POLITECNICO DI MILANO

Scuola di Architettura Urbanistica e Ingegneria delle Costruzioni

Corso di Laurea Magistrale in Ingegneria dei Sistemi Edilizi

Filling the gap between design and implementation in Building Management System: an integrated lifecycle workflow to align project objectives and enhance cross-stakeholder collaboration

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Anno accademico 2025/2026

ABSTRACT

The construction sector remains a critical area in terms of environmental impact. Despite ongoing efforts, it is currently responsible for approximately 34% of global energy consumption and 37% of CO_2 emissions.

The management and supervision of building systems, and consequently their proper operation, play a fundamental role in achieving low-carbon or zero-carbon building targets. In this context, alongside traditional automation and control strategies, increasing attention must be given to the continuous management and monitoring of systems through Building Management Systems (BMS).

Although it has been demonstrated that BMS can enable energy savings in the range of 15–20%, BMSs are still often perceived as "black boxes"; therefore, if not properly designed, implemented, and operated, they may fail to achieve their intended performance objectives. Building operation is inherently complex, and its effectiveness depends on several factors, including the quality of the design process, economic constraints, and, crucially, the level of collaboration and communication among stakeholders.

In current practice, the lack of structured guidelines supporting the lifecycle of a BMS—from early design stages through to implementation and operation—represents a significant limitation, potentially leading to the inefficiency of building automation and management systems.

The research presented in this thesis is based on a review of the existing literature and relevant industry guidelines, complemented by the analysis of a real case study. The investigation is structured using the RIBA Plan of Work as a reference framework to define the different phases of the BMS lifecycle. The case study highlights how insufficient integration of the automation system within the design and construction process can contribute to increasing the performance gap between expected design outcomes and actual building performance.

The aim of this thesis is therefore to define a design workflow for BMS that supports the entire system lifecycle. The proposed workflow identifies objectives, roles, responsibilities, deliverables, and information requirements for each phase, promoting greater integration between design, construction, and operation, and enabling a performance-oriented management approach based on continuous monitoring. The proposed workflow ultimately seeks to contribute to bridging the gap between design and operational phases of BMS, fostering an integrated lifecycle approach to both building systems and automation.

ABSTRACT (ITALIAN VERSION)

Il settore delle costruzioni rimane un'area critica quando si parla di impatto ambientale. Nonostante gli sforzi, ad oggi il settore edilizio è responsabile di circa il 34% del consumo di energia globale e del 37% delle emissioni di CO_2.
La gestione e supervisione degli impianti e, di conseguenza, il loro corretto funzionamento svolgono un ruolo fondamentale negli edifici che vogliono essere "zero carbon". In questo scenario, accanto alla sola automazione e controllo degli impianti, è necessario concentrarsi anche sulla loro gestione e monitoraggio, grazie ai Building Management Systems (BMSs).
Nonostante sia stato dimostrato come questi sistemi permettano una riduzione del consumo energetico di circa il 15-20%, i BMSs sono visti ancora come delle "scatole nere"; pertanto, se non progettati e utilizzati in maniera corretta, possono non essere efficaci rispetto agli obiettivi prefissati. La gestione di un edificio è infatti un processo complesso, la cui efficacia dipende da vari fattori, tra cui la corretta gestione della fase progettuale, la componente economica, la collaborazione e la comunicazione tra gli attori coinvolti.
Nella pratica progettuale attuale, la mancanza di linee guida in grado di supportare le fasi di vita di un BMS, dal concept iniziale dell'opera fino alla sua messa in opera, rappresenta una criticità che può comportare l'inefficienza del sistema di gestione e automazione.
La ricerca effettuata nella presente tesi si basa sullo studio della letteratura e delle principali linee guida del settore, integrata con l'analisi di un caso reale. L'indagine è stata svolta impiegando il RIBA Plan of Work come riferimento per strutturare le diverse fasi del ciclo di vita del BMS. Il caso studio presentato vuole essere un esempio di come la mancanza di integrazione del sistema di automazione nel processo di progettazione e realizzazione dell'edificio possa portare ad ampliare il performance gap tra quanto previsto in fase di progetto e il comportamento reale dell'edificio.
Lo scopo della tesi è quindi quello di definire un workflow progettuale che identifichi gli obiettivi di ciascuna fase, definendo ruoli, responsabilità e deliverable associati al BMS lungo l'intero ciclo di vita e favorendo al contempo la comunicazione e la collaborazione tra cliente, progettisti e appaltatori.
Il workflow proposto mira quindi a contribuire a colmare il divario tra fase progettuale e gestione operativa del sistema BMS, favorendo una maggiore integrazione tra progettazione, realizzazione e gestione operativa e supportando una gestione basata sul monitoraggio continuo delle prestazioni.

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AHU	Air Handling Unit
AI	Analogic Input
AO	Analogic Output
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	Building Automation
BACS	Building Automation Control System
BAS	Building Automation System
BMS	Building Management System
CMMS	Computerized Maintenance Management System
DCS	Distributed Control System
DHW	Domestic Hot Water
DI	Digital Input
DO	Digital Output
DDC	Direct Digital Controller
EC	Electronically Commutated
FATs	Factory Acceptance Tests
FCU	Fan Coil Unit
FM	Facility Management
HVAC	Heating, Ventilation and Air Conditioning
IT	Information Technology
IoT	Internet of Things
IUCs	Intelligent Unitary Controllers
LAN	Local Area Network
MS/TP	Master Slave/Token Passing
O&M	Operation and Maintenance
OT	Operational Technology
PICV	Pressure-Independent Control Valves
PLC	Programmable Logic Controller
RIBA	Royal Institute of British Architects
SATs	Site Acceptance Tests
WLAN	Wireless Local Area Network

1 INTRODUCTION

1.1 THE ROLE OF THE BUILDING SECTOR IN THE ENERGY TRANSITION: CURRENT STATUS AND OBJECTIVES

The annual report of the International Energy Agency (IEA) [1] states that the construction sector is responsible for 30% of global final energy consumption and 26% of global energy-related CO2 emissions (of which 8% are direct emissions from buildings [Fig. 1], and 18% are indirect emissions due to the production of electricity and heat uses).

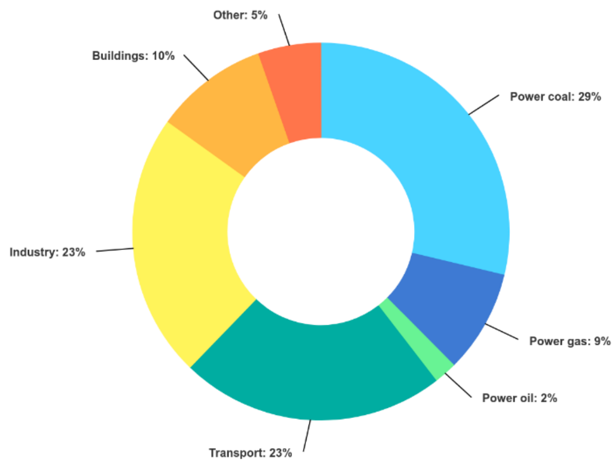


Figure 1: Share of energy demand growth - Source: IEA (2023)

Population growth and the increase in built floor area, together with the widespread use of appliances and air-conditioning systems, are causing a continuous rise in energy demand, resulting in a significant environmental impact.
According to the IEA report, electricity uses in buildings accounted for nearly 60% of overall growth in 2024. This is due to the higher demand for cooling linked to extreme temperatures during the summer season.

Energy in buildings is used for heating, cooling, domestic hot water production, lighting and much of this energy still comes from fossil fuels, which in 2011 made up 81.23% of global consumption.
Today, fossil fuels still represent more than half of global energy sources, although renewables have reached 38%, and nuclear energy is also used to a significant extent.
The trend becomes particularly clear when analysing investment data from recent years: investments in fossil fuels have remained relatively stable, while investments in “clean” energy sources have seen steady growth since 2021.

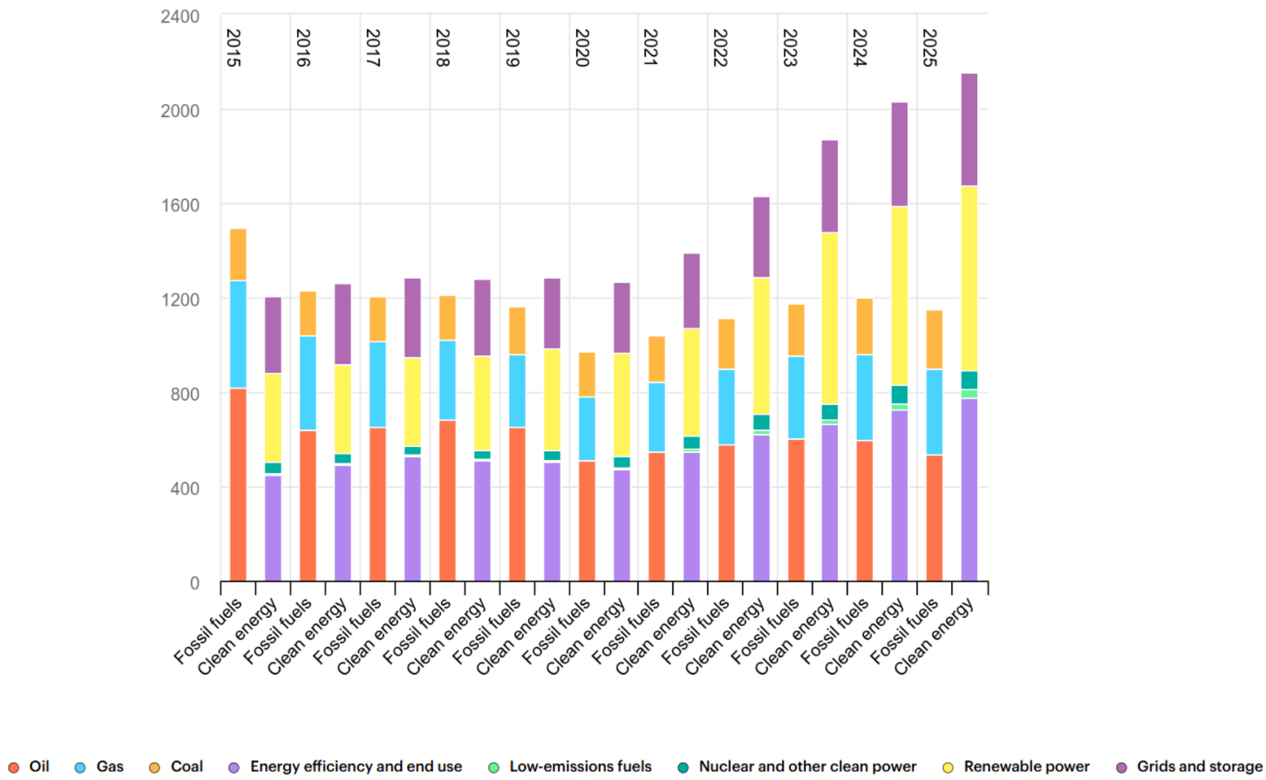


Figure 2 Global investment in clean energy and fossil fuels, 2015-2025 – Source: IEA (2025)

Despite the data reported by the IEA—which indeed show an increase in the use of renewable energy sources alongside the growing adoption of technologies such as photovoltaic systems and mechanical ventilation—the building sector is still far from meeting the 2030 targets: all new buildings must comply with “zero-carbon-ready” building codes, and at least 20% of the existing building stock must be renovated to reach the same level of performance. Achieving this target is considered essential to align with the scenario projected for 2050, namely the global achievement of net-zero CO_2 emissions, in line with the Paris Agreement goal of limiting global warming to 1.5 °C [2].

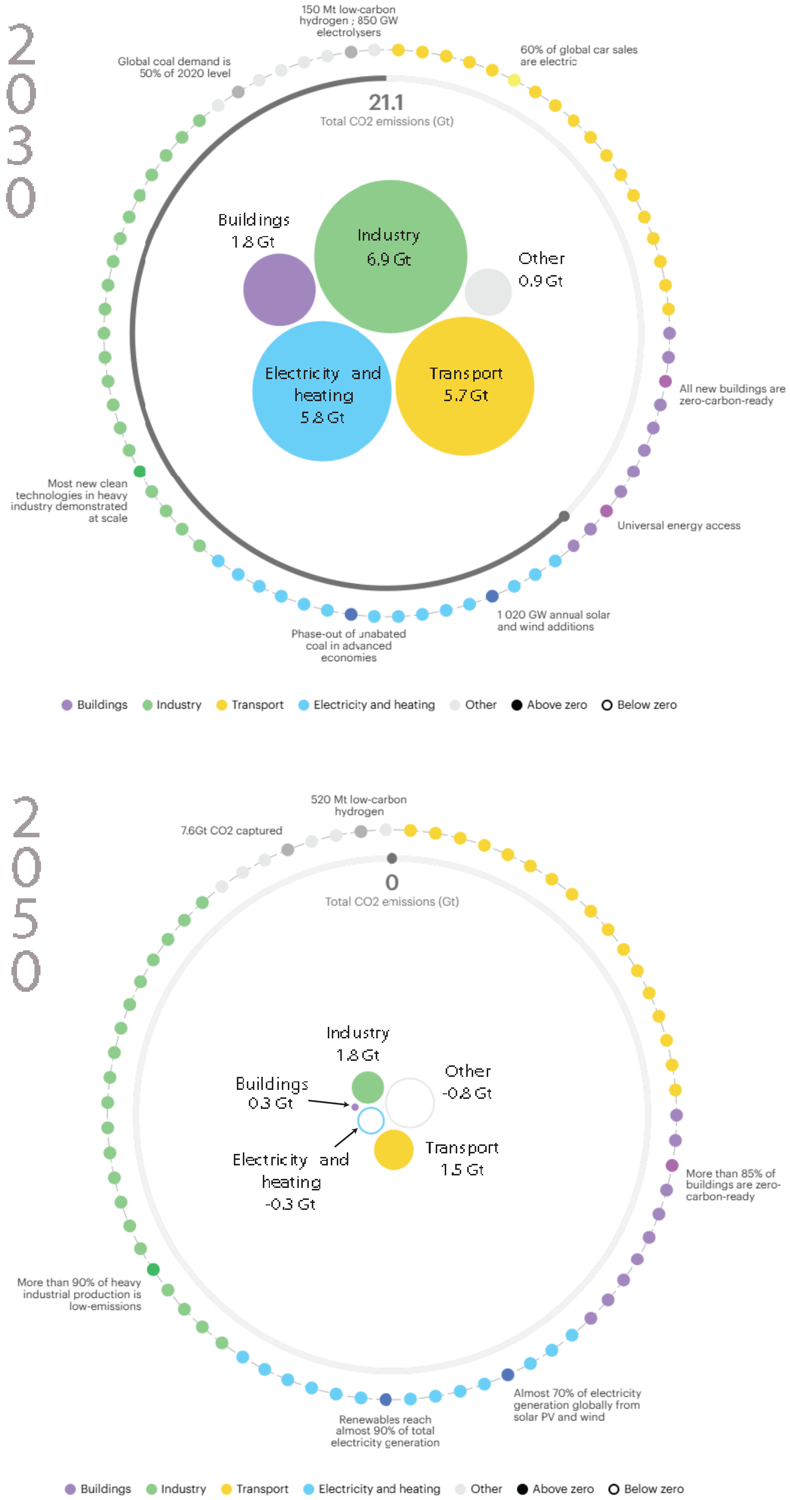


Figure 3 Global decarbonization milestones for 2030 and 2050 – Source: adaptation from Net Zero by 2050 Roadmap, IEA (2021)

To achieve the established targets, a rapid increase in energy efficiency, the decarbonization of energy systems, the electrification of end-uses, and the widespread adoption of low-emission and renewable technologies across all sectors—including buildings, transport, and industry—are required.

In this context, building energy codes have been a central tool for many countries over the past fifty years to improve the energy performance of newly constructed buildings. Building energy codes refer to mandatory technical regulations that set minimum energy-performance requirements for buildings, with the aim of reducing energy consumption and associated emissions.
According to the latest IEA Buildings Envelope Tracking Report [3], around 80 countries have mandatory or voluntary codes currently in place. This represents a 30% increase in the number of countries with energy codes since the 2015 Paris Agreement.
At the European level, the main legislative instrument promoting the improvement of building energy performance is the Energy Performance of Buildings Directive (EPBD) [4]
In particular, in its 2024 revised version, the EPBD is described as a directive that:

> *"[...] promotes the improvement of the energy performance of buildings and the reduction of greenhouse gas emissions from buildings within the Union, with a view to achieving a zero-emission building stock by 2050 [...]" (European Union, 2018)*

To meet the targets set for 2050, the construction sector cannot limit itself to interventions on the building envelope and the adoption of renewable energy sources. The EPBD therefore promotes the design of high-efficiency buildings by encouraging technological solutions that integrate monitoring and control of energy consumption.
In particular, the EPBD highlights the importance of Building Automation and Control Systems (BACS), of which Building Management Systems (BMS) represent the most advanced form. These systems enable the monitoring and regulation of the main building services (heating, cooling, ventilation, lighting), contributing to the achievement of the energy-efficiency and emission-reduction objectives established by European legislation.
Within the European regulatory framework, in addition to the EPBD, there is also a set of technical standards such as EN 15232 [5], which defines the energy-efficiency classes of automation and control systems.
The purpose of automation systems is to measure a building's energy use and to monitor its operating conditions, thereby providing the necessary information on the building's energy performance. Furthermore, the data related to energy consumption make it possible to further improve the building's energy performance by reducing waste and associated costs.

1.2 The role of Building automation in energy management and indoor comfort

Building Automation and Control Systems (BACS) are automation systems that manage and control a building's technical installations, such as heating, cooling, HVAC (ventilation and air conditioning), lighting, safety systems, fire-protection systems, and more. BACS therefore enable monitoring, regulation, and optimization of energy consumption, reducing inefficiencies and improving indoor comfort for building occupants [6].

Building automation thus represents a strategic element for achieving the energy-efficiency and decarbonization targets set by the European Union. Around 85% of the European building stock was constructed before 2000, and 75% exhibits insufficient energy performance. For this reason, the integration of automated solutions is essential for reducing energy costs and ensuring the transition towards zero-emission buildings by 2050.

This objective is set out in the Energy Performance of Buildings Directive (EPBD), which introduces specific requirements for automation and control in non-residential buildings. The EPBD establishes that such buildings must be equipped with BACS capable of monitoring energy consumption, analysing performance, and ensuring indoor environmental quality.

In addition, the EPBD requires that Energy Performance Certificates become digital and that national building-stock data be made available through centralized national databases. The aim of these measures is not only to improve the energy management of individual buildings, but also to create an integrated digital ecosystem that is essential for effective energy-efficiency and sustainability policies.

1.2.1 Building management System (BMS)

Among today's automation systems, Building Management Systems (BMS) play a key role. These systems integrate the core Building Automation System (BAS) with additional functionalities: monitoring and maintenance (Computerized Maintenance Management System – CMMS) and energy management (Energy Management System – EMS). Through the integrated management of HVAC systems, lighting, ventilation, safety, and other building services, the BMS enables the optimization of building operation, reducing energy waste and improving overall efficiency [7].

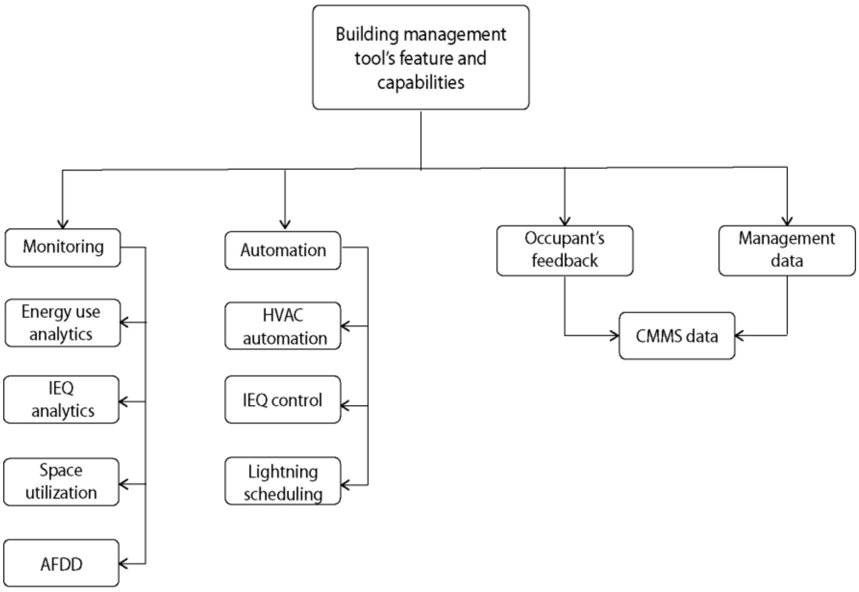


Figure 4: Common features and capabilities of commercially available building management tool – Source: elaboration from Current state and future challenge in building management: Practitioner interviews and a literature review – T. Abuimara et, all. (2021)

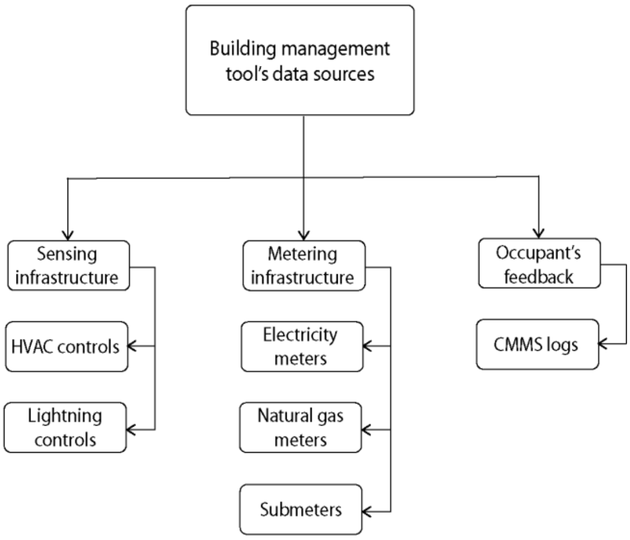


Figure 5: Common building management tools data sources – Source: elaboration from Current state and future challenge in building management: Practitioner interviews and a literature review – T. Abu-imara et, all. (2021)

The reduction of energy consumption implies not only a decrease in CO_2 emissions released into the environment—thus generating environmental benefits—but also economic savings related to the procurement and use of energy.

Beyond energy savings, the BMS contributes to occupants' comfort and well-being by intelligently regulating environmental parameters such as temperature, humidity, air quality, and lighting. This is made possible through the analysis of user behaviour: during the design phase, predictive analyses can be carried out based on models that simulate occupancy patterns according to the building's intended use. This integrated approach allows for the creation of comfortable and healthy spaces that adapt to users' needs without compromising energy efficiency.

