that details the logic and functionalities to be developed as project outcomes, followed by defining the ontology and semantics of relevant information pertaining to building management. Finally, the methodology for modeling building information is illustrated, and the pilot buildings chosen to demonstrate the project's methodology are presented.

Keywords

Occupancy-based Building Management, Digital Building Management, Information Management Framework, Ontology and Semantics, Classification Systems

Approvals

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Summary

Introduction

Predictive approaches, based on occupancy data integrated into a common digital framework, can improve building stock management by supporting the correct allocation of technical and economic resources during the actual operation of buildings [1]. In fact, occupancy impacts every aspect of the life of a building (i.e., energy consumption, maintenance costs, safety management). Nevertheless, occupancy data collected during the operation of buildings through automated systems such as BAS (building automation systems) and CMMS (computer maintenance management systems) are rarely used to improve building management, whose costs can reach up to 75% of the initial construction cost.

The EU recently proposed a whole life-cycle digital logbook for buildings as a digital repository supporting building management tasks. However, integrating dynamic occupancy data into this type of digital repository and using these data to predict the impact of alternative strategies are relatively unexplored fields. Moreover, a common digital framework for building management, based on common languages/interfaces/data matching methods, is still lacking, as underlined by the EU.

The proposed predictive approach will be based on a set of analytic methods (e.g., ML, MAS) applied to the main pillars of building management (operation, maintenance, safety) and multicriteria approaches, thanks also to the availability of experimental data from 30 buildings managed by three local public authorities. As shown in the general flowchart in Figure 1, the framework and database will be defined by focusing on the main aims of the project, which are (i) optimizing the economic resource allocation, (ii) increasing indoor comfort and well-being, and (iii) setting a long-time renovation roadmap." The general issues will be directly focused on chosen pilots, which are representative of the complexity of building stocks managed by private or public bodies. Pilots will both provide stored (but still unused) historical data and allow the additional collection of new data. Measurements will be performed during the project, and data will be collected from CMMS and BAS to improve and further validate the proposed approach for data collection, structuring, and analysis. In this way, DIGITMAN, strictly related to a set of EU strategies (e.g., A digital future for Europe, Next-generation EU plan) and the Italian PNNR, will have a particular impact on the digitalization of the Italian public sector, considering that about 10% of the total Italian building stock is managed by public authorities.

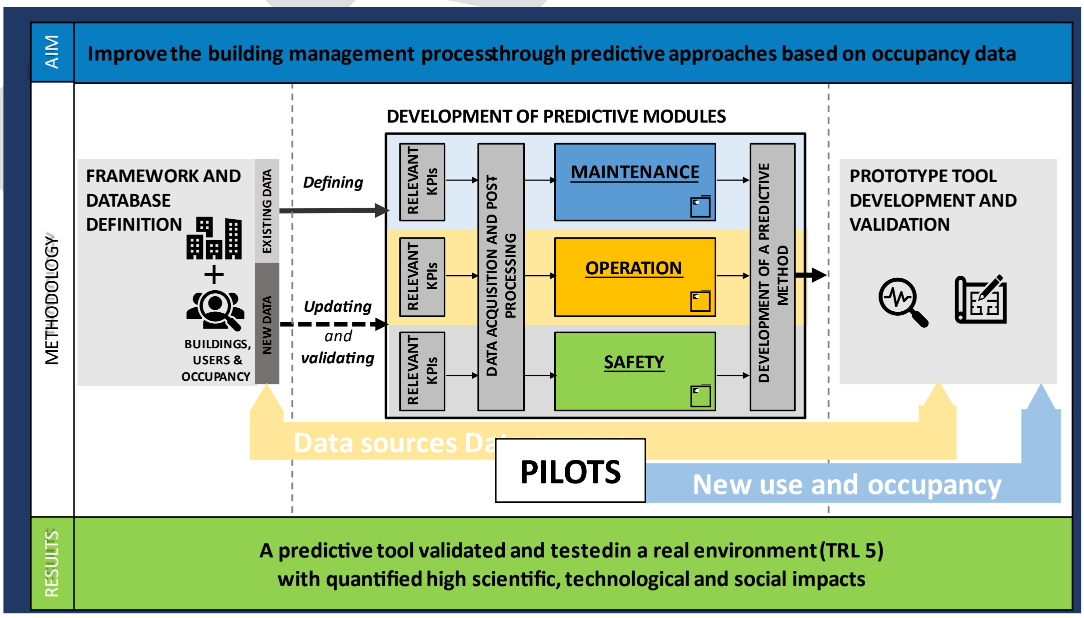

Figure 1: overall DIGITMAN flowchart.

Given the above, this deliverable traces the background of the work (Section 1) by then defining the logic, ontology, and semantics of the framework (Section 2) and finally providing a complete overview of the case studies adopted in the project (Section 3).

1 Groundwork

The background of the DIGITMAN project essentially relies on the issues affecting occupancy-based building management, thus connecting the occupants with the building features and the different operational tasks (Section 1.1), and on the specific definition of the adopted building management hierarchy, which is consistent with the main work pillars (Section 1.2).

1.1 Occupancy-based building management

While most buildings are designed for occupants, with the function of providing comfortable, healthy, usable, and secure spaces, human-building interaction remains one of the least mature fields of building science [2, 3]. However, a *Scientometrics* analysis (Figure 2) shows a growing interest in the field due to the growing availability of methods and devices to acquire information about occupants' behavior. They can support the implementation of predictive approaches to improve operation, maintenance, and safety, which are the three pillars of building management and human-building interaction.

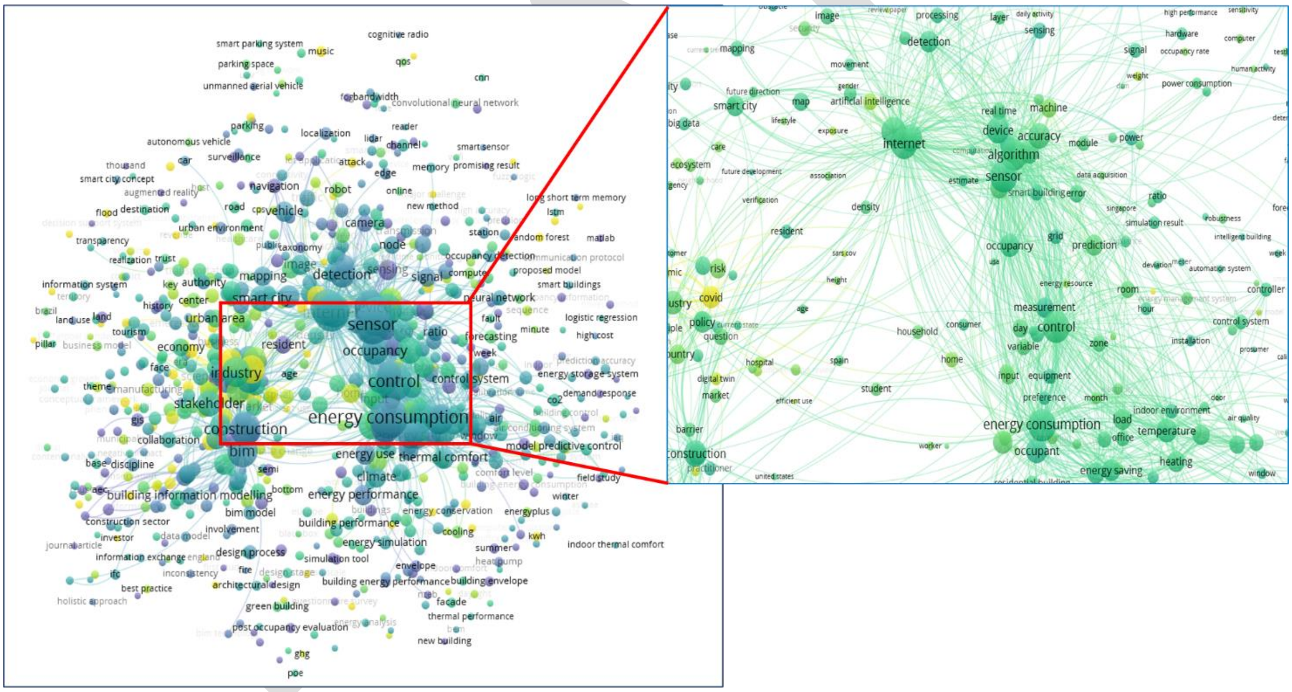

Figure 2: Co-occurrence network, based on a "scientometric" analysis of titles, abstracts and keywords of 5500 papers (building management topic). Colors represent the publication year (from Purple=2019 - to Yellow=2022). The bubble size represents the number of occurrences, the arcs represent the link between occurrences. Analysis has been performed using Voswiever code.

Post-occupancy evaluations suggest that buildings are often uncomfortable, have safety issues, are difficult for occupants to control, are expensive to manage, and operate inefficiently with regard to occupants' preferences and presence. BASs (Building Automation Systems) and CMMSs (Computer Maintenance Management Systems) technologies were introduced to manage complex buildings and building-stocks, but collected data are rarely used to improve building management, considering the occupants' complexity and diversity. For large and distributed organizations, building management costs can reach up to 75% of the overall life cycle cost [4]. Thus, introducing occupant-based predictions can potentially promote innovative strategies, support decision-making, and reduce operation and maintenance (O&M) costs. A recent review on building management [5] also shows how the research community should be involved in improving these processes. Three topics, relying on digital approaches, are proposed: (i) AI-supported building management procedures for fault detection, diagnostic, and predictive control; (ii) data extraction and visualization support to transform stored data into information to optimize processes; (iii) advanced occupants' feedback and behavior-based technologies. Gunay et al. [1] developed a review to identify the state of data analytics for improving building O&M, showing that existing untapped or underutilized data sources, e.g. CMMS, can significantly optimize the building management process. For instance, Zhao et al. [6] developed a conceptual framework to apply digital twin technologies and use information stored in CMMSs and BMSs for building management improvement. The authors organized a framework (Figure 3) showing how data about occupants' behavior collected during the operation of buildings (e.g., BAS, CMMS) can support the development of AI-based functions to introduce predictive management approaches.

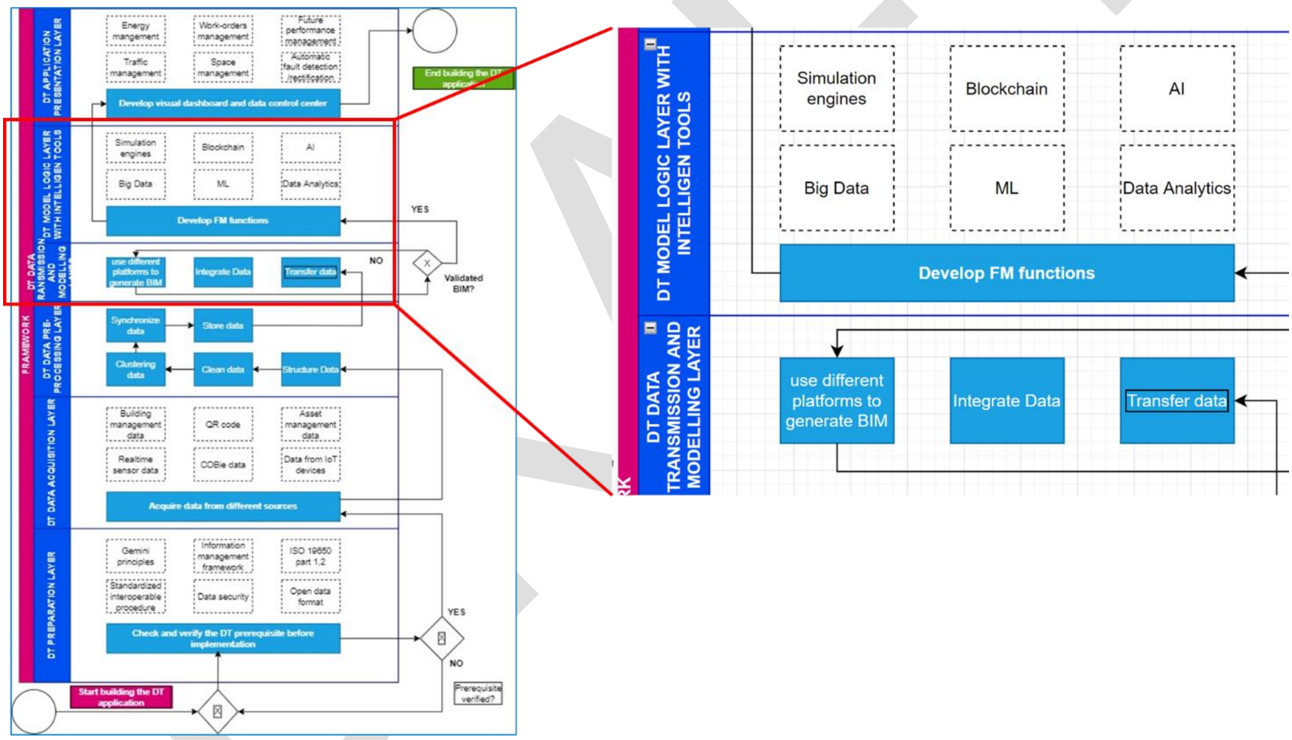

Figure 3: Conceptual framework to apply digital twin technologies. Source: [6]

Introducing AI into building management procedures has also been discussed by Molina-Solana et al. [7]. Predictive management approaches need the support of deep knowledge of occupants' behavior and the acquisition of dynamic occupant data [2, 8]. The EU [1, 9–11] recently published guidelines to foster the introduction of a tool for building management digitalization [12], also supporting the creation of a common European framework [13–15]. However, several issues must still be solved [16, 17], i.e.: define common languages, interfaces, and protocols for a common framework; find methods to grant data matching (blockchain); improve usability; and above all, shift from a static data collection approach to a more dynamic one, including, also, dynamic occupant data.

Only by acknowledging the occupancy dynamic data (i.e., occupants' movement, activities and use of the spaces over time, dynamic energy and maintenance needs, and safety procedures), is it possible to predict the impact of alternative strategies, define a clear renovation roadmap and correctly allocate economic and technical resources. Occupancy dynamic data, collected through BMSs integrated with new technologies (i.e., real-time use, sensors), and also through CMMSs, could be analyzed by text mining [4, 5] and machine learning methods [17–19] and used as the basis to predict the impact of future scenarios. However, it is important to underline that the biggest building stock owners in almost all State Members are public authorities [9]. Around 10% of the Italian building stock is directly managed by local public authorities [23], which is generally underdeveloped in digitalization. Building-related data managed by public authorities continue to be scarce, of unreliable quality, and limited accessibility [9, 20]. The lack of a common data repository leads to additional costs and inefficiencies [9]. Hence, the proposal of a project addressed to improve the digital management of the building stock starting from occupancy data can have a particular impact on the renovation of the public sector, on the reduction of public expense by introducing more effective procedures [10], also supporting other EU high-profile policy initiatives, such as "A Europe fit for the digital age", the "European Green Deal" and its Renovation Wave [21], the new Circular Economy Action Plan and the forthcoming Strategy for a Sustainable Built Environment.

DIGITMAN can contribute to the optimal allocation of technical and economic resources for the management of large building stocks while at the same time supporting the administrations in adopting new digital processes, developing practical tools and methods joined in a decision support system that could spread the "digital know-how" in the AEC domain for the operations of retrofit and management of building stocks (Figure 4).

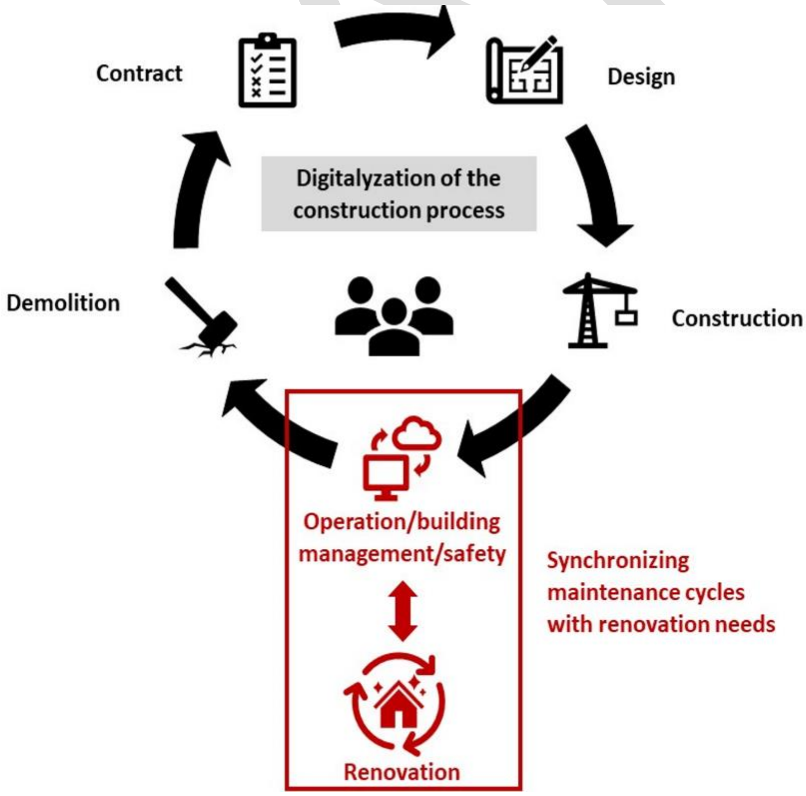

Figure 4: The building lifecycle and the scopes of DIGITMAN, marked by the red box).

About 10% of the Italian building stock and large building stocks are mainly managed by local public authorities. The amount of money spent annually to manage these buildings is very large due to their age, complexity, and dimension. About 60% of the buildings managed by local public authorities were built before 1980, and a relevant part comprises listed buildings. To improve this stock, about 10 billion € were introduced in the national resiliency and recovery plan (PNRR), but these resources are quite largely inadequate. Estimations suggest that the overall refurbishment of the public Italian stock (more than 1 million buildings and 350 million sqm) could require more than 250 billion € and that the annual expense for management activities (operation, maintenance, safety) could reach 5 billion €. The extraordinary cost and the time necessary to reach a whole deep renovation of this building stock requires strategies and tools to plan the correct allocation of technical and economic resources and to support the necessary renovation roadmap while reducing O&M costs towards the improvement and the decarbonization of the building stock.

The EU Commission highlighted the necessity of supporting the renovation process of building assets through the digitalization of the management process, introducing, for example, the digital logbook [10], a common European framework for the whole lifecycle digital repository for buildings. The EC has also funded numerous projects on this specific topic, such as ALDREN [22] and EENVEST projects [23].

However, several issues remain to be solved to reach this goal. From a technical point of view, it is necessary to define common languages, interfaces, and protocols for a common framework, find methods to grant data matching (blockchain) and improve the digital tools' usability. Above all, from a conceptual point of view, it is necessary to shift from a "static" data collection approach to a "dynamic" approach, including dynamic occupant data (i.e., occupants' movement, activities, and use of the spaces over time; dynamic energy and maintenance needs; safety procedures). Considering the occupation dynamic data, it is possible to predict the impact of alternative strategies, define a clear renovation roadmap, and correctly allocate economic and technical resources. Moreover, these strategies should be coupled with selecting proper indicators that the stakeholders can exploit, i.e., building managers, to have a clear overview of the current and future building status [24–26].

1.2 Building management hierarchy

To solve the general issues defined, DIGITMAN proposes a common digital framework and a modular prototype tool (technology readiness level-TRL 5) for collecting the more relevant building information, describing the dynamic state of the building (including occupancy), improving the daily management process, and predicting the impact of new scenarios on the building management activity. These tools support and contribute to the decision-making process of building stock managers, supporting the daily activities and giving reliable estimations of the costs of the different renovation measures (e.g., new uses of the buildings/areas, new occupancy levels, refurbishment alternatives) in a long-term vision (i.e. considering possible alternative use scenarios).

In particular, DIGITMAN will consider the following three main pillars of building management:

1. **Operation** (activities that are meant to ensure occupants' well-being, e.g., energy control, lighting control, etc)
2. **Maintenance** (activities, planned [27] and unplanned, necessary to maintain the functionality of the buildings and avoid failures during operation [28, 29], e.g., intervention on building components/systems, etc.)
3. **Safety** (activities necessary to grant occupants' safety [1], e.g., emergency plan definition/control, fixed/movable safety devices control, etc.)

A modular approach will be introduced to face issues from these pillars: the whole digital framework will be developed, and a specific limited set of predictive modules will be developed. In this way, the building manager's tasks can be supported by a unique and interconnected tool (Figure 5).

The maintenance pillar [4, 30–34] concerns the quantity and quality of required interventions for daily maintenance activities, according to the current and future building conditions, by including their priority and type. In this sense, the probability, by number, type, and localization of new maintenance requests due to new occupancy scenarios could also be estimated.

The operation pillar [1, 35–38] mainly concerns (A) the automatic identification of optimal energy profiles and building control (air temperature, RH, CO_2 level) according to different occupancy scenarios and building characteristics and (B) simulation-based prediction of the impacts of future occupancy scenarios on schedule planning and energy consumption.

The safety pillar [39–42] is focused on fire safety as relevant tasks in building management for both costs and regulation-related issues, and in view of the strict connection between occupancy, use and building features (in terms of hazards and vulnerability due to hosted activities), and management requirements. The pillar mainly concerns the prediction of possible occupancy conditions requiring building interventions and risk-assessment/management planning actions by the building manager. This framework deeply relies on the regulations regarding fire safety thanks to fire safety engineering, according to the modular and easy-to-implement concepts of Italian Fire code [43].