1.2.2 Case Studies

Conceptual applications of Building Management Systems are illustrated through the case studies presented below. The analysed examples highlight the key role of BMS in the optimization of plants systems, continuous performance monitoring and integration of renewable sources, promoting more efficient and conscious energy management.

The Empire State Building [8] in New York is a well-known example of an efficient BMS implementation. This action was motivated by the need to address the significant impact of commercial buildings on the city's overall energy usage and greenhouse gas emissions, which account for a significant portion of New York City's environmental footprint. Combined with strategies applied to the building envelope, the Building Management System enabled a 38% reduction in energy consumption, resulting in annual savings of 4.4 million dollars.

Another example of BMS applied to the Knollys and Stephenson House [9], an office building located in Croydon, in the United Kingdom. In this case the intervention involved a recalibration of the control logics, based on the analysis of the real operating data of the building. After nine months of optimization of the building systems through the BMS, energy consumption was reduced by 28%, accompanied by a corresponding decrease in operating costs and CO_2 emissions. The action also led to economic benefits; in fact, there was a saving of around 171.000 pounds.

The use of a BMS also facilitates the integration of renewable energy sources (photovoltaic, wind, geothermal, etc.) [10], optimizing the building's self-consumption. The BMS coordinates energy produced from renewable sources with the building's actual energy demand, thanks to real-time monitoring, thereby reducing energy waste.
An example of how the BMS has a key role in the use of renewable energy sources is the Crystal in London [11]. It was conceived as an international scientific hub and designed to be one of the most sustainable buildings in the world. Its BMS manages more than 2,500 devices, optimizing lighting, shading systems, HVAC, and geothermal installations. In this case, energy consumption has been reduced by more than 40–50%, with CO_2 emissions 70% lower than those of traditional buildings. The Crystal also demonstrates how the implementation of a BMS can [contribute to achieving high score in environmental certifications. In this case, LEED Platinum and BREAM Outstanding were obtained.

In Italy, there are also clear examples of the benefits of Building Management Systems. In Milan, Gioia 22 [12] demonstrates the advantages of efficient building operation through BMS integration.
Gioia 22 is the first Italian skyscraper classified as Nearly Zero Energy Building (nZEB) and the BMS has a key role in the coordination between HVAC systems, monitoring systems, IoT sensors and the photovoltaic system integrated in the façade. In this case, energy consumption is 75% lower than in traditional office towers.

1.3 BMS AS A "BLACK BOX"

Building automation and control systems are designed to support the efficient operation of building systems while ensuring occupant comfort. However, the actual operation of the system does not always reflect the expected performance. The management of buildings is a complex process that depends on various factors: the expertise of professionals, hardware and software tools, coordination of management activities, and occupant behaviour.
For this reason, BMSs can be perceived as complex "black boxes" [13] by many professionals, which might influence how these systems are designed, configured, and managed. To ensure that efficiency, comfort, and sustainability objectives are achieved during operation, it is crucial to identify the main issues present in the various phases of the BMS lifecycle.

1.3.1 BMS Design

Problems related to BMS emerge already in the design phase, particularly when defining the system architecture, control levels, and integration methods among subsystems. One of the main design challenges lies in the choice of communication protocols and control platforms, which are often influenced by proprietary solutions and supply constraints. As a result, interoperability and future flexibility of the system may be limited. Another critical aspect to consider during design is the phenomenon of vendor lock-in [14]—that is, dependence on a single provider of hardware, software, and/or services. In this case, since devices, protocols, and control platforms are tied to the same manufacturer, integrating components from other brands can be complicated and costly. In BMSs, vendor lock-in can limit interoperability between subsystems, reduce operational flexibility, and increase maintenance and upgrade costs. For this reason, the use of open and standardized protocols, such as BACnet or Modbus, is recommended to ensure long-term flexibility of the BMS.

Another design limitation concerns the incomplete definition of BMS specifications. This often happens because the system is treated as a simple extension of the HVAC system, rather than as a tool for managing the entire building [15]. Not considering the complex structure of the BMS—which includes data architecture, alarm management strategies, and cybersecurity

policies—compromises the operational efficiency of the system, as initial design choices do not allow for adequate management of subsystems.
Another important topic is the integration between BMS and digital design tools such as BIM (Building Information Modelling). Although it represents an optimal strategy for improving building energy efficiency, there are several challenges in the combined use of BMS and BIM: the BMS generates a large amount of often unstructured data, and therefore it is necessary to develop dedicated frameworks and plug-ins to incorporate them into a BIM model, a process that is often costly. Overcoming these issues requires advanced technological solutions, such as integrated energy analysis tools, plug-ins for data visualization, and standardized protocols to ensure compatibility between platforms.
The problems described can be linked to various causes, such as a lack of knowledge about the operation of the BMS or subsystems, or a lack of coordination among stakeholders with different objectives: BMS designers are interested in using the most efficient system possible, while the building owner is focused on optimizing construction time and costs [16].
Facility managers, on the other hand, are responsible for the day-to-day operation of the building and the BMS during the operational phase. They are therefore interested in user-friendly interfaces and remote control of key system parameters. When a facility manager responds adequately to BMS alarms triggered by detected defects, potential system failures can be prevented. However, predictive maintenance requires a higher initial investment and remains a relatively recent concept. As a result, it is still under development due to the complexity of enabling systems to autonomously determine when and where maintenance is required. Furthermore, system dysfunctions may occur due to the integration of different components throughout the system lifecycle, leading to interoperability issues [17].

1.3.2 Execution and Commissioning

During the execution and commissioning phase, the issues identified during system design become apparent. Commissioning refers to the process of verifying, calibrating, and fine-tuning building systems—in this case, the BMS as a whole—to ensure they operate according to project specifications and expected performance standards. Comparing design performance with the actual operation of the system helps identify potential anomalies. If verification operations during this phase are insufficient or performed superficially, there can be consequences not only for the building's energy performance [16] but also for incorrect programming of systems (such as sensors and automatic controls) [18]. There are also repercussions on operating and maintenance costs [19], since problems not detected in time can evolve into faults requiring intervention after the systems are operational. Finally, the consequences affect occupant comfort [20], as non-optimized systems make it difficult to maintain stable and comfortable environmental conditions.

During this phase, networks, communication protocols, firewalls, and access credentials are also configured. These are critical elements for protection against vulnerabilities and cyberattacks. Thus, cybersecurity is fundamental even at this stage, since design choices previously influenced by economic and time constraints become concrete [21].

1.3.3 Commissioning and Operation

In the operation phase, deficiencies identified in previous phases result in poor quality data collected by the system, which are therefore unreliable and difficult to interpret. Poorly calibrated sensors, undetected faults, or configuration errors are the primary causes of energy inefficiency and suboptimal comfort conditions [22].

It can therefore be concluded that the limitations of the Building Management System do not stem from single technological shortcomings, but from a combination of design, execution, and management factors that affect the entire lifecycle of the building.

The most evident and impactful result of BMS malfunction is the building's energy inefficiency. The discrepancy between the actual performance of the building and the expected performance is known as the building performance gap. Studies in Italy [23] and Denmark [24] have reported a gap of up to 30% between estimated and actual energy consumption.

1.4 LITERATURE REVIEW

To date, there is no specific design methodology for BMS, which exacerbates the previously described issues. The current regulations (EPBD [4], UNI EN ISO 52120-1:2022 [25]) do not constitute an actual design guideline but rather serve as a reference for defining efficiency classes, providing methods to establish the minimum requirements for BMS functions.

The Energy Performance of Buildings Directive – EPBD identify Building Automation as a key enabler for improving the operational energy performance of buildings, with the goal of reaching the "zero emissions" target by 2030. The directive submit the requirement and scope of automation and control systems in buildings, focusing on non-residential one. So, it's explained *what* a BAS should do, but not *how* the design process should be outlined.

UNI EN ISO 52120-1:2022 provides a structured method for assessing the functional impact of automation. The standard identifies 4 automation class, from A to B, corresponding to an increasing progressive increase in the control, supervision and optimization capabilities of systems. To allow for clear identification, the normative structures automation functions according to the main systems, such as HVAC, lightning, ventilation, energy management). The purpose of the ISO 52120 is to evaluate the level of automation of a BAS, providing a functional classification that allows comparing different systems in terms of control, supervision and energy management capabilities.

The two regulations cited deal specifically with energy performance and the functional classification of automation. Getting into the merits of the design method it is necessary to cite the set of standards UNI EN ISO 16484:2024 [26], divided into 6 parts. UNI EN ISO 16484-1:2024 represents the only document that specifically approaches automation system design as a structured process, while the other parts focus on hardware, functional, application, application and communication aspects. The standard defines the main phases of the BACS project, from system design, installation, and completion, as well as operator documentation and training requirements. However, it remains mainly limited to the automation system, without clarifying how this is incorporated into the entire design process of the building or the different phases of its life cycle. This approach highlights a significant limitation of the norm and reflects a recurring criticality in design practice, in which Building Management systems are often developed autonomously or late with respect to the building project, contributing to coordination issues and overall system performance.

This weakness underlines the need for an integrated design workflow that combines BMS design to the construction project stages, reducing the risk of errors, inconsistencies, and critical issues during construction and management.

The regulatory approach remains mainly oriented to the performance results and functions of automation, rather than the way such systems are conceived and developed within the design process. However, there are several technical guidelines, not regulatory, developed by industry organizations, that offer practical guidance on BMS design and implementation, including ASHRAE Guideline 13, CIBSE Guide H, BSRIA publications, and eu.bac guidelines.

ASHRAE Guideline 13 - *Specifying Building Automation Systems* is a guideline that support designers in producing the BAS specifications, but only once the system has already been conceptually defined [27]. So, it can be considered as a complementary document to the legislation. The guide provides detailed advice for designing technical specifications of Building Automation Systems applied mainly to HVAC systems, addressing issues such as system architecture, input/output structure, communication networks, software configuration, testing, and final system documentation. It is also supplemented by information appendices that include examples of technical specifications, references to open communication protocols, such as BACnet, case studies of interoperability between systems, and preliminary guidance on cybersecurity applied to building automation systems.

In the United Kingdom there are two guidelines published by Chartered Institution of Building Services Engineer (CIBSE) and Building Services Research and Intelligence Association (BSRIA).

CIBSE has drawn up several documents regarding control systems. The first one is *Guide H – Building Control Systems [28]*, which is a general technical guide to supporting building services design, including BACS and BMS. This document offers directives on good design practice including aspects related to control, management and optimization of system in complex buildings. *CIBSE Commissioning Code C – Automatic Controls* [29] is referred to commissioning phase and clarifies the connection between design of controls and the delivery and commissioning phase. The *Guide M - Maintenance Engineering and Management* [30] talks about maintenance and management of buildings, specifying the role of control and management systems. Last two documents, *Digital Engineering Series* [31] and *Technical Memoranda* [32], do not deal directly and specifically with BA, but the first one can be used to define cybersecurity strategy, and the second one is useful when it comes to data-driven operation or continuous monitoring. As the other guideline described, CIBSE focuses on the performance and the correct technical execution of the automation system, but it's a useful operational support if integrated with the design process.

While CIBSE focuses mainly on best practice, BSRIA guidelines pay its attention to the design process and the real performance of buildings, with particular attention to the design, commissioning and in-service management phases of plant systems. BSRIA documents referred to BMS are *BG 6 – Design framework for building services [33]*, which provides a design framework for building devices, with guidance on roles, deliverables, and audits a different design phases; *Commissioning Job Book / Commissioning Codes [34]*, which deals with structured commissioning management; guidelines about BMS and performance, like *Effective BMS [35]*, *Building performance evaluation [36],* regarding the optimization of real performance, performance gap and the use of data in exercise.

BSRIA Guidelines are complementary to ISO normative and other guides such as ASHRAE and CIBSE. Also in this case documents are not open-access, representing a limit in their use in some work and academic environments.

The European Building Automation and Controls Association (eu.bac) is the European organization representing manufacturers and stakeholders in the building automation and control sector. The association offers guidelines and certification protocols that help designers define the functional requirements of the BMS and the achieved energy efficiency [37]. Through its checklist and certification protocols, the guideline aims to ensure that automation systems meet minimum requirements for energy efficiency and comfort. Therefore, eu.bac acts as a certification and quality verification tool for systems. However, the proposed guideline does not define detailed technical specifications for configuring control points, sensor placement, trend management, or integration logic between different systems.

All these documents indicate that detailed design practices exist, but even if they can be an operational support to the automation design process, they do not provide a shared design workflow that systematically integrates the BMS within the building design process.

Additionally, a common limit in using them to support BMS design practice is that they are not open-access documents. Both the ASHRAE guides and the main CIBSE technical guides, and BSRIA guidelines are in fact accessible only by purchase or subscription, an aspect that reduces their diffusion and accessibility.

The lack of a consolidated normative framework for BMS design has encouraged the development of academic and project-specific approaches. Despite the fact that these guidelines propose structured design methodologies, they are generally formulated for single projects, pilot studies or specific contexts, limiting their applicability beyond the individual case.

Research initiatives such as the BuildCOM project propose structured methodologies focusing on BMS auditing, commissioning and continuous performance optimization, focusing on the importance of process-oriented approaches beyond system installation [16].

Besides academic research, some large institutions have developed internal BMS design workflows to support campus renovation strategies. An example is the *Building Management Systems Design Guidelines* developed by the University of British Columbia [38]. The purpose of this document is to assist the Design of Building Management System installations in buildings at the University of British Columbia, and it consists of a description of requirements that the installed system must observe.

Similar owner-driven frameworks can be found in the Building Management and Control Systems Standards developed by the University of Sydney [39], the BMS requirements defined by the Australian National University [40], and the BMS Design Standards adopted by the University of Auckland [41]. All their documents want to be guidance on design inputs, documentation, roles and verification steps within the context of campus projects. This approach confirms that structured BMS design workflows are currently developed only in isolated, owner-driver contexts, instead of a shared framework integrated into the building design process.

1.5 PURPOSE AND SCOPE OF THE THESIS

As demonstrated, in design practice the BMS is approached as a separate system and is developed in the advanced stages of the project without real alignment with the strategic decisions made in the early stages.

The necessity of bridging the gap between design and implementation does not come only from a literature analysis, but also from the direct experience gained in the ARUP Milan office. Despite the integrated and multidisciplinary approach that characterizes design in Arup, the lack of a workflow dedicated specifically to BMS has as consequence criticality in the definition of performance objectives and continuity between project phase and operational phase.

Such issues have emerged in the analysis of a real case study developed during professional experience, in which the absence of a structured workflow caused a misalignment between what was foreseen in the design phase and the actual operation of the system.

This case study constitutes an excellent starting point to identify and in a concrete way the criticalities associated with the current approach and to highlight the need for a structured and shared methodology.

This study aims to define an effective design workflow to support integrated design and interdisciplinary collaboration within Arup's professional practice. The proposed guideline intends to define roles, responsibilities, objectives and deliverables at different stages of the project, promoting greater continuity between design and operation and more effective communication between designers, clients and operational figures.

From a methodological point of view, the thesis adopts the RIBA Plan of Work as a reference framework, using it to integrate BMS related activities within the standard phases of the building process.

Following the literature review presented in the previous chapter, the definition of the proposed workflow was developed through a four-step methodological approach.

The process started with the analysis of a case study along all the design phases, which enabled the identification of the main critical issues and gaps between design and implementation. This investigation provided the basis for the drafting of a structured workflow, developed as a guideline aimed at bridging these mismatches and a replicable methodological proposal adaptable to similar design contexts.

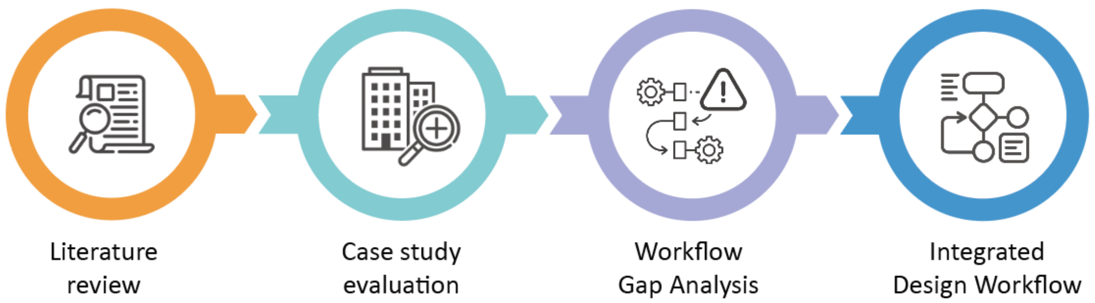


Figure 6: Methodological workflow of the thesis - author's elaboration

1.6 THESIS STRUCTURE

The thesis will consist of the following chapters:

Chapter 2: This chapter first describes the role of the BMS in the management of a building, the principles that should guide its design, and then delves into the system architecture. Finally, it provides an overview of the regulations concerning building automation.

Chapter 3: this chapter provides the basis for understanding the BMS communication network, describing its standards, protocols and interaction between them.

Chapter 4: this chapter is dedicated to the description of the case study, highlighting the main critical issues related to BMS design across the RIBA Plan of Work stages.

Chapter 5: this chapter focuses on the design of the BMS during the RIBA stages 0–2, with particular emphasis on key components such as stakeholder roles and responsibilities, point lists, energy classification frameworks and the definition of KPIs.

Chapter 6: the steps analysed in this chapter correspond to RIBA stages 3-4. In particular, the chapter explores the development of detailed design requirements, including control strategies, and graphical interface specifications. Furthermore, it analyses the tender phase, defines tender documentation and gives an example of criteria for tender evaluation.

Chapter 7: this chapter addresses the implementation and operational phases of the Building Management System, corresponding to RIBA Stages 5, 6 and 7. The aim of this chapter is to analyse the fundamental steps involved in the installation, delivery and use of the BMS, with particular attention to commissioning, handover processes and in-use operation.

Chapter 8: in this chapter, the subject of cybersecurity is addressed, the risks to which an automation system can be subject are described and what may be the strategies to be implemented to protect the BMS from a cyber attack

2 BASIS OF BUILDING MANAGEMENT SYSTEM

2.1 BUILDING AUTOMATION SYSTEMS: FROM ANALOG REGULATION TO BUILDING MANAGEMENT SYSTEM

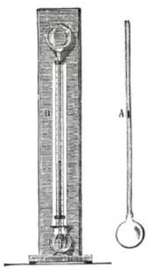
Although building automation was formally standardized only in the early 2000s, the concept as we know it today is the result of a long evolutionary process. The first analogue control systems in buildings date back to the 17th century, when the Dutch engineer Cornelius Drebbel invented the thermostat. Originally developed to regulate the temperature inside egg incubators, this invention marked the beginning of a significant evolution in building automation, later supported by major technological advancements such as electricity, electronics, and the internet. These developments eventually led to the widespread diffusion of Building Automation and Control Systems (BACS).

With the progression towards intelligent buildings (smart buildings), however, the need emerged for management systems that go beyond simply controlling and regulating individual subsystems. Modern buildings require a centralized system that not only supervises technical installations but also integrates multiple systems and optimizes their operation through the analysis of stored, data-driven information. This role is fulfilled by what are known as Building Management Systems (BMS).

A timeline is presented below, illustrating the key milestones in the evolution of automation systems, from the invention of the first control device to today's advanced management systems.

1600s

The first device used to control building performance was the thermostat. Invented in the 1600s by the Dutch engineer Cornelius Drebbel, it was originally developed as a temperature regulator for egg incubators. The device measured the internal temperature and, if it deviated from the set point, acted to restore optimal conditions through simple on/off operation. Today, this type of control is considered the precursor of modern control systems and forms the basis of what is now known as feedback control.



1884

Following Thomas Edison's invention of the incandescent bulb, the need emerged for safe, insulated switches suitable for direct current (DC). These were soon followed by electrical outlets and toggle switches, enabling manual control of indoor lighting comfort. From the early 20th century, artificial lighting became an essential element of residential comfort.

1925

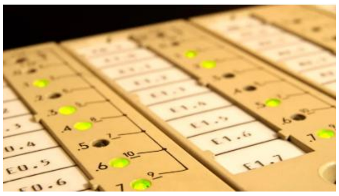
In 1925, *Nicolas Minorsky* invented the *PID controller*, a closed-loop control mechanism initially developed for ship steering. It was later applied to create the first analogue device capable of regulating the supply temperature of heating systems. The PID controller represented an evolution of Drebbel's 17th-century thermostat: rather than relying on simple on/off operation, it acted continuously to keep controlled variables at their set point.

1960s

The earliest automation systems were designed to detect faults in commercial buildings. *James Sutherland*, an engineer at Westinghouse Electric, developed Echo IV (Electronic Computer Home Operator), a prototype domestic computer capable of managing air-conditioning, performing accounting tasks, and generating shopping lists.

1969

Programmable Logic Controllers (PLCs) became the first commercially available digital computers for industrial process control. Designed for reliability and flexibility in harsh environments, they were also used in early smart-home applications. Their architecture relied on a central processing unit (CPU) connected to peripheral modules that handled inputs and outputs. This setup enabled the monitoring of sensors and the activation of actuators through programmable control logical laying the groundwork for today's building automation systems, including heating and HVAC management.



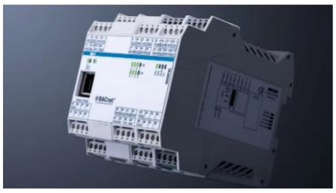
1979/1980

The introduction of Direct Digital Control (DDC) marked the transition from pneumatic and analogue equipment to digital solutions offering greater flexibility, precision, and centralized programmability. Interoperability and centralized management became possible thanks also to the diffusion of Ethernet as a universal data-exchange standard, valued for its affordability, speed, and ubiquity.

1986

Building Information Modelling (BIM) systems emerged as the first software tools capable of modelling, integrating, and storing all relevant building data. Their ability to keep information continuously updated provided a solid foundation for the development of modern building automation systems.

1990s



During this decade, standard communication protocols enabling interoperability between different automation systems were introduced—first BACnet, followed by KNX. KNX offered a global standard that harmonized automation procedures. This transition marked the birth of the true Building Management System (BMS), allowing multiple systems to be monitored and controlled through a single interface.

2000s

The advent of the Internet transformed building automation: with the spread of Wi-Fi and the emergence of the Internet of Things (IoT), devices and sensors could now be connected through networks. This period saw the rise of cloud-based management systems, enabling remote monitoring and control.

2010s

Building automation systems began integrating machine learning and artificial intelligence, enabling predictive and adaptive control capable of adjusting operations in real time. In addition, the introduction of digital twins—virtual representations of buildings and their systems—made it possible to run simulations and optimize performance digitally before applying changes to the physical building.

2020s

The integration of IoT and AI into building management systems has led to buildings capable of autonomously adapting to both short and long-term climatic conditions. Machine learning enables continuous optimization of operations to achieve maximum efficiency and sustainability.

Source: author's own elaboration based on data from *Bosch Building Technologies* [42] and *Tyrrell Analytics [43]*; images from *Bosch Building Technologies [42]*

2.2 DEFINITION AND PURPOSE OF THE BMS

The term Building Management System (BMS) refers to an energy management system integrated with additional capabilities, such as equipment monitoring, protection of equipment against power failure, and building security [44].

It is a supervisory and control system that centrally manages a building's facilities, such as climate control (HVAC), lighting, security, energy, and other subsystems.

Its aim is to optimise the building's energy performance, ensure occupant comfort, and consequently achieve cost savings. This is accomplished through constant monitoring of facility operations, data collection, and the application of automatic control logics [45].

The BMS is based on a hierarchical structure in which sensing, control, and supervisory functions are distributed across different functional layers [46]. The system is commonly structured in three levels: Field Level, which includes sensors and actuators for data collection and action execution; Controller Level, where programmable devices process information and apply control logic; and Management Level, dedicated to supervision and analysis, using software to enable centralised monitoring and control. These levels are interconnected using standard communication protocols, such as BACnet and Modbus, which ensure interoperability and secure data exchange. The main devices include sensors for temperature, humidity, and air quality; actuators for facility regulation; controllers such as PLCs and DDCs; and servers hosting the supervision software [47].

To be effective, the BMS should not merely manage the facilities but also perform advanced functions such as data historization, report generation, and alarm management.
Data collection and historization are central functions of a Building Management System, as they allow inefficiencies and anomalies in facilities to be identified, supporting optimisation and contributing to reduced energy consumption, and consequently, lower CO_2 emissions and operational costs. The acquired data include environmental parameters (temperature, humidity, CO2 concentration, illuminance), energy parameters (electric, thermal, and water consumption), and operational parameters (facility status, maintenance activities). The information gathered enables energy efficiency assessments by converting data into performance indices: Key Performance Indicators (KPIs). Through these indicators, it is possible to monitor energy consumption, air quality, and comfort parameters. Finally, the BMS can manage alarm notifications from installed sensors and devices, including fire and intrusion detection systems. Alarms can be categorised by their priority (critical, general, low-level) or by their operation type (digital, analogue, mismatch) [16][48][49].

2.3 Control Philosophy

Applying control strategies to building facilities can lead to a reduction in energy consumption of approximately 15–20% [13]. However, BMSs are often perceived as “black boxes” by many professionals, which may influence how these systems are designed, configured, and managed. Establishing some simple, general principles for efficient and effective control could help demystify BMSs and promote deeper discussions among plant engineers, building managers, and BMS engineers about developing control strategies to enhance performance.
BMS engineers are experts in implementing efficient control strategies but are usually not involved during the design phase and tend to avoid contractual risks associated with deviating from specifications.
Moreover, their work in new buildings occurs at the end of the project, when time is often limited due to delays and pressure to finish as quickly as possible. In existing buildings, contractual incentives for facility management aim to minimise costs rather than maximise value, which can limit spending on BMS subcontractors.
Tom Randall, in his article “Unlocking the secrets of the black box: control strategies for engineers”, proposes general principles for control strategies:

- Demand-based control
- Efficient supply
- Intuitive and user-friendly interface

Randall also emphasises the importance of collaboration and trust among the parties involved, namely designers and operators.

2.3.1 Demand-Based Control

The first principle, demand-based control, is itself based on two concepts:

- Alignment between demand and supply
- Avoiding energy waste caused by control conflicts

Aligning demand and supply means that the provision of services, such as HVAC, lighting, and hot water, should reflect the actual demand of the building. The goal is to avoid both under sizing, which compromises occupant comfort, and oversizing, which leads to energy waste. Implementation should include occupancy-based control strategies, such as using CO2 sensors or data from PIR sensors, to dynamically regulate ventilation and other services in response to real-time usage patterns.

Controlling energy demand also involves eliminating control conflicts between systems, such as simultaneous heating and cooling, which cause energy waste and occupant discomfort. Strategies to address this problem may include applying suitable dead bands (≥2K) between heating and cooling setpoints, coordinating control between air handling units (AHUs) and terminal units through aggregated demand logic, and grouping terminal units by dominant mode (heating or cooling) to simplify operation. The aim of these measures is to help reduce unnecessary energy use and improve thermal comfort.

2.3.2 Efficient Supply

The principle of efficient supply implies not only that the BMS itself operates efficiently, but also that its selection is made judiciously.

It is necessary to choose the most energy-efficient system available to meet service requirements, so the optimal solution will be selected based on real-time demand and prevailing environmental conditions. The control strategy should prioritise systems that minimise energy consumption while maintaining performance, based on the system's dynamic operation.

An efficient system allows optimisation of system parameters to enhance energy performance. Techniques include modulating temperatures and flow rates based on valve positions, ensuring that systems operate within their most efficient range. Variable speed drives (VSDs) should be integrated into the BMS to enable dynamic control of pumps and fans. Furthermore, heat pumps and chillers should be managed in the appropriate sequence to maximise efficiency, ideally in consultation with manufacturer specifications.

2.3.3 Intuitive and User-Friendly Interface

Randall highlights the importance of an intuitive interface designed according to the target user, whether it is the BMS Head-End supervisory server, the computer used by the Facility Management (FM) team, or wall-mounted HMI touchscreens intended for general personnel.

Each interface should provide clear and accessible control and monitoring functions, appropriate to the user's role.

2.4 BMS Structure

The design of a Building Management System is based on a hierarchical architecture that enables data collection from each facility component, which are then processed with the aim of transforming them into regulation and optimisation actions.

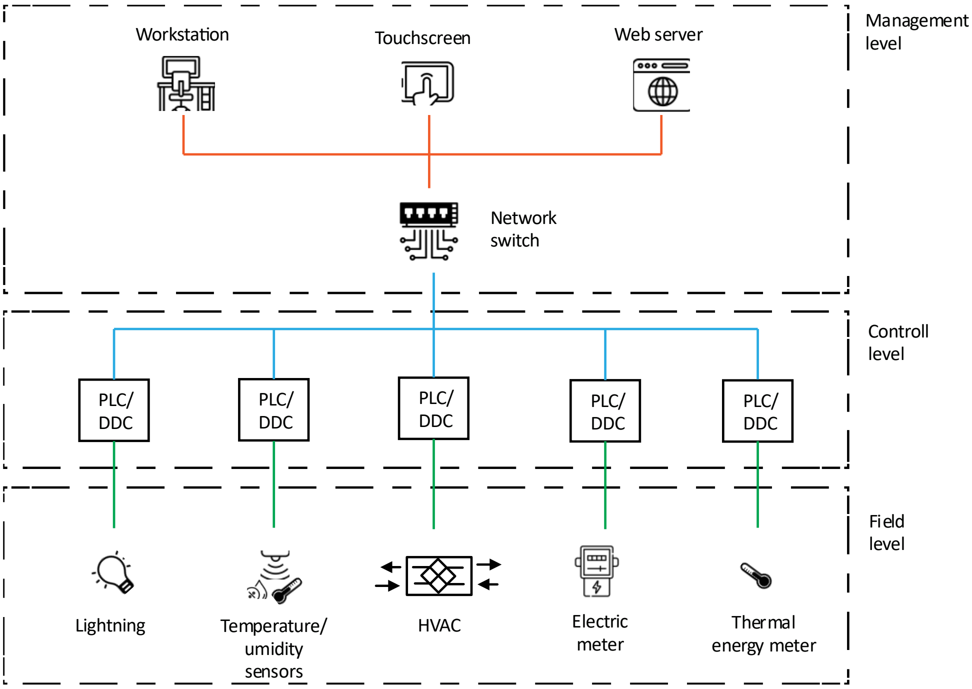


Figure 7: BMS Structure - author's elaboration

The BMS is organised into three levels, each with its specific function:

- Field level: includes sensors and actuators that collect data (temperature, humidity, CO2) and send commands to facilities.
- Control level: includes controllers (PLC, DDC) that process data and apply regulation logic to facilities.
- Management level: includes servers and HMI interfaces for monitoring, analysis, reporting of collected data, and integration with external systems.

The three levels are integrated through a hierarchical architecture and standard communication protocols, guaranteeing real-time interoperability and data exchange.
The Building Management System is the integrated set of physical devices and infrastructures that cooperate to monitor and control a building's facilities. Each component plays a specific role: from sensors detecting environmental conditions, to actuators performing regulatory actions, to controllers processing data, and the supervision platforms enabling centralised management [47].

2.4.1 Field Level

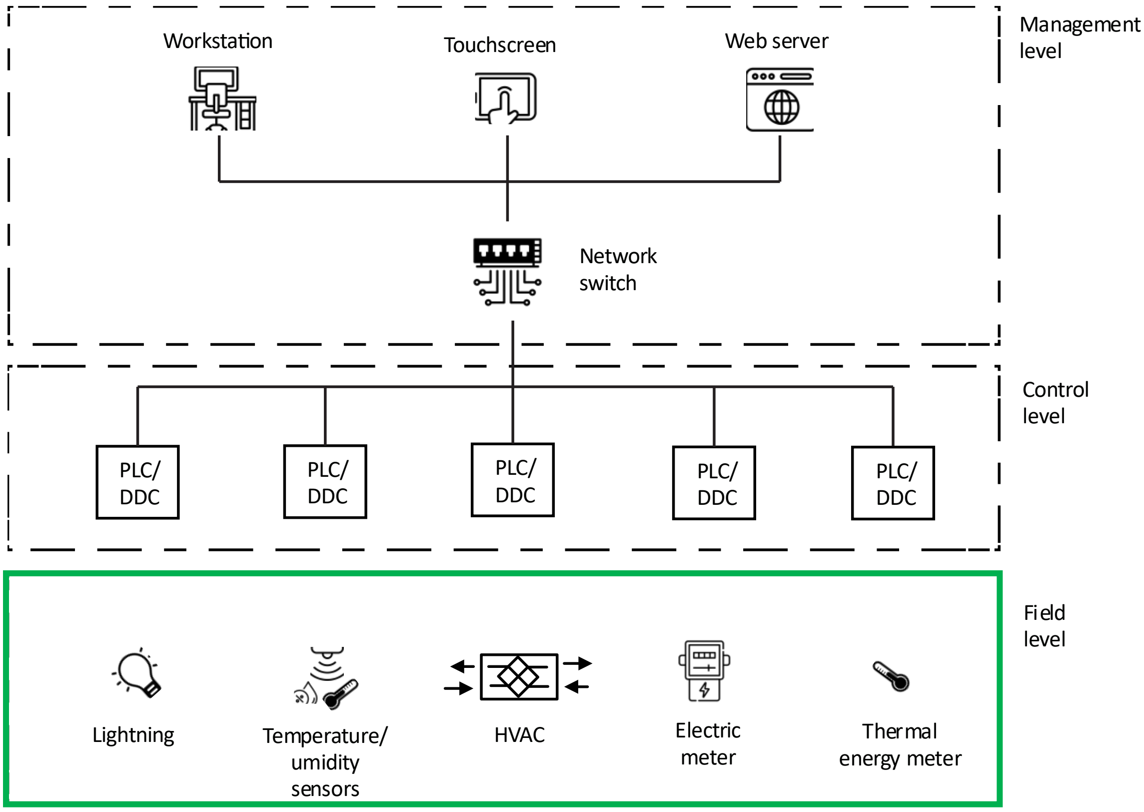


Figure 8: BMS Structure, focus on Field Level - author's elaboration

The field level consists of physical devices such as analogue and digital sensors, detectors, regulators, actuators, badge readers, cameras, speakers, switches, and lighting units, both standard and equipped with local intelligence. These devices, in addition to acquiring data and executing commands received from the higher level, must be able, when required, to make autonomous adjustments.

These elements communicate with the upper level via field buses and standard protocols such as Modbus or BACnet MS/TP, enabling reliable and interoperable information transfer. Here, parameters such as temperature, humidity, air quality are detected, and commands are executed to open valves or regulate ventilation [47].

2.4.1.1 Field devices

Field devices represent the lowest level of the architecture and are responsible for collecting data and executing actions.

The devices included in the field level are:

- IUCs
- Sensors and actuators
- Package units equipped with integrated communication

The sensors measure environmental parameters such as temperature, humidity, pressure, CO_2 concentration, brightness and the presence of people. Receiving this data allows for efficient control of HVAC systems, lighting, and air quality.
Actuators, on the other hand, receive from the controllers and act on the operation of the systems, for example by opening or closing valves, adjusting shutters, turning on lights or changing the speed of the fans.
Intelligent Unitary Controllers (IUCs) are controllers that monitor and control VAV cassettes, FCUs, heat pumps, etc. [27]

2.4.2 Control Level

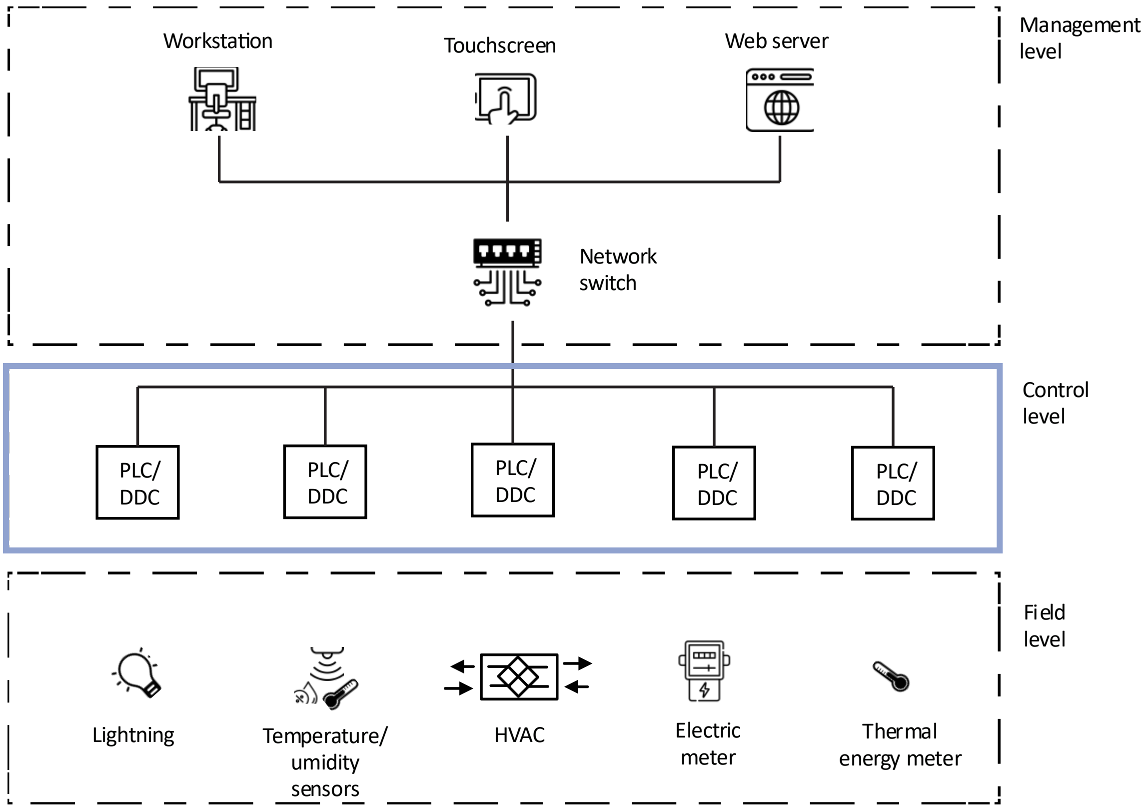


Figure 9BMS Structure, focus on Control Leve - author's elaboration

The Control Level, known also as Automation level, is the core of automation: data from sensors are processed and converted into commands for actuators, ensuring the proper operation of facilities. This task is entrusted to programmable devices, including PLCs (Programmable Logic Controllers) and DDCs (Direct Digital Control). Communication with the Management Level occurs via IP networks, using protocols such as BACnet/IP or Modbus TCP/IP, allowing fast and secure data transmission to supervision platforms [27].

2.4.2.1 Control devices

Control layer devices include:

- Controllers

- A touchscreen display for local control
- Field bus routers
- Protocol conversion gateway

Controllers process data from sensors and apply regulation logic. There are two main types of me:

- PLCs (programmable logic controllers): These were created for industrial automation and stand out for their robustness, flexibility, and ability to handle complex processes. They are programmable in standard languages such as Ladder or Structured Text and allow you to implement custom logic, making them ideal for systems that require high reliability and integration with industrial machinery.
- DDC (direct digital controller): These are designed specifically for the HVAC industry and building management: they offer pre-configured functions for direct control of temperature, humidity and ventilation, simplifying installation and maintenance.

All controllers must have peer-to-peer communication, meaning each controller can send and receive information from others independently, without the need for a central exchange point to mediate the information. Another important requirement is that controllers must have stand-alone functionality, so that in the event of a BMS system failure they continue to function normally and communicate with each other.

Communication between the control devices is mainly via an Ethernet network that also connects to the management layer devices. Communications from the controller layer to the field layer can be via a communication port on a Controller or via an IP–fieldbus router.

Dedicated protocol interface devices, which convert from one protocol to another (e.g. BACnet to Modbus), are also expected to reside at this level.

Protocol conversion gateways allow you to convert one protocol into another (for example from BACnet to Modbus). This need arises mainly from the need to standardize the protocols of equipment that often has a different factory protocol than the one used for the BMS system. Without protocol conversion, the devices would not be able to communicate.

At this level, it is also necessary to provide local touchscreen displays, generally mounted on the frames of electrical panels. It would be preferable for these to connect directly to the Ethernet network rather than to a port on a Controller [27].

2.4.3 Management Level

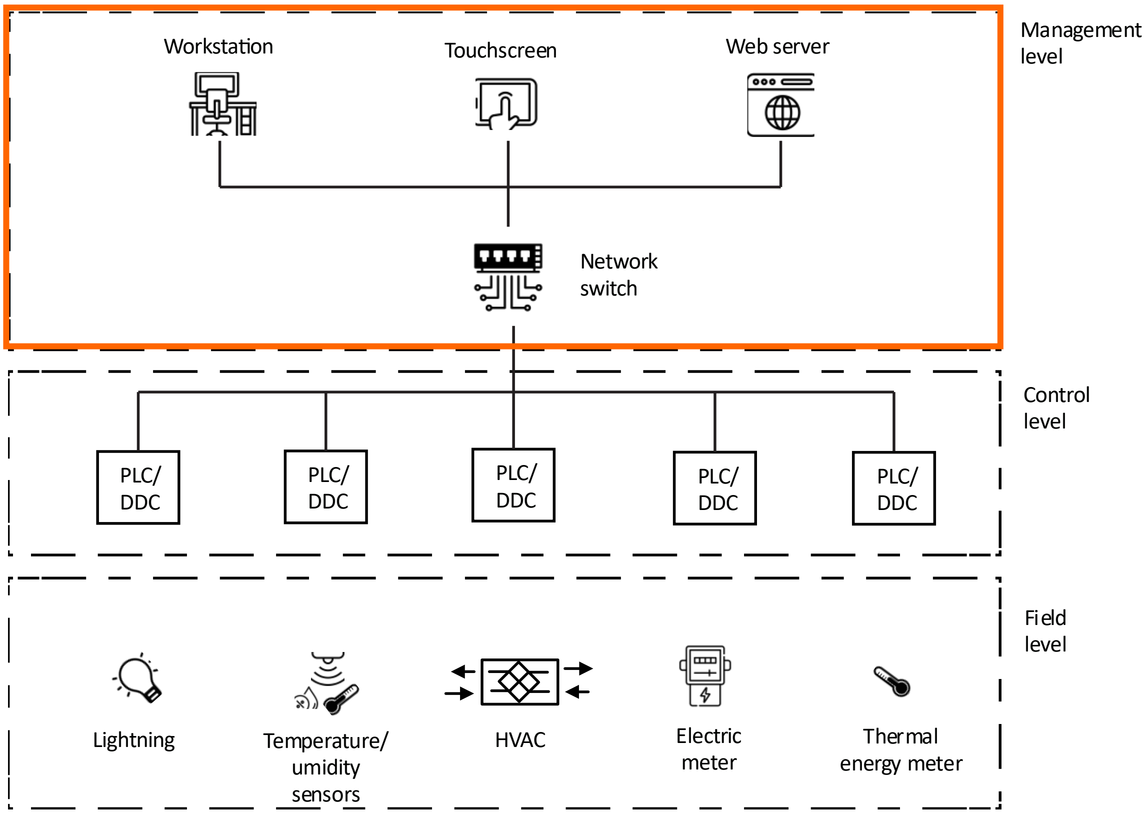


Figure 10: BMS Structure, focus on Management Level - author's elaboration

The Management Level is the highest tier, where BMS software centralises control and provides tools for analysis, reporting, and energy optimisation. Operators can monitor the status of facilities, manage alarms, and plan maintenance interventions. Integration with the Controller Level is made possible by open protocols and client-server architectures, often extended to the cloud to ensure remote access and scalability. Thus, the three levels do not operate as separate entities, but as an integrated system exploiting common standards to ensure interoperability, reliability, and flexibility [47].

2.4.3.1 Supervision hardware

Management layer devices include:

- BMS Server
- BMS Workstation
- Web servers
- Web browsing computers
- Touchscreen displays and mobile devices (tablets, smartphones)
- Internet routers

2.4.3.1.1 Server setup, workstations and communication network

The BMS system should be equipped with a primary server and a workstation for the operator, connected to UPS. The workstation should be the main interface that allows you to monitor and manage the systems.

In some cases, it may be necessary to place several touchscreen displays in specific locations to allow local monitoring and management of specific systems, such as the HVAC system.

The servers, each equipped with a video monitor, mouse, and keyboard, must be installed with the rack server in a secure location, such as the IT technical room.

All devices that make up the BMS must communicate with each other over TCP/IP Ethernet.

2.4.3.1.2 Graphical interface and accessibility

The graphical interface must be easy to navigate and intuitive for all users, even those who have no engineering knowledge of the system, such as residents of a building or shop assistants. For the interface to be easily navigable, the graphics can be set up so that each element that constitutes the system can be viewed in plan and can be queried directly from the graphics page.

The system graphics should be visible simultaneously from multiple devices, such as the workstation and a smartphone, and must be able to be clearly visible and therefore adapt to the device used for navigation.

Each user must have their own login credentials, and specific interface functions can be assigned for each; therefore, read-only graphics pages can be set up, or system settings can be managed.

2.4.3.2 Navigation structure

In the system interface, it must be possible to query each element of the system through graphical navigation.

Depending on the level of information detail, the navigation structure is divided into levels as follows:

- Level 1

  Graphic screen summarizing all buildings connected to the BMS.

  If there is only one building, level 1 coincides with level 2
- Level 2

  Dashboard with representation of the state of each floor, primary system temperatures, active alarms.
- Level 3

Representation of the systems on each floor, through a cross-section of the building with similar systems listed in columns or through tabular menus, which can then link to a Level 3 graphic where there are too many systems to be listed in a single graphic.