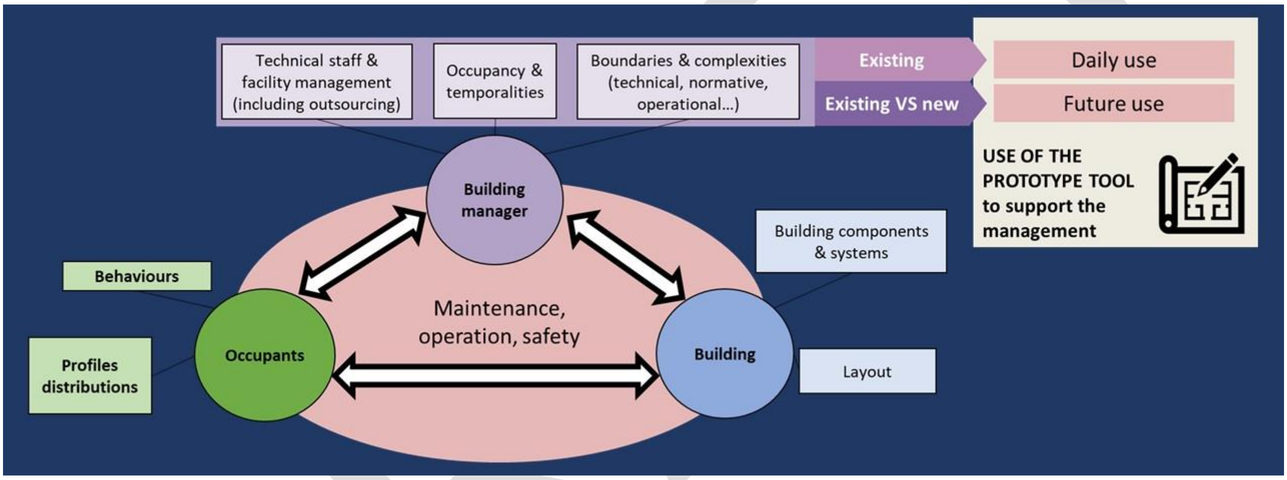

Figure 5: Overall system representation in respect of the main three DIGITMAN, that are maintenance, operation and safety, which are correlated to the building manager tasks and their connection in the whole operational framework, that DIGITMAN output tools can support.

2 Framework and criteria

This section of the document outlines the framework underlying the development of DIGITMAN and the methodological criteria adopted for information management within the project. In the first part (section 3.1), the project's underlying intentions are explained, including the logic behind the operation of the DIGITMAN applications and the functionalities to be developed. The second section (section 3.2) defines the semantic and ontological rules that form the informational basis of the project, enabling a uniquely shared identification of information among the various project partners and between the project and external data providers. Finally, the last section (section 3.3) illustrates the methodology for realizing the BIM models of the investigated buildings, presenting a topology-based modeling approach as a semi-automated method for built asset digitization.

2.1 Logics and functionalities

According to the main pillars defined in Section 1.2, two main logics have been developed to define current/daily support tools and future conditions support tools in building management and planning. The logics are:

- **WHAT-IF** logics: it ensures **Medium-long term predictions** (support to future decisions) based on hypotheses about future scenarios, derived from new uses and occupancies, as well as retrofitting/adaptation tasks of the building stock
- **HOW-TO** logics: it ensures **Short-term predictions** (support to actual decisions) based on past (trained) and real-time information, derived thus from the current use and occupancy of the building stock, within the current built environment scenario conditions.

	automate the facility manager's daily activities:	***predict the impact of new occupancy scenarios on the economic and technical resources to allocate in the future:***
M	Automatic identification of the technical category and priority of the users' maintenance requests	Probability of number, type and localization of new maintenance requests due to new occupancy probabilistic scenarios (*NO refurbishment*)
O	Automatic identification of optimal building control (air temperature, RH, CO_2 level) according to different occupancy scenarios and building configurations	Prediction of future energy needs according to different occupancy scenarios and building configurations
S	Automatic detection of fire safety issues due to the number of people/use of building/area in respect to the original safety plan	Probability of new building interventions, for new fire safety potential issues, due to new occupancy probabilistic scenarios

Figure 6: DIGITMAN modules according to the three research pillars: some of the primary leading examples.

For each point, the first step concerns how to define the functionalities and the purposes for which the tool should be developed. Mainly, this can be due by explicating the "What-If" scenarios related to occupancy conditions in buildings useful for building management purposes (divided into the Maintenance, Operation and Safety pillars). From a logical perspective, if scenarios (to be evaluated through the tools) are clear, the choice of the related Key Performance Indicators (KPIs) for evaluating them is simply and effectively directed to the actual needs for which the tool will be developed. In this sense, to restrict the field of investigation to DIGITMAN goals, scenarios are made based on two categories of strategies related to occupancy: A. variations in occupancy ; B. occupant-centric controls. In both cases, occupancy-related modifications can be also correlated to the revision of the building layout and components features. In the "How-to" process, analysis are devoted to understand how current data can be used to improve the current building management, thus supporting the building managers in the optimization of operational tasks.

Given the above, and in connection with DIGITMAN pillars, Figure 6 shows some examples of predictive modules and functionalities that could be developed during the project to reach the proposed aims.

2.2 Ontology and semantics

Digitalization processes for building management necessitate a foundational shift that transcends mere technological adoption. This shift requires establishing a universally accepted cultural approach based on developing standardized languages. This aspect, pivotal to facilitating data interchange and collaboration, has been historically addressed within the AECO realm where common vocabularies, schemas, ontologies, and protocols have been spreading to enable efficient, integrated, and standardized digitalization of building data systems, ensuring coherence and compatibility across various platforms, disciplines, and actors.

After providing a brief description of reference ontologies and classification systems developed for digital building management in the literature in recent years, this section illustrates how the need to standardize the information flows within digital systems for building management is addressed in the DIGITMAN project.

2.2.1 Reference classification systems, standards, and ontologies for building management

2.2.1.1 Classification systems for building management

One of the early attempts to standardize AECO's language was made through classification systems. Classifying items is a common technique characterized by the systematic organization of information, which humans employ to simplify the complexity of the real world. A classification system serves as a means for people to communicate effectively on various topics by offering a set of concepts that help reduce the subject's intricacy to a manageable level [44].

Since extensive datasets are generated throughout the various phases of a building's lifecycle, a standardized classification system that facilitates efficient data exchange among different fields of expertise is essential to manage, track, and utilize this data effectively. In classification systems, in fact, terms are defined, and knowledge of a specific field is structured to make such knowledge accessible to a broader audience beyond the specialists directly involved in that field.

The need for such systems led to the initiation of research into the organization of building information, with significant developments starting to emerge in the 1950s when the first classification system for the construction industry, SfB [45], was introduced. The growing adoption of digital tools and technologies, coupled with the publication of ISO 12006-2 in 2001, has further fueled the popularity of this research topic in recent years, as shown in Figure 7 [46] Over the past seven decades, numerous national classification systems have been created for the construction industry on a global scale. Considering the international recognition and importance they have garnered, it is noteworthy to mention the following ones: CI/SfB [45] and Uniclass [47] in the UK; and MasterFormat [48], UniFormat [49] and OmniClass [50] in the USA and Canada (Figure 8). However, the widespread development of these systems has not resulted in the establishment of a universally recognized and internationally adopted system within the construction industry. Instead, there are certain more established and widely shared classification systems than others, often due to specific contextual and local factors.

According to the findings of the literature reviews conducted by Kula and Ergen [51] and Royano et al. [46], the most commonly used classification systems during the FM phase are UniClass and OmniClass, which is based on both UniFormat and MasterFormat. What distinguishes these systems is their approach to grouping products based on their function rather than their systems, a characteristic that proves particularly advantageous for building operation and maintenance purposes. These systems adhere to open standards in accordance with international norms such as ISO, making them a crucial factor in the selection of a classification system.

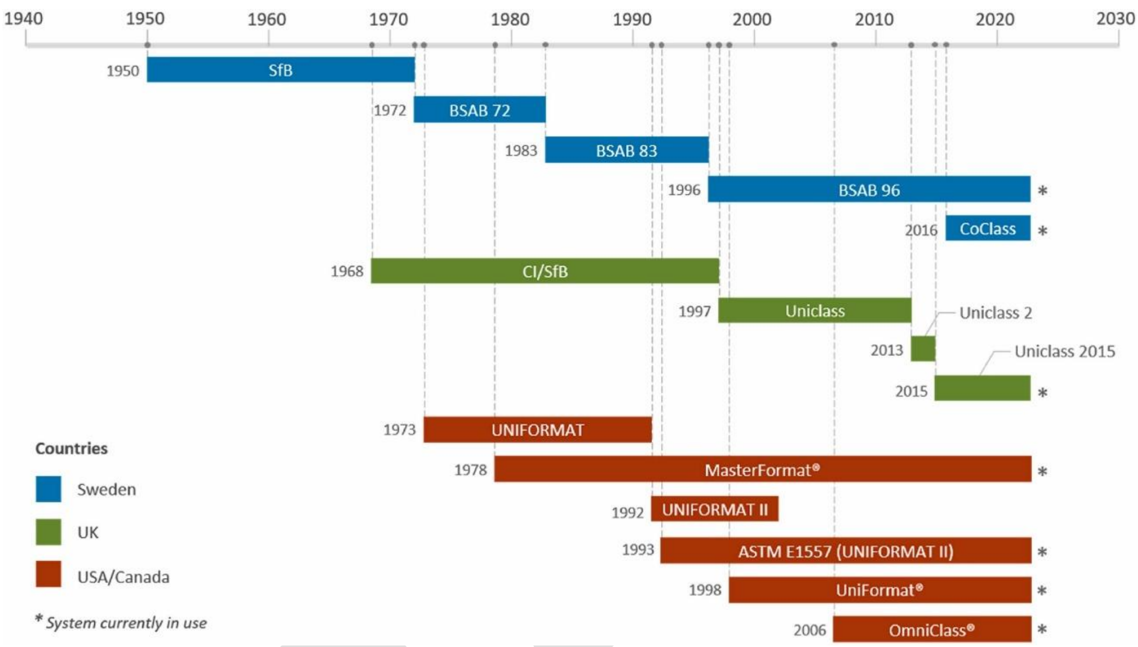

Figure 7. Timeline of building classification systems from Sweden, the UK and the USA/Canada (© Royano et al., 2023[46]*)*

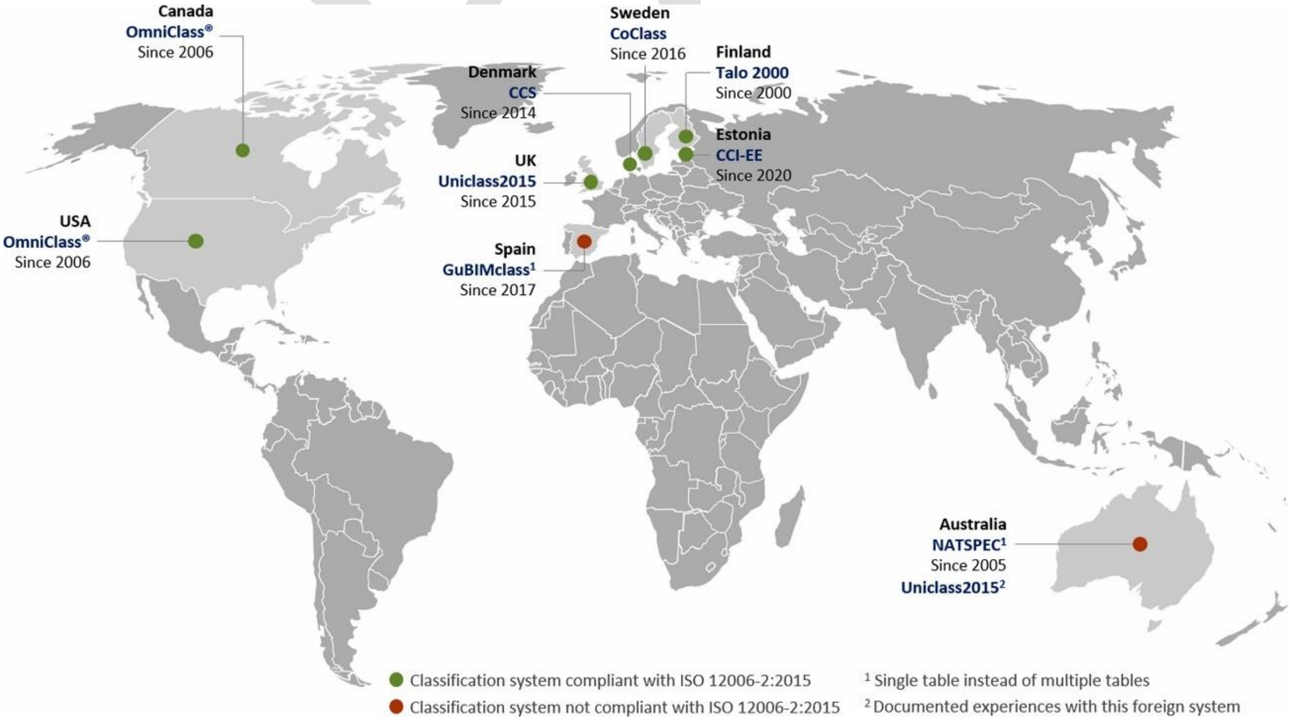

Figure 8. Map of building classification systems analyzed by Royano et al. (© Royano et al., 2023[46]*)*

Here is a brief description of them.

- **MasterFormat** [48] developed by The Construction Specifications Institute (CSI) and Construction Specifications Canada (CSC), is primarily used in North America for organizing construction specifications and cost estimation [52]. Its primary structure is based on work results [68]. MasterFormat employs an element coding system with four levels, typically consisting of six digits arranged hierarchically. In some cases, a fifth level, which can be a digit or a letter, may be used for added detail [53]. Because MasterFormat is based on work results, it encompasses mounted equipment and materials. However, its work breakdown structure is not organized by functionality but focuses solely on elements and systems [52]. For example, a centrifugal pump may be found under fire protection and water distribution systems, but it is not classified as a centrifugal pump, as it may be needed for FM purposes. While MasterFormat is an international classification system, it may not fully meet all FM requirements [51].
- **UniFormat**, like MasterFormat, has been created by CSI and CSC. However, unlike MasterFormat, UniFormat employs a classification system based on functional elements, describing these elements solely in terms of their functions without considering their materials or systems [53]. It follows a hierarchical structure with a 5-level coding system and aligns with ISO 12006-2 [49]. Additionally, it can be expanded by incorporating codes from MasterFormat. While UniFormatTM allows for the integration of MasterFormat codes, it remains hierarchical and lacks an object-oriented approach. It is particularly well-suited for FM due to its grouping of elements based on their functions and adherence to international standards.
- **Uniclass** is an internationally recognized classification system that originated in England in 1997. It is primarily designed to organize various phases within the construction lifecycle. Initially aligned with ISO TR 14177, it underwent a revision and was subsequently adapted to ISO 12006-2 standards [53]. Typically utilizing a 4-level coding system, it occasionally extends to 5 levels, employing 2-digit codes to represent each level. Uniclass tables have been specifically designed for asset management and FM purposes[47]. An extensive list of elements for FM purposes is provided by Uniclass, each associated with appropriate systems based on their function. The classification of Uniclass is not unambiguous. For instance, a copper pipework can be used in both gas supply systems and hot/cold water supply systems [51]. Due to its faceted structure and alignment with international standards, Uniclass proves to be a suitable classification system for the facilities management phase.
- **OmniClass** is a comprehensive classification system designed to encompass the entire lifecycle of a structure, from its inception to demolition [54]. It aligns with ISO 12006-2 standards and is well-suited for object-oriented classification [50, 52]. OmniClass tables can be utilized individually to identify specific elements or combined for more comprehensive classification. The coding system in OmniClass begins with a table number and extends to five or six levels, with two digits assigned to each level. Notably, some OmniClass tables are based on different classification systems: Table 21, 'Elements,' derives from UniFormat; Table 22, 'Work Results,' is based on MasterFormat; and Table 23, 'Products,' draws from EPIC. The 'Products' table, in particular, is well-suited for facilities management and is organized similarly to a product catalogue, allowing easy identification of items based on their functional categories. For instance, in a product catalogue, a water pump would be found under the plumbing section rather than under the water distribution system section. Additionally, OmniClass serves as the foundational classification system for the National Building Information Standard (NBIMS) developed by buildingSMART [55]. It is also in harmony with the classification system used in

the Construction Operations Building Information Exchange (COBie), making it compatible with BIM systems [51].

As mentioned earlier, in their recent literature review conducted in 2023 [46], Royano et al. pointed out that there remains a lack of global consensus regarding the utilization of a shared classification system for the built environment. To face this gap, the international non-profit organization CCIC is actively crafting a unified and comprehensible language for managing building information, to be employed concurrently across various countries and within all technical disciplines and industries. Regarding its potential adoption, Royano et al. argue that additional efforts are required to (i) finalize the core tables, which are common to all participating countries, (ii) assess the appropriateness of the core table content in local applications, and (iii) develop national component tables.

Another significant lesson learned derived from the research of Royano et al. underscores the importance of recognizing that, while the utilization of classification systems throughout the asset lifecycle is increasingly promoted, these systems are primarily designed to classify information gathered during the design and construction phases. In the case of existing buildings, this data may not always be readily available and must be collected on-site as part of technical inspections, which can pose various difficulties. Therefore, it is imperative to initiate a new avenue of research aimed at addressing the challenges associated with identifying and classifying such information during the operation and maintenance phase. This particular approach presents numerous possibilities for enhancing the management of existing buildings, such as the potential implementation of a novel functionality-oriented classification system.

2.2.1.2 Standards for building management

The need to standardize and harmonize definitions and language related to building components and, more importantly, construction and management processes has also led to the development of international standards. These international standards are developed and published by ISO (International Organization for Standardization) and can be voluntarily adopted at the national level by each member state. Some of the most important ISO standards that deal with digital asset management are grouped in Table 1.

Within the AECO sector, a crucial standard for data modelling is the IFC format, which was developed by buildingSMART International. IFC, which stands for Industry Foundation Classes, is «a standardized, digital description of the built asset industry. It is an open, international standard (ISO 16739-1:2018) and promotes vendor-neutral, or agnostic, and usable capabilities across a wide range of hardware devices, software platforms, and interfaces for many different use cases»[56].

The IFC standard stands out internationally for its unique approach. Unlike typical standards that are issued 'for users', buildingSMART International employs a validation phase within the developer community before releasing a revision. As a result, the IFC standard is primarily validated by its users, making it a 'user-validated' standard in the international context.

IFC is intended to represent all aspects related to the construction industry digitally. These are essentially 'building information classes,' which are data models capable of describing the entities that make up a project, including their attributes and the relationships between them, often including geometric information. IFC entity description follows a hierarchical approach, starting from the scale of a site (IfcSite), building (IfcBuilding), or infrastructure (IfcRoad), down to the materials that make up a portion of the work (IfcMaterial), establishing connections between all elements in the hierarchy. These elements range from physical entities such as IfcWall or IfcDoor to virtual ones like IfcZone or IfcBuildingStorey [57]. These relationships allow for the creation of various hierarchies, such as spatial hierarchies, which break down a building into multiple levels or functional-technical hierarchies that group all elements contributing to a specific function into an IfcSystem. Additionally, they can group similar elements into an IfcGroup, which can be represented based on common characteristics, process assignment, or other criteria [90].

The fundamentals of IFC description involve identifying a digital entity (IfcObjectDefinition), specifying the characteristics of that entity (IfcPropertyDefinition), and mapping the possible relationships that exist between entities (IfcRelationships), enabling by this way the reconstruction of the whole building as an integrated system. IFC's definitions and properties serve as a common foundation for digitising the building system, allowing the harmonization and alignment of different classification systems.

Table 1: Reference international standards in digital asset management of buildings.

Standard	Description
ISO 55000 – Asset Management	*Provides an overview of asset management, its principles and terminology, and the expected benefits of adopting asset management.*
ISO 19650 - Information Management Using BIM	*Part 1 - Concepts and Principles: outlines the concepts and principles for information management at a stage of maturity described as BIM* *Part 2 - Delivery Phase of the Assets: specifies requirements for information management in the form of a management process within the context of the delivery phase of assets and the exchanges of information within it, using building information modelling.* *Part 3 - Operational Phase of the Assets: specifies requirements for information management in the form of a management process within the context of the operational phase of assets and the exchanges of information within it, using building information modelling.* *Part 4 - Asset Lifecycle: specifies the detailed process and criteria for decision makings when executing an information exchange as defined by the ISO 19650 series to ensure the quality of the resulting project information model or asset information model.* *Part 5 - Security-Minded Approach: specifies the principles and requirements for security-minded information management at a stage of maturity described as BIM, as well as the security-minded management of sensitive information that is obtained, created, processed and stored as part of, or in relation to, any other initiative, project, asset, product or service.* *Part 6 - Health and safety information: delves into the safety-oriented approach within the context of BIM, digital built environments, and advanced asset management.*
ISO 6707 - Buildings and civil engineering works Vocabulary	*Contains the terms and definitions of general concepts to establish a vocabulary applicable to buildings and civil engineering works.*
ISO 16739 - Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries	*Part 1 - Data Schema: describes the IFC data schemas, represented as an EXPRESS schema and an XML schema, and reference data, represented as definitions of property and quantity names, and formal and informative descriptions.*
ISO DS 22014 - Building Information Modelling (BIM) - Information Delivery Manual (IDM) - Methodology and Format	*This standard specifies the methodology and format for the IDM within the scope of BIM*

The strategic importance of the IFC lies in its ability to map relationships. These relationships are key in defining all the criteria for membership and dependency crucial to the design and construction process, or in representing an existing building. This mapping facilitates a comprehensive and interconnected understanding of the building process and structure. The criteria for these relationships are diverse and range from functional connections managed through IfcRelConnects to associations with external sources of data and documents (IfcRelAssociates) and even the transcription of rules for the technological-functional decomposition of a system into constituent parts (IfcRelDecomposes). Each of these relationships allows monitoring of an entity's membership in a hierarchically superior system, which can communicate its requirements. This, in turn, enables continuous checks to ensure that the project/existing building or its digital counterpart complies with current regulations or contractual specifications, evaluating whether the attributes of dependent elements conform to the requirements of the higher-level classes [90].

The IFC standard currently serves as the main reference for organizing building-related data. However, despite its numerous advantages, it also has limitations as a data model for built asset management.