- Level 4

  Representation of systems in 2D, overview or schematic.

  For complex plants, there may be a general overview of the system that links to a more detailed graphic of the individual subsystem.

  For simpler systems, such as UTA, an overview is not necessary, so from Level 3 you can directly access the UTA graphics
- Level 5

  Detail of system parameters, its setpoints, operating logics
- Level 6

  User-customizable blank graphics screen

Levels 4 and 5 represent the actual state of the plant systems, allowing the operator to verify their operation and make diagnoses.

2.5 Regulatory References

The building sector is responsible for a significant portion of global energy consumption and greenhouse gas emissions, making it one of the main areas of focus for global climate policies. The Paris Agreement of 2015, adopted at COP21, set ambitious targets to limit global warming to 1.5°C, prompting governments and institutions to introduce binding measures for energy efficiency in buildings [50]. In response, the European Union has developed the Green Deal and the Fit for 55 packages, which include the Energy Performance of Buildings Directive (EPBD), recently updated in 2024 [4].

The EPBD establishes requirements for the adoption of Building Automation and Control Systems (BACS) in non-residential buildings and, gradually, in residential ones, defining technical criteria through the UNI EN ISO 52120-1:2022 standard [25], which replaces the previous EN 15232.

The EPBD is a European directive, so each Country must transpose the text into national legislations. The most recent version of the EPBD requires that the transposition must be done by 2026, failure to meet these deadlines may result in the Commission initiating infringement proceedings, as already occurred in 2026 for several Member States that did not submit their draft plans on time. In this context, national transposition is not a mere formal requirement, but a necessary step to make European measures on energy efficiency, system digitalisation, and building automation enforceable at national level, ensuring consistent minimum requirements and harmonised control mechanisms across the EU.

2.5.1 UNI EN ISO 52120

UNI EN ISO 52120-1:2022 has replaced UNI EN 15232-1, expanding and updating its contents. As stated in the standard itself, its purpose is to provide:

- a structured list of control, automation and technical management functions for buildings that contribute to the energy performance of buildings; the functions have been classified and organised according to the building services and the related automation and control (BAC);
- a method for defining minimum requirements or any other specification regarding the control, automation and technical management functions of a building that contribute to its energy efficiency, applicable to buildings of different complexity;
- a factor-based method for an initial estimate of the effect of these functions in types of buildings with typical usage profiles;
- detailed methods for analytically assessing the effect of these functions in a particular building.

2.5.1.1 Methodology

The standard defines two possible calculation methodologies for determining the contribution of automation and regulation to the energy performance of buildings: a method called *detailed* and a method *based on factors*.

The first method is usable when detailed information about the building, HVAC systems and, in particular, the type of automation, regulation and management functions is available. The detailed method "would allow the classification of a building automation and regulation system according to a series of criteria defined in this standard."

The factor-based method is instead a simplified method, allowing "a simple calculation of the impact of the functions of a building based on an energy performance (a measured consumption or a calculated requirement) correlated to a specific classification of BACS efficiency of the building."

Therefore, while the second method allows rapid analyses of the impact of BACS on energy performance, the detailed method makes it possible to carry out an accurate evaluation when it is necessary to precisely define the quality of the automation and control system, provided that detailed information on the building is available.

The standard does not simply describe the two methods but provides a series of technical tools. To use the detailed method, a classification of all automation functions applicable to the building systems (heating, cooling, ventilation, lighting, etc.) is provided.

Each function is associated with increasing levels of quality, each of which operationally describes: the minimum operating requirements, the accepted control logics and the expected performance. The correlation between the functions and the efficiency class is expressed through tables provided by the standard.

As for the factor-based method, the standard provides standardised coefficients, the BACS efficiency factors, which represent the energetic effect of control strategies, calculated according to the type of building and the system considered.

2.5.2 Energy Performance of Buildings Directive

The EPBD (Energy Performance of Buildings Directive) forms the foundation of the European regulatory framework for achieving the "zero emissions" target by 2030. In this context, the automation of building systems takes on a strategic role, becoming a regulatory requirement to ensure efficiency and reduce consumption.

The EPBD provides a series of definitions regarding sustainability, including that of the building automation and control system, which is described as:

> *"…a system comprising all products, software and engineering services that can support energy-efficient, economical and safe operation of technical building systems through automatic controls and by facilitating the manual management of those technical building systems." (European Union, 2018)*

The directive outlines the functions of the building automation and control system, specifying that the system shall guarantee continuously monitoring, logging, analysing and allow adjustments to improve performance.

Additionally, the responsible for the facilities or technical building management must be informed about opportunities for energy efficiency improvement and it's important that the system is able to communicate with all technical building systems across different types of proprietary technologies, devices and manufactures ((European Union, 2018).

The directive introduces the requirement for automation and control systems in non-residential buildings, where technically and economically feasible. In particular, the EPBD defines two thresholds based on the rated output of HVACS systems (European Union, 2018):

1. by 31 December 2024, for buildings with an effective rated output above 290 kW;
2. by 31 December 2029, for buildings with an effective rated output above 70 kW.

The same objectives must be applied to the lighting system, which must be equipped with occupancy detection functions to ensure efficient operation (European Union, 2018).

The EPBD does not set specific energy-efficiency targets for residential buildings; instead, it establishes that minimum equipment is required: the system must monitor electrical consumption and system's efficiency and informs building owners or managers in the case of a significant variation and when servicing is necessary.

In non-residential buildings the principal scope of the automation system is to control functionalities of the generation, distribution, storage and use of energy and, where applicable, hydronic balance, with the purpose of adjusting energy consumption.

The directive talks also about the importance of data exchange. Cybersecurity is a critical theme and the EPBD specifies that the rules on access to data shall be carried out in accordance with Regulation (EU) 2016/679, known also as GDPR (General Data Protection Regulation), of the European Parliament and the Council.

2.5.3 UNI EN ISO 16484

UNI EN ISO 16484:2024 [26] represents the main international regulatory reference for defining the design and implementation process of Building Automation and Control Systems. The standard outlines the fundamental phases of the project of building automation systems, providing a structured guideline for BA design. Part 1 of the UNI EN ISO 16484 identifies four macro phases - *design*, *engineering*, *installation* e *completion* - which include the definition of technical requirements and specifications, the detailed design of hardware and software functions and architecture, the installation and commissioning of the system, up to the activities of handover, acceptance and production of documentation as built, respectively. The standard also recognizes the importance of identifying roles and technical documentation.

Each part of the regulation focuses on a specific aspect of automation. After Part 1, which has already been described, Part 2 focuses on hardware devices and field components, defining their general requirements. Part 3 introduces a classification of automation and control functions, providing a structured reference for the functional description of BACS systems. In Part 4, how automation functions are implemented and organized within control systems is described. The last Part focuses on communication and interoperability between systems, with reference to the use of open protocols such as BACnet.

Although UNI EN ISO 16484 defines the design and implementation process in a structured way, it stops at the initial stages of the BACS life cycle, excluding continuous operation, maintenance and optimization activities, which are instead fundamental for performance over time.

2.5.4 European regulatory framework

As already mentioned, the EPBD requires European Member States to: establish renovation trajectories and minimum energy performance standards (MEPS) for the non-residential stock; tighten provisions on technical building systems and automation, extending the scope of BACS obligations in non-residential buildings and ensuring capabilities for continuous monitoring, logging, analysis and adjustment of energy use; and align new-build pathways with zero-emission building (ZEB) criteria on a fixed timetable. These requirements are framed to be transposed in national legislation and completed by secondary acts (technical codes, calculation methodologies, etc.).

In the following tables is shows a selection of EU Countries that have already completed transposition of the EPBD in its first version and are updating their frameworks to implement the 2024 recast. For each Country the table identifies the principal legal instrument that transpose the EPBD.

Country	EPBD transposition
Italy	Decreto legislativo 48/2020 [51]
France	Décret n° 2020-887 [52]
Germany	Gebäudeenergiegesetz (GEG) [53]
Spain	Real decreto 390/2021 [54]
Netherlands	Bbl – Besluit bouwwerken leefomgeving [55]
Ireland	S.I. No. 749/2024 [56]
Poland	Energy Performance Act [57]
Portugal	Decree-Law No. 101-D/2020 [58]

Table 1:EPBD implementing legislation across selected countries – author's elaboration

3 COMMUNICATION NETWORK

The three levels on which the BMS is based can communicate with each other through a network infrastructure organised in three layers: the primary network connects management and control levels, a secondary network facilitates communication between the control level and the primary network, and, finally, the field network enables interaction between field devices and controllers.

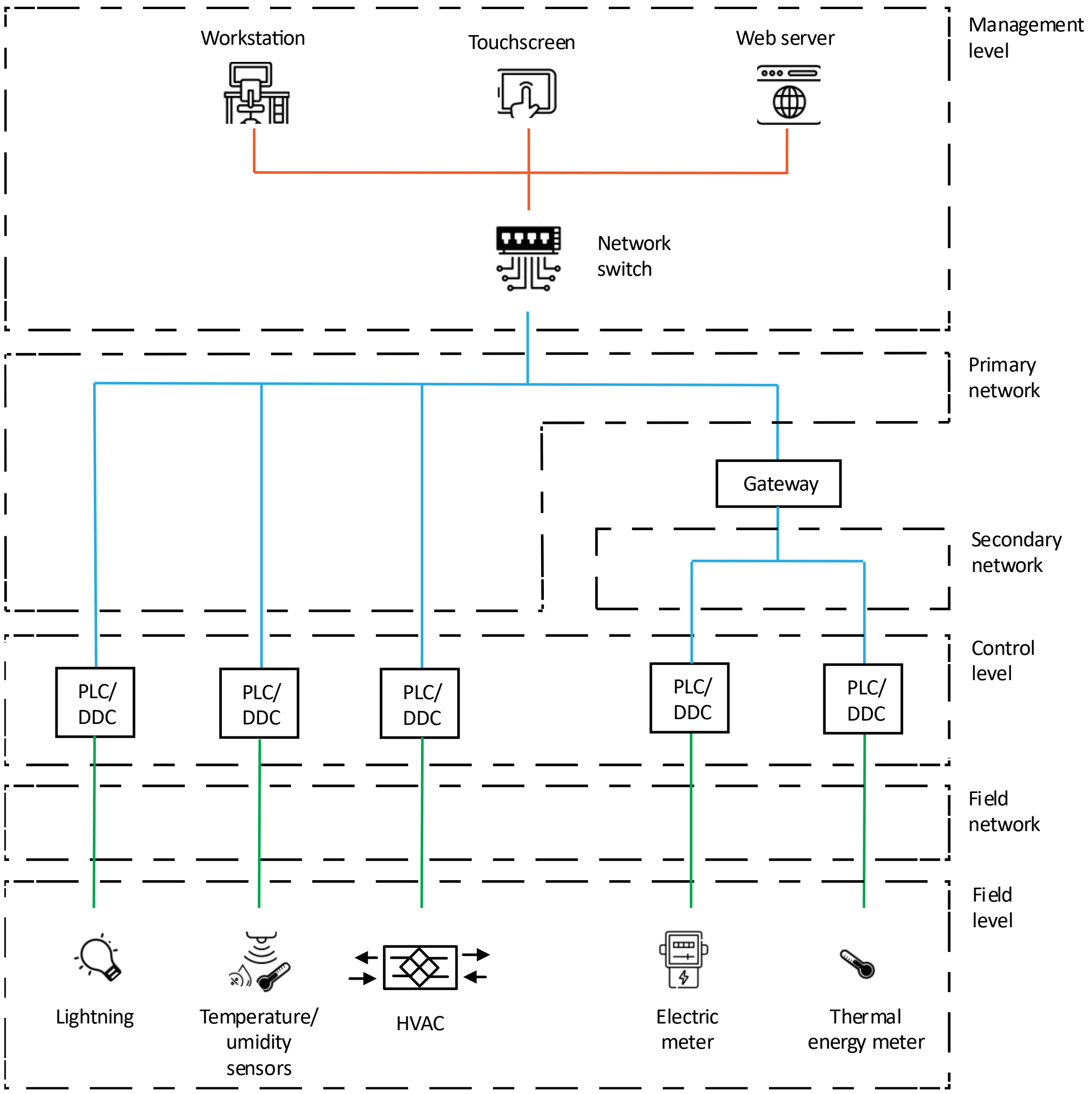


Figure 11: BMS architecture and network - author's elaboration

3.1 PRIMARY NETWORK

The primary network may be separated or shared with the building's LAN (Local Area Network), or communication can occur via WLAN (Wireless Local Area Network).

The operation of the primary network relies on network switches, devices that connect various nodes and efficiently manage their communication [47].

3.1.1 Network switch

In a LAN each node can communicate with each other tanks to a network switch. To identify nodes in a network the switch uses MAC-address, also known as physical addressing, that correspond to the data link layer in the OSI-model (see section 3.4).

If all nodes are in contact at the same time, there is the risk of data collision in the network. To avoid this problem, a switch uses micro segmentation, so only two nodes can communicate at the same time [47].

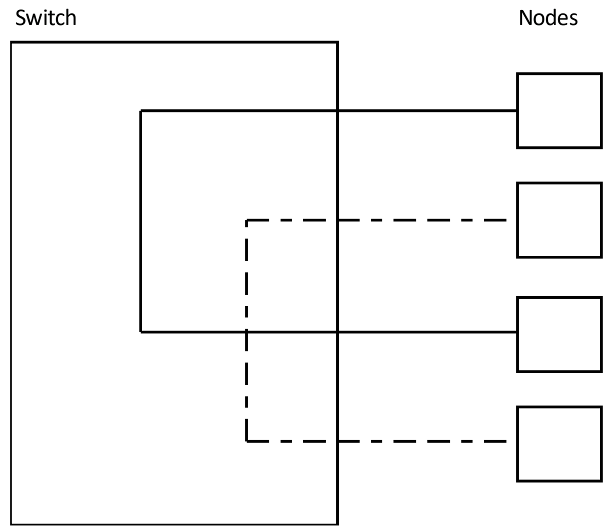


Figure 12: Description of micro segmentation in a switch. - Source: Kensby J.; Olsson R. (2012)

In function of the layer of the OSI-model in which the switch works, there are two different categories of switches: data link layer in the network layer, where the IP address is used as identification; multilayer switches, which can switch the data on MAC-address or direct the incoming data with IP addresses [47].

3.2 SECONDARY NETWORK

Secondary network connects Control level and Primary level. Its scope is gathering devices in the Control level that operate with different protocol from the protocol in the Primary network to allow the communication with the rest of the system. If only one protocol is used, the Secondary network can be avoided [47].

3.3 Field Network

The field network is intended to connect field devices (actuators, sensors, etc.) with the control level. The connection between the two levels can be established in various ways [47]:

- Direct cabling (hard wired)
- Fieldbus
- Power line
- Wireless

3.3.1 Direct Cabling

If field devices are connected via direct cabling, each device is individually linked to the control level. The type of signal sent depends on the device being managed: for example, weather station information is digital, while valve control is analogue. This method is optimal for systems requiring a limited number of connections [47].

3.3.2 Fieldbus

This type of network uses twisted pair copper cables for connections between levels. Technologically, cabling can be organised in two configurations: trunk or daisy chain.

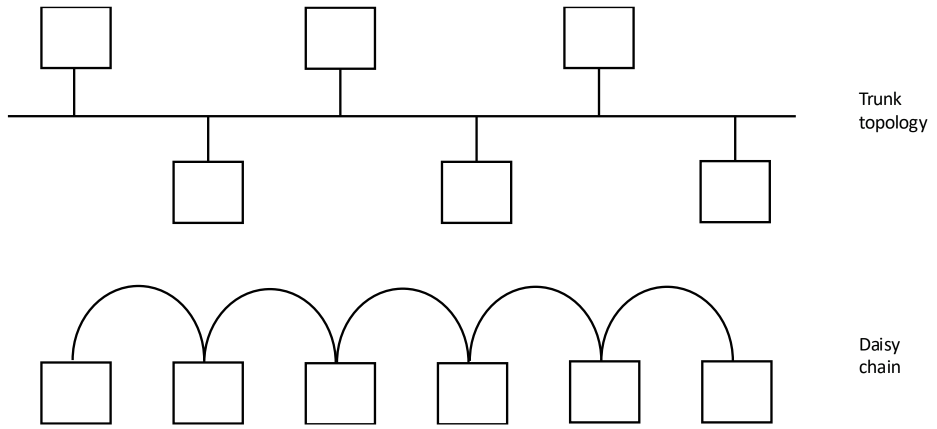


Figure 13 Trunk topology, the devices are connected to a main bus cable with another cable. Daisy chain, the main bus cable is directly connected to each device. – Source: Kensby J.; Olsson R. (2012)

In the trunk configuration, a main backbone runs through the facility with branches to individual devices. In the daisy chain configuration, devices are connected in series along the same cable.

The number of devices connectable to a single bus can range from a few dozen to several thousand, depending on the protocol used, cable length, and type of connection.

Communication lines may be subject to signal reflection, which occurs when an electrical wave encounters a discontinuity in the cable or a poorly terminated end. This effect can interfere with new incoming signals, causing communication errors. The phenomenon is reduced when data are transferred at low speeds, as with field buses [47].

3.3.3 Power Line

Some communication standards also support power line communication via 230 V/50 Hz cables connecting standard electrical sockets. Signals can share the same line because data communication uses a higher frequency band (95–125 kHz), so there is no interference. Signal reflection is avoided by maintaining a low transmission speed. The functioning and architecture of this connection are similar to the fieldbus system [47].

3.3.4 Wireless Connection

The most widely used wireless communication technology for field networks is radio frequency in the mid-frequency band (868 MHz). Data are transmitted by modulating the frequency, phase, or amplitude of radio waves. Typically, a transmitter's maximum coverage is about 30 metres horizontally inside a building with light partition walls, such as wood or plasterboard. In the case of concrete walls or particular conditions, transmission distance may be significantly reduced. To extend a transmitter's coverage, amplifiers can be used, often integrated into field level devices themselves [47].

3.4 COMMUNICATION STANDARDS

When two computers communicate, they exchange data. Proper communication requires a protocol, i.e., a set of rules managing communication between computers on a network. Different protocols may be used for different purposes: one for transporting the message, another for directing it correctly [47].

The functions of protocols are to transmit data, direct it to the correct recipient, check for communication errors, and deliver the message to the final device. These functions are described by a framework called the OSI model, which explains how data travel from one device to another through a network comprising seven layers. A single protocol can perform only one function and is thus limited to one layer of the OSI model. When there is a suite of protocols, all communication functions can be covered, operating across multiple layers of the OSI model. The best-known suite is the Internet protocol suite, commonly known as Transmission Control Protocol over Internet Protocol (TCP/IP).

While the protocol defines the rules for sending data from one device to another, fieldbuses are the physical medium for communication, such as cables and connectors. Thus, the protocol prepares the message to be sent, the fieldbus carries it along the network to the final devices, which read and act upon it according to the protocol's rules [47].

3.4.1 OSI-model

The Open Systems Interconnection model (OSI) is a layered framework for communication in network, standardized by ISO [47]. The model is made up of seven layers, each of which has its own functionality from physical hardware to software applications. The design of the layers allows for interaction with the adjacent layer below. During the transfer of information from a higher layer to a lower layer, the second layer processes and adds its own special tags to the information before it is transferred to the next layer.

Information tags could be destination address, source, checksum, etc.

The seven layers can be summed up as follows:

- Layer 7 – Application layer

  The purpose of this layer is to ensure that two applications can communicate over a network through the representation of information.
- Layer 6 – Presentation layer

  This layer is where the data types from the application layer are defined and translated. In order to do that, it is necessary to explain how the information is presented.
- Layer 5 – Session layer

  The Session Layer's role is to set up, manage, and terminate connections between two nodes (computers).
- Lyer 4 – Transport layer

  The role of this layer is to transfer data between source and destination processes. It also defines data transfer mode and the type of protocol that should be used.
- Layer 3 – Network layer

  While the transport layer transfers data, the network layer has the scope of defining the source and destination of the data. Routers and switches are utilized to enable data transfer on the network.
- Lyer 2 – Data link layer

  The only way to transfer data between two hosts is by converting the bits from the physical layer into frames. This layer is where this commutation takes place.
- Layer 1 – Physical layer

  Digital signals are transmitted through the physical medium, which includes twisted pair, optical cable, and wireless.

3.5 BUILDING AUTOMATION STANDARD PROTOCOLS

Protocols enabling communication between Field Level and Controller Level include Modbus RTU, BACnet MS/TP, and LonWorks, designed to handle analogue and digital signals from sensors and send commands to actuators in real time [47].

Moving from Controller Level to Management Level utilises higher-performance networks, generally based on Ethernet or IP, with protocols such as BACnet/IP, Modbus TCP/IP, and, in more advanced architectures, OPC UA. This allows large amounts of data to be transferred to the supervision software, where they are historized, analysed, and presented via graphical interfaces. The choice of open protocols is crucial for ensuring interoperability between devices from different manufacturers and for integrating the BMS with external systems, such as IoT platforms, cloud, and mobile applications.

Building Management System (BMS) protocols are sets of rules and formats that enable communication between various devices and subsystems in a building (HVAC, lighting, security, access, etc.). In practice, they are the "language" that allows sensors, actuators, and controllers to exchange data and work together in an integrated and automated manner.

- Open protocols: public standards favouring interoperability between devices from different manufacturers (e.g., BACnet, Modbus, KNX). They are flexible and scalable, ideal for complex buildings.
- Proprietary protocols: developed by a single manufacturer, work only with their devices. They limit integration and tie the client to the supplier.

The comparison between protocols is shown the following table. It's illustrated in which field each protocol can be used and if it needs licences.

Protocol	Primary network	Field network	Licence required
Modbus			
• **ASCII**		X	
• **RTU**		X	
• **TCP**	X		
BACNET	X		
KNX	X	X	X
LonWorks		X	*
TCP/IP	X		
DALI		X	**

* In the past, implementing LonWorks required the use of proprietary components and tools (e.g. Neuron Chip); today, being standardized as ISO/IEC 14908, the protocol is no longer subject to third-party licenses.

**The DALI protocol does not require any license to use it; only the trademark and certification 'DALI⍰2' are regulated by the DALI Alliance and subject to related compliance testing.

Table 2: Common BMS protocols and associated application domains. Source: author's elaboration from Kensby J.; Olsson R. (2012)

3.5.1 BACnet

BACnet stands for Building Automation Control Networks. It is a data communication protocol developed by ASHRAE, known as "ANSI/ASHRAE 135-2016" and as international standard "ISO 16484-5". It supports most activities in buildings, including heating, ventilation and air conditioning, lighting, fire protection, and physical security devices (access control and intrusion detection systems) [47].

3.5.1.1 Objects

BACnet is an object-oriented and service-based protocol. Each device and its objects must contain an Object identifier in order to trace devices and objects in a network. BACnet defines 18 standard types of Objects and 123 different Proprieties. Certain *Properties* are mandatory for each *Object*, other are optional.

Manufacturers can develop their own objects is that is necessary but there are some required properties, called Object's Instance [47]:

- *Object identifier*
- *Object name*
- *Object type*

3.5.1.2 Services

Interaction between devices occurs through *Services*, which allow the system to read, write or notify information associated with objects. BACnet defines 32 Services and classifies them into five categories [47]:

- Alam and Event
- File Access
- Object Access
- Remote Device Management
- Virtual Terminal Services

Services can be categorized as "*confirmed*" or "*unconfirmed*". In the first case, the BACnet device can initiate the *Service* request or process and respond to a received request, or both. If the status is "*unconfirmed*" it means that no reply is expected.

The only service required by all devices is the Read Property, additional Services are implemented according to function and complexity of the device.

3.5.1.3 Communication

The protocol is based on a server-client communication between nodes within the network. The communication starts as a polling sequence where a device (the server) requests the value of an object from another device (the client) which then returns the requested information.

Communication can also occur according to a peer-to-peer logic. In this case the communication is initiated by a trigger event, such as a change in the value of an object. When this event occurs devices that have subscribed to notifications for that object receive updates automatically [47].

3.5.1.4 Transport

The architecture of BACnet protocol is based on the OSI-model, using only Physical, Dats Link, Network and Application layer. The most common way to carry the data with BACnet is BACnet/Ethernet, also known as BAC/net/IP. There are other ways to transport data in the network, such as MS/TP (Master Slave/Token Passing) and Arcnet, which is not used in Europe but is common in America [47].

3.5.1.5 Licence and testing

BACnet International is a non-profit organization, so the protocol has no licence. It coordinates a network of regional group all over the world, such as BACnet Interest Group – Sweden (BIG-SE) and BACnet Testing Laboratories (BTL), which are responsible for testing and certifying [47].

3.5.2 Modbus

Modbus is a communication protocol developed by Modicon, now Schneider Electric, in 1979, used for both building automation and manufacturing industry. This protocol uses master/slave to manage communications between control units and intelligent devices, especially sensors in data acquisition systems, such as chillers, boilers, and fans. Master/slave communication works by polling, meaning the master sends queries to the slave to detect changes in values or the presence of alarms.

There are three main versions of Modbus protocol [47]:

- Modbus ASCII
- Modbus RTU
- Modbus TCP

The fundamental difference is that while Modbus ASCII and RTU are transmitted over a serial Modbus network, TCP uses a protocol over an Ethernet network, allowing web access to the system. Also, Modbus RTU uses server/client communication, ideal for complex network systems where multiple devices need to communicate simultaneously and the client itself initiates communication; in master/slave, the master must initiate communication.

A Modbus massage is placed in a massage frame, and it contains following information [47]:

- Start
- Address
- Function
- Data
- LRC/CRC (error checking)
- End

Since they are based on different protocols, various Modbus versions cannot communicate with each other except via a gateway to translate the languages.

3.5.2.1 Error checking

Error checking is Modbus mechanism to verify the integrity of transmitted messages. To execute error checking two methods ca be employed [47]:

- Parity checking
- Frame checking

Parity checking is used for simple error detection, it's not able to manage issues. The device could be arranged for even, odd or no parity. During message transmission one parity bit is added, based on whether it's even, odd or not. The device that is receiving the message recalculate parity on received parity bits and compares it with the received parity bit. If the values do not match, the character is considered incorrect.

Frame checking has a different operation depending on whether the Modbus protocol is ASCII or RTU. For ASCII the frame check is a LRC – Longitudinal Redundancy Check. In this case it is the last field in the character frame that contains the frame check calculation of the message except for the start and the end character. In RTU the frame check is a CRC – Cyclic Redundancy Check, that is stronger than LRC. CRC frame can detect multiple error, applying a polynomial-based algorithm to the entire message frame.

3.5.2.2 Licence and testing

Since 2004, the Modbus Organization has been responsible for maintaining and developing the Modbus protocol. The protocol is published as open software, and all related documentation and specifications are freely available for download. Members of the Modbus Organization also have access to development tools and implementation examples. In addition, the organization conducts testing and certification for products developed using Modbus ASCII, RTU, and TCP. However, certification is not mandatory, meaning that products can be marketed as Modbus-compatible even if they do not fully adhere to the standard implementation guidelines [47].

3.5.3 KNX

The KNX protocol was developed from three previous protocols: EIB, EHS, and BatiBUS. The architecture of KNX is based on a simplified version of the OSI-model, in particular the Session and Presentation layers are left empty.

KNX is mainly used in the field network, but KNX IP makes the protocol able to be used also in the primary network. It can communicate with other protocols, such as BACnet e DALI, before routers were responsible for converting the KNX protocol [47].

3.5.3.1 Communication

The communication in the Physical layer can takes place through three main different medias [47]:

- Twisted pairs
- Power line
- Radio frequency

Communication via twisted pairs means that that data and power are transmitted over one twisted cable. When power line is used data is transmitted through the power line in the building. The communication across the network is bi-directional. This means that communication occurs in a single direction at the time and the response is given back to the requesting device over the same communication channel. Radio frequency is used for wireless communication between short-range devices.

3.5.3.2 Telegram

Information over the network is sent using telegram [47].
Telegram is a sequence of fields containing data used to transport information between devices. Depending on which media is used, the KNX telegram is designed.
For example, for twisted pair the telegram has the structure illustrated below:

Control 8 bits	Source address 8 bits	Receiver address 16+1 bits	Routing 3 bits	Lenght 4 bits	Checksum 8 bits

Figure 14: KNX telegram for twisted pair – Source: ZVEI (2006)

In this configuration, the control, routing, length and checksum fields intent is to guarantee that the telegram is complete and that any data is missing during the transmission. The source and receiver addresses match with the physical address of the device transmitting and receiving the telegram. Information that should be transmitted is contained in the Data field. The message could consist for example in instructions, temperature, alarm.
For communication through power line the twisted pair telegram is implemented with other fields, specific for power line networks. The first additional field synchronization field which indicate the start signal for the receiver. The last field contains the system id. Only devices with the same system id can communicate with each other.

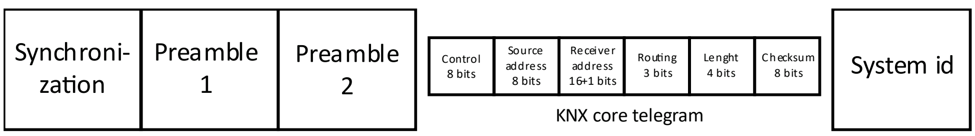


Figure 15: Power line telegram for KNX. – Source: Kensby J.; Olsson R. (2012)

The last one configuration is radio frequency telegram. In this case the message is transmitted in several data packages separated by checksum. Even if this method allows not to use a wired network, it implies less reliability, so security measures are adopted, such as checksum. This strategy enables the receiving device to verify whether the telegram has arrived complete and without errors during transmission.

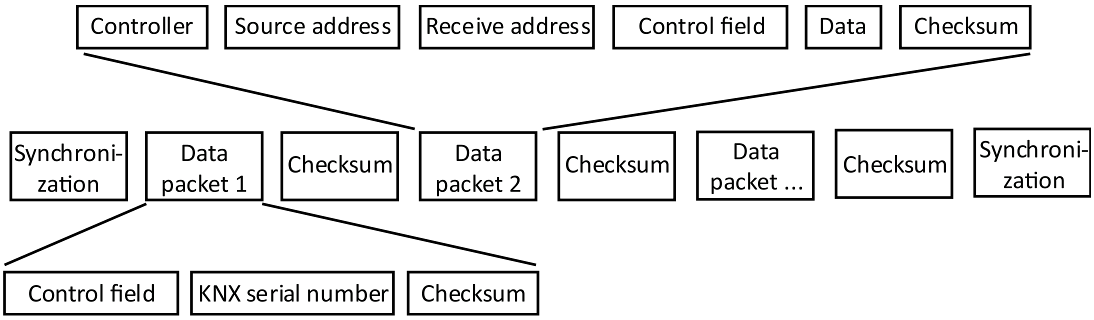


Figure 16: Radio frequency telegram for KNX – Source: Kensby J.; Olsson R. (2012)

3.5.3.3 Licence and testing

To have access to all documentation and specification of KNX it's necessary to establish a membership with KNX Association.

KNX products are tested and certificated by the Association. In addition, these products will be branded with KNX logotype to ensure that the standard is met. The certification is also a guarantee that the product is compatible with other third party developed products [47].

3.5.4 LonWorks

The LonWorks is also known as the LonTalk protocol, and it can be used only in LonWorks networking platform. This protocol was developed by Echelon Corporation and was accepted as an ANSI standard in 1999 [47].

It Is based on the OSI-model and uses all the seven layer, each one has a different task to perform [47]:

- Layer 7 - Application compatibility
- Layer 6 - Data interpretation
- Layer 5 - Control
- Layer 4 - End-to-end reliability
- Layer 3 - Message delivery
- Layer 2 - Media access and framing
- Layer 1 - Electrical interconnection

3.5.4.1 Communication

The LonWorks protocol bases his operation on a master-slave principle or directly without a central controller. This protocol can be used only in the Field network [47]. This protocol allows an efficient transmission thanks to the possibility to compress data packets, which makes packets smaller.

The LonWork protocol can transmit messages through several media. The most common are twisted pair, power line, and LonWork over IP. Radio frequency is not so common but can be an option.
There are some differences that can be discriminating in choosing the physical media, such as the speed of the network, how many devices that can be attached and the maximum distance of cables in the network.

There are many methodologies of addressing that can ensure that the packets are delivered to the correct address and at a minimum cost of bandwidth [47]:

- *Physical address*
  The physical address of a device is unique and it's the same from when the device is produced to the end of its life cycle.
- *Device address*
  Device address is given to a device when is installed in the network. Because of increasing the efficiency of the network, the device address is most used then the Physical.
- *Group address*
  Group address is used when a message should be transmitted to a significant number of devices
- *Broadcast address*
  Broadcast address is an adjunct of Group addresses

There are four different messages that can be transmitted with the LonWork protocol [47]:

- *Acknowledged messaging*
- *Repeated message*
- *Unacknowledged messaging*
- *Authenticated service*

3.5.5 DALI

The Digital Addressable Lighting Interface (DALI) is the most widely used protocol for lighting control in automated buildings. The first version dates back to 1990s and was introduced by y International Electrotechnical Commission (IEC) and DiiA (Digital Illumination Interface Alliance). At first the protocol was having only the control gears, and simple control commands.

With the release of version 2 new features were added to the protocol, such ash Application Controllers, Input Devices (e.g. Sensors), Bus Power Supplies, and various control commands [59].

3.5.5.1 DALI network and communication

A typical DALI network is made up at least by one controller, one bus power supply and one DALI ballast [59].

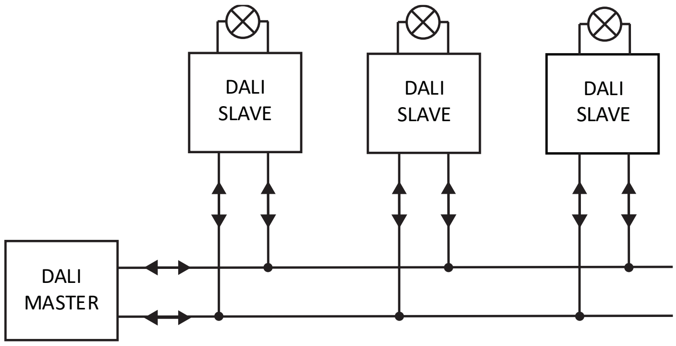


Figure 17: Dali Functional Diagram – Source Sahu R. (2019)

The communication between devices is two-way. It means that the slave device can report to the master at the same time as can answer a query.

DALI network set consists of basically three types of mechanism [59]:

1. *Control gears*: are usually Sensors or Ballast used as *slaves*. Usually they are known as Receivers, but sometimes they can also transmit the reply according to the query.
2. *Control device*: consists of a master controller that allows the network to control all devices. It is usually a transmitter but can also be used as a receiver, depending on the application.
3. *Bus power supply*: is a power supply, designed according to the DALI standard. Its goal is to maintain the DALI standardized power level on the serial bidirectional bus.

In a typical application, the DALI can control up to 64 different slaves (ballasts) within the same control system. It's possible to transmit commands to single ballasts or to a group of ballasts.

The DALI bus consists of two wires, which provide a differential signal. Data is transmitted in frames, which can be of two types [59]:

- *Forward frame*. It consists of 19 bits in total: one start bit, two information bytes (address byte and data byte) and two stop bits (fig x). The two middle bytes carry the useful information, while the start and stop bits allow devices to recognize the beginning and end of the telegram respectively, ensuring correct interpretation of data on the bus.

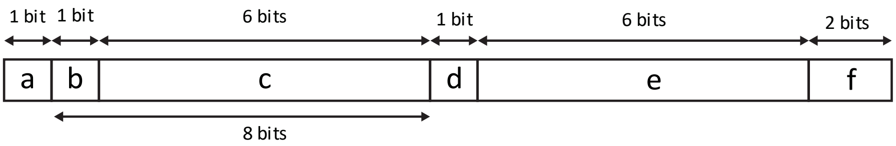


Figure 18: Structure of Forward Frame – Source Sahu R. (2019)

- *Backward frame*. It consists of 11 bits in total: one start bit, one information bytes, in which the response of the slave is contained, and two stop bits (fig x).

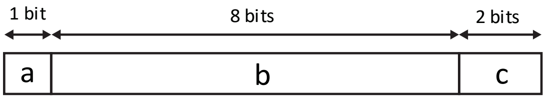


Figure 19: Structure of Backward Frame – Source Sahu R. (2019)

3.5.5.2 Types of command

According to the DALI standard, commands sent in the frame can be grouped into 4 main categories, based on the function they perform [59]:

1. *Direct/indirect arc power control commands*: this command can be used to regulate the power level of the ballast.
2. *Configuration commands*: with this command the ballast can be configured, for example: add to a group or store level.
3. *Query commands*: this command allow to interrogate the slave about tatus in-formation (for example: power level or version number). The slave can send a backward frame.
4. *Special commands*: used to initialize and setup the ballast. After receiving an 'INITIALIZE' command, most commands are only processed in 15 minutes.

3.5.5.3 Licence and testing

The DALI protocol is specified in international standard IEC 62386 and is conceived as an open standard. This means that the protocols freely implemented by any manufacturer without the payment of a licence. However, the DALI and DALI-2 trademark are managed by DiiA. The use of such product is permitted only to manufacturers who join the association subject their devices to a formal conformity certification process, aimed at ensuring multi-vendor interoperability. So, even if is a free protocol, the licence represents a market requirement rather than a technical obligation [59].

3.6 Communication Between Different Protocols

Even if installing the same protocol at all network levels is preferable, it not always is possible to use only one protocol for the entire system. So, when different protocols are implemented, it’s necessary to define how they can communicate with each other [47].

3.6.1 OPC

There are different ways of handling communication between partes of an automation system that use different protocols. One of them is the OPC. It stands for OLE (Object Linking and Embedding) for Process Control.

OPC is made up from a combination of hardware and software installed into a building automation network. The design of the system depends on the number of devices and protocol: the greater the number of systems and protocols the more complex the system is.

For example, if the network is composed of three devices all using different protocols and a data acquisition database [47], the database must be able to understand all three protocol in order to gather data efficiently (fig.20). When also a HMI (Hum Machine Interface) is installed, also the HMI must have the ability to understand the three protocol. (fig. 21)

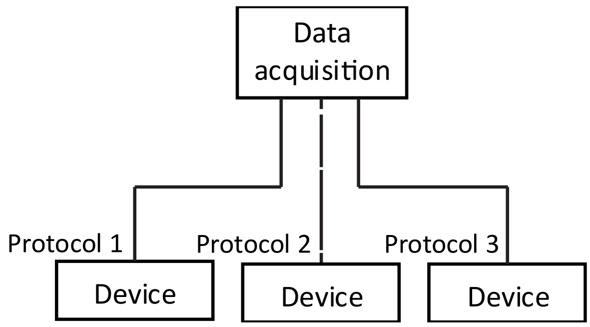


Figure 20: System with three devices using three different protocols, which are connected to a data acquisition device. – Source: Kensby J.; Olsson R. (2012)

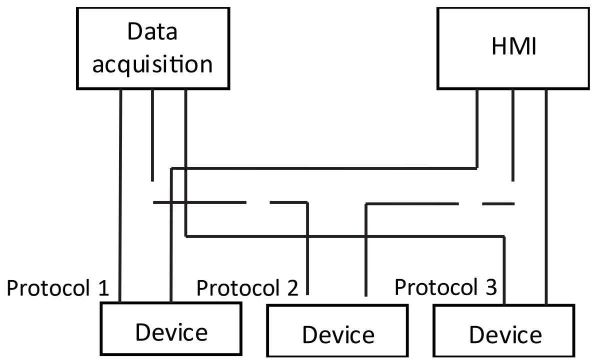


Figure 21: System with three devices using different protocols, which are connected to a data acquisition device and a HMI. - Source: Kensby J.; Olsson R. (2012)

The complexity of the network increases with the increased number of wires and devices. One of the strategies to simplify this system is to install a OPC server for each device (fig 22). Another way could be use only one OPC (fig 23)

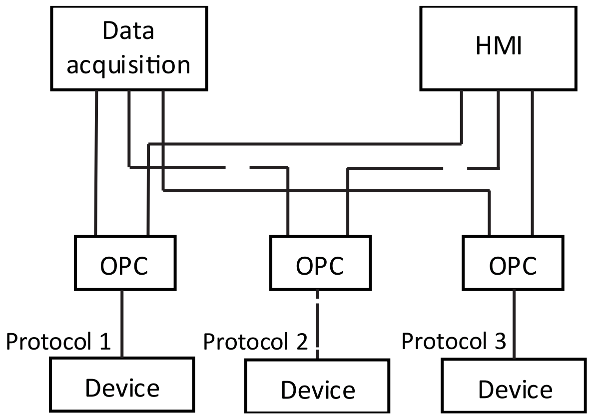


Figure 22: System with three devices using different protocols connected to three OPC servers, which translate the protocols into a standard interface. - Source: Kensby J.; Olsson R. (2012)

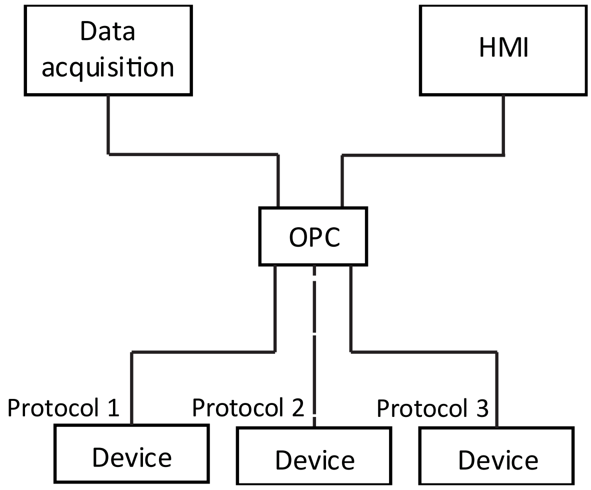


Figure 23: System with three devices, using different protocols, connected to one - Source: Kensby J.; Olsson R. (2012)

Drivers are software implemented on a PLC, RTU, server or any other device to allow the translation between software and hardware. The purpose of drivers is to understand how to interpret data from a device sent by a specific protocol. This way, for example, data acquisition software does not have to know how the device works: it is the driver who entirely manages the translation and interpretation of the information [47].

3.6.2 Gateway

A gateway can consist of either hardware or software, or a combination of both. The gateway installed has the scope of translating data between two networks using different protocols and physical media, for example between a Modbus RTU and BAC/net network. This solution is commonly used when there is the necessity to connect an IP-based Primary network and a serial-based Field network. A gateway can operate only in four top layers of the OSI model [47].

4 Evaluation of the BMS design workflow in the case study through a RIBA-based approach

4.1 Methodological framework: RIBA Plan of Work

On the international level, from a purely design perspective, there are guidelines concerning the overall building process. In most countries, these guidelines are established by professional bodies or industry organizations.

Each country has its own official standard, but it often happens that designers must work with international clients, so the RIBA Plan of Work is used as an international methodology. This is a guideline supporting the organization of the entire process of designing, constructing, and managing a building. The project's life cycle is divided into eight sequential phases, from strategic definition to building use, with each phase specifying objectives, key activities, and required outputs. The plan is not just meant to support design but also helps define relationships between clients, designers, and contractors, improving coordination, risk management, scheduling, and communication throughout every stage of the project.

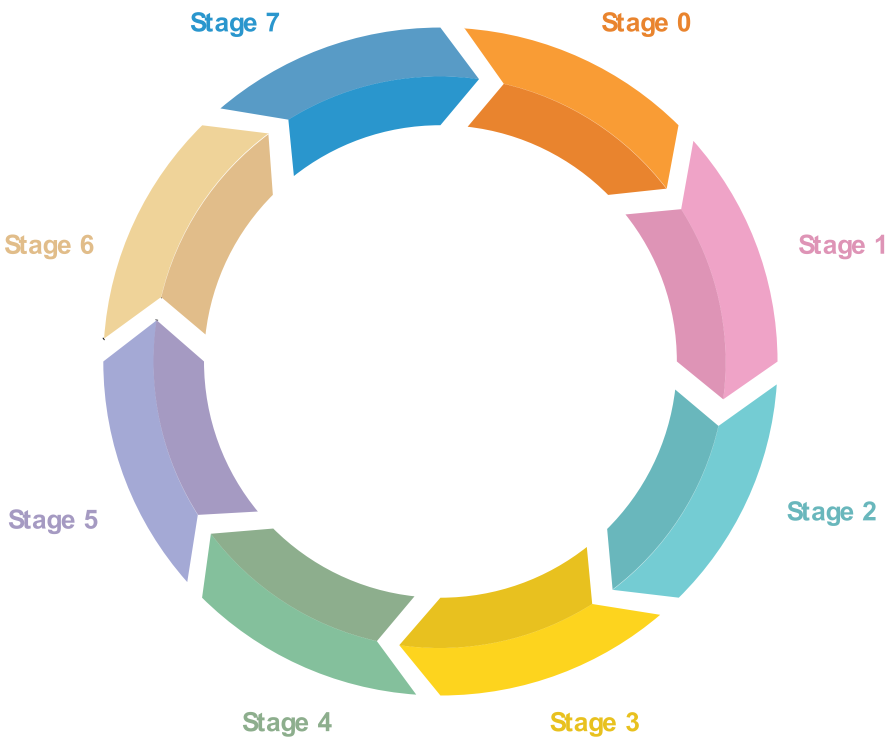


Figure 24: RIBA Stages – Source: author's elaboration from RIBA Plan of Work (2020)

The Royal Institute of British Architects (RIBA) was founded in 1834 in London to ensure "*… the general advancement of Civil Architecture, and for promoting and facilitating the acquirement of the knowledge of the various arts and sciences connected therewith…*" (RIBA n.d.).