The IFC data model presents a 'knowledge' problem. First, due to its complexity, IFC is often misunderstood and oversimplified by practitioners, leading to its underutilization as merely a tool for exporting BIM models. This misconception results in improper data exportation, affecting the models' utility for management and contradicting the interoperability and data interpretability goals of the IFC standard. As a result, the interoperability issue, despite being promoted by IFC itself, is hindered by the standard. Second, IFC presents a technical issue of reading and writing files. This problem is, in some ways, both a cause and a consequence of the cultural gap within the IFC schema, described above. It arises from the fact that software for reading or writing often does not have access to all the classes and attributes of IFC. Thirdly, there is a significant issue concerning the depth of understanding of the standard. Asset Management teams often lack knowledge about what they should request and where to correctly input particular data in the IFC framework [58]. This gap in understanding affects the industry's effective utilization and implementation of the standard. Deepening knowledge of the standard becomes crucial to indicate which IFC classes should receive the information clearly. Otherwise, generic models may be generated, rich in data but lacking practical functionality.

Moreover, it should be noted that IFC alone cannot comprehensively describe all aspects and circumstances of building management [59]. For example, it remains challenging to securely enrich an IFC file with time series and dynamic data using currently available software. For this reason, buildingSMART International is expanding the scope of IFC by collaborating with other interconnected standards related to asset management. While awaiting these future developments driven by buildingSMART, the scientific community has been moving towards the standard and ontology federation principle. The federation principle is based on the assumption that IFC alone and any other ontology related to building asset modelling cannot integrate all the information about a built asset. Therefore, it is necessary to use various ontologies (or standards) specifically designed to cover specific aspects of a building and federate them to enable a comprehensive and coherent digital description of the asset throughout its lifecycle.

The need for federating ontologies and standards, coupled with the ever-increasing demand to access various sources of open construction data from the cloud, has materialized in the definition of semantic web technologies for the built environment [57], [58]. These can be used to formally represent data and metadata on the web. They can enable the benefits of ontologies in describing concepts, relationships between entities, and categories of things coming from different datasets on the web, offering significant advantages such as reasoning over data and operating with heterogeneous data sources. In other words, these technologies can combine the need for data access with that for formal representation of buildings to achieve not just a common language but also standardized services.

2.2.1.3 Ontologies for building management

IFC alone is not capable of describing all the aspects of building management. Moreover, its intricate structure makes it not straightforward to implement this schema organically within web applications for building management. For these reasons, additional ontologies are used complementary to IFC to treats about specific aspects of buildings not covered by IFC or to streamline the data mapping process within digital applications.

Lygerakis et al. (2022) identified the most important ontologies for buildings through a review article [60] and categorized them according to the phase they refer to, i.e., design or operation. Table 2 and Table 3 show the synthesis of their work.

Table 2. Reviewed ontologies for building design by Lygerakis et al. (2022).

Name	Scope/Description	Year
ifcOWL	*Descriptive OWL representation of IFC schema*	*2016*
simpleBIM	*Simplified version of ifcOWL*	*2017*
Green Building XML (gbXML)	*Information exchange between BIM and Energy Models*	*2000*
Tubes	*High-level description of building service systems*	*2020*
SimModel Ontology	*Exchange of energy simulation data*	*2014*
EnergyADE	*Exchange of energy simulation data*	*2014*

Table 3. Reviewed ontologies for building operation by Lygerakis et al. (2022).

Name	Scope/Description	Year
Semantic Sensor Network/Sensor, Observation, Sample, and Actuator (SSN/SOSA)	*Focuses on sensors in buildings*	*2011*
Web Thing Model (WoT)	*Model to describe the virtual counterpart of physical objects in the Web of Things*	*2015*
oneM2M BaseOntology's	*Provide syntactic and semantic interoperability between oneM2M and external systems*	*2016*
One Data Model (OneDM)	*Model to support a common language for the Internet of Things*	*2018*
Smart Energy Aware Systems		*2016*
ThinkHome	*Ontology that includes concepts needed to realize energy efficient and intelligent control mechanisms*	*2011*
Building Ontology for Ambient Intelligence (BOnSAI)	*A smart building ontology for ambient intelligence*	*2012*
DogOnt	*Model for all devices being part of IoT inside a smart environment*	*2008*
Ontology of Smart Building (SBOnto)	*Smart Building Ontology*	*2017*
Smart Applications REFerence (SAREF)	*Matches existing assets in the smart applications domain*	*2014*
Project Haystack 3	*Hierarchical representation of buildings entities and concepts utilizing tagsets*	*2014*
BASont	*Building Automation and Monitoring*	*2012*
Project Haystack 4	*Hierarchical representation of buildings entities and concepts utilizing tagsets*	*2019*
Haystack Tagging Ontology (HTO)	*Streamlining Data from IoT based on Project Haystack*	*2016*
Brick Schema	*Metadata and data points from building advancement and needs based on end-use applications*	*2016*

Name	Scope/Description	Year
Google Digital Building Ontology	*Represent structured information about buildings and building-installed equipment*	*2020*
Semantic BMS ontology (SBMS)	*BAS-protocol-independent model of intelligent building systems*	*2016*
CTRLont	*Model of Control Logic in Building Automation Systems*	*2017*
Green Button	*Building Automation and Monitoring*	*2011*
RealEstateCore (REC)	*Usage analysis and optimization and presence analysis of a building structure*	*2017*
Building Topology Ontology (BOT)	*Representation of physical and conceptual objects of a building and the connections between them*	*2019*
Building Automation and Control Systems (BACS)	*Supports the modelling control behavior in a BAS, physical devices of BAS and their location in the building and connection to technical equipment and appliances*	*2017*
Knowledge Model for City (KM4City)	*Representation model for city and mobility*	*2014*
EM-KPI Ontology	*Enhance energy management at district and building levels*	*2017*
Facility Smart Grid Information Model	*An abstract information model of what the Smart Grid looks like from the perspective of a facility*	*2014*
RESPOND	*Manage real-time optimal energy dispatching, considering all energy assets on-site*	*2020*

The following predominant ontologies mentioned in the tables are chosen as references for developing the ontological framework presented in the next paragraphs and supporting the development of the research project. They are Industry Foundation Classes (IFC)[1]; Building Topology Ontology (BOT) [61]; Brick [62]; Semantic Sensor Network (SSN) [63]/Sensor, Observation, Sample, and Actuator (SOSA) [64]; and EM-KPI Ontology (EKO) [65]. IFC, the open BIM standard supported by buildingSMART, is the most recognized schema for BIM data. Its integration with semantic web technologies is allowed by the IFC web ontology language (ifcOWL). The Building Topology Ontology (BOT) is a simplified ontology proposed by W3C that exclusively addresses the core building concepts revolving around the building's topology, including physical and conceptual components and their relationships. Brick is an open-source schema that standardizes the semantic descriptions of buildings' physical, logical, and system assets and interrelationships. Its primary focus is on smart building applications and equipment representation. SSN describes sensors and their observations, features of interest and samples, procedures, and actuators. It is often used to describe BAS data with semantic tags. SOSA, instead, redesigns SSN to provide a lightweight, general-purpose specification for modeling the interactions between entities involved in observations, actuation, and sampling. Finally, EKO enhances multilevel energy management and energy performance information exchange.

Table 4 compares the capabilities of these schemas, adding to them the Topologic's ontology (TOP), the ontology supporting the Topologic software toolkit [66], which will be further discussed later in the document. Figure 9 provides instead an overview of some of the mentioned ontologies.

All these ontologies may allow for organizing concepts within graph structures. Such graphs comprise nodes (or vertices), denoting entities and subjects, alongside edges representing the connections between these nodes (relationships or links). Both nodes and edges can be characterized by semantic attributions and property descriptions [67]. Organizing domain concepts and information in knowledge graphs (KGs)

[1] ifcOWL Ontology. https://standards.buildingsmart.org/IFC/DEV/IFC4/ADD2_TC1/OWL/index.html (last access: 05/07/2024)

allows for, first, assigning semantic and ontological meaning to data, as well as enabling semantic query, extraction and analysis of data from complex data structures; second, proficient visualization and, therefore, comprehension of a knowledge domain and its segmentation into knowledge sub-domains.

Beyond these capabilities, KGs also excel in analyzing extensive datasets entrenched in diverse formats. Moreover, if coupled with semantic web technologies [68], KGs can allow fast accessibility to information on the web, an issue that has become a priority for modern digital decision support systems.

Table 4: Comparison between different data schemas and ontologies.

Schema	Geometry	Topology	HVAC systems	Sensor systems	Operational relationships	Dynamic observations	Key performance indicators
IFC	*Yes*	*Yes*	*Yes*	*Yes (generic)*	*Yes (generic)*	*No*	*No*
BOT	*No*	*Yes*	*No*	*No*	*No*	*No*	*No*
Brick	*No*	*Yes*	*Yes*	*Yes*	*Yes*	*No*	*No*
SOSA	*No*	*No*	*No*	*Yes*	*Yes*	*Yes*	*Yes (generic)*
EKO	*No*	*Yes*	*No*	*No*	*Yes*	*Yes*	*Yes*
TOP	*Yes*	*Yes*	*No*	*No*	*No*	*No*	*No*

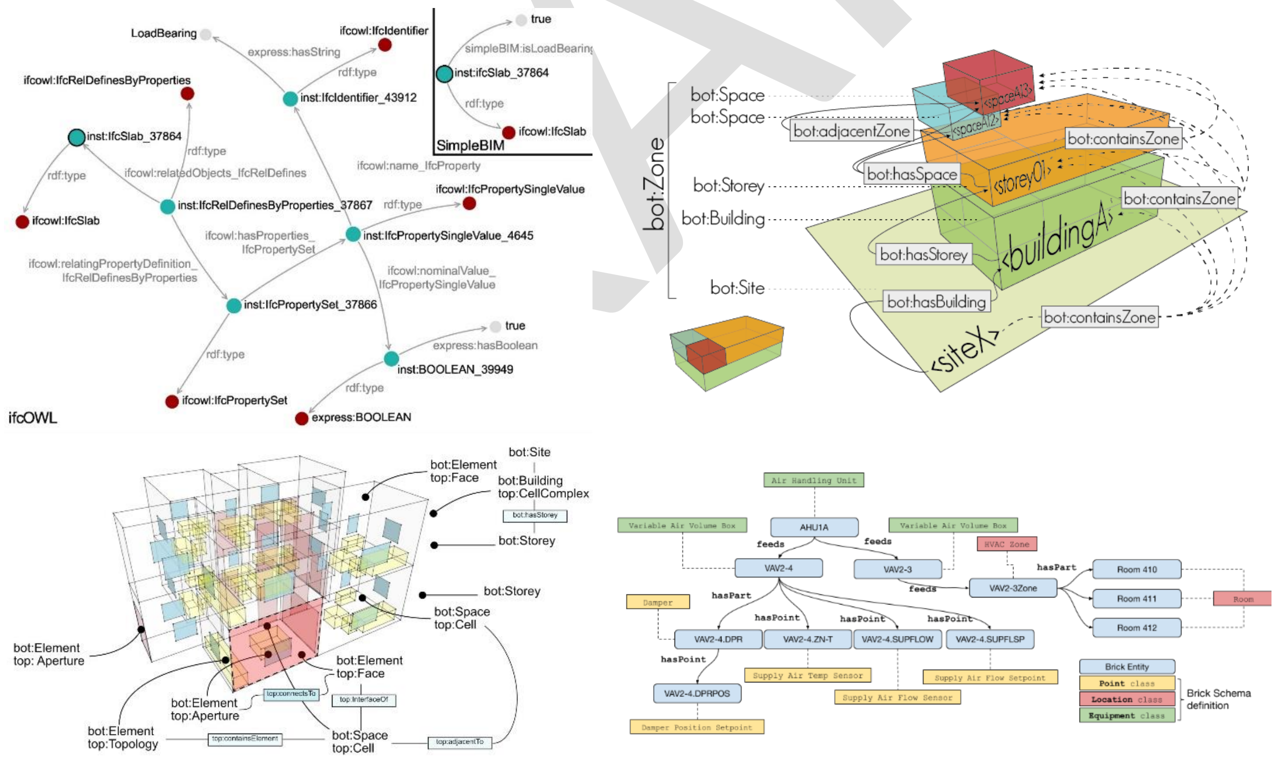

Figure 9. Examples from the ifcOWL, BOT, TOP and Brick ontologies.

2.2.2 DIGITMAN Ontology Definition

Leveraging on some of the described classification systems, standards and ontologies, DIGITMAN assumes that buildings can be represented as graphs consisting of nodes (subjects) and edges (predicates). To represent information in an organized manner, nodes are classified into element classes, while edges define various types of relationships.

In DIGITMAN, the graph representation is based on a specific ontology that serves as a unified data representation model for the project. This ontology is developed by federating established ontologies in the AECO sector, including BOT, IfcOWL, Brick, SSN, SOSA, TOP and EKO. Additionally, it incorporates new definitions created specifically for DIGITMAN (DGM) to address some maintenance and safety issues, whose representation is not explicitly addressed in these ontologies.

The DIGITMAN's ontology is subdivided in different modules to provide partial representation of the information domain within building management. These are:

- Spatial Element Module (Figure 10);
- Interface Module (Figure 11);
- Equipment Module (Figure 12);
- Evacuation Module (Figure 13);
- Maintenance Module (Figure 14);
- Property Module (Figure 15);
- Key Performance Indicator Module (Figure 16).

2.2.2.1 Spatial Element Module

This module allows mapping spatial elements within a portfolio. All these objects establish a hierarchy necessary for representing the building's spatial configuration, allowing for the detailed specification of physical locations and the inclusion of elements (such as sensors or equipment devices).

At the foundational level, the ontology employs the BOT's zones (i.e., 'bot:Building', 'bot:Site', 'bot:Storey', and 'bot:Space').

Moreover, the ontology uses Brick to add spatial elements like 'brick:Portfolio', 'brick:Region', and 'brick:Zone'. The first represents a collection of built assets managed by a single administration. The second represents a unit of geographic space, usually contiguous or somehow related to a geopolitical feature, which for university buildings often coincides with the notion of "district" or "campus". The third, on the other hand, refers to the grouping of spaces, which can be done for functional, energy, system, or fire safety reasons.

Additionally, there is 'dgm:BuildingCluster' which represents a group of buildings clustered for administrative reasons. For example, in universities, these clusters can refer to the various faculties managed by university entities

2.2.2.2 Interface Module

The interface module allows for the description of interface elements. Interfaces represent the generalization of buildings' construction components that bind topologies. Like BOT's Interfaces and Topologic's Faces, they are used to identify adjacency relationships between two spaces or zones when necessary.

This module includes the 'top:Face' elements and the 'top:Aperture' elements from the TOP ontology. Faces include vertical, horizontal, or inclined interfaces that subdivide spaces and zones from other spaces and zones or from the external environment. From a topological point of view, faces can be walls (a vertical or inclined face that bounds or subdivides spaces), slabs (a horizontal face that normally encloses a space vertically, separating it from the ground or other spaces), or roofs (a horizontal or pitched face that encloses a space from above). Apertures are openings in faces that allow the passage of people or light, such as doors (an aperture that provides controlled access for people and goods, allowing passage from one space to another), windows (a transparent aperture that allows light and natural air to enter and lets occupants see the outside environment), and holes (an opening that allows passage from one space to another through horizontal or vertical interfaces).

In this module, BOT is used to model 'bot:interfaceOf' relationships, representing the connection between interface elements and the spaces and zones they bind. Moreover, the 'top: connectsTo' relationship is used to map the hosting relationship between apertures and faces.

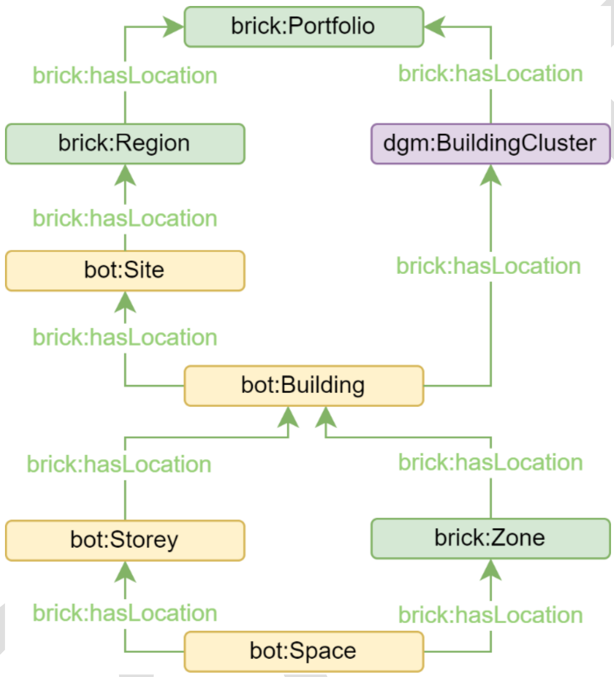

Figure 10. DIGITMAN's ontology. Spatial Element Module.

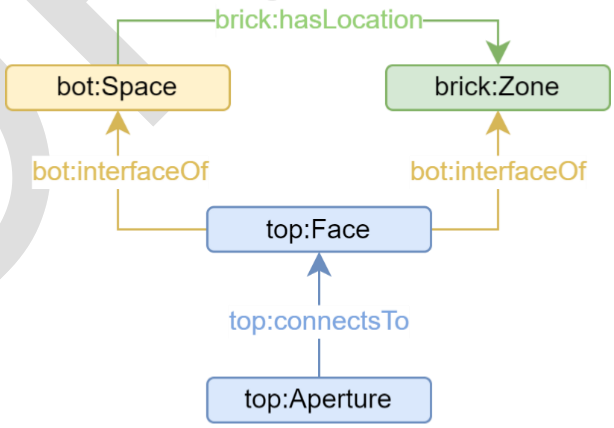

Figure 11. DIGITMAN's ontology. Interface Module.

2.2.2.3 Equipment Module

The equipment module allows for describing equipment and sensor elements and their relationships with the spatial elements.

IfcOWL allows for the representation of sensor elements, considered as physical electronic devices, using the 'ifc:Sensor' class. Moreover, Brick enables mapping sensor elements as 'brick:Sensor'. While there seems to be an overlap with 'ifc:Sensor', Brick sensors are denoted as 'brick:Point', which are input points symbolizing the value captured by a device or instrument engineered to detect and measure various variables. This indicates that a single IfcSensor device can embody multiple points (thanks to the 'brick: hasPoint' relationship). For instance, a 'brick:HumiditySensor' and a 'brick:TemperatureSensor' points may continuously provide data to an 'ifc:Sensor' device.

Equipment elements are instead treated as 'brick:Equipment' elements. These elements can be grouped into 'dgm:Subsystem' and/or 'brick:System', intended as combinations of equipment and auxiliary devices (e.g., controls, accessories, interconnecting means, and termi-nal elements) by which energy is transformed so it performs a specific function such as HVAC, service water heating, or lighting.

The physical link between sensor/equipment elements and spaces is given by the relationship 'brick:hasLocation'. Moreover, operational link between the systems and the spatial elements is given by the 'brick: feeds' relationship.

The ontology further incorporates the SSN and SOSA ontologies through the 'sosa:Observation' and 'sosa:ObservableProperty' classes. These are pivotal for modeling the data generated by sensors (thanks to the sosa: madeBySensor' relationship) and the observational processes in a semantically rich context.

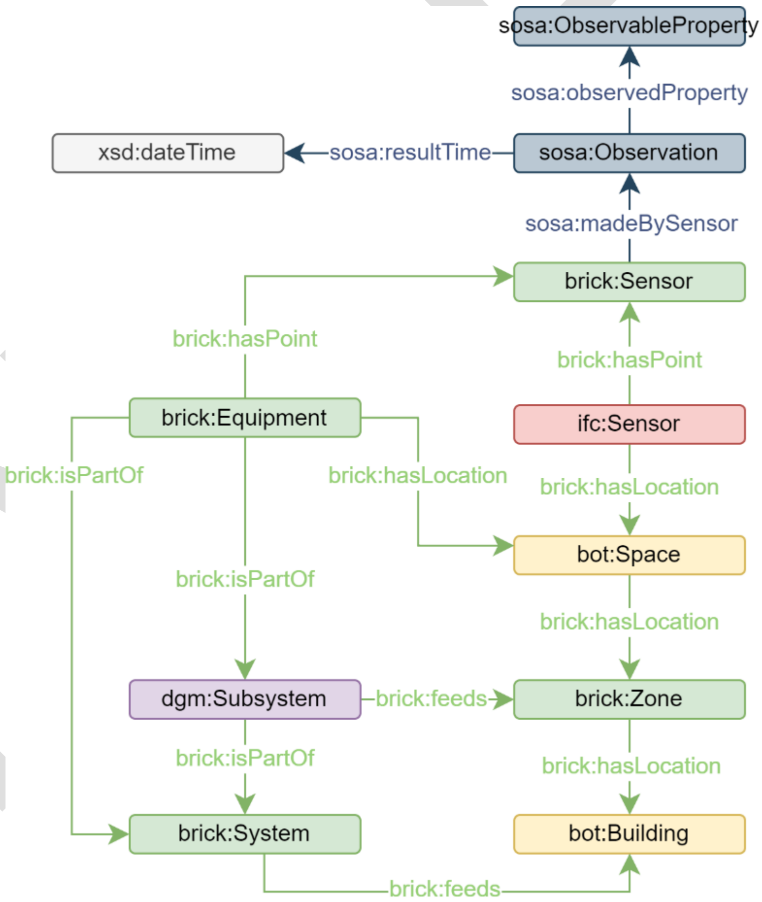

Figure 12. DIGITMAN's ontology. Equipment Module.

2.2.2.4 Evacuation Module

The evacuation module describes the building's evacuation systems. The ontology is primarily composed of DIGITMAN-specific classes, designed to align the ontology's objectives with the definitions provided by the Italian fire prevention code.

The building's evacuation system is defined as 'dgm:EvacuationSystem'. The system consists of a network is composed of a set of edges and nodes that form one or more routes. The nodes can be 'bot:Space', 'top:Aperture' or 'dgm:OpenAirSpace'. The edges are parts of the path that connect each node. The set of edges and nodes related to a single path within the evacuation network forms a route (for example, the path that leads from one space to another space), identified as 'dgm:route'. The set of multiple routes thus forms the evacuation network.

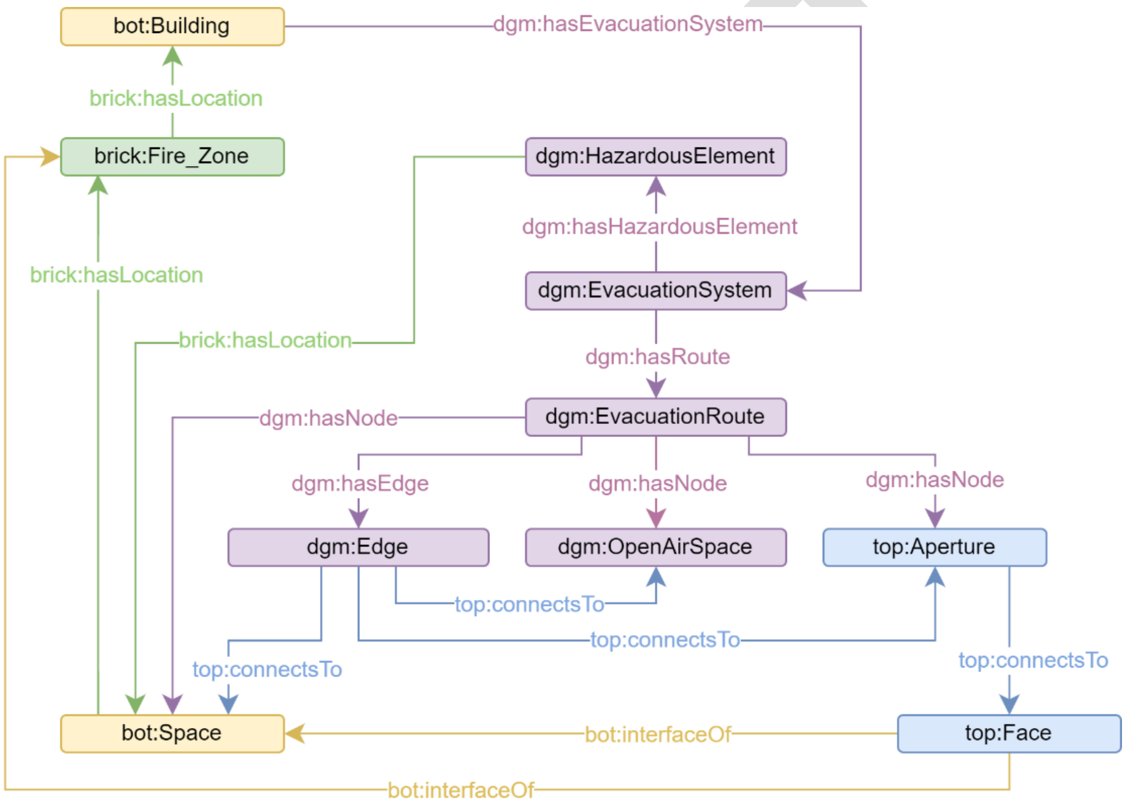

Figure 13. DIGITMAN's ontology. Evacuation Module.

2.2.2.5 Maintenance Module

This module allows for the representation of maintenance activities conducted in buildings. It primarily consists of two classes, 'dgm:MaintenanceActivity' and 'dgm:MaintenanceRequests', added by DIGITMAN to the federated ontology.

The 'dgm: MaintenanceActivity' class helps identifying the maintenance activities conducted within the spatial elements of the portfolio (i.e., 'dgm:BuildingCluster', 'bot:Building', 'bot:Storey', and 'bot:Space'), to which is linked thanks to the 'brick: hasLocation' relationship. These activities are initiated by 'dgm:MaintenanceRequests', which are the requests done by building management operators to the maintenance services for conducting maintenance in the buildings and their spaces.

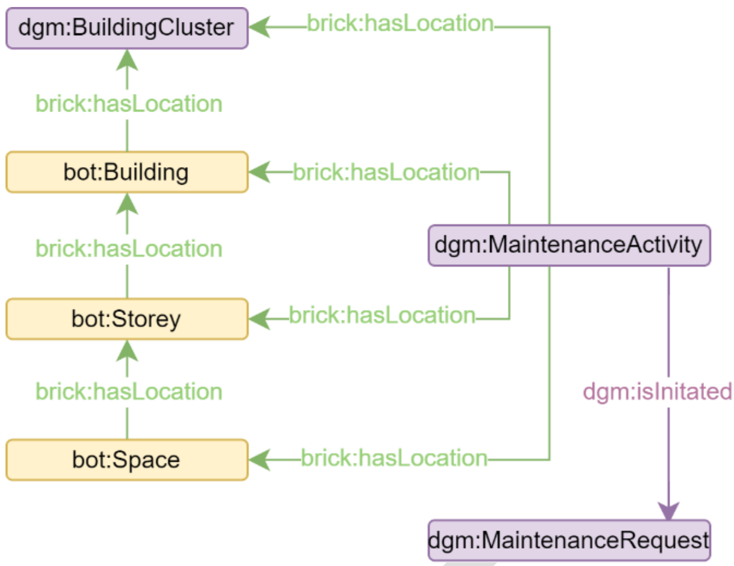

Figure 14. DIGITMAN's ontology. Maintenance Module.

2.2.2.6 Property Module

The property module allows associating properties and groups of properties to the spatial elements that compose the ontology.

IfcOWL, which is used in the ontology to map the properties of spatial elements as 'ifc:Property' within 'ifc:PropertySet', instrumental in providing detailed descriptions of element properties and their attributes. The relationship between property sets and the elements is given by the 'ifc: HasPropertySets' relationship, while the one between property sets and properties is given by 'ifc:HasProperties'.

Although not explicitly shown in the diagram, property sets can also refer to interface, equipment, evacuation, and maintenance elements.

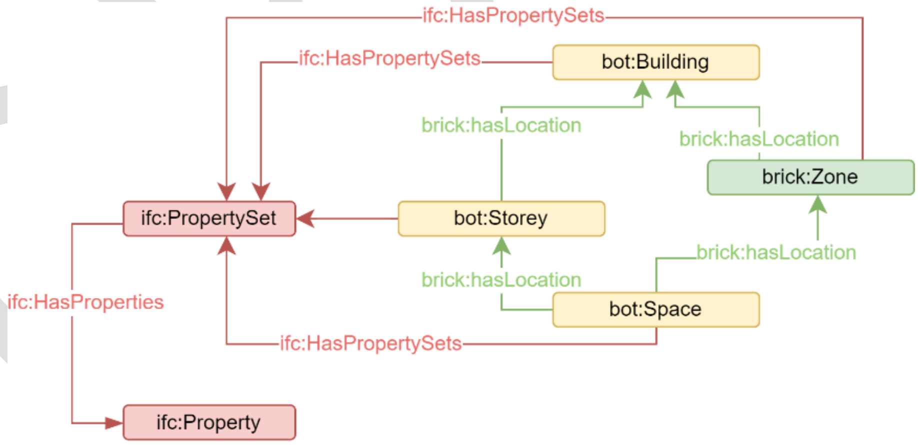

Figure 15. DIGITMAN's ontology. Property Module.

2.2.2.7 Key Performance Indicator Module

The key performance indicator module allows adding performance metrics to spatial elements.

At the core of the module is EKO, an ontology designed to account for the performance aspects of buildings. EKO, includes classes such as 'eko:KPI', 'eko:KPICalculation', and 'eko:KPIValue'. These classes are used to define, calculate, and store the values of performance metrics, which are crucial for evaluating building performance. The 'eko:hasAssociatedObject' relationship provides the necessary linkages between performance-related and spatial concepts. Additionally, this part of the ontology integrates time-related classes, such as 'time:Instant' and 'time:Interval', to represent temporal aspects, which are essential for capturing the dynamics of performance data and observations over time.

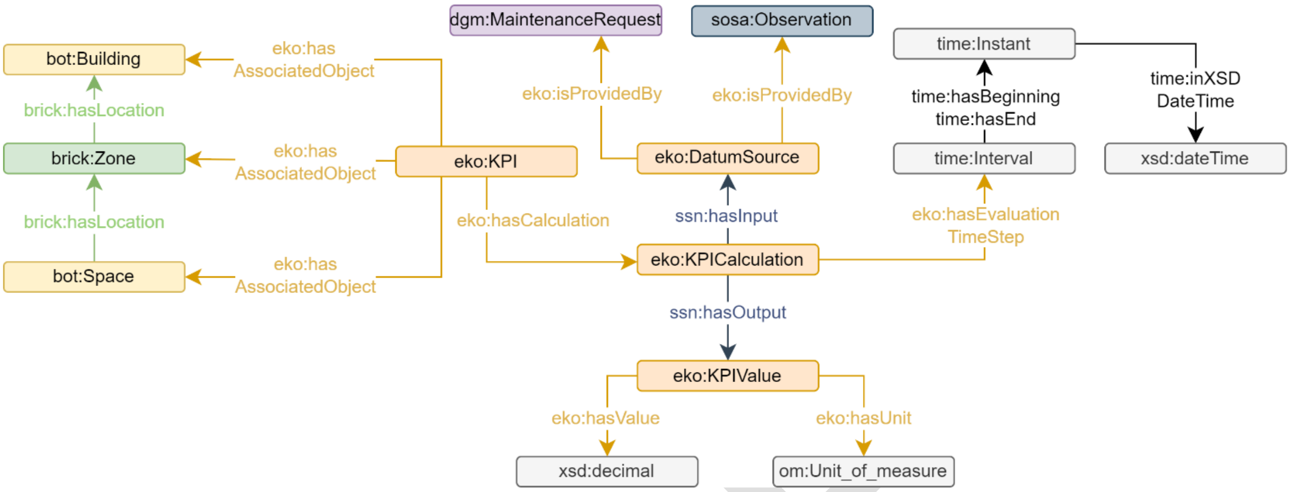

Figure 16. DIGITMAN's ontology. KPI Module.

2.2.2.8 Syntax

For modeling data in a consistent manner within graph structures, DIGITMAN is supported with a syntax that employs the JavaScript Obejct Notation for Linked Data (JSON-LD) to digitally represent entities and their interconnections in graphs. JSON-LD is a streamlined format for Linked Data, leveraging the prevalent JSON structure to enable JSON data to function seamlessly globally[2] . It significantly improves the ease with which data can be read and written by humans, offering a clear advantage over other formats like the EXPRESS format used in IFC. Due to its extensibility and adaptability, this data model allows the serialization of data and the creation of graph-based data models. Additionally, it is lightweight, rendering it suitable for data exchange within web environments and the development of web APIs and applications.

Specifically, DIGITMAN adopts the JSON-LD format to represent static elements and their connection in graph databases, whereas it sources dynamic data, like sensor observations and maintenance requests, from databases respectively tailored for unstructured (document databases) and structured time-series data (relational databases), which are more adept at managing large data volumes than graph databases (Figure 17).

Within the JSON-LD data format, each building element corresponds to a JSON object. This JSON object functions as a dictionary, possessing a unique identifier, the indication of its class within the ontology, and the relationships with the other objects within the KG. This data format is read by specific function and transformed into a KG.

Figure 18 presents examples of JSON-LD syntactic descriptions. The 'context' section enables the mapping of terms used in the document to Internationalized Resource Identifiers (IRIs) to provide precise meanings. In this part, reference ontologies (such as Brick and BOT) are mentioned, as well as the keys used in various JSON dictionaries to describe the objects. On the other hand, the 'graph' section describes the nodes that form the graph and maps the existing relationships between them ('relationships' keys). Deliverable 1.3 provides DIGITMAN's semantic data in the JSON-LD format.

[2] JSON for Linking Data: https://json-ld.org/ (last access: 05/07/2024)

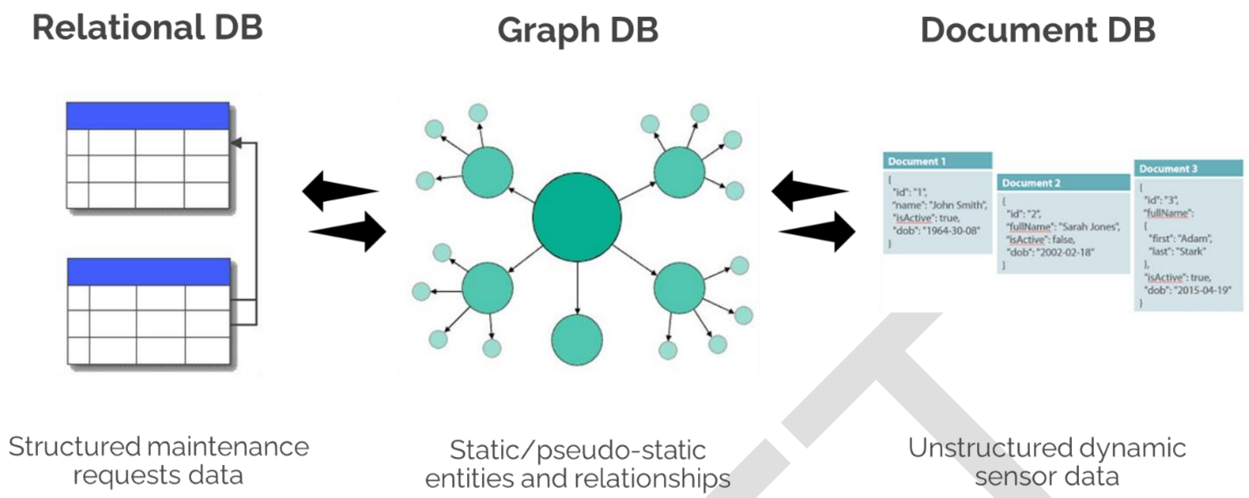

Figure 17. Graph, relational and document databases in DIGITMAN.

```
{
"@context": {
    "bot":"https://w3id.org/bot#",
    "brick":"https://brickschema.org/schema/Brick#",
    "ifc":"https://standards.buildingsmart.org/.../OWL#",
    "name":"http://schema.org/name"
    },

"@graph": [
      {
        "@id": "storeyX",
        "@type": "bot:Storey"
      },
      {
        "@id": "space1",
        "@type": "bot:Space",
        "relationships": {
            "brick:hasLocation": [
                  {
                    "@id": "storeyX", "@type": "bot:Storey"
                  }]}
      },
      {
        "@id": "sensor1",
        "@type": "ifc:Sensor",
        "relationships": {
            "brick:hasLocation": [
                  {
                    "@id": "space1","@type": "bot:Space"
                  }]}
      },
```

```
{
        "@id": "temperaturePoint1",
        "@type": "brick:Sensor",
        "relationships": {
            "brick:isPointOf": [
                  {
                    "@id": "sensor1","@type": "brick:Sensor"
                  }]}},{
        "@id": "PSet_SpaceThermalRequirements1",
        "@type": "ifc:IfcPropertySet",
        "name": "PSet_SpaceThermalRequirements",
        "relationships": {
            "ifc:IfcPropertySetDefinition": [
                  {
                    "@id": "space1",
                    "@type": "bot:Space"
                  }]},
        "ifc:hasProperties": [
              {
                "@type": "ifc:IfcPropertySingleValue",
                "name": "SpaceTemperatureWinterMin",
                "nominalValue": {
         "type": "ifc:IfcThermodynamicTemperatureMeasure",
                    "value": 20
                  }
              }
            ]
          }
        ]
      }
```

Figure 18. Example JSON-LD representation.

2.3 Selected DIGITMAN classification system criteria

Previous research developed a review-based comparison of consolidated classification systems all over the world, by outlining the advantages of the OMNICLASS™ one, which ensure the complete respect of all the requirements [51], i.e. to be: object-focused rather than properties-focused; update-prone; flexible to add new elements to the whole structure and substructures; developed considering international standards; commonly used in construction sector; usable by different disciplines, ensuring data transfer; compatible with Building Information Modelling (BIM) and thus ensuring BIM integration using the related data. In fact, the higher the number of satisfactory items, the more the advantages to use the related classification system.

OMNICLASS has been used as reference taxonomy in many previous research works and applications (i.e. ensuring also the application to standard IFC files[3]), OMNICLASS is mainly characterized by the possibility "to combine multiple existing classification systems for many subjects into a single unifying system based on ISO 12006-2, Organization of Information About Construction Works—Part 2: Framework for Classification of Information"[4]. To this end, it is composed of fifteen tables representing the construction environment and the related information in a structured and discrete way, using a multi-level description (i.e. from level 1 to level 4), and associating unique identification codes to each item in each table:

- Table 11 - Construction Entities by Function
- Table 12 - Construction Entities by Form
- Table 13 - Spaces by Function
- Table 14 - Spaces by Form
- Table 21 - Elements
- Table 22 - Work Results
- Table 23 - Products
- Table 31 - Phases
- Table 32 - Services
- Table 33 - Disciplines
- Table 34 - Organizational Roles
- Table 35 - Tools
- Table 36 - Information
- Table 41 - Materials
- Table 49 - Properties

In particular, in view of the building and facilities definition and representation, main tables considered in this work relates to: (1) Table 13, to ensure the representation of spaces within the topological models, depending on their function, and thus to take into account occupancy-based issues; (2) Table 22, to ensure the representation of activities in the building, by mainly referring to operational tasks performed by the facility managers in the three main pillars of the research.

Since the application context of DIGITMAN project could be affected by peculiar conditions and previous internal classifications (which could be also correlated to the regulatory systems and facility management structurings), in both the cases, Tables from OMNICLASS can be adapted to ensure the best representation of context-sensitive spaces and activities. Nevertheless, as the leading rational within the project, 1st levels modifications or integrations should be generally avoided to make the overall structure consistent with the original classification system. On the contrary, 2nd to 4th levels integrations and modifications could be widely performed.

In this sense, the OMNICLASS tables could be used to align all the research pillars, including the safety-related issues, i.e. by organizing fire-safety classification (i.e. nomenclature) from the national regulation [43] to the international one.

[3] https://biblus.acca.it/classificazione-omniclass-degli-oggetti-ifc/ (last acess: 03/07/2024)
[4] https://wbdg.org/resources/omniclass (last acess: 03/07/2024)

2.4 DIGITMAN rationale for topological approach

Building Information Modelling (BIM) and Building Performance Simulation (BPS) are recognized technologies in the building management sector. On the one hand, BIM enables the semantic and geometric representation of buildings, along with all their spatial and construction properties. On the other hand, BPS allows for the analysis of building performance (e.g., in terms of energy efficiency or safety conditions). BIM and BPS modelling procedures, however, can be time- and resource-intensive, especially when dealing with extensive building stocks. To face this challenge, DIGITMAN further developed and tested a method ideated from UNIBO in previous research [69] or semi-automating the generation of BIM models of existing buildings for building management purposes. This method, called 'Topological BIM' (TBIM), allow to produce building digital models composed of elements rigorously and automatically connected through relationships that organize spatial and construction information according to a standardized procedure, ensuring fast digitalization and interoperability with BPS software both for operation and safety issues, as will be explored in next phases of the project (WP3 and WP4).

2.4.1 Theoretical framework

Topological modeling of buildings can help integrate the product-oriented with the space-oriented view of BIM, which is essential for orienting BIM towards BPS uses. On the one hand, topology modeling can allow for structuring building information around spatial elements. On the other hand, it can allow for the representation of the interface components that directly affect building performance (such as partition and opening components) and connect them to the spatial elements they bind. Indeed, according to most architectural topological conceptions, a building can be viewed as a collection of spatial elements that aggregate and relate to each other through containment, adjacency, and passage relationships. Bounded by interface elements (e.g., walls, floors and roofs), these spatial elements can be represented as objects in a schematic form and characterized by relationships and attributes.

The theoretical framework for defining TBIM is based on the following theoretical principles, defined as 'spatial reasoning', 'conditional information modeling', 'semi-automation', 'semantic flexibility', and 'progressive data enrichment'.

- **Spatial reasoning** in BIM involves structuring building information around spatial objects instead of physical elements. This perspective prefers using geometrically succinct and conceptual digital models. It contrasts the current course of many BIM processes that develop highly detailed digital models to precisely depict projects' three-dimensional form and inventory [70], an approach that can create gaps in the semantic content of BIM models and, at the same time, lead to information overproduction when details are not needed [71].
- **'Conditional information modeling'** (or 'rule-based information modeling'), usually associated with model validation and checking activities [72, 73], refers to the process of modeling building knowledge by semi-automatically assigning data to spatial and construction elements on the basis of predefined topological and semantic rules and conditions.
- **Semi-automation**. The conditional modeling approach thus allows for semi-automated semantic data enrichment in the BIM process. This procedure is denoted as 'semi-automated' as manual-made rules and conditions are implemented and used to determine how properties are assigned to different elements within the BIM model. Unlike full automation, semi-automation involves human operators in rule assignment, thereby preserving human agency in modeling the building knowledge. For heritage building representation, semi-automation provides human control over information and information flows, proving useful for critically interpreting the building's composition.

- **Semantic flexibility** is crucial for allowing BIM to be utilized with external third-party applications, such as performance simulations. Current BIM software often struggles to interpret information that is not explicitly defined in either native or universally recognized BIM schemas, like the IFC. For example, standard BIM cannot currently capture and store dynamic information, such as the data gathered by sensor systems or results generated from dynamic performance analyses [74, 75] In the realm of performance-based design and management, achieving semantic flexibility is essential for ensuring that various digital platforms and models can work together seamlessly. This interoperability is critical to applying specialized knowledge from various domains to uses that extend beyond traditional BIM tasks.
- **Progressive data enrichment**. When digitally modeling existing buildings, progressive data enrichment means acquiring and assigning difficult-to-find data only when available and effectively needed. For instance, in the context of building management, a simple initial model may only contain basic information about space dimensions. As the model is well-conceptualized, the spaces can be gradually enriched with new information (such as energy requirements for conducting energy audits or safety requirements for planning safe occupancy) as necessary. The knowledge process is, therefore, dynamic and iterative, and it can evolve throughout the building's lifecycle in response to emerging needs over time. This adaptability, combined with a good understanding of the informational and relational implications, a well-structured ontology, and a straightforward embedded knowledge structure, can empower the construction of digital models with remarkable capabilities.