With this purpose, in 1963 the RIBA Plan of Work was introduced as a methodological framework available to architects for organizing projects, which over the years has become a reference tool for the entire construction sector, including the engineering aspects of building design.
Originally, the guideline consisted of six stages. With the first revision in 2013, Stage 0 was added, acknowledging the need for greater strategic reflection at the beginning of a project, and Stage 7, focused on the use and life cycle of the building. A dedicated Urban Planning section was also introduced to support the planning approval process [60].
The methodological structure is continuously updated to keep pace with developments in the construction industry, and RIBA remains open to feedback from clients and design teams.
The Institute still adheres to the principles of its origins, emphasizing that: "In a constantly changing world, bringing clarity to each stage allows all parties involved to develop their own innovations without the continual need to discuss strategic matters concerning who should do what and when."
Building Management System (BMS) design generally falls within Stage 5, therefore at an advanced stage of building design.
However, the life-cycle phases of the BMS can be aligned with the building's own life cycle.
To gain a better understanding of the context in which the design of a Building Management System is implemented, the objectives and activities for each phase are reported in the next paragraphs [60].

4.1.1 Stage 0: Strategic Definition

This stage stablishes the strategic foundations of the project by defining the client's requirements and assessing feasibility. At this stage, design solutions are not developed; instead, strategic options, risks, constraints, budget, and long-term objectives are evaluated. Key aspects include site analysis, inclusivity, sustainability, life-cycle performance, and regulatory context. Lessons learned from previous projects may inform decision-making. The main outputs are a feasibility study and a project budget aligned with the client's needs. Stage 0 is closely linked to Stage 7, reflecting the circular nature of the RIBA process [60].

4.1.2 Stage 1: Preparation and Briefing

This stage translates strategic objectives into technical requirements through the development of the Project Brief. This document defines project objectives, quality aspirations, and sustainability targets. Stage 1 also establishes the project's information framework, including responsibility matrices, the Project Execution Plan, and the Digital Execution Plan, which clarify roles, workflows, and information-production methods for subsequent stages [60].

4.1.3 Stage 2: Concept design

It focuses on developing the architectural concept in coordination with engineering disciplines. The design process is iterative and includes regular reviews with the client and stakeholders. Proposals must respond to site conditions, spatial requirements, and budget constraints, while maintaining an appropriate level of detail to support development without prematurely fixing technical solutions [60].

4.1.4 Stage 3: Spatial coordination

The purpose of this stage is to ensure that architectural and engineering systems are spatially coordinated before detailed technical specifications are produced. The approved concept is not fundamentally altered, although minor adjustments may be introduced through formal change-control procedures. Successful coordination at this stage enables a smooth transition to technical design and supports the planning application process [60].

4.1.5 Stage 4: Technical design

Technical Design involves the production of all information required for manufacturing and construction. Based on the responsibility matrix, design information may be prescriptive or performance-based, depending on procurement strategy and the role of subcontractors. Responsibilities for coordination, review, and final design accountability are clearly defined [60].

4.1.6 Stage 5: Manufacturing and Construction

This phase covers the physical realisation of the building. Clear assignment of responsibilities for quality control, inspections, and progress monitoring is essential. The stage concludes with Practical Completion and includes preparation of operational documentation, ensuring that information required for building use and management is complete and verified [60].

4.1.7 Stage 6: Handover

Stage 6 begins with building handover and the start of aftercare. Remaining defects are addressed, users are trained, and post-occupancy evaluation is conducted to assess building performance. A project review captures lessons learned, contributing to knowledge development across future projects [60].

4.1.8 Stage 7: Use

Use represents the operational phase of the building. Facility and asset management strategies guide performance optimisation over time, supported by tools such as digital twins. In line with circular-economy principles, the end of the building’s life may lead to refurbishment, reuse, or deconstruction, reconnecting the process to Stage 0 [60].

4.2 CASE STUDY

To support the workflow described, an existing building will be considered as a case study. It regards the refurbishment of a seven-storey mixed-use building for office and commercial use situated in Milan. Arup Italia developed the project focusing on façade renovation, MEP retro-fitting and the interior fit out of all spaces.

Figure 25: Elevation of the case study building – Source: case study documentation.

The design project was led by key concept identified during the first stage of the intervention:

- Visibility and identity
- Use and enhancement od spaces
- Optimisation (time and costs)
- Flexibility
- Sustainability and wellbeing
- Efficiency

The building is spread over eight floors above ground and has underground levels and the re-development interventions involved the various portions of the building in different ways. The intervention on the mezzanine floor had the aim of converting it into a space with a more public purpose than the other levels and included both construction and plant works.

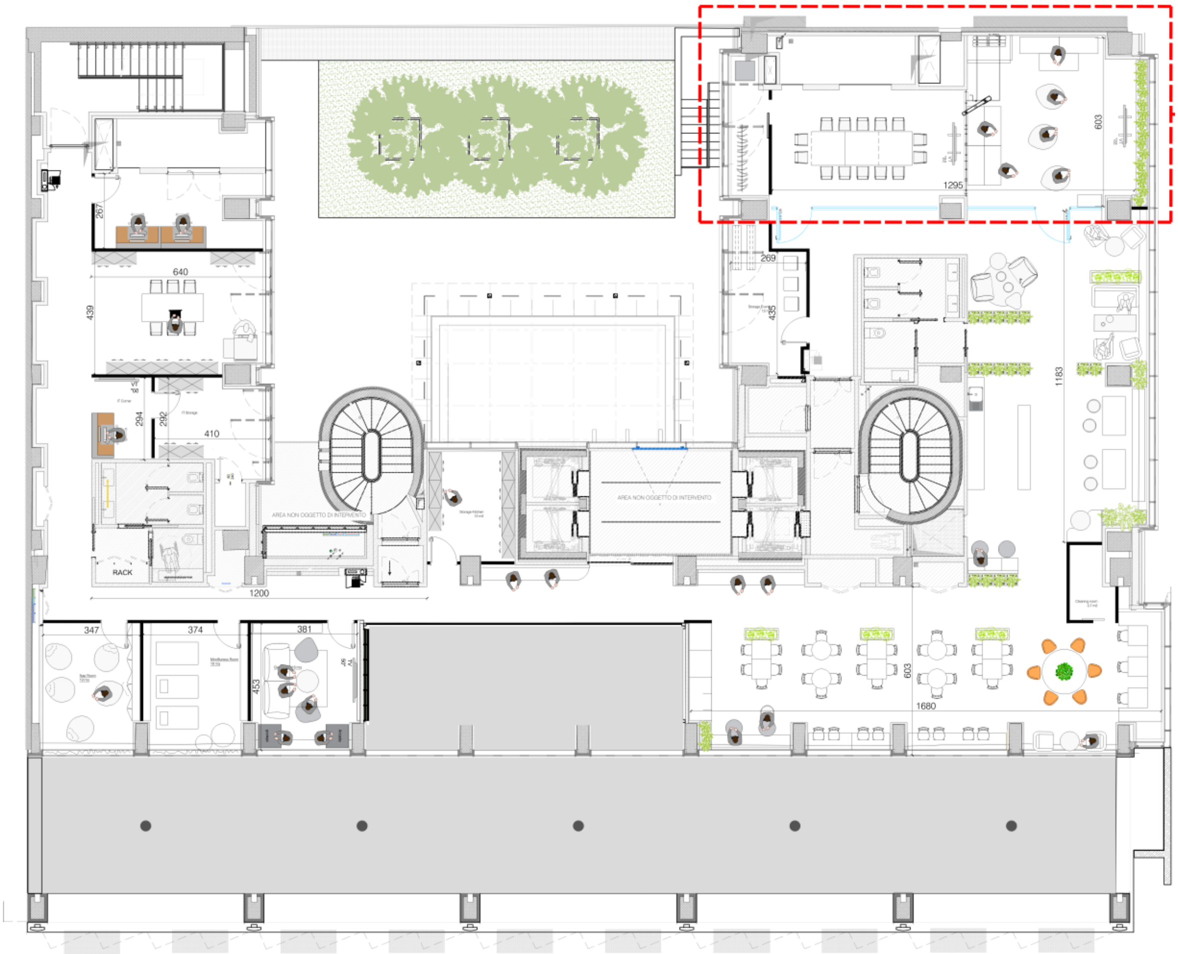


Figure 26: Plant layout mezzanine floor– Source: case study documentation.

The underground level and floors 1,2 and 3 have not undergone substantial changes to the architectural layout; interventions have been limited to plant modifications aimed at optimizing the existing systems.

Figure 27: Plant layout floors 1-2-3 – Source: case study documentation.

Floors 4 to 7, like Floors 1 to 3, are designed for offices use and being among the first areas delivered, were subject to the initial phases of intervention.

Figure 28: Plant layout floor 5– Source: case study documentation.

4.2.1 Plant strategy

The HVAC strategy combines water-based terminal systems with dedicated ventilation. Two-pipe chilled beams installed at ceiling level take care of the air conditioning of the rooms, while indoor air quality is managed by dedicated air handling units. The treated outdoor air is supplied to the occupied spaces through the chilled beams.

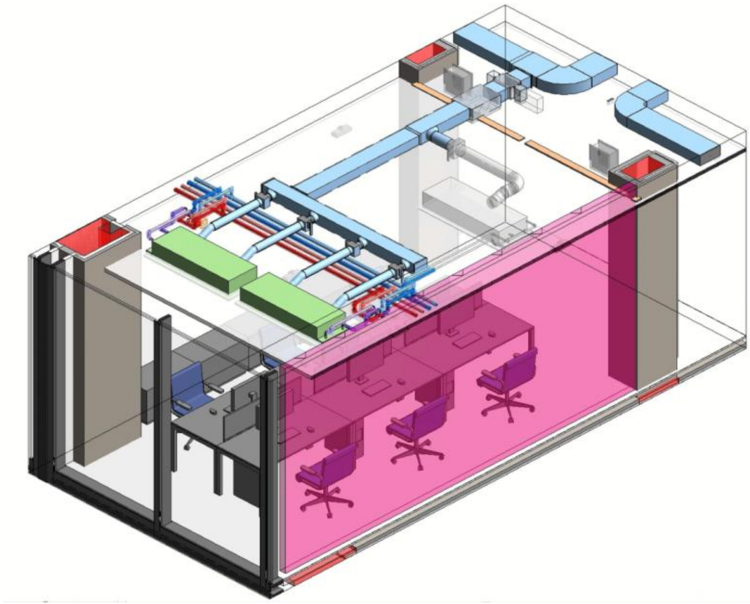


Figure 29: Main horizontal HVAC system distribution typical floor - Source: case study documentation.

In addition to the chilled beams, the hydronic network also serves other end-users within the building, including AHU heating and cooling coils, radiant panels at ground floor level, radiators, and domestic hot water (DHW) production, as well as the thermal demands associated with the commercial areas.

Hot and chilled water for the above services is generated by central polyvalent water-to-water heat pumps, which are capable of simultaneously producing heating and cooling energy according to the system demand.

The polyvalent units are supplied by a groundwater circuit: groundwater is extracted via dedicated wells and hydraulically separated from the heat pump source loop through heat exchangers.

To enhance operational resilience and guarantee continuity of service, additional air-source heat pump units installed at roof level are included as a backup generation layer, ensuring that heating and cooling service can be maintained even under fault conditions.

4.2.2 BMS strategy

In the case study the BMS has primarily been designed for managing indoor quality and comfort, with different automation levels depending on the plan system function.

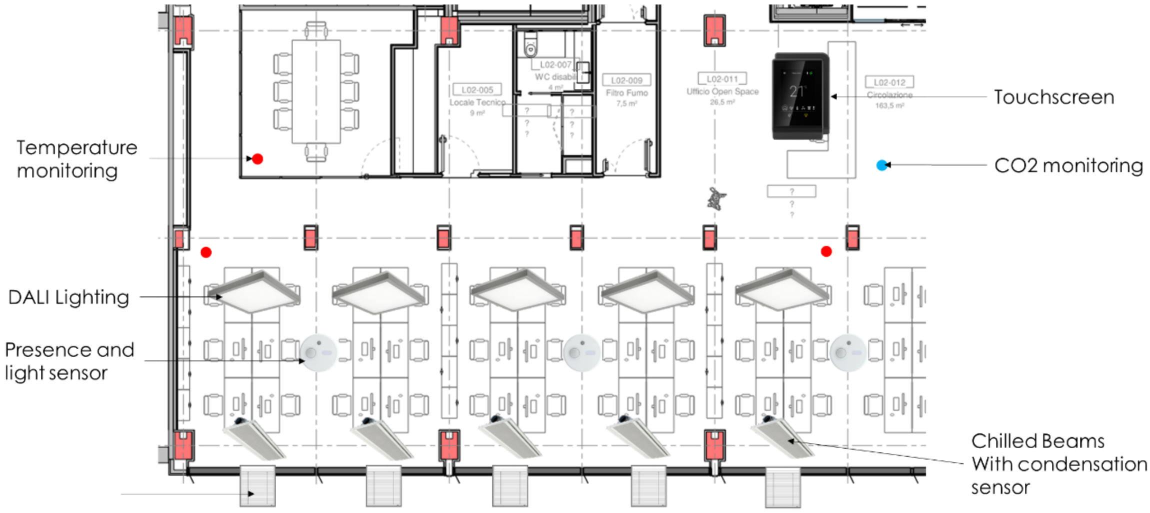


Figure 30: BMS strategy typical floor - Source: case study documentation

The roof is equipped with a weather station capable of detecting illuminance values and managing the solar shading system. Based on the detected values, the BMS controls the opening or closing of the blinds in order to regulate the ingress of natural light.

Regarding artificial lighting, presence sensors are installed to manage the luminaires through an ON/OFF control logic.

Ceiling temperature sensors were installed for regulating thermal comfort controlling the operation of the chilled beams. The beams are operated according to a master–slave group logic, in which a main unit (master) commands the secondary units (slaves).

In addition to ceiling temperature sensors, CO_2 sensors are also installed. The detected values do not activate ventilation or control strategies but are used exclusively for monitoring indoor air quality. Consequently, the ventilation system is connected to the BMS only for monitoring the air handling units (AHU). Their management is limited to setting predefined boundary values set during the installation phase, such as the supply air temperature offset.

The BMS also allows for the supervision of the building's energy, electricity, and water consumption, enabling utility monitoring. Recorded consumption data is collected for operational control and consumption monitoring to optimize the building's operation, also with a view to sustainability.

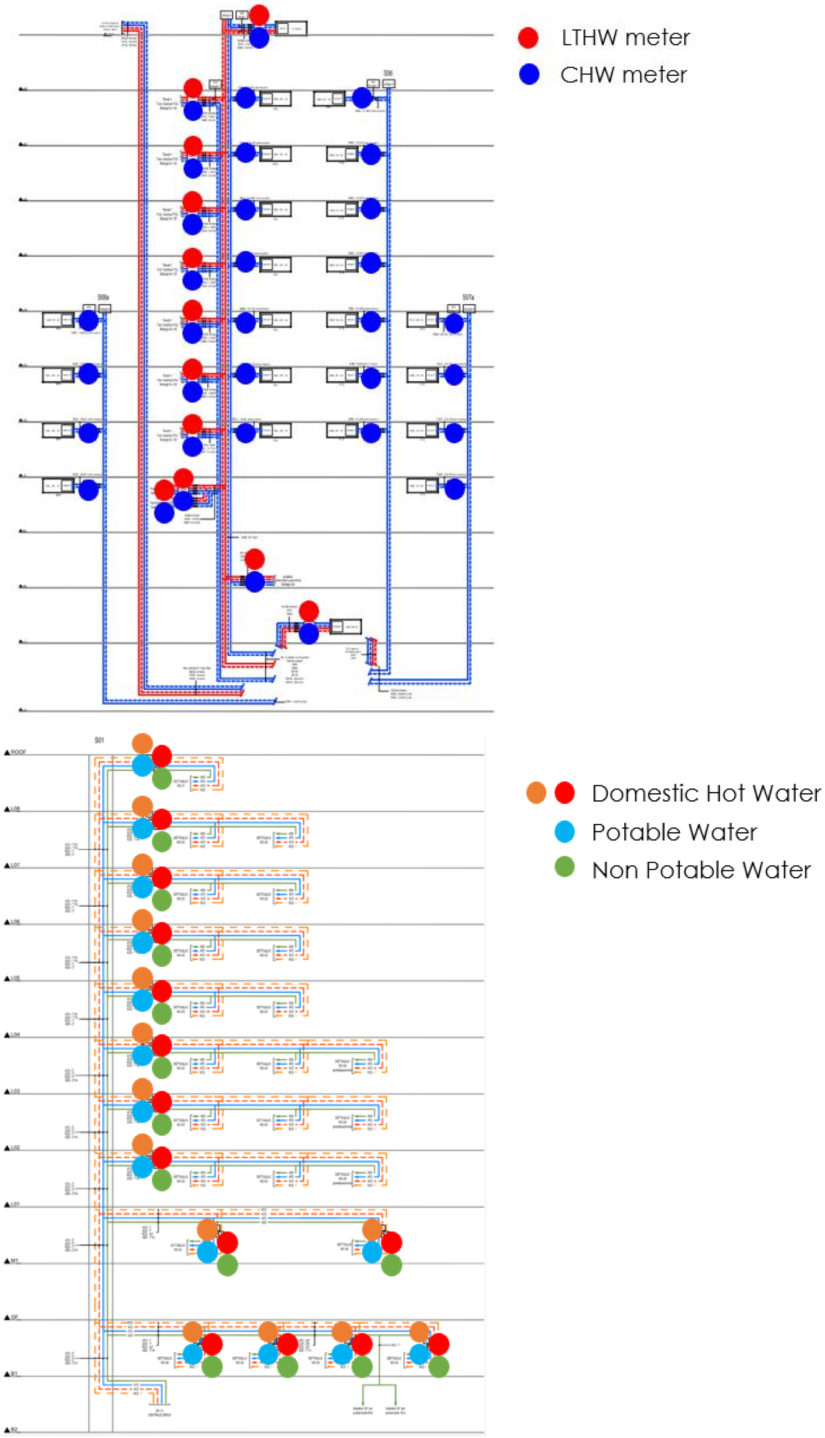


Figure 31: BMS, metering strategy - Source: case study documentation

The domestic hot water generation system can also be monitored by the BMs, as can the primary hot and refrigerated water generation circuits for utilities, such as AHU batteries and chilled beams.

4.3 THE CASE STUDY THROUGH THE RIBA FRAMEWORK

The refurbishment project doesn't follow the RIBA process but has been delivered in two phases:

- Phase A – preliminary and schematic design including the building permit submission to the local authorities, followed by detailed design development and preparation of the tender package for the selection of a General Contractor.
- Phase B – construction until project completion.

Phase A and phase B represents two macro-phases that encompass within them the different operational phases of the RIBA workflow. Phase A can be traced back to stages from 1 to 4, which include brief preparation, concept design, spatial coordination and technical design. Phase B coincides with stages 5 and 6, relating to construction, testing and handover.

Strategic definition (RIBA 0) should be identified with the first brief with the client before the feasibility study, while the final stage (RIBA 7) is still progressing given that performance tests have not yet been carried out, even though the building is already in use, so it is possible to observe its operation.

Project phase	RIBA stages	Description
Strategic definition	RIBA 0	Initial client brief defined prior to the feasibility study.
Phase A	RIBA 1-4	Encompasses brief preparation, concept design, spatial coordination, and technical design.
Phase B	RIBA 5-6	Covers construction, testing, and handover.
In use	RIBA 7	Currently ongoing: although the building is operational, performance testing has not yet been completed, allowing for observation of its operation.

Table 3: Comparative mapping of the case study macro-phases against the RIBA Plan of Work stages – author's elaboration

According to RIBA Plan of Work, each project stage is defined by specific tasks and stage outcomes. This structured approach to design is also applicable to the building management system, where design, coordination and delivery evolve progressively through defined phases. The following table summarises the core tasks and key stage outcomes related to BMS for each phase of the RIBA Plan of Work.

	Core tasks during the stage	Stage outcome at the end of the phase
0 Strategic Definition	Prepare client requirements Review feedback from previous projects Definition of objectives (comfort, energy, reporting); first choices on level of automation/monitoring and indicators to be tracked	The best means of achieving the Client Requirements confirmed
1 Preparation and Briefing	Define roles and responsibilities Define functional requirements Define metering/monitoring philosophy and control strategy principles	Project Brief approved by the client
2 Concept Design	Define preliminary BMS architecture Define main integrations (HVAC, meters, lightning)	Preliminary point list
3 Spatial Coordination	Coordination between disciplines (dimension of electrical panels, positioning of sensors, etc.) Defining graphic user interface	Coordinated drawings Updated point list Confirmation of integration criteria Consistency check of drawings/implants with BMS requirements
4 Technical Design	Detailed point list Define BMS technical specifications and operating logics	BMS specification and detailed drawings Technical package for tendering/procurement/ construction

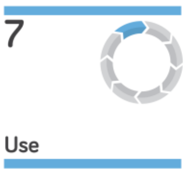
	Supplier submittal review Site visits and coordination meetings Product quality control Factory Acceptance Tests (FATs) Site Acceptance Tests (SATs) Point-to-point testing / point checkout procedure Snag list and non-conformities	Review comments and approval status Test reports Updated snag list Evidence of point checkout and corrective actions
	Verification of functional and performance requirements User and Facility Management training Final documentation handover	As-built documentation O&M manuals BMS trend data handover Commissioning and functional test records
	Monitoring of real operational performance Analysis of trend data and energy consumption Monitoring of KPIs Lessons learned feedback	Performance reports Updated asset and system documentation

Table 4: Core tasks and key stage outcomes related to BMS for each phase of the RIBA Plan of Work. – Author's elaboration. Images from RIBA Plan of Work (2020)

This framework is applied to the case study analysis enabling a stage-by-stage assessment of whether the design process has been correctly followed and whether the relevant documentation has been produced, through a comparison between expected and actual deliverables.

4.3.1 RIBA 0: Strategic Definition

In the case study the strategic definition phase consisted in the definition of the objectives of the intervention, identifying main themes including [60]:

- Maximise the building visibility and strengthen the building identity with a complete façade refurbishment with the building partially let.
- Maximise the use of space and occupancy level with the creation of new, contemporary open-space offices layout (fit-out Cat. A) with maximised ceiling height and natural lighting.
- Increase building efficiency and functionality by complete retrofitting of the MEP system with the building partially let.

It is evident how the BMS did not explicitly emerge from the brief with the client, but the defined requirements are directly or indirectly linked to the theme of building automation.