2.4.2 Methodology

This section illustrates the methodology developed for delivering the TBIM models and deriving the BEMs from them. The application comprises four conceptual steps: (1) 3D modeling, (2) topology modeling, (3) information enrichment, and (4) BIM modeling.

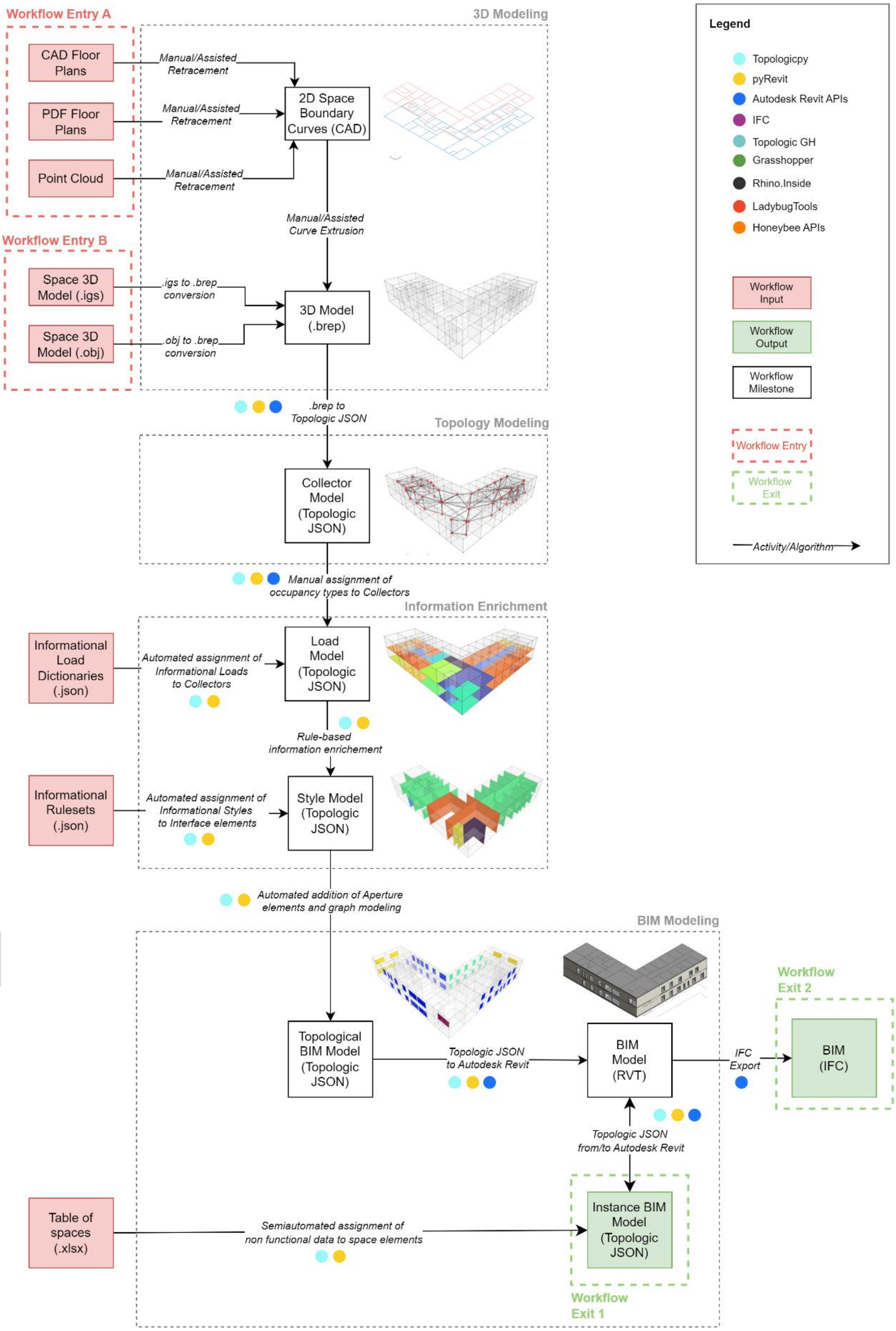

Figure 19. Workflow for the generation of TBIM.

The methodology for delivering the TBIM models is depicted in Figure 11. The workflow can vary based on the available inputs, adapting to different input entries and tools. Topologic is used as a modeling environment in the workflow to generate the TBIM. Autodesk Revit is instead chosen as the BIM modeling environment. Python serves as the programming language for developing the functions to create the TBIM models. Specifically, the Topologicpy package [66] is the core of these functions. Since Topologicpy does not have a graphical user interface (GUI), PyRevit [76] allows the user to apply the modeling steps within Autodesk Revit, acting as its plugin.

2.4.2.1 Spatial hierarchy

The basic assumption is that, in the workflow, information is modeled according to a predefined spatial hierarchy independently from the tool used. The spatial hierarchy stands that:

- A building can be represented as an IfcBuilding or a Topologic CellComplex.
- A space within the building can be represented as an IfcSpace or a Topologic Cell.
- A zone within the building, intended as a group of spaces, can be represented as an IfcZone or Topologic Cluster.
- Partition elements, including walls, roofs, and slabs, delimiting the spaces within the building can be represented as IfcWalls, IfcRoofs, IfcSlabs, or Topologic Faces.
- Openings, including windows, doors, and holes, hosted in a partition element can be represented as IfcWindows, IfcDoors and IfcOpenings or Topologic Apertures.

This spatial hierarchy can also be aligned with BOT and Brick schemas for LBD applications, as seen in the previous parts of the text.

2.4.2.2 Step 1: 3D modeling

The first step involves creating the geometry of the building (Figure 20). This is achieved by modeling a closed 3D volume for each space within the building as a BRep object. This object, which represents the gross geometry of the space, is then converted into a Topologic cell, the basic spatial element within the building's model. The 3D model can be made manually or through automated processes depending on available tools. For instance, as in this paper, CAD or PDF drawings can be retraced to extract, manually or automatically, the gross boundary curves of the spaces and subsequently extrude them into a three-dimensional format. Similarly, point clouds can be segmented and processed manually or automatically to derive the profiles delimiting the spaces and extruding them to create closed 3D volumes.

2.4.2.3 Step 2: Topology modeling

In the second step, the topological relationships between the essential elements of the model are created. At this stage, although the cells do not have any information attached, they are ready to be filled with new data. For this reason, they are called 'Informational Collectors', as they serve as the main data collectors in the modeling process.

Specifically, to transform the geometrical elements into topological elements, the Topologic cells are aggregated into a higher-order spatial entity, i.e. the cell complex. This operation, conducted thanks to Topologicpy's 'Topology. ByBRrep' method within PyRevit, allows the linking of each cell composing the building to each other cell through face adjacency relationships. The outcome of this step is the 'Collector

Model', a Topologic cell complex in the Topologic JSON format composed of interconnected cells and faces (Figure 21).

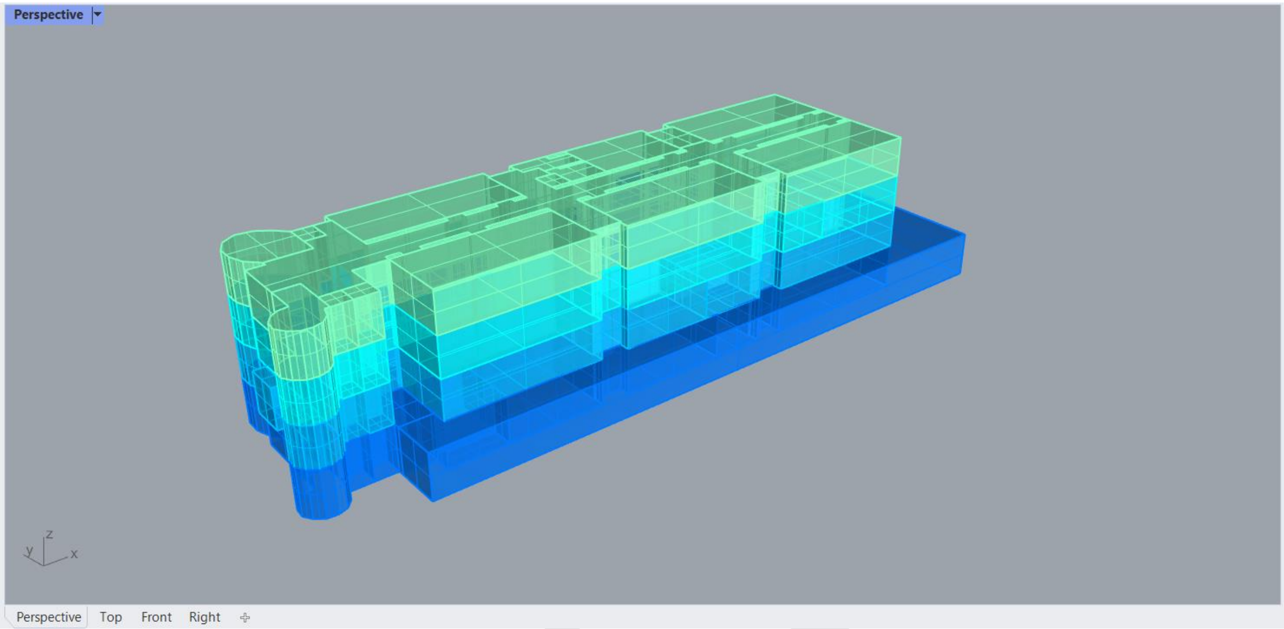

Figure 20. The 3D model of a DIGITMAN's case study building in Rhino.

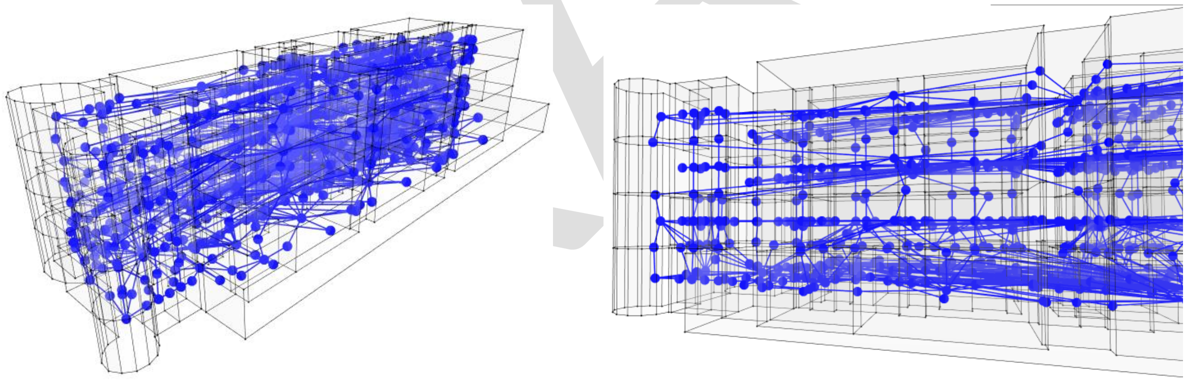

Figure 21. The Collector Model of a DIGITMAN's case study building in Topologicpy.

2.4.2.4 Step 3: Information enrichement

In the third phase, information is assigned to the elements composing the cell complex (i.e., the cells and the faces). This procedure is performed in PyRevit through conditional modeling with the primary objective of semi-automatically setting the data needed for energy analysis.

First, functional data is added to the informational collectors by attaching the so-called 'Informational Load Dictionaries' (ILD). These consist of JSON dictionaries, each corresponding to a specific space function (e.g., office, classroom, corridor, restroom, etc.) and containing related data (e.g., temperature, humidity, ventilation and lighting setpoint values, as well as occupancy density and people capacity, but not only). To enrich the collectors with new information, a specific space function is assigned to each collector and the corresponding ILD is transferred to the respective cell, enriching it with the data related to the chosen function. For example, a certain temperature setpoint value (e.g., 20°C) can be assigned to all the offices by defining it in an ILD designed explicitly for office spaces. Similarly, another setpoint value can be set for all the corridors (e.g., 16°C).

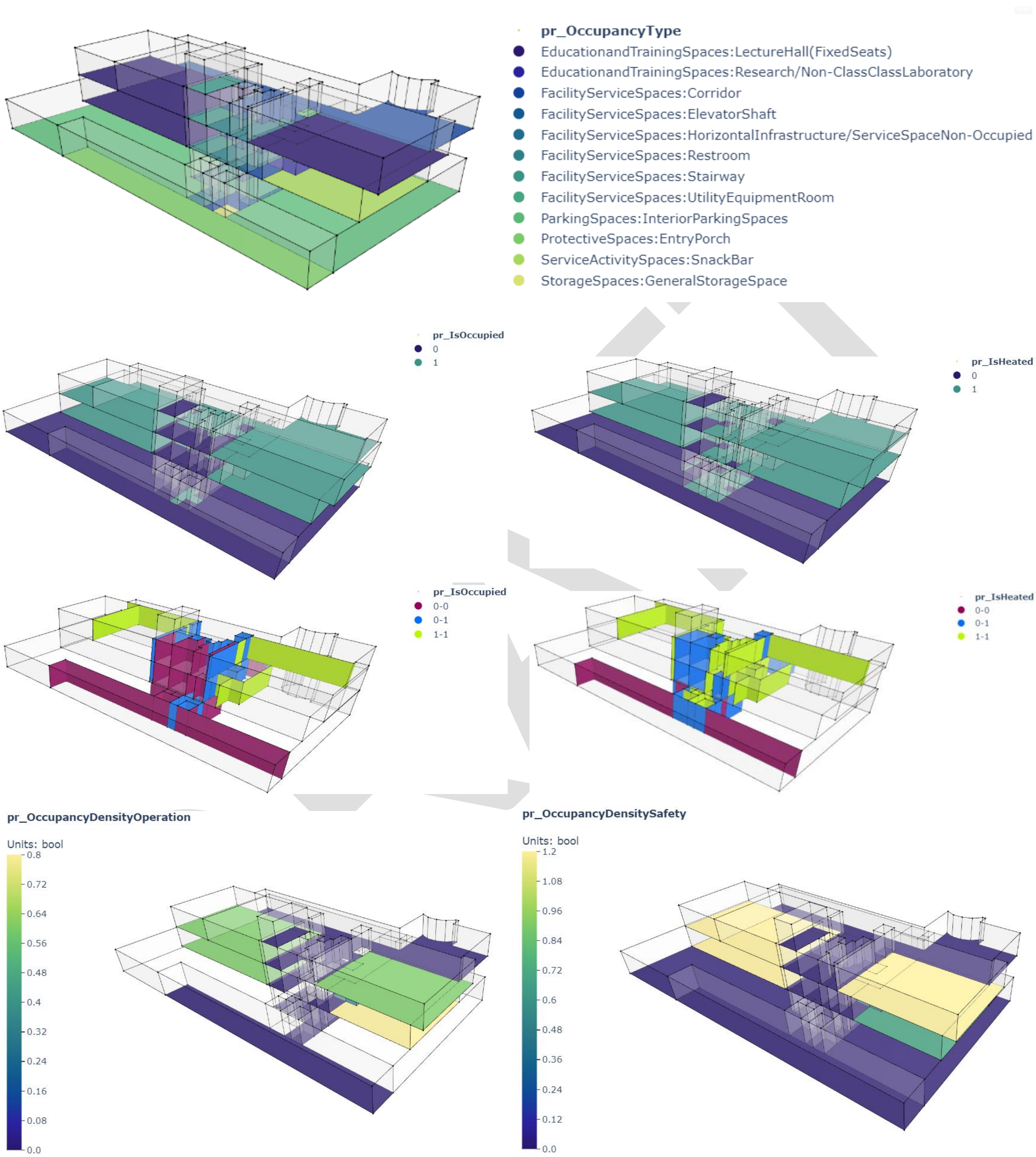

Figure 22. The Load Model of a DIGITMAN's case study building in Topologicpy.

Second, after adding the data to the collector cells, this data is also transferred to the adjacent faces by executing topological queries. The faces belonging to the cell complex are classified according to their topological type as 'internal vertical', 'external vertical', 'internal horizontal', 'bottom horizontal', and 'top horizontal'. Then, the query is executed, and data is attached to the faces as a Topologic dictionary. This procedure is iterated for each face by (a) querying the cells adjacent to the face, (b) extracting the information attached to these cells, (c) creating a new Topologic dictionary containing the extracted information, (d) and transferring the new dictionary to the face. Following the previous example, through this process, an internal vertical face adjacent to an office on one side and a corridor on the other can be designated as separating a space at 20°C from a space at 16°C, along with other properties. The result of this step is called the 'Load Model', a Topologic cell complex containing the ILDs' information (Figure 22).

Subsequently, the faces undergo further data enrichment. This enrichment is achieved using the so-called 'Informational Rulesets' (IRSs). An IRS is a data dictionary collecting 'conditions' and 'styles' applicable to the faces. The conditions dictate the property values a face should have so that the IRS can be applied to the face itself, while the styles represent the new data to be assigned to the face if it meets the specified conditions. In simpler terms, when all the conditions of an IRS match the properties of a face, the styles' data is attached to that face. The assignment of styles' data also occurs through topological queries. All the IRS dictionaries are iterated over each face within the cell complex. For each face, the conditions' values are accessed and compared to the face's properties. If the values match, a new dictionary containing the styles' properties (and data) is created and added to the face; otherwise, the iteration continues. In the case of multiple IRSs matching with the same face, styles' values are overwritten. The outcome is the so-called 'Style Model', a Topologic cell complex in the Topologic JSON format that contains both the ILDs' and IRSs' data (Figure 23).

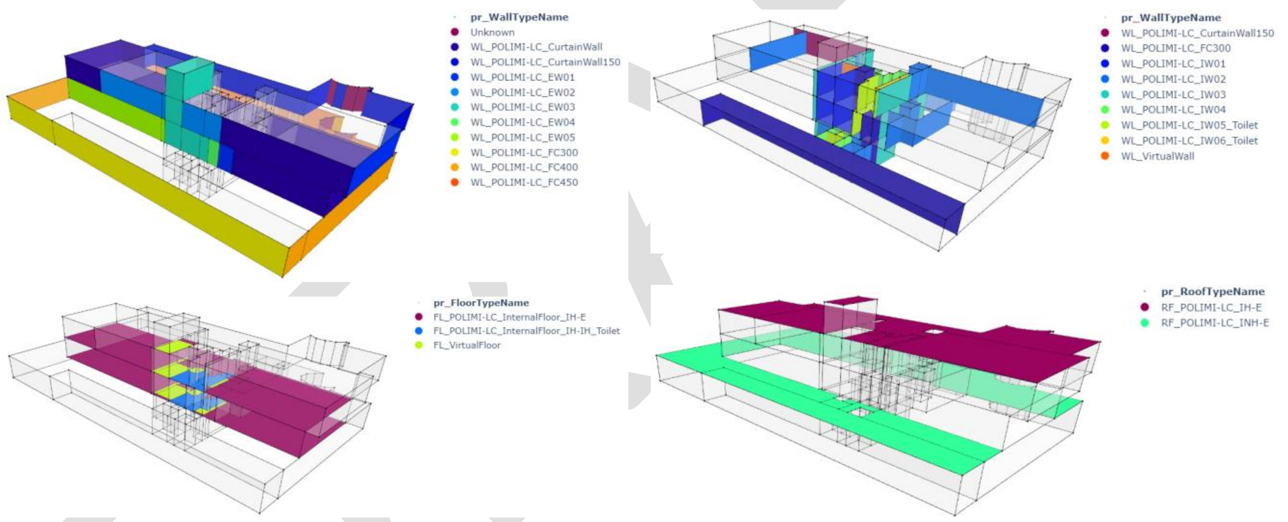

Figure 23. The Style Model of a DIGITMAN's case study building in Topologicpy.

In this study, this conditional data enrichment process is applied to the Load Model to assign construction and aperture data to the faces. For instance, a specific U-value can be set for all external vertical faces adjacent to heated or unheated spaces. Or, a certain number and type of doors or windows can be assigned to all the faces adjacent to the cells with a certain function, and so on.

2.4.2.5 Step 4: BIM modeling

At the beginning of the fourth stage, the cells and the faces composing the cell complex are already informed with all the data assigned through the procedures described in the previous passages, which mainly include indications about the functional and energy requirements of the spaces and the construction characteristics of the faces. This data is used within PyRevit to generate the TBIM and BIM models at this step.

To complete the modeling procedure, the apertures of the building are first created. These consist of doors, holes, and windows; doors provide horizontal passage between horizontally adjacent cells, holes between vertically adjacent cells, and windows between the cells and the external environment. The apertures are created as face elements in Topologicpy on the basis of the data attached to the faces, which include information about the size of the apertures, their material type and thermal properties. Once the geometries of the apertures are created, they are linked to the related data through new Topologic dictionaries and added to the Style Model thanks to the 'Topology. AddApertures' method of Topologicpy. Then, the cell complex is transformed into a Topologic graph and graph visualization and analysis are used to check if the modeling procedure produced errors and, in this case, to correct them. The result is the 'Topological BIM Model', a conceptual model consisting of a Topologic cell complex composed of cells, faces, and apertures semi-automatically informed with data useful for energy analysis Figure 25). This model is not only a simple collection of spatial and topological elements, but a system of objects interrelated through topological relationships suited for a direct transformation into BIM and BEM models.

For visual clarity, Figure 24 depicts the application of the first four stages of the workflow in some simple examples of buildings built in Topologicpy.

Starting from the Topologic TBIM, an Autodesk Revit BIM model is then automatically created for export to IFC. Technically, this procedure involves using Topologicpy and Autodesk Revit APIs within PyRevit to convert the Topologic cell complex into a Revit building. This conversion is performed by aligning Topologic's class hierarchy with Revit's element classes and using Autodesk Revit API methods to convert Topologic elements into Revit elements. Specifically, Topologic cells are converted into Revit spaces, Topologic's vertical faces into Revit walls, Topologic's horizontal faces into Revit floors and roofs, and Topologic's apertures into Revit's windows, doors, and holes.

After creating the TBIM model in Topologic, manual modifications are made to certain instance objects to produce the so-called Instance BIM (IBIM) (Figure 26). For example, openings (automatically modeled at the center of faces in the previous step) are moved to the desired position, or errors in assigning construction types to faces are manually corrected. Additionally, properties that cannot be modeled on a functional basis (e.g., safety-related properties) are added to the spaces. This addition is made by inputting in PyRevit the so-called "table of spaces" and "table of buildings" provided in Deliverable 1.3.

All these modifications, made in Revit, are then automatically recorded in the Topologic model. The result is a simplified BIM model (in Revit, IFC, and Topologic JSON formats) containing most of the necessary information for energy or safety analyses. This model serves as the primary foundation for the What-If applications that will be developed in WP3 and WP4.

Figure 25 presents some output models in three different formats related to selected case studies for DIGITMAN, which are shown in the next section. These models are attached to Deliverable 1.3.

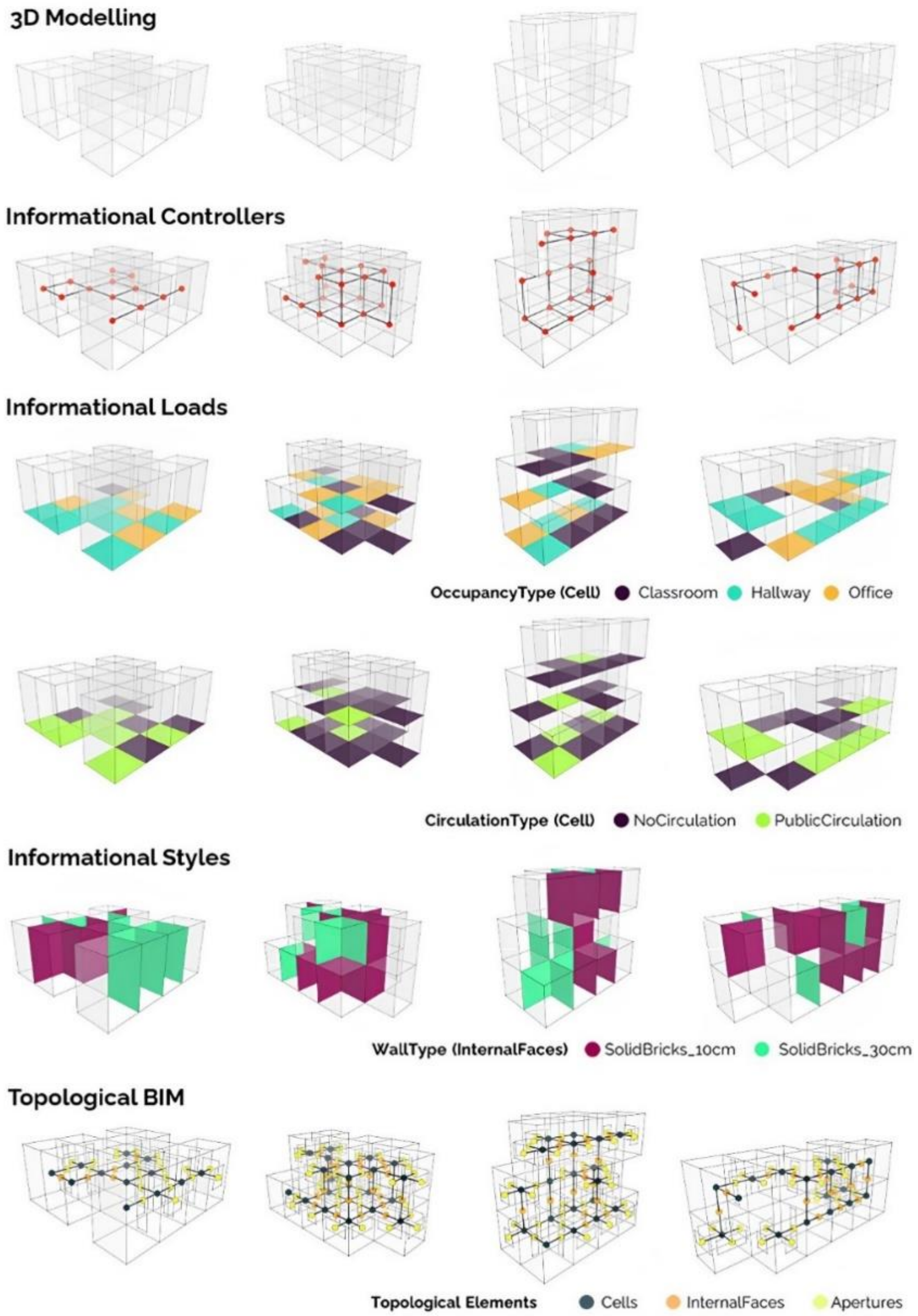

Figure 24. Conceptual demonstration of the workflow. From the top to the bottom: (a) 3D modeling of some example buildings in Topologicpy; (b) creation of the informational collectors; (c) assignment of the informational loads to the collectors by space occupancy type; (d) assignment of the styles to the internal faces; I generation of the TBIM models with added openings and graph visualization.

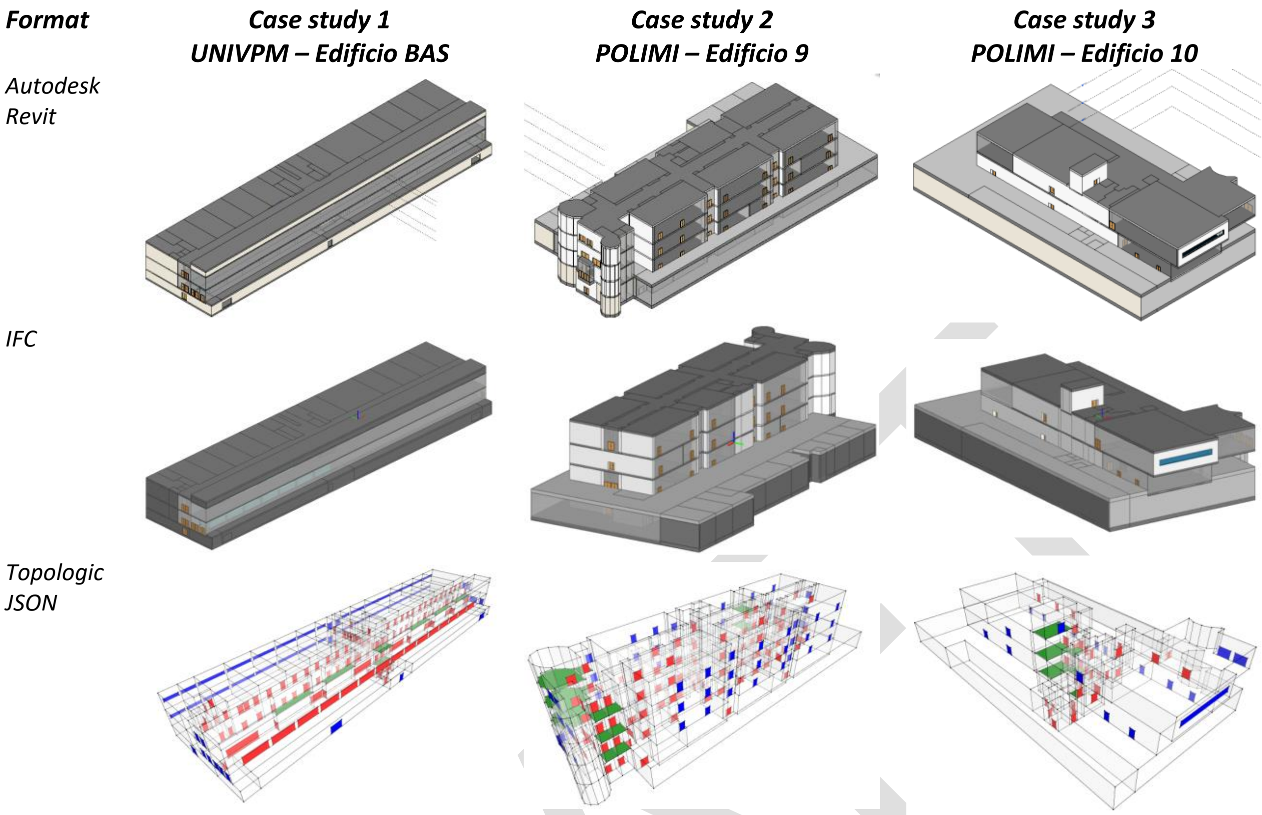

Figure 25. The IBIM models created for the DIGITMAN project case studies.

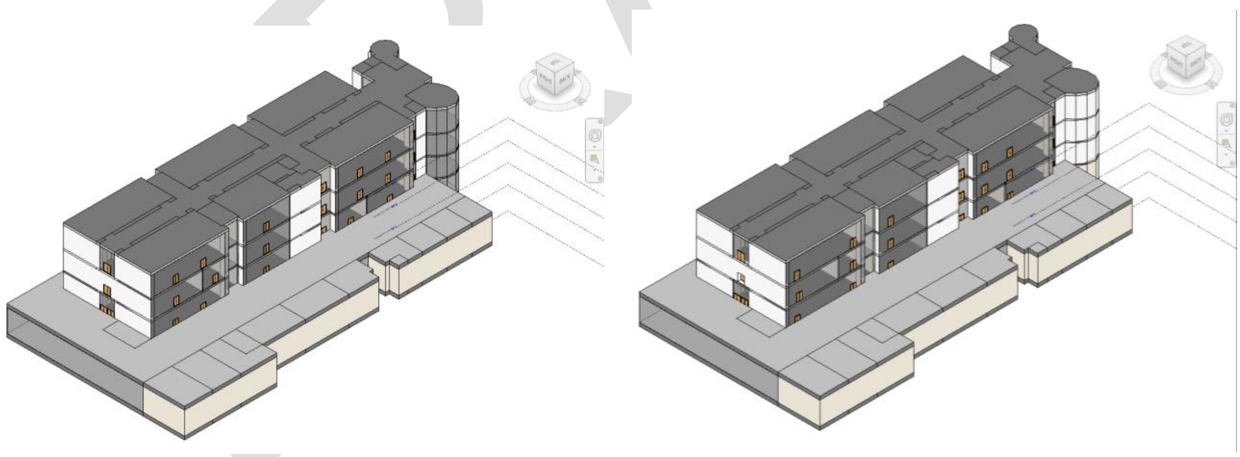

Figure 26. The TBIM (on the left) and the IBIM (on the right) of a DIGITMAN's case study building in Revit.

3 Case study

This section describes the pilot case studies chosen to demonstrate the methodology implemented within the project. In section 4.1, the choices made as the basis for the selection of case studies, taken within the context of real estate assets belonging to university administrations, are explained. Section 4.2, instead, describes the specific portfolios and buildings investigated in the project, along with the types of data collected to support the project's development activities.

3.1 Case study selection

The selection of the case study has been driven by the need to obtain a representative sample of the diverse and extensive building stock currently existing in Italy. The selection process adhered to three main principles as outlined below:

- **Data Acquisition for Predictive Methods**: Collecting data essential for developing predictive methods aimed at enhancing the daily management processes.
- **Impact Prediction of New Scenarios**: Gathering data to create methods capable of predicting the impact of new scenarios on building management activities.
- **Validation of the Digital Framework**: Testing the efficacy of the developed digital framework, via the prototype tool, in improving the decision-making process for building stock managers regarding building transformations.

The three pilot studies, each conducted by a partnering university, effectively represent the diverse and intricate nature of Italy's building stock. These pilots involve buildings managed by local public authorities, specifically universities, and include a variety of structures; the first pilot, at the Polytechnic University of the Marches, features a large and varied collection of buildings constructed over the past four decades. This diversity provides a broad perspective on the challenges and opportunities in managing a heterogeneous building stock. The second pilot, at the Polytechnic of Milan, comprises a more uniform set of recently built structures. This homogeneity allows for focused analysis on the management of modern, standardized buildings. The third pilot, at the University of Bologna, includes a small number of 20th-century listed buildings designed by famous architects. These historic structures offer insights into the preservation and management of architecturally significant buildings. A brief description of the examined stock is as follows:

- **Pilot 1**: This pilot includes a heterogeneous set of 23 buildings at the Polytechnic University of the Marches (UNIVPM), constructed between 1976 and 2010. The buildings cover 135,000 m^2 and serve teaching, research, and administrative purposes, with 100 classrooms accommodating 16,000 students.
- **Pilot 2**: This pilot features a homogeneous set of 5 buildings at the Polytechnic of Milan (POLIMI), built in 2013. The buildings cover 47,000 m^2 and are used for teaching and research, with 29 classrooms serving 2,850 students.
- **Pilot 3**: This pilot consists of 2 listed buildings at the University of Bologna (UNIBO), constructed between 1935 and 1965. The buildings cover 25,600 m^2 and are designated for teaching and research, with 42 classrooms serving 5,000 students.

In view of the above, due to their complexity in terms of occupancy, dimension, number of buildings in the building stock, and of representativity of the national building stocks features in terms of construction years (compare Table 5), and preliminary verification of major data availability, the UNIVPM and POLIMI pilots have been selected within the DIGITMAN process, although the methods can be replied both to pilot 3 and otgher case studies.

Table 5. Local public authorities national building stock. Source: MEF Open data (2018).

Construction period	Gross Floor Area (GFA - m^2)
Built before 1919	1.448.419
Built from 1919 to 1945	1.131.311
Built from 1946 to 1960	601.844
Built from 1961 to 1970	876.544
Built from 1971 to 1980	648.745
Built from 1981 to 1990	1.358.015
Built from 1991 to 2000	1.483.177
Built from 2001 to 2010	1.596.993
Built after 2010	623.756
Total	9.768.804

3.2 Case study description

As introduced in the previous section, two pilot studies have been selected to evaluate and test the previously described framework. This section provides a more detailed description of the case studies conducted at UNIVPM and POLIMI.

3.2.1 UNIVPM case study

UNIVPM building stock is divided by the composing buildings complexes, which are associated with specific Identification codes (IDs, defined by the building facility manager), as shown in Table 6. Table 6 also shows the main intended use of each buildings complex, the number of composing buildings, the overall Gross Floor Area (GFA [m^2]), and the year(s) of construction and/or last deep renovation intervention. Each building is generally equipped with centralized fire alarms, ventilation, and heating systems (with fan coils), while cooling systems are installed only in limited areas. The building stock hosts offices for about 1000 workers (teachers, researchers and technical staff), as well as classrooms and laboratories hosting up to about 17.000 students per day. As shown by Table 6, most building surfaces relate to educational and research uses.

3.2.1.1 BAS building at UNIVPM

In the overall building stock, DIGITMAN focuses on the "Blocco Aule Sud" (BAS) building of the Università Politecnica delle Marche (UNIVPM), which is located in Ancona, on via Brecce Bianche at the Montedago campus shown in Figure 27, thanks to data availability and to the fact that the case study is complex enough to ensure the tools application under supervised conditions.

The BAS is a single building with 2 storeys (ground floor, first floor) and a basement with a rectangular plan measuring 108.5 x 23.3 m developed along the East-West direction. The main entrance is positioned on the short east side on the ground floor (green arrow, Figure 27), while the parking lots are accessible from the basement (yellow arrows). Two fire escape stairs are located at opposite ends of the BAS (red areas).

*Table 6. Building stock characteristics for UNIVPM. Each building complex is associated with an Identification code (ID), its denomination and main intended use, the number of composing buildings, the related GFA, the year(s) of construction and/or the last deep renovation intervention. *: outdoor facilities, such as fields for agriculture and horticulture-related research, are excluded since they are not object of general maintenance issues; "n.a.": not assessed in view of the specific building complex features.*

IDs	Buildings complex denomination	Main intended use	Number of buildings	GFA [m^2]	Year(s) of Construction and/or rehabilitation
L6-047-001	Rectorate and central administration	Administrative offices	3	5611	1976
L6-047-002	Central administration	Administrative offices	2	4678	1976
L6-047-003	Central administration - facilities	Garage	1	168	1976
L6-047-004	Faculty of Economics	Educational & research	6	59721	1996
L6-047-005	Faculty of Medicine and Surgery	Educational & research	5	65160	1995-2008
L6-047-006	Faculties of Engineering	Educational & research	18	199959	1990-2005
L6-047-007	Faculties of Science	Educational & research	5	11794	1997-2008
L6-047-008	Faculty of Agricultural Sciences	Educational & research	7	17402	1982-2017
L6-047-009, L6-047-010, L6-047-011, L6-047-013	Extension and Research Center in Agriculture (mainly outdoor areas + storage buildings)*	Research	12	3881	n.a.
L6-047-012	Solar Pond (outdoor facilities)	Research	0	0	n.a.
L6-047-014	Botanical garden (mainly outdoor areas + storage buildings)*	Research	2	1622	n.a.
L6-047-017	University sport facilities (indoor and outdoor)	Sport facilities	8	57471	1971

A seismic joint separates the structure into two main blocks that develop lengthwise, both structurally and functionally. The southern block houses the classrooms on the ground floor and the first floor. The load-bearing structure is framed in prefabricated reinforced concrete: the columns are anchored at the base with fixed supports and have a constant section throughout the height (50 x 50 cm), realizing a grid of 8.40 x 7.20m; the beams are arranged according to the longer side and hinged to the columns. All floors are made of pre-stressed hollow-core concrete. The basement, also prefabricated hosting a garage and technical rooms, is stiffened by reinforced concrete walls anchored to the columns. The inter-floor height is 3.20m in the basement, while it is 4.40 m on the two storeys above the ground. All the rooms on the ground floor and first floor (classrooms, bathrooms, bars) have dimensions equal to one or two modules of 7.20 x 13.0 m with plasterboard walls (Figure 28). All classrooms are furnished with wooden seats and desks fixed to the ground.

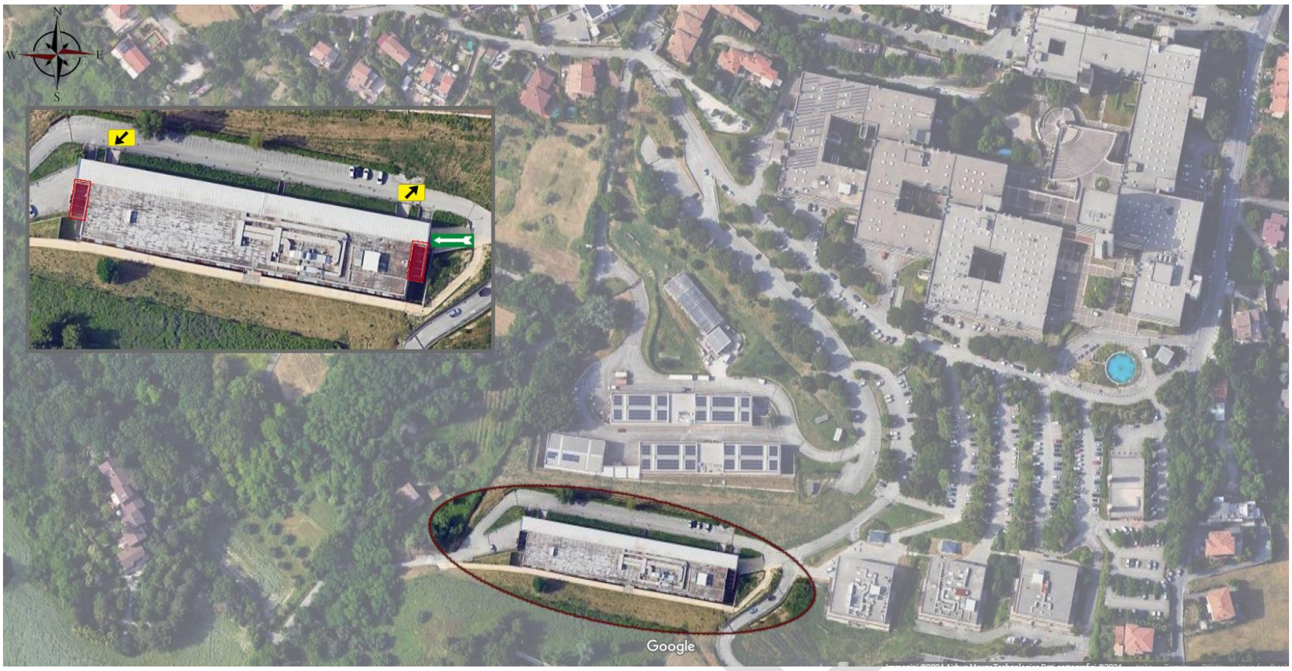

Figure 27: aerial view of the Montedago ("Polo Trifgogli") campus (background), and of the BAS building (enlargement on the top-left). The green arrow indicates the main entrance (ground floor), yellow ones the parking lots (basement), and the red areas indicate the fire escape stairs.

Figure 28: BAS ground floor (above) and first floor (down).

The northern block is a steel structure with two double-height spans set on the first floor and the roof. This body serves as an entrance, distribution to the classrooms, and an open-space study area with tables and benches as fixed furniture. Specifically, the north façade of the BAS features a curtain wall in double/triple glazing glass, allowing natural light to enter to reduce the need for artificial lighting during the day and cooling during the summer (Figure 30). Vertical connections on the upper floors are provided by two elevators (including the basement) and five steel staircases adjacent to the joint (Figure 30). The basement is accessible by external ramps. In the two floors above the ground, the structural system is equipped with 43 dissipative braces in V or inverted-V shape made of metal tubes with a diameter of 23 cm, each equipped at the end with a Buckling Restrained Axial Damper (BRAD, Figure 31).

The electrical energy demand of the BAS is met by a mix of distributed generation and electricity grid. HVAC systems are managed by air handling units (AHU) that ensure adequate air exchange. The thermal energy demand is met by a mix of technologies powered by natural gas; these technologies are installed in a central thermal plant and then distributed to the different buildings of the campus, including the BAS, through a district heating network. The thermal energy demand for cooling is met by chillers powered by the district heating network to locally produce the necessary cooling energy to meet their cooling demand.

Figure 29: BAS north façade view.