In particular, the objectives of increasing the building efficiency and maximizing occupant's comfort, imply the need for a system of supervision capable of monitoring the performance of the systems and supporting the operational management. Also, the control of natural lighting through the solar shading system, identifies the BMS as a useful enabling tool, even though it was not formally required at this stage.

4.3.1.1 Observations and key criticalities

During the development of the feasibility study the BMS was not taken in consideration. The absence of consideration of the theme leads to a lack in the definition of the prerequisites that form the basis for the subsequent project phases. At this stage, a survey should be carried out to understand the client's needs in relation to the BMS and define the objectives of strategic character, such as the future operational management of the building, and the role of data in monitoring. The absence of these explicit needs carries the risk that the BMS will subsequently be conceived and developed as an isolated technical system, rather than as an integrated tool to support the overall project activities [60].

4.3.2 RIBA 1: Preparation and briefing

The analysis of the case study project documentation revealed that Stage 1 primarily consisted of consolidating the objectives and verifying their compatibility with the existing building by drafting the feasibility study.

Following the identification of the existing systems and the observation that they have their normal life span and need to be replaced. the MEP team developed a set of design options.

The MEP concept was developed around client's requirements and specific project's condition:

- Energy efficiency and renewable energy: the MEP concept is developed to minimize the net energy consumption of the building thank to high efficiency technologies and the use of renewable energies.
- Comfort and wellbeing: different types of room terminals were assessed with particular attention to thermal and acoustic comfort. The mechanical ventilation concept allows for flowrates and air filtering levels to achieve a high indoor air quality.
- Resilience: the building systems concept allows them to react promptly to external changes guaranteeing minimum level of comfort and operation continuity.

Although design objectives consistent with the adoption of an automation system as a tool to support building performance were defined, no evaluation about a smart building or a building management system was made in this sense.

According to the RIBA Plan of work the briefing phase must translate the strategic objectives defined in the RIBA 0 phase including project objectives and functional requirements, first performance requirements and the organizational and information framework.

Although the official project proposal explicitly refers to smart buildings, advanced monitoring and control systems, and IoT applications, no references to building automation or smart building strategies are included in the feasibility study.

In line with the RIBA Plan of Work, the definition of roles and responsibilities would be expected to occur during Stage 1; however, in the case study, this phase did not include the explicit involvement of automation or smart building specialists.

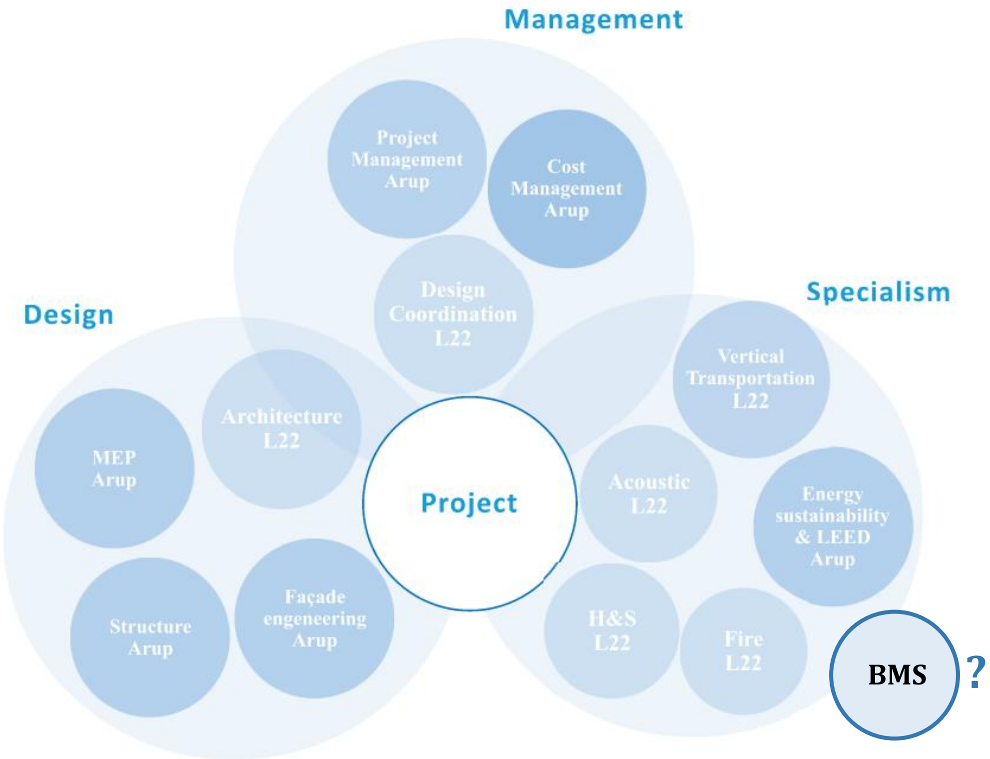


Figure 32: Project organization - Source: case study documentation

4.3.2.1 Observations and key criticalities

The management of RIBA phase 1 continues to present the gaps highlighted in the previous phase. The transition from strategic objectives to informational or operational functional requirements of the BMS is absent. At this stage it would have been useful to define the use of the BMS by the facility manager and the role of exercise data. These gaps imply a slippage of strategic decisions on the BMS towards the next stages, making the system increasingly independent with respect to the project globality, not yet being integrated into the process. In addition, RIBA Stage 1 represents a key moment for the definition of roles and responsibilities within the project team. However, no explicit role dedicated to the BMS, such as a BMS specialist, was defined. The absence of a clearly identified figure responsible for translating strategic objectives into BMS requirements further contributed to the lack of continuity between early project phases and subsequent design stages.

4.3.3 RIBA 2: Concept design

RIBA Stage 2 (Concept Design) is intended to define the overall design strategy, including the conceptual approach to building services systems. However, the review of the Concept Design documentation shows that no reference is made to building automation or to a Building Management System, which is therefore not addressed as part of the project strategy at this stage.

In terms of sustainability, the project aims to achieve environmental certifications, such as LEED and WELL, whose performance requirements implicitly rely on the implementation of smart building strategies.

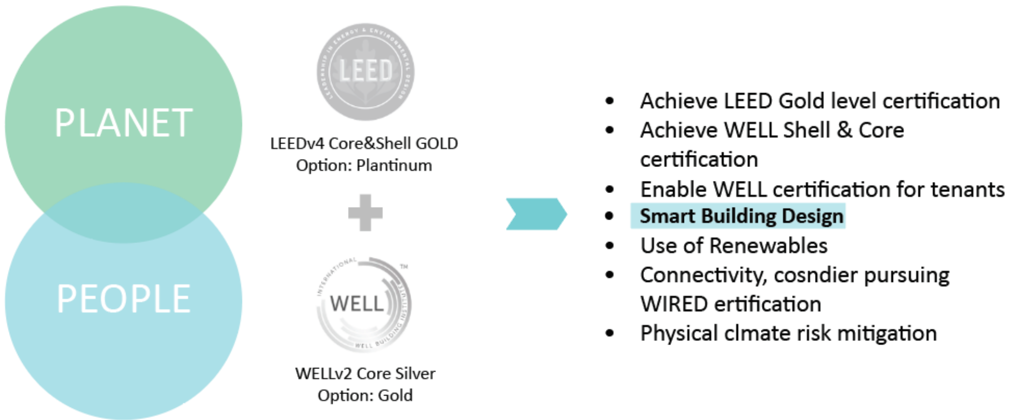


Figure 33: Sustainability objectives - Source: author's elaboration from case study documentation

Although these objectives have been defined at a strategic level, they have implicitly introduced requirements related to energy consumption, the quality of indoor environments, and the need to implement a building automation system.

As a result, the Building Management System was not explicitly considered during the Strategic Definition phase but intended as a tool that would subsequently support performance monitoring and compliance with certification requirements.

In the subsequent phases of the project, some requirements and objectives related to the BMS were defined, but they can be traced back to strategic choices specific to RIBA 1 and 2. The BMS strategy was actually defined only after the delivery of the schematic design phase, when several architectural and MEP design choices had already been consolidated. The BMS strategy developed included the definition of the system architecture. The proposed technical architecture outlines a multi-layer structure, comprising data and application layers, a central BMS platform, and the integration of base build, fit-out and other building systems.

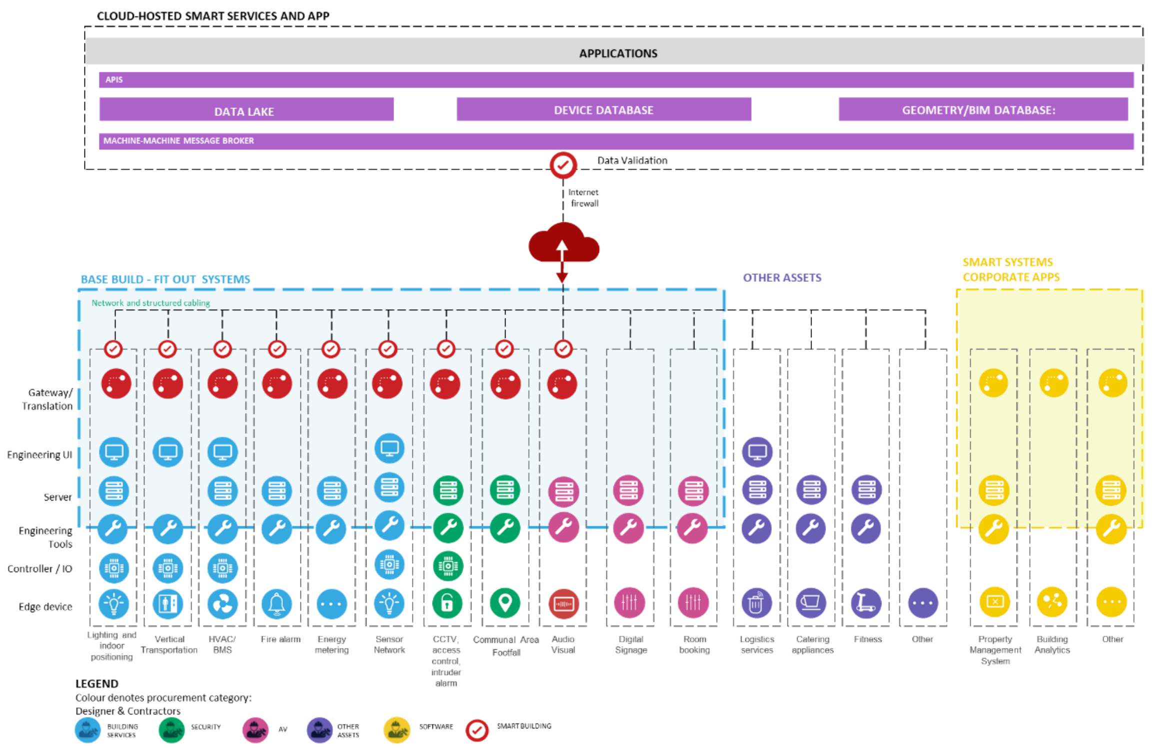


Figure 34: BMS technical architecture - Source: case study documentation

Within the BMS strategy, a distinction was made between the functionalities assigned to the tenants for the office areas and those managed centrally for the common areas of the building. This separation reflects both operational responsibilities and the intended level of control for different spaces. This choice influences the architecture of the system and the level of automation implemented in different partes of the building.

Tenant areas - Offices					
Functionalities	**Basic BMS**	**Advanced BMS**	**Compulsory for LEED**	**Planned in project – open space**	**To be provided by tenant**
HVAC System control	•		• *To monitor the amount of fresh air*	•	
Temperature control & monitoring	•			• *N. 2 sensors for orientation which control groups of chilled beams via 6-way valves*	• *Tenant should provide additional sensors based on the final layout*
Humidity control & monitoring	•			• Humidity sensors On the main return air duct to regulate AHU	• *Tenant could provide additional sensors based on the final layout. Only to monitor Humidity locally*
CO2 monitoring		•	• *Local CO2 sensors to be provided*	• C02 sensors on the main return air duct to regulate AHU	• *Tenant must provide additional sensors based on the final layout.* *Only to monitor CO2*.*
Chilled beam condensation sensor	•			•	
Lighting control (presence sensors)		•	•	• *PIR presence sensor in toilet areas and open space*	• *Tenant must provide additional sensors based on the final layout ***
Daylight control (dimmer)		•	•	• *Light sensors in open space areas*	• *Tenant should provide additional sensors based on the final layout*

• Tenant to provide (required) • Tenant could provide (optional)

* *CO2 monitors must have an audible or visual indicator or alert if the CO2 concentration exceeds the setpoint by more than 10%.*

** *An occupancy sensor that turns off the lighting within 30 minutes of leaving a space shall be installed*

Figure 35: BMS requirements and description of tenants' areas - Source: case study documentation

Common Areas				
Functionalities	**Basic BMS**	**Advanced BMS**	**Compulsory for LEED**	**Planned in project**
HVAC System	•		•	•
Temperature control & monitoring	•			•
Humidity control & monitoring	•			• On common return air to AHU
CO2 monitoring		•		• On common return air to AHU
Lighting control (presence sensors)		•	•	• PIR presence sensor in corridors, toilet areas and car park
Daylight control (dimmer)		•	•	• Light sensors in entrance space
Solar gain control				
Security system monitoring (TVCC+anti-intrusion)				•
Fire detection system monitoring				•
Energy consumption metering and monitoring			•	•
Smart access control				•

Figure 36: BMS requirements and description of common areas - Source: case study documentation

Several key functionalities were defined within the BMS strategy, including the metering strategy, the management of the solar shading system, the user interface design, and the adoption of a "touchless building" philosophy. These strategic choices were intended to address operational efficiency, user experience and building management requirements, and they define the scope of the BMS in terms of monitoring, interaction and automation.

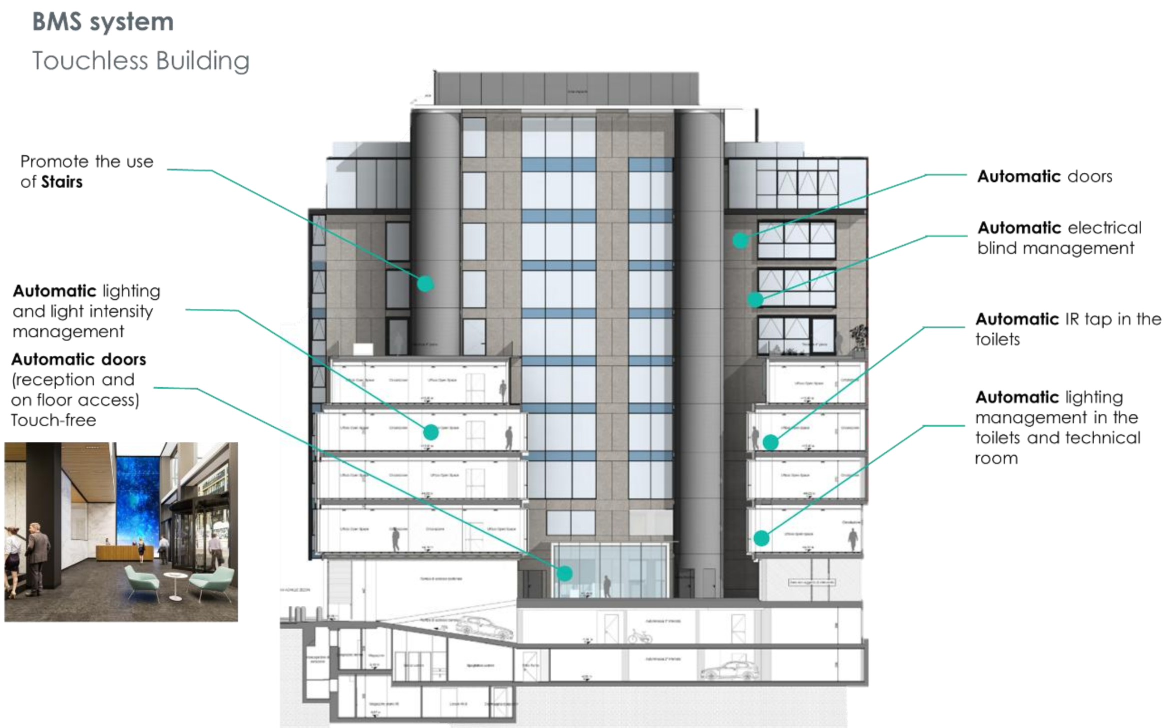


Figure 37: Touchless building strategy - Source: case study documentation

4.3.3.1 *Observations and key criticalities*

At this design stage, the design of the systems is not yet complete, as some fundamental strategies must be defined in the subsequent phases. However, it is at this stage that is essential to have clear the role of the BMS and how this integrates with the other systems of plant, in accordance with the performance and sustainability objectives of the project.

In the analysed case, no structured BMS strategy was defined during this phase, but it was designed in the most advanced stages of the project.

Without the definition of these details, arrived at this stage, the gap between plant systems and BMS is further accentuated and the management system remains a standalone component.

4.3.4 RIBA 3: Spatial coordination

In the preliminary design report the BMS is finally included as a design topic. Building Management System levels of control are shown and required functionalities are defined. The table provides an overview of potential BMS functionalities across several domains, including HVAC supervision, energy metering, indoor environmental quality monitoring, lighting and shading control, security systems and workplace-related services. However, these functions were not associated with a clearly defined role of the BMS within the project, nor were they explicitly linked to strategic performance, operational or sustainability objectives defined in earlier stages.

Functionalities	Basic BMS	BMS +	BMS for LEED/WELL	Advanced smart building
HVAC Systems	●	●	●	●
Temperature/Humidity control	●	●	●	●
Energy metering	●	●	●	●
Fire detection system monitoring		●	●	●
Security system monitoring		●	●	●
Lighting control		●	●	●
Daylight control			●	●
Personal comfort control				●
Occupancy monitoring			●	●
CO2 monitoring		●	●	●
Air quality (PM10, PM2.5, CO and Ozone) monitoring			●	●
Way finding & smart parking				●
Room & catering booking				●
Efficient facility management				●
Workplace and colleague finding				●
Energy consumption monitoring		●	●	●
Smart access control				●

Figure 38: BMS level of control - Source: case study documentation

4.3.4.1 *Observations and key criticalities*

Even if the issue is considered in the preliminary design, the definition of the functions to be implemented in the BMS is an activity delegated to the previous phases. During the RIBA 3 the architecture of the BMS and its coordination with other systems should be defined, with functional and spatial indications coherent with the MEP project.

The way the BMS topic is handled at this stage is the evidence that the automation system was considered as a separate element and not as an integrated system.

4.3.5 RIBA 4 : Technical design

During the RIBA stage 4 BMS technical specifications should be defined. Technical specifications, together with graphic work and the Bill of Quantities (BOQ), constitute the technical and economic basis for the tender phase.

In the basic design development, preliminary BMS architecture and functionalities are defined.

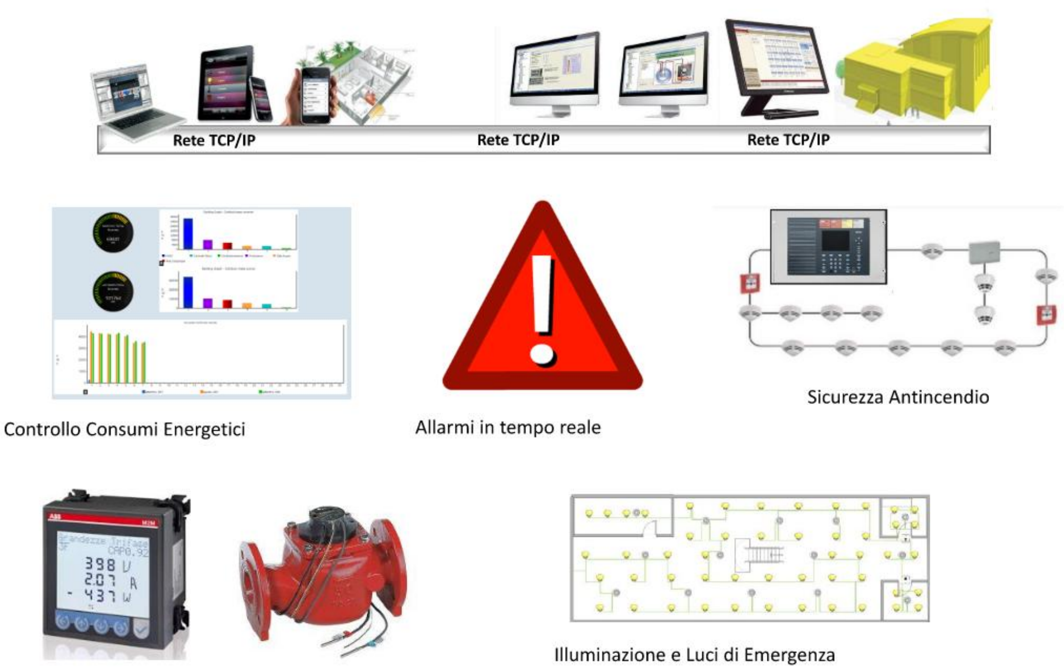


Figure 39: Proposed BMS strategy -Source: case study documentation

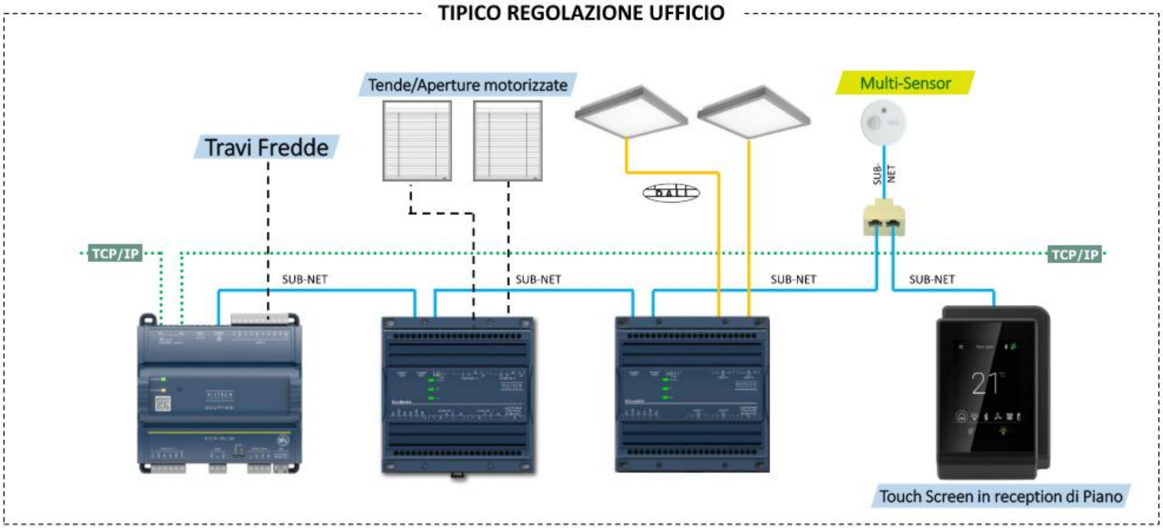


Figure 40: Proposed BMS strategy for a typical office - Source: case study documentation

In the case study there is not a dedicated BMS Special Technical Report, instead references to the BMS appear within the mechanical and electrical Basis of Design documents.