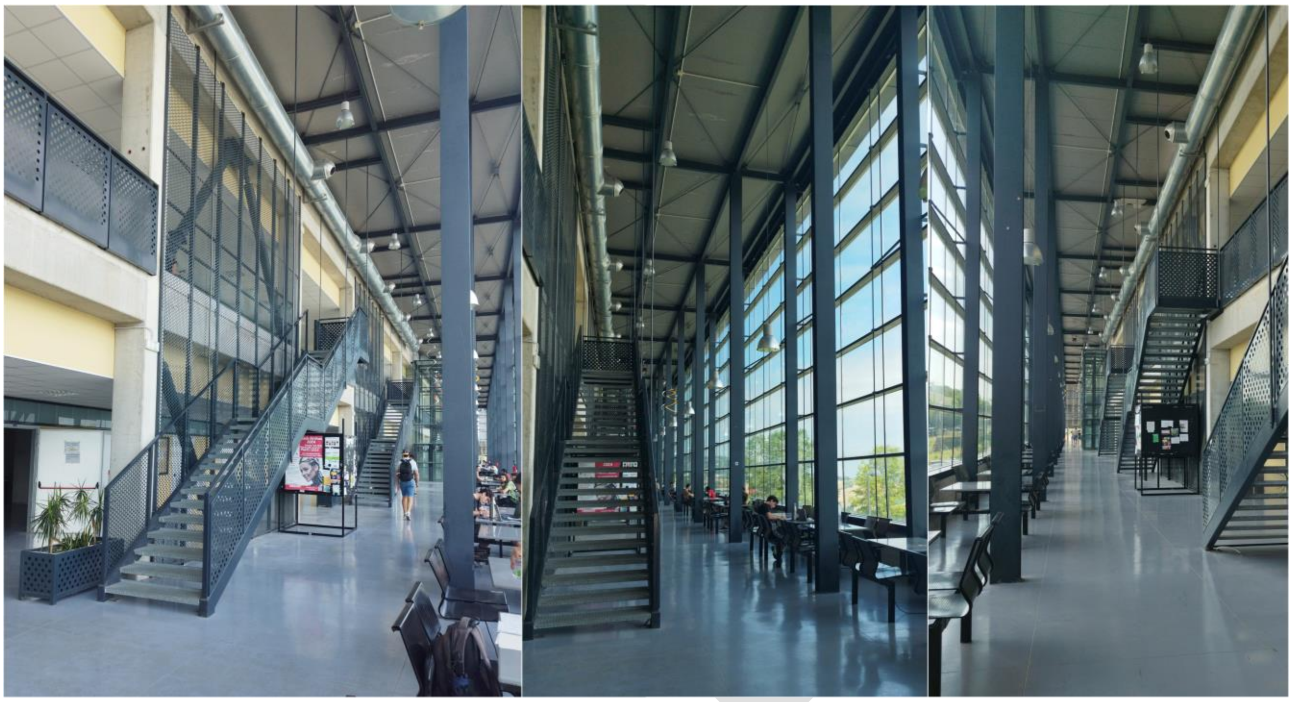

Figure 30: indoor area of the BAS, details of the stairs and of the steel structure.

Figure 31: Detail of a dissipative brace.

3.2.2 POLIMI case study

The building asset owned by Politecnico di Milano (POLIMI), shown in Table 7, is extremely vast and continuously expanding, in accordance with the needs and the increasing number of students. The Politecnico di Milano comprises six main building clusters, totaling 143 structures. These include 109 buildings in Milan, 5 in Como, 13 in Piacenza, 6 in Cremona, and 2 in Mantua. All the buildings have mixed intended uses, including educational, administrative and research areas, except for LCF07, MIC01, MIC03, MIC04 and MIC10, which are mainly residential buildings.

Table 7: Building stock characteristics for POLIMI. Each building complex is associated with an Identification code (ID), its denomination and main intended use, the number of composing buildings, the related GFA, the year(s) of construction and/or the last deep renovation intervention.

IDs	Buildings complex denomination	Number of buildings	GFA [m^2]	Year(s) of Construction and/or rehabilitation
LCF04	Via Ghislanzoni	9	34083.56	1840 – 2022
LCF07	Residenza Loos	1	6644.97	1840 – 2002
COE02	Via Castelnuovo	1	2665.91	1989
COE04	Via Anzani	1	3082.56	2005
COE08	Via Zezio	1	5699.56	2016
CRG01	Via Sesto	3	9110.03	1987
CRH02	Strada per Rivolta D'Adda	3	650.49	1987
MIA01	Piazza Leonardo da Vinci 32	15	91964.60	1927 – 2022
MIA02	Via Bonardi	12	52798.85	1927 – 2022
MIA03	Via Bassini	10	33512.51	1927 – 2022
MIA04	Via Golgi 40	4	16695.12	1927 – 2022
MIA05	Via Mancinelli	1	17263.90	1927 – 2022
MIA06	Via Colombo 40	5	5111.81	1927 – 2022
MIA07	Via Colombo 81	1	2146.17	1927 – 2022
MIA09	Viale Romagna	1	16654.61	1927 – 2022
MIA11	Piazza Leonardo da Vinci 26	1	3237.69	1927 – 2022
MIA14	Via Golgi 20	2	9822.89	1927 – 2022
MIA15	Via Pascoli 70	3	1894.06	1927 – 2022
MIB01	Via La Masa	33	124397.98	1989 – 2024
MIB02	Via Durando	12	72885.96	1989 – 2024
MIC01	Residenza Pareto	1	10657.14	1927 – 2022
MIC03	Residenza Einstein	1	9881.48	1927 – 2022
MIC04	Residenza Marie Curie	1	11814.54	1927 – 2022
MIC09	Off Campus	3	447.57	1927 – 2022
MIC10	Residenza Newton	1	11808.14	1927 – 2022
MID01	Via Calabria	1	4949.91	1927 – 2022
MIF01	Tortona 37	1	816.32	1927 – 2022
MNI01	Via Scarsellini 15	1	8052.79	1994
MNI02	Via Scarsellini 2	1	1238.02	1994
PCL01	Via Scalabrini 76	1	7592.09	1863 – 1997
PCL04	Via Scalabrini 113	12	4836.52	1863 – 1997

3.2.2.1 Building 9 and 10 at POLIMI

The inventory under examination pertains to the Polo Territoriale di Lecco, consisting of 5 buildings covering an area of 47,000 m2 dedicated to teaching and research. The hub comprises 29 classrooms designed to accommodate 2850 students, as presented in Figure 32. This cluster of buildings was recently constructed in 2013 and is part of a refurbishment plan that includes four historical buildings that were originally a hospital built in 1883. The most recent buildings are made with prefabricated concrete structures and cladded with dry technologies.

The campus is located in the outskirts of Lecco (45° 51’ N, 9° 23’ E). Lecco, an Italian city situated in the northern part of the peninsula, is characterized by a temperate Mediterranean climate with dry and warm summers. According to the Köppen-Geiger climate classification, Lecco experiences a climate that features a coldest month with an average temperature above -3 °C, at least one month with an average temperature exceeding 22 °C, and at least four months with an average temperature above 10 °C. During the rainiest winter month, precipitation is at least three times higher than the driest summer month, and the driest summer month receives less than 40 mm of rainfall. Summer days begin at the end of May and extend until October.

The classrooms under analysis are located on the first floor of two buildings, designated as A1.3 and B1.5, respectively, within Buildings 9 and 10 as shown in Figure 34. As these buildings are relatively new, the thermal performance of the building is high and indoor comfort is guaranteed thanks to the accurate study of the envelope.

Figure 32: Aerial photograph providing an overview of the entire Polo Territoriale di Lecco

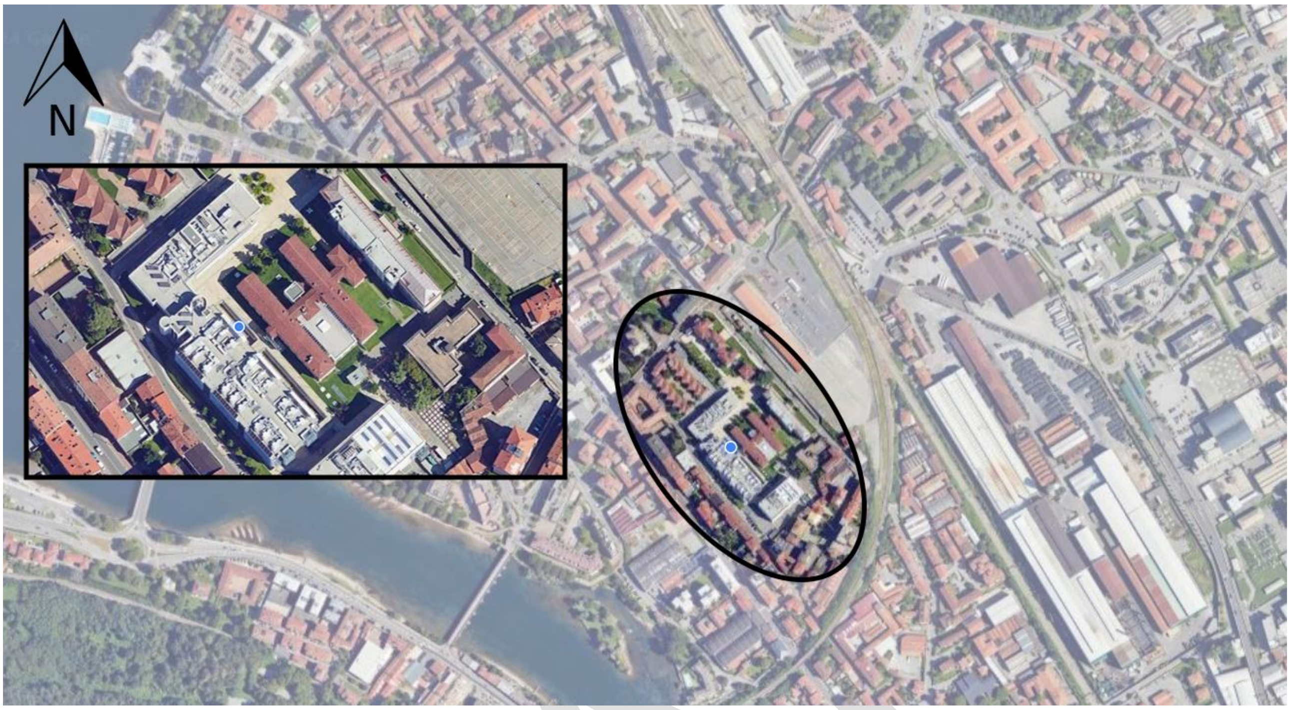

Figure 33: Aerrial view of "Polo Territoriale di Lecco".

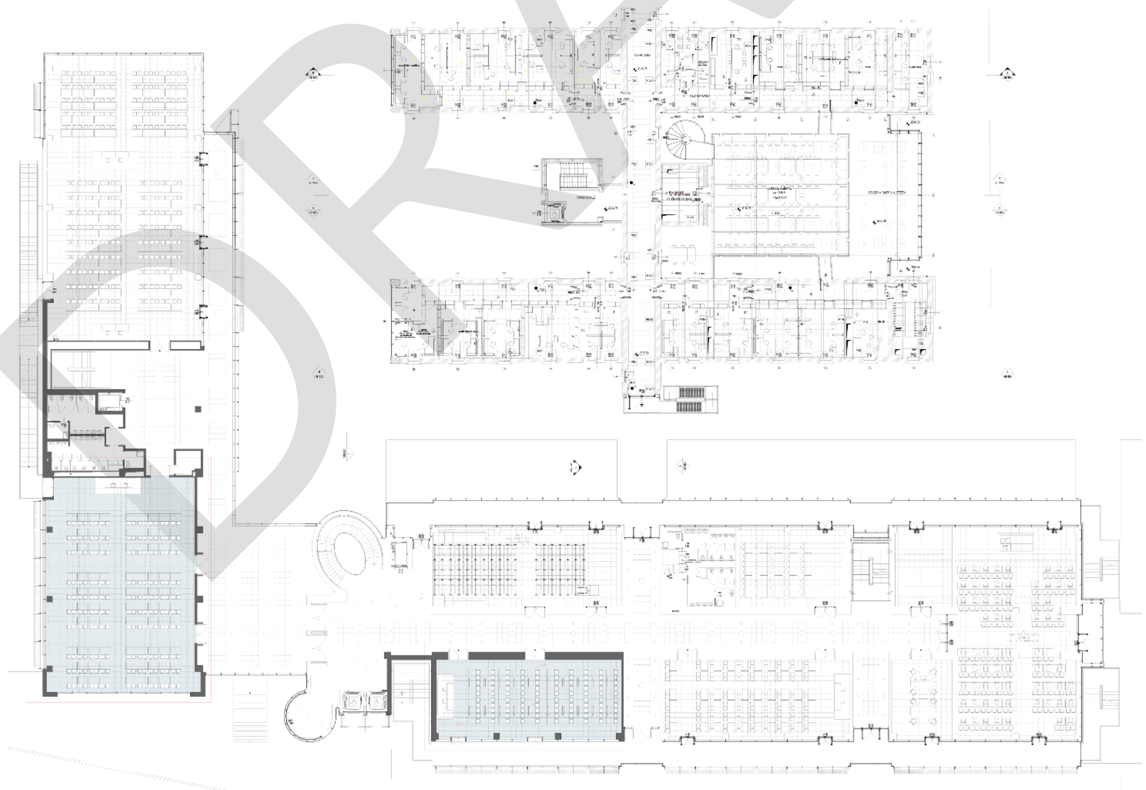

Figure 34: Plan representing the first floor of buildings 9 and 10, also known as Building A and B, and room location

Figure 35: External view of building 10. On the left side the west façade view, on the right side the east façade view.

Figure 36: Internal view of the first floor of building 10. On the left side is shown the open space and in the background is visible the shading system position on the south façade. On the right side the distributive space is shown.

Figure 37: External view of building 9. On the left side the west façade view, on the right side the east façade view.

Figure 38: Internal view of the first floor of building 9. On the left side is shown the distributive corridor in the underground floor. In the middle it's show the main stair. On the right side the distributive corridor, common in all the floors above ground.

3.2.2.2 Classroom A1.3 at LECCO campus

Classroom A1.3, situated in Building 10, features dual frontage facing outward; specifically, the northern frontage comprises a fully glazed facade, while the western frontage has a ribbon window that spans nearly the entire length of the wall. As previously mentioned in the case study description, the room is located on the first floor. Beneath this space is a restaurant/bar with a different air conditioning setup and a distinct occupancy schedule, while above this space is the outdoors, where the ventilation systems, solar thermal panels, and heat pumps are situated. The floor area, height and volume of the room are respectively 373,02 m^2, 3.80 m, and 1417,48 m^3. Such as all the other rooms in this building, this room has a dedicated HVAC systems, described in its characteristics in Table 9, which operate autonomously and self-adjust his parameters to better perform and guarantee a comfortable indoor environment based on the parameters set on a daily basis. The Table 8 depicts the average occupancy of this classroom. These data are provided by the administration and are based on on-site measurements taken at the beginning of the semester. They may vary each semester depending on the demand for space and the distribution of classroom usage. Therefore, the values are only representative for the specific semester during which the measurements were taken. It is noteworthy that, in addition to its educational purpose, the classroom is available for individual study and conferences during times when it is not scheduled for lectures, so the mean occupancy can vary during nonscheduled moments.

Table 8: Mean occupancy in classroom A1.3 during the spring semester

Day	09:15	10:15	11:15	12:15	13:15	14:15	15:15	16:15	17:15	18:15
Monday	98	98	98	98	/	98	98	98	98	/
Tuesday	71	71	71	71	/	/	/	/	/	/
Wednesday	/	/	/	/	/	115	115	115	115	/
Thursday	/	/	/	/	/	66	66	66	66	/
Friday	/	/	/	/	/	/	/	/	/	/

Table 9: Air Handling Unit (UTA 10) characteristics

Parameter	Value
Supply air flow	11,000 m^3/h
Return air flow	10,000 m^3/h
Maximum return air flow	10,000 m^3/h
Minimum return air flow	6,000 m^3/h
Maximum supply air flow	11,000 m^3/h
Minimum supply air flow	6,000 m^3/h
COP Plate Energy Recovery	60 %
Supply static pressure	280 Pa
Supply fan power	9 kW
Return static pressure	180 Pa
Return fan power	4 kW
Primary cooling/heating coil power	90 kW
Cooling water in/out	8/13 °C
Secondary heating coil power	20 kW
Heating water in/out	35/30 °C

Figure 39: Picture took in the front part of Room A1.3

Figure 40: Picture took in the rear part of Room A1.3

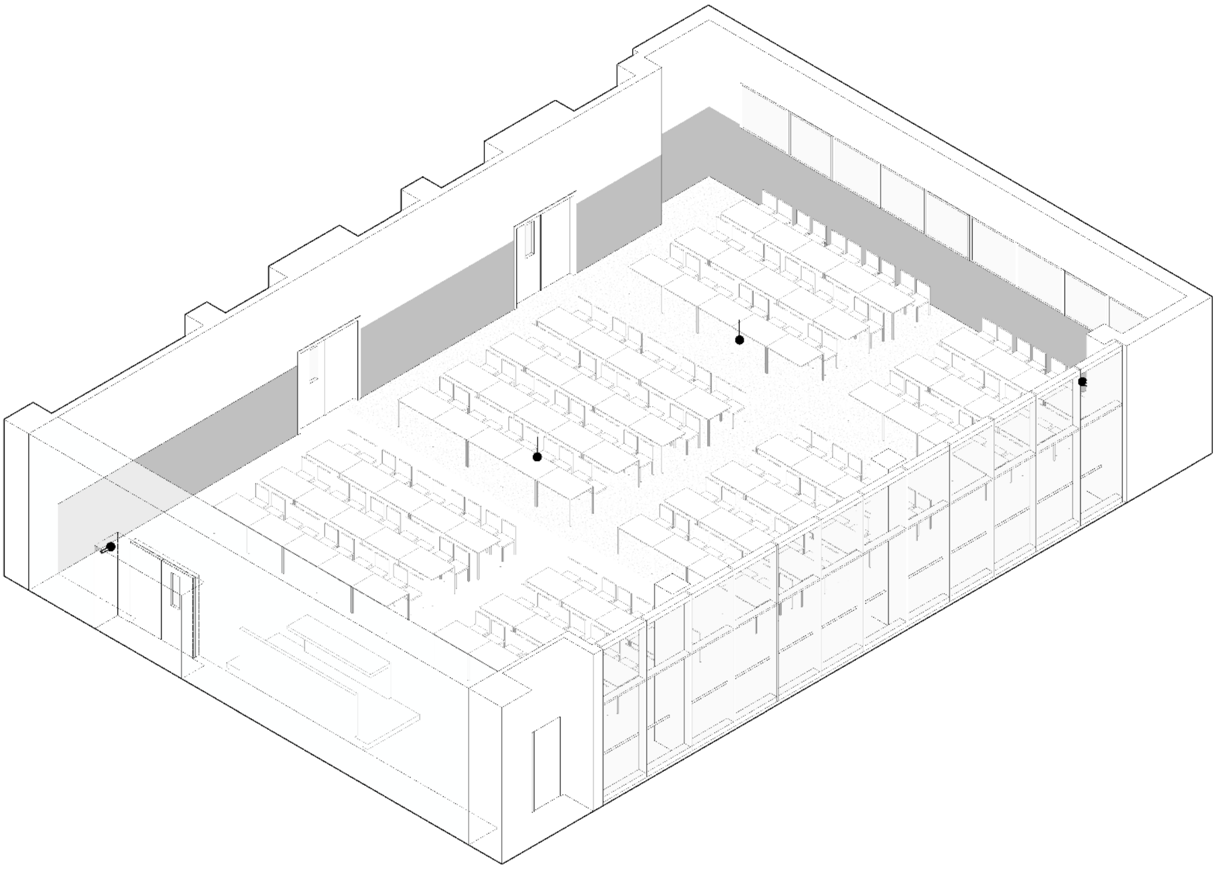

Figure 41: Axonometric view of room A1.3

3.2.2.3 Classroom B1.5 at LECCO campus

Classroom B1.5, located in Building 9, solely encompasses a western frontage facing outward, characterized by a continuous facade. As said before, this classroom is located at the first floor and in the spaces above and below the room are positioned other classrooms with the same climatization method and same theoretical indoor temperature. The dimensions of this space, like floor area, height and volume are respectively 170 ,71 m^2, 3.80 m and 648,70 m^3. Like many other spaces within this complex, the room in question is equipped with a dedicated HVAC system, described in its characteristics in Table 11. This system functions independently, adjusting its parameters autonomously to enhance performance and ensure a consistently comfortable indoor climate, in accordance with the daily settings prescribed. The Table 10 depicts the average occupancy of this classroom. These data are provided by the administration and are based on on-site measurements taken at the beginning of the semester. They may vary each semester depending on the demand for space and the distribution of classroom usage. Therefore, the values are only representative for the specific semester during which the measurements were taken. As other classrooms, also this room has the availability for individual study and conferences when there are no scheduled lectures.

Table 10: Mean occupancy in classroom B1.5 during spring semester

Day	09:15	10:15	11:15	12:15	13:15	14:15	15:15	16:15	17:15	18:15
Monday	15	15	15	15	/	17	17	17	17	/
Tuesday	/	/	/	/	/	15	15	15	15	/
Wednesday	/	/	/	/	/	/	/	/	/	/
Thursday	35	35	35	35	35	/	/	/	/	/
Friday	35	35	35	35	/	41	41	41	41	/

Table 11: Air Handling Unit (UTA 19) characteristics

Parameter	Value
Supply air flow	7,200 m^3/h
Return air flow	6,600 m^3/h
Maximum return air flow	6,600 m^3/h
Minimum return air flow	3,900 m^3/h
Maximum supply air flow	7,200 m^3/h
Minimum supply air flow	3,900 m^3/h
COP Plate Energy Recovery	60 %
Supply static pressure	280 Pa
Supply fan power	5.5 kW
Return static pressure	150 Pa
Return fan power	2.2 kW
Primary cooling/heating coil power	60 kW
Cooling water in/out	8/13 °C
Secondary heating coil power	10 kW
Heating water in/out	35/30 °C

Figure 42: Picture took in the front part of the Room B1.5

Figure 43: Picture took in the rear part of the Room B1.5

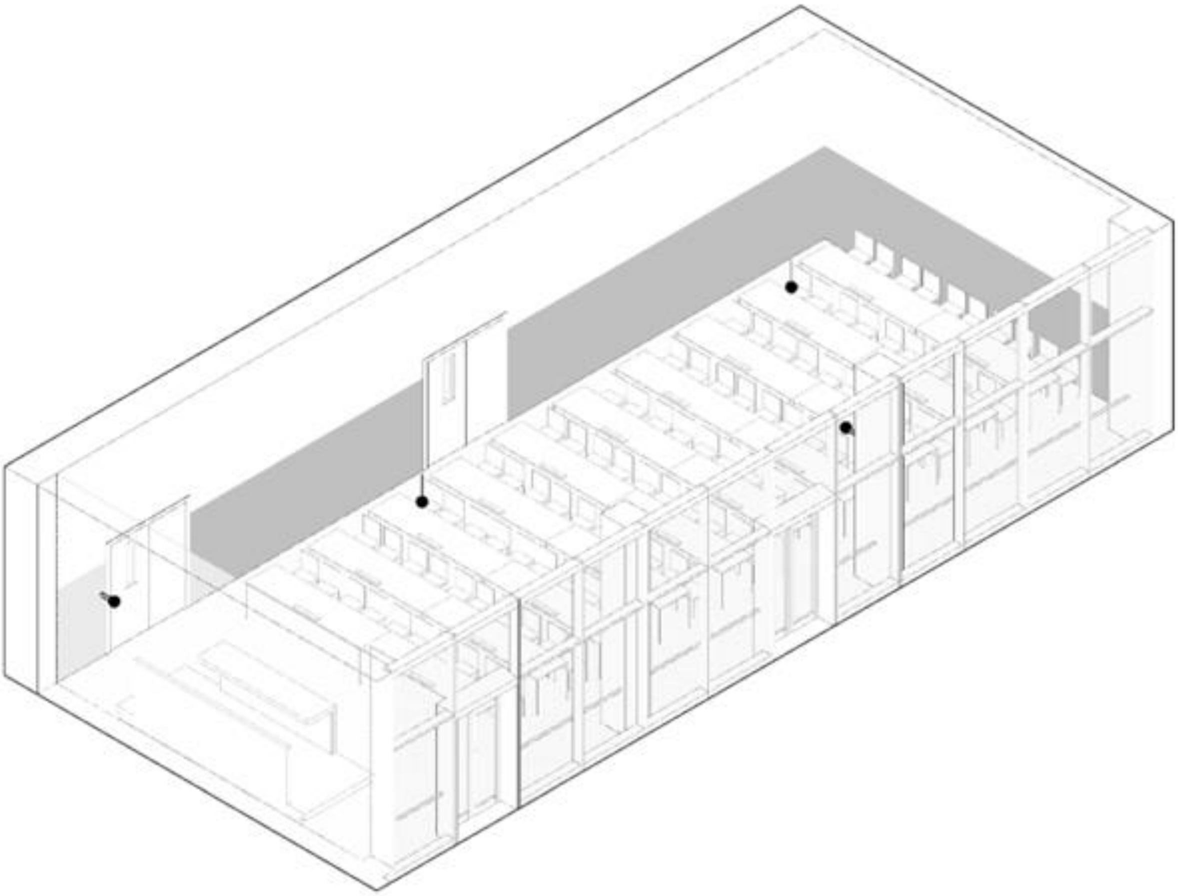

Figure 44: Axonometric view of Room B1.5

3.2.2.4 Sensor set-up description

The monitoring activity in the classrooms was conducted using certified instrumentation capable of detecting spot conditions of air temperature, relative humidity, atmospheric pressure, illuminance, carbon dioxide levels, micro-particulate matter, and volatile organic compounds. The data gathered by these sensors are collected by the border router positioned in the ceiling of the room and sent, trough ethernet connection, to a cloud online platform owned by LSI Lastem and, trough this platform, it is possible to download and pre-process data. The electric consumption, related to the supply and exhaust fan, are collected through amperometric clamps connected to a sensor that send data to an online platform owned by the manufacturing company. Additionally, the temperature of the conducting liquid before and after the heating/cooling coils and the carrier liquid flow are directly monitored by the relevant HVAC systems. The data acquisition system consists of two data loggers, each connected to a sensitive element. These data loggers communicate with a Raspberry Pi 4, which is connected to the internet via an Ethernet cable. The Raspberry Pi 4 transmits the data to a server located at the university every 5 seconds. The specifics of the instrumentation implemented are presented in Table 12.

Table 12: Instrumentation characteristics.

Indoor Environmental Quality Sensor		
LSI Lastem - Sphensor PRMPB0402		
	**Air Temperature sensor**	**Value**
	Measurement range	- 30 °C to 60 °C
	Total Accuracy	±0,1 °C; Max ±0,3 °C (at 20 °C to 60 °C) ±0,2 °C; Max ±0,3 °C (at -40 °C to 20 °C; 60 °C to 80 °C)
	Resolution	0,015 °C
	Relative Humidity sensor	**Value**
	Measurement range	0 % to 100 %
	Total Accuracy	±1,5 %; Max ±2 % (at 25 °C; 0 % to 80 %) ±2 %; Max ±3 % (at 25 °C; 80 % to 100 %)
	Resolution	0,01 %
	Atmospheric Pressure sensor	**Value**
	Measurement range	600 hPa to 1100 hPa
	Total Accuracy	0,18 hPa (at 25 °C) ±0,6 hPa (@ -40 °C to 85 °C)
	Resolution	0,1 hPa
	Illuminance sensor	**Value**
	Measurement range	0,1 to 90 klx
	Total Accuracy	±5% MV ± 5 lx
	Resolution	1 lx
	Sensitivity	3 lx
LSI Lastem - Sphensor PRMPA0423		
	**CO_2 sensor**	**Value**
	Measurement range	0 to 5000 ppm
	Total Accuracy	<± (50 ppm + 3% of measured value)
	Resolution	
	Volatile Organic Compounds sensor	**Value**
	Measurement range	0 to 60000 ppb
	Total Accuracy	Ethanol: 15 % of measured value H_2: 10% of measured value
	Resolution (ethanol, H_2)	0,2 % of measured value
	Drift (ethanol, H_2)	1,3 % of measured value
	Particulate Matter (1, 2.5, 4, 10) sensor	**Value**
	Measurement range	0 to 1000 μg/m³
	Precision	PM1 e PM2.5: 0 to 100 μg/m³ ±10 μg/m³

		100 to 1000 μg/m³ ±10 % of measured value PM4 e PM10: 0 to 100 μg/m³ ±25 μg/m³ 100 to 1000 μg/m³ ±25 % of measured value
	Thermal drift	0 to 100 μg/m³ ±1,25 μg/m³/year 100 to 1000 μg/m³ ±1,25 % of measured value/year
RIELS Instruments - RIF600S		
	**Control Unit**	**Value**
	Operating voltage	85÷264 VAC / 8÷36 VDC
	Repeatability	≥ 0,2 %
	Precision	≥ 1 %
	Temperature Sensor	**Value**
	Precision	± 0,8 °C (@ 100 °C)
	Accuracy	± 1 %
	Clamp-On TS1 Sensor	**Value**
	Tubing diameter range	DN25÷DN100
	Operative sensor temperature	0÷70 °C
smart-MAIC – D103-22		
	**Current sensor**	**Value**
	Lines (phases)	3
	Current Measurement (phase)	50 mA to 100 A
	Active energy precision	0.5 %
	Voltage/Current precision	< 1 %
	Operating Temperature Range	-40 to +70 °C
LSI Lastem – Wheater station		
	Temperature Sensor	**Value**
	Measurement Range	- 40 °C to 80 °C
	Accuracy	0.1 °C (@ 0°C)
	Relative Humidity Sensor	**Value**
	Measurement Range	0 % to 100 %
	Accuracy	±1% (@5% to 95%)
	Resolution	0.1 % (A/E-Log)
	**Globe Temperature Sensor**	**Value**
	Measurement Range	- 20 °C to 80 °C
	Accuracy	±0,1 °C (@ - 20 °C to 50 °C) ±0,15 °C (@ 50 °C to 70 °C)
	Global Radiation Sensor	**Value**
	Measurement Range	0 W/m2 to 1500 W/m2
	Specter Range	285 nm to 3000 nm
	Operative Temperature Range	- 40 °C to 80 °C
	Wind speed Sensor	**Value**
	Minimum Wind Speed	0.25 m/s
	Accuracy	0 m/s to 25 m/s: ± 0,25 m/s or 3% >25 m/s: 2% ± 0.1 m/s or ±1%
	Resolution	0.06 m/s
	Wind Direction Sensor	**Value**
	Measurement Range	0 ° to 360 °
	Minimum Wind Speed	0.15 m/s
	Accuracy	1 %
	Resolution	0.3 °

Sensor location

Each classroom is equipped with 4 sensors, two PRMPB0402 and two PRMPA0423. Two sensors have been placed at the front of the classroom and two at the back, in order to achieve as wide a coverage as possible on the parameters detectable within the classrooms. The sensors that monitor gas levels are located at a height of 3.30 m from the ground and are positioned so as not to suffer interference and turbulence from the movements of the mechanical ventilation systems. The temperature sensors at the front of the classrooms are positioned at a height of 1.20 m, while at the back they are positioned at a height of 2.50 m. The sensors located on the front side of the classroom, near the professor's lectern, have been equipped with a protective shell to prevent any impacts from occupants who might pass too close and risk to damage them. The weather station, located near the buildings under analysis, is responsible for measuring the external environmental parameters outlined in Table 12. The purpose of these measurements is to correlate the external parameters with the internal ones and to calculate the Predicted Mean Value (PMV) and the Predicted Percentage Dissatisfied (PPD). Each classroom on the Lecco Campus is equipped with an individual HVAC system that serves the reference classroom. On these, three-phase power meters have been placed that measure the amperage used by the mechanical components. In addition, on the HVAC system pertaining to classroom B1.5, temperature sensors and ultrasonic flow meters have been placed to detect the flow of the carrier fluid that is used in the batteries and measure the thermal power absorbed by the system. The various HVAC systems are controlled by a Building Management System (BMS) software developed by Siemens. Once the air outlet parameters (including Air Temperature, Relative Humidity, and CO2 concentration) are configured, the BMS software adjusts the opening percentage of the intake, outtake, and recirculation shutters for the enthalpy heat recovery system. Additionally, it controls the opening percentage of the valve for recirculation in the pre-heating/cooling battery, humidification battery, and post-heating battery. To ensure the desired performance, five different temperature sensors are positioned: one outdoors, another after the enthalpic heat recovery system, a third after the humidification battery, and the remaining two right at the air intake.

Classroom A1.3

Here are presented the sensor position in classroom A1.3. As illustrated in pictures (Figure 45, Figure 46 and Figure 47) the sensors are positioned to cover the widest area possible and to gather data from the whole volume.

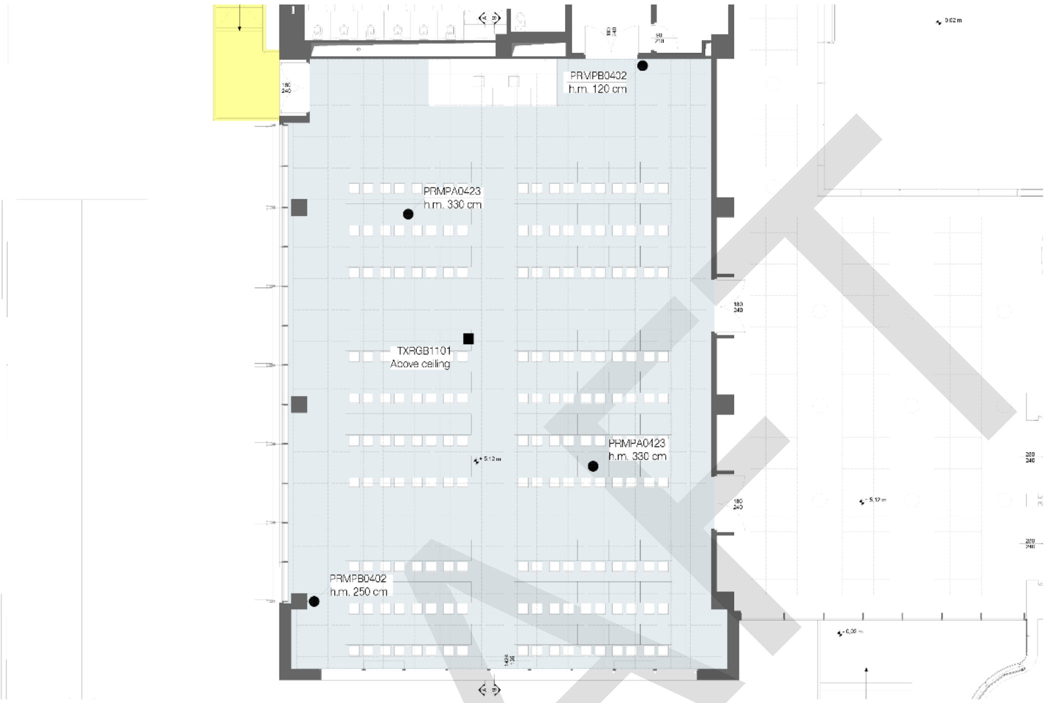

Figure 45: Plan view of classroom A1.3 illustrating the sensor location.

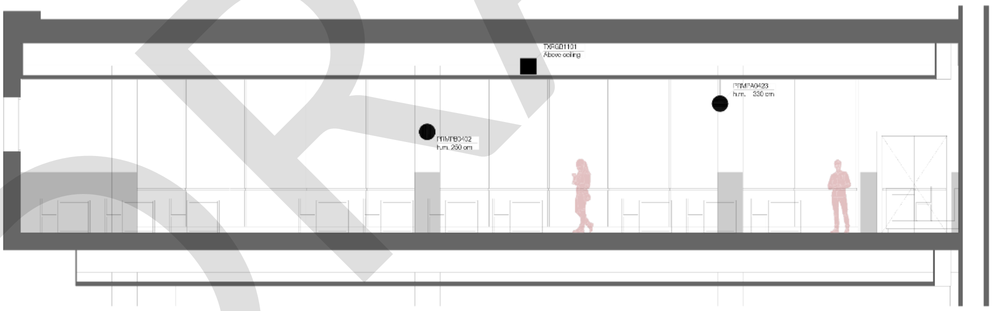

Figure 46: Section of classroom A1.3 illustrating the podition of sensos on the north side of the room.

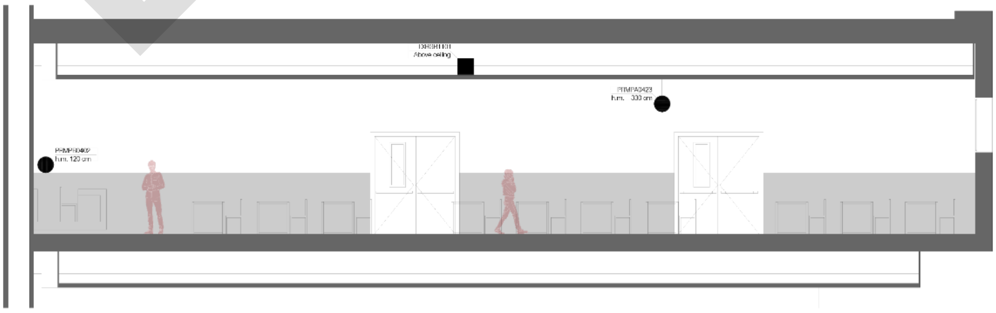

Figure 47: Section of classroom A1.3 illustrating the podition of sensos on the south side of the room.

Classroom B1.5

Here are presented the sensor position in classroom A1.3. As illustrated in pictures (Figure 48, Figure 49, and Figure 50) the sensors are positioned to cover the widest area possible and to gather data from the whole volume. Additionally, a schematic representation of the AHU is visible in Figure 51.

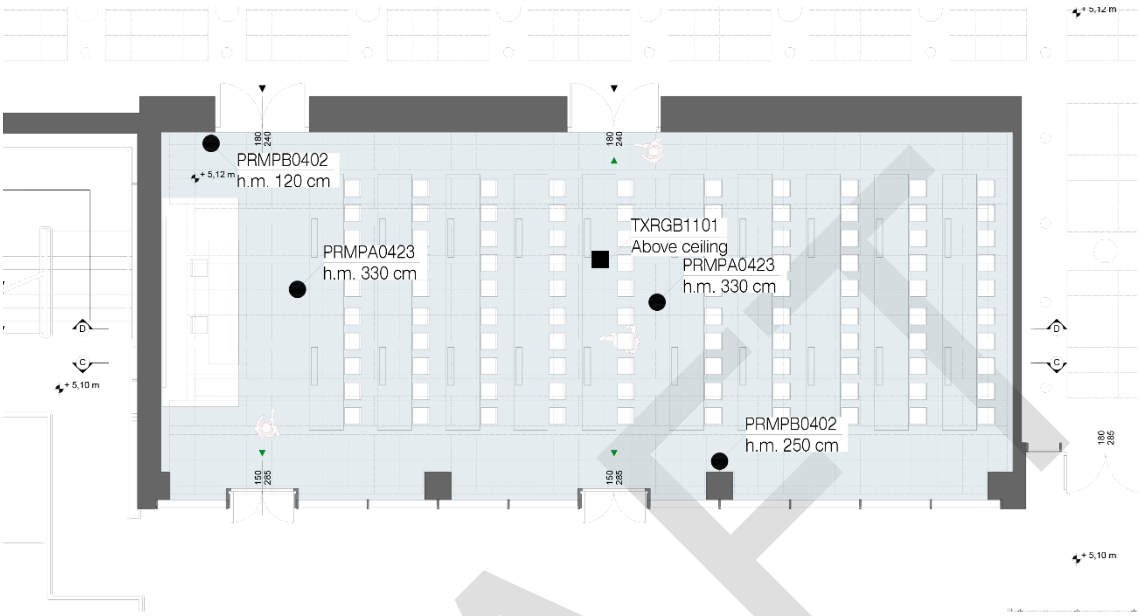

Figure 48: Plan view of classroom B1.5 illustrating the sensor location.

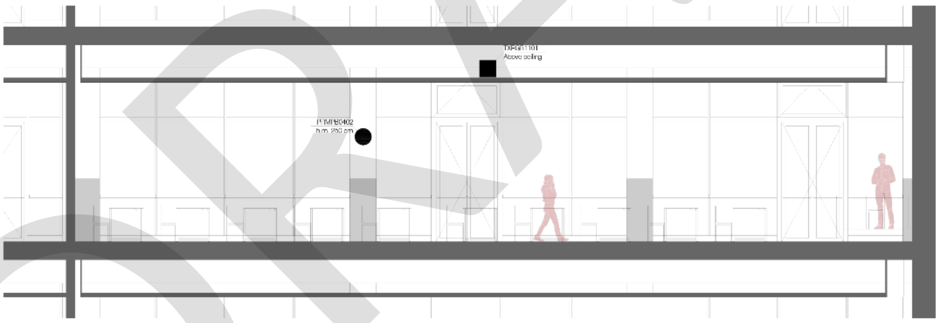

Figure 49: Section of classroom B1.5 illustrating the podition of sensos on the west side of the room.

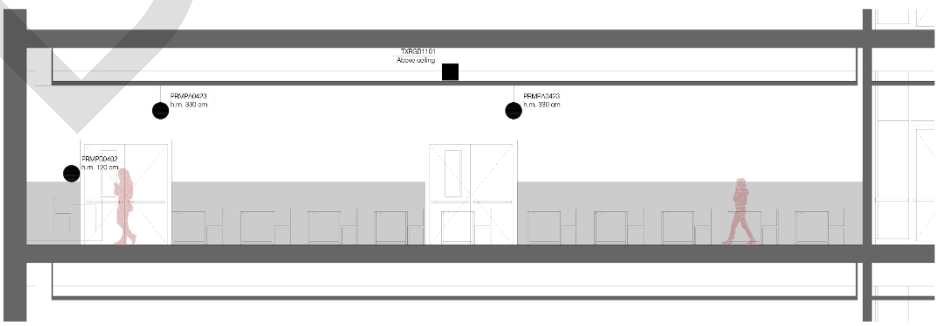

Figure 50: Section of classroom B1.5 illustrating the podition of sensos on the est side of the room.

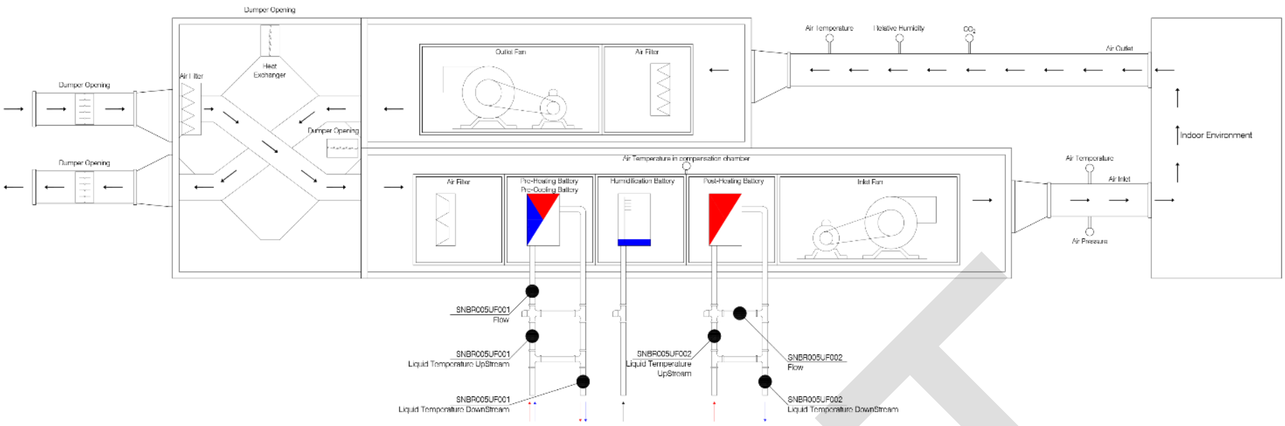

Figure 51: Schematic representation of the AHU afferent to classroom B1.5

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