In both documents, the BMS is described from a technical perspective providing a high-level overview of the system architecture and outlining the main layers of the BMS as well as the plant systems intended to be monitored or controlled, but no operating logic is described in detail. This description clarifies the scope of integration at system level but remains largely generic in nature.

In particular, while the documentation identifies which systems are connected to the BMS, it does not define the control logics, operational sequences or decision-making strategies governing system behaviour. As a result, the BMS is presented primarily as a supervisory layer linked to the plant systems, rather than as an active control and management tool fully aligned with performance, operational and sustainability objectives.

During the tender phase, the selection of the BMS supplier was primarily driven by the system's compatibility with the field protocols. However, no structured evaluation among different suppliers is documented.

4.3.5.1 Observations and key criticalities

It should be noted that there are no dedicated BMS schematics, architectural diagrams, or coordination drawings provided at this stage. The BMS is only mentioned through textual references within the mechanical and electrical documentation, without visual representations of system architecture, data flows, or interfaces with the plant systems.

Another criticality that emerges at this stage and the absence of clearly defined control logics and sequences of operation.

The absence of clearly defined technical specifications may have also contributed to an inadequately structured tender phase. Without a set of requirements to establish objective evaluation criteria, it is difficult to carry out a consistent assessment of suppliers, ultimately limiting the possibility of a transparent and well-informed selection process.

4.3.6 RIBA 5: Manufacturing and construction

During this stage, the implementation of the BMS takes place, with completion expected by the end of the phase. Furthermore, the BMS implementation timeline should not extend beyond the building completion timeline, as this is essential to ensure optimal performance of the building systems from the beginning of their operational life.

During the BMS installation phase, snag lists were developed based on scheduled site inspections, allowing for the identification and tracking of defects and incomplete works in preparation for functional testing. The analysis of the case study highlights a critical issue in the coordination between construction activities and BMS implementation, as, despite the building being occupied by tenants, the automation system was still undergoing verification and correction phases, suggesting a potential misalignment between building handover and full system completion.

The snagging activities revealed multiple issues related to control logic, system configuration, and data visualization. For example, heat exchangers of the primary energy circuit were operating simultaneously instead of following a duty/standby logic, and temperature control strategy with chilled beams was not implemented according to the project requirements.

Other anomalies included incorrect or unclear graphical representations within the BMS interface and missing parameters trend.

During the BMS verification phase, several issues emerged as the control logics implemented within the system had not been explicitly defined by the BMS provider. This lack of clarity significantly hindered the verification process, necessitating frequent direct consultation with the technician to understand the system operation. For example, the control logic governing the interaction between the weather station and blinds was not clearly defined. No documentation describing the implemented logic was available, and the control parameters were not evident from the BMS interface.

The activities of stage 5 should also include inspection of component installation and functional verification of individual systems, such as fire protection, electrical infrastructure, hydronic circuits. In the case study, these tests were performed at the level of individual systems but did not ensure the integrated operation of the BMS. This lack of integrated verification can be attributed to the fact that the system was still undergoing implementation and correction phases at the end of the construction stage, preventing full system validation prior to commissioning.

4.3.6.1 Observations and key criticalities

The analysis of the case study highlights critical issues related to the coordination between BMS implementation and the overall construction process. This misalignment compromises the ability of the BMS to effectively control and optimise building systems during the initial phase of operation. Moreover, the absence of trends did not allow the performance analysis of some systems until such monitoring was implemented. Another consequence of the absence of a fully implemented BMS was the impossibility of carry out functional testing and, consequently, the assessment of system performance before the handover of the building.

4.3.7 RIBA 6: Handover

Stage 6 primarily consists of commissioning activities, including functional and performance testing of building systems. These activities are carried out once all systems are fully installed and operational, in order to verify their integrated performance and compliance with the design intent prior to handover.

As already highlighted in Stage 5, the absence of a fully implemented BMS has slowed down the phase of functional test testing and, consequently, the assessment of system performance. The incorrect operation of the BMS has led to numerous user complaints in already occupied environments. These issues are primarily associated with inappropriate control logic of the chilled beams and incorrect temperature setpoints. Setpoint misconfiguration was also identified within the domestic hot water (DHW) generation circuit: the low temperature setpoint of the storage tank, combined with delayed maintenance, resulted in the circulation of inadequately heated hot water. This condition not only compromised user comfort but also introduced potential health risks, particularly related to the proliferation of Legionella.

Given the multiplicity and severity of the critical issues identified, it was deemed necessary to undertake targeted interventions. These included conducting additional inspections, progressively updating the snag list to reflect emerging faults, and implementing continuous supervision of the system, including through remote monitoring tools.

The critical issues identified during the inspection and monitoring phase have been reported in a snag list, which was progressively updated through the process. A selection of these pre-commissioning issues is presented in the following table.

ID	INSPECTION 16/9/2025	MONITORING 18/06/2026	STATUS
1	**Groundwater circuit**		
a.	It has been observed that the heat exchangers operate in parallel, in deviation from the design conditions, which require alternating operation of the two units, with one active and the other on standby. Hydraulic connections should be adjusted to restore operation in accordance with the design requirements.	In some days, parallel operation of the heat exchangers has been observed. Clarification is required regarding the control strategy (is the second heat exchanger activated manually?).	**To be monitored**
b.	The temperature value measured is 25°C, exceeding the limit required by the Client (maximum supply temperature 21°C). The limit value, which cannot be modified, should be clearly displayed in the graphical interface.	In recent weeks, the supply temperature of the groundwater has often exceeded 21°C, reaching peaks above 25°C. This condition is also due to higher intake temperatures compared to the estimated values.	**To be monitored**
c.	For the well water pumps, simultaneous start-up and frequent cycling have been observed, leading to system oscillations. Adjustment of the PID controllers is required to reduce oscillations.		**Fixed**
d.	The system graphic does not include the filtration section.		**Fixed**
2	**AHUs**		
a.	The airflow values indicated in the BMS are not always consistent with the design data and, in many cases, differ from those reported in the functional control schedules.	- AHU 3 appears to be offline - The airflow rates of the AHUs should be verified to ensure consistency with the fit-out design values - It has been noted that some AHUs present return airflow rates higher than the supply airflow rates.	**To be monitored and verified**
b.	The CO_2 sensors specified in the design are missing on the return air of the floor AHUs	It has been noted that the installation of the sensors is currently not foreseen.	**Not resolved**

	and should be integrated into the BMS.		
c.	The dampers installed on the AHU exhaust ducts are not displayed in the interface. The corresponding BMS control logic and interface should be implemented.	The dampers have been connected to the AHU control panel and open and close according to the AHU operation. However, their actual status is not reported in the BMS.	Partially fixed
2	**Cilled beams**		
a.		For some chilled beams, an inconsistency has been observed between a 50% valve opening position and the corresponding water flow rate.	To be monitored
b.		For some chilled beams, the water flow rate exceeds the maximum setpoint limit. Clarification is required regarding the reference documentation used for setting these setpoint values.	To be monitored
c.		Some chilled beams are operating in heating mode, although they are indicated in the BMS as operating correctly in cooling mode	To be monitored

Table 5: Pre-commissioning snag list - Source: case study documentation

During the commissioning phase, a series of tests were carried out, including acoustic tests, verification of control logic (such as the activation logic of the rooftop heat pumps), and functional checks of the chilled beams.

Tests were carried out step by step. First, the thermal plant was checked, including the verification of DHW production and the activation of the groundwater wells. This was done by verifying consistency between the values measured on site and those displayed in the BMS, as well as by checking the control logics.

Once the correct operation of the heat pumps activation logic for chilled water production was verified, the testing proceeded with the functional verification of the chilled beams.

These were performed through direct inspection of the valves and of the hydraulic system, also verifying that the temperature measured by the room sensors was consistent with the values displayed in the BMS.

The presence of the BMS controls contractor allowed for the adjustment of some chilled beams that were operating anomalously. It was not possible to operate on all units, as some were located in areas accessible only to the tenant.

During commissioning, missing or incorrect control logics were implemented or corrected, including the proper cascade shutdown of the heat pumps and the management of the blinds based on weather station inputs.

At the end of commissioning, some issue remained open, including the operation of some chilled beams; therefore, at the time of writing, the handover phase cannot be considered officially completed.

In addition, it should be noted that during commissioning, only the summer test case was carried out, while the winter operating condition had not yet been tested, leading to an incomplete verification of system performance.

4.3.7.1 Observations and key criticalities

The analysis of this stage highlights how the late implementation and improper configuration of the BMS during the design phase significantly compromise both system performance and user experience in an already occupied environment.

The case therefore demonstrates the effects of inadequate management of the BMS process, whose impact extends beyond building performance alone. Indeed, these deficiencies affect occupant comfort, lead to operational inefficiencies, and generate economic repercussions associated with corrective interventions, system reconfiguration, and prolonged commissioning activities.

4.3.8 RIBA 7: Use

Although commissioning primarily belongs to RIBA 6, in practice Stages 6 and 7 may overlap, as some activities, such as performance testing, can only be carried out under real operating conditions during the early use phase. This is consistent with the case study, where some issues identified over commissioning are still present throughout the initial use phase.

At the time of writing, the handover phase is still ongoing and has not yet been fully completed. As a result, a comprehensive assessment of the building's performance cannot yet be reliably carried out. Indeed, the presence of unresolved issues and partially functioning systems would likely lead to unrepresentative and potentially misleading results, rather than reflecting the actual performance of the building under normal operating conditions.

4.3.8.1 Observations and key criticalities

It can be observed that, until the performance commissioning phase is fully completed, it is not possible to determine the actual behaviour of the building under full operational conditions.

This case study highlights how shortcomings in the early design stages can propagate through the subsequent phases and ultimately affect the final operational performance of the building, particularly if corrective actions are not implemented in a timely manner.
The workflow proposed in the following chapters is intended to support the BMS design process, with the aim of preventing the issues identified in the case study from recurring systematically due to the absence of a structured and well-defined design approach.

5 FROM STRATEGIC DEFINITION TO CONCEPT DESIGN (RIBA 0-2)

5.1 STRATEGIC DEFINITION

The objective of RIBA 0 shall be defining the strategic role of the BMS within the project. In this phase the dialog with the client is fundamental to understand their requirements and clarify the level of control, integration and automation expected for the building. Is therefore necessary to clarify to establish whether the BMS is intended to cover all building systems or only selected disciplines, and whether it should support advanced supervisory and management functions or be limited to basic control.

The outcome of Stage 0 may be the decision to initiate the project, in this case the definition of BMS requirements may be deferred to Stage 1.

5.1.1 Efficiency classes

Within RIBA Stage 0, the definition of project requirements should explicitly include the targeted level of BACS energy efficiency, establishing a clear basis for subsequent design decisions and performance objectives.

In this context, European standards on the energy performance of buildings require minimum levels of automation for non-residential buildings. Specifically, EN ISO 52120 states that, in the absence of a specific requirement, a level of efficiency equivalent to class C must be ensured. Therefore, it is essential during the design phase to define the target objective: this will determine the structure of the BMS and its operating logic.

EN ISO 52120 describes the characteristics of each class:

1. High energy performance: this corresponds to automation systems with levels of precision and completeness in automatic control that guarantee high energy efficiency for the generation system. The control devices must be able to manage HVAC systems by considering factors such as air quality, occupancy rate, and include additional integrated functions that allow interaction between multiple disciplines.
2. Advanced: spaces must be served by an advanced automation and control system (BACS) for the management and centralized control of each building system. The control systems in each room must be able to communicate with the BACS.
3. Standard: this applies when the solution consists of a traditional automation system, with a minimum level of performance. Traditional BACS refers to an automation system with

basic controls, often local; in addition, the adjustments are not managed by advanced logic and there is little integration between systems.

4. Not efficient: this includes traditional automation and control systems that are not energy efficient.

To define the energy performance of the entire system, it is necessary to associate an efficiency class with each function that has a significant impact: the impact of a function is not considered relevant if the share of energy consumption related to the service controlled by the function is less than 5% of the building's total energy consumption.

The BACS functions that affect the energy performance of a building are listed in Table 5 of EN ISO 52120, summarized below:

1. Regulation of heating systems → this function includes temperature control, demand-based regulation, and dynamic hydraulic balancing. Efficiency levels range from a system without automatic regulation to regulation for individual environments via BACS depending on presence. Similarly, hydraulic balancing can be without automation or carried out through dynamic balancing for each emitter.
2. Regulation of domestic hot water supply → involves regulating the temperature of the hot water storage, considering different production methods (electric heat pump, solar collector, etc.);
3. Regulation of cooling systems → same function as heating system regulation;
4. Regulation of ventilation and air conditioning → this function allows the management of indoor air quality conditions as well as humidity conditions, also based on the presence of people in the environment;
5. Regulation of lighting → the lighting conditions of indoor spaces can be managed according to different parameters such as the presence of people and daylight. Lighting management can be manual or automatic thanks to the presence of occupancy sensors;
6. Regulation of shading systems → managing shading systems has two fundamental functions: avoiding overheating and glare by providing protection from solar radiation. Regulation can be manual (Class D), motorized with manual control, motorized with automatic control, and combined with other systems (lighting, HVAC, other shading).

Domestic hot water supply control	
Function	**Level of control**
Control of DHW storage charging with direct electric heating or integrated electric heat pump	Automatic on/off control
	Automatic on/off control and loading time start
	Automatic on/off control, timed loading start and multi-sensor storage management
Control of DHW storage charging using heating water generation	Automatic on/off control
	Automatic on/off control and loading time start
	Automatic on/off control, timed loading start and multi-sensor storage management
Control of DHW storage charging with solar collectors and supplementary heat generation	Manual control
	Automatic control of solar storage loading (priority 1) and storage supplementary (priority 2)
	Automatic control of solar storage loading (priority 1) and storage supplementary (priority 2) with demand-based or multi-sensor management of accumulation
Control of the pump of domestic hot water recirculation	No control, continuous operation
	With timed program

Table 5 — BACS and TBM functions affecting the energy performance of buildings -Source: author's elaboration from EN ISO 52120-1

5.2 PREPARATION AND BRIEFING

5.2.1 Roles

The design of a BMS should involve various professional figures: from designers to the BMS specialist, including the system manufacturers. The fact that the implementation of the BMS comes into play in the advanced stages of the design process leads to a lack of clarity in the definition of roles and responsibilities.

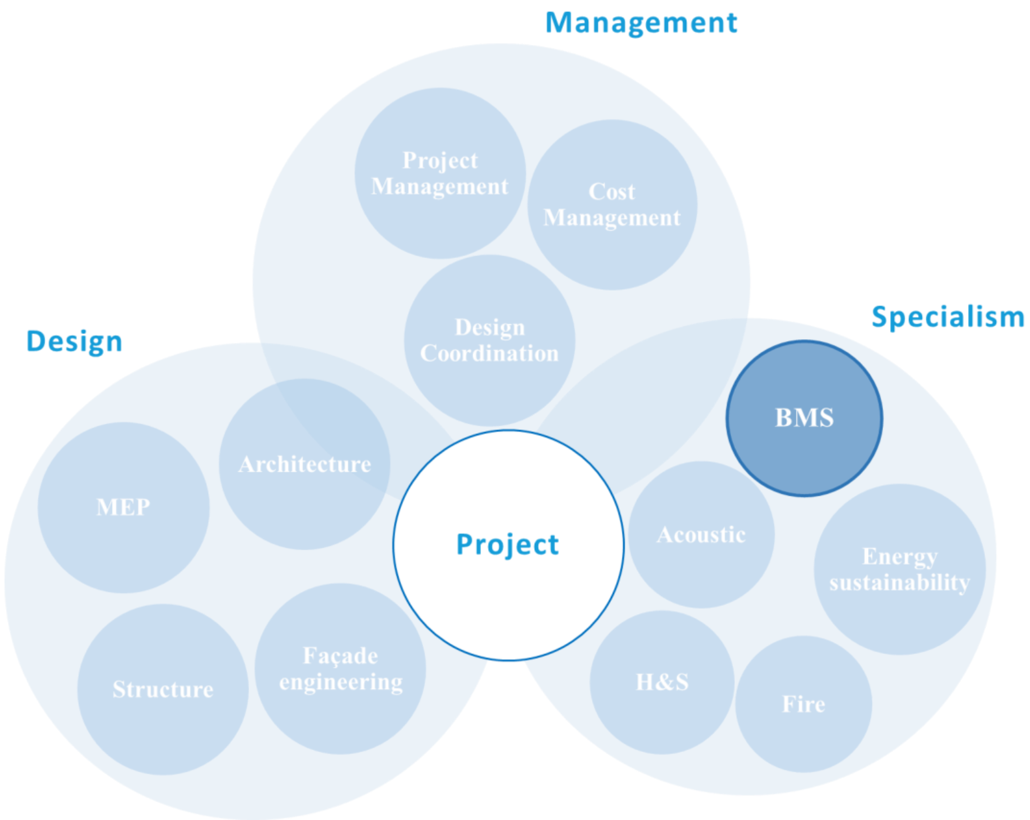


Figure 41: Role diagram of project stakeholders - Source: author's elaboration from case study documentation

According to ASHRAE Guideline 13, several actors are involved in the definition of a BMS. The guideline emphasizes the importance of coordination between the building owner, the BMS designer, consulting engineers, system integrators and IT stakeholders, ensuring that the system requirements are clearly defined during the design and specification phases.

ASHRAE does not have a “roles and responsibilities” section where contractual roles are formally defined; however, the main actors involved in the BMS design process clearly emerge throughout the document.

In particular, the BMS designer is plays a central role in the definition of the automation system. He is responsible for translating the project objectives and the client’s requirements into the system architecture, control strategies and technical specifications, while coordinating with other project stakeholders to ensure a coherent and integrated BMS design. He may be a consulting engineer, a licensed professional engineer, a facility master system integrator or other. The ASHRAE Guideline explicitly encourages the designer to clarify, at an early stage, the scope of work of the automation system. This process is driven by a series of guiding questions aimed at clarifying the client's expectations, the systems to be included in the BMS, and the desired level of control, integration and management, in line with the strategic decisions typically made during RIBA Stage 0.

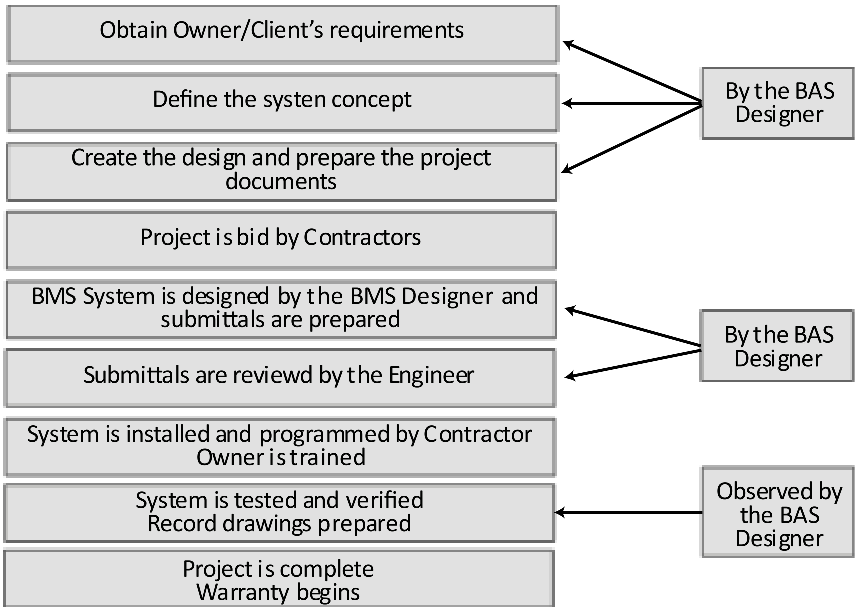


Figure 42: Step in providing a BAS – Source: author's elaboration from ASHRAE Guideline 13 - Specifying Building Automation Systems

The roles introduced below are defined based on the recommendations and intended use of ASHRAE Guideline 13 and are adapted to the RIBA Plan of Work framework.

	Role	Main responsibilities
0 Strategic Definition	Building owner/client	• Define the intended role of the BMS in the building and the level of control and automation • Approve the target BMS efficiency level
	BMS Designer	• Translate client ambitions into a BMS scope of work • Identify which building systems are included in the BMS
	Facility management	• Provide operational needs and future expectations
1 Preparation and Briefing	BMS Designer	• Formalise BMS functional requirements • Define preliminary BMS architecture
	Building owner/client	• Confirm alignment with project objectives
	Consulting/MEP Engineer	• Assess feasibility with building systems
2 Concept Design	BMS Designer	• Define control philosophy • Draft preliminary point list
	Consulting/MEP Engineer	• Ensure integration with HVAC and other systems
3 Spatial Coordination	BMS Designer	• Verify consistency with BMS design intent
	Consulting/MEP Engineer	• Coordinate BMS with spatial and system layouts
4 Technical Design	BMS Designer	• Review control logic and configurations
	Controls Contractor	• Develop detailed BMS technical solutions
	Consulting/MEP Engineer	• Define logic control and finalize point list • Support technical coordination with other disciplines
5 Manufacturing and Construction	BMS Designer	• Clarify design intent when required • Supervise BMS implementation in the building
	Controls Contractor	• Install BMS hardware and software • Configure and program the BMS • Perform testing and commissioning
6 Handover	Controls Contractor	• Deliver BMS documentation and training
	Building owner/client	• Accept the BMS at handover
	Facility management	• Take over system operation

7  Use	Facility management	• Operate and maintain the BMS • Monitor performance and energy use
	Building owner/client	• Define long term optimisation objectives

Table 6: Roles and Responsibilities across RIBA Plan of Work stage – Source: author's elaboration. Images from RIBA plan of Work (2020)

5.2.2 Preliminary BMS Structure

Having understood the energy efficiency objective of the BMS, we can begin to define its structure, starting from the type of system we want to use.

5.2.2.1 Types of BMS

Building Management Systems today come in different types and can be classified according to the architecture (centralized or decentralized), the place of management (cloud-based or on-premises), the level of integration. BMS can also be classified according to the type of controllers used: DDC or PLC [63].

5.2.2.1.1 Classification according to the type of implementation

Depending on where the management software and operational data reside, the system can be defined as on-premises or cloud-based. On-premises systems are installed and managed internally within the building or in the operator's data centre; in this model, the control infrastructure is under the full responsibility of the organization, which can foster stringent security and compliance requirements. Cloud-based BMSs instead use cloud computing infrastructure to host software and store data remotely, allowing access from anywhere, greater scalability, and ease of integration with external technologies like IoT and AI. The current trend is toward cloud or hybrid solutions due to the need for remote system management and the need for tools capable of managing increasingly complex buildings.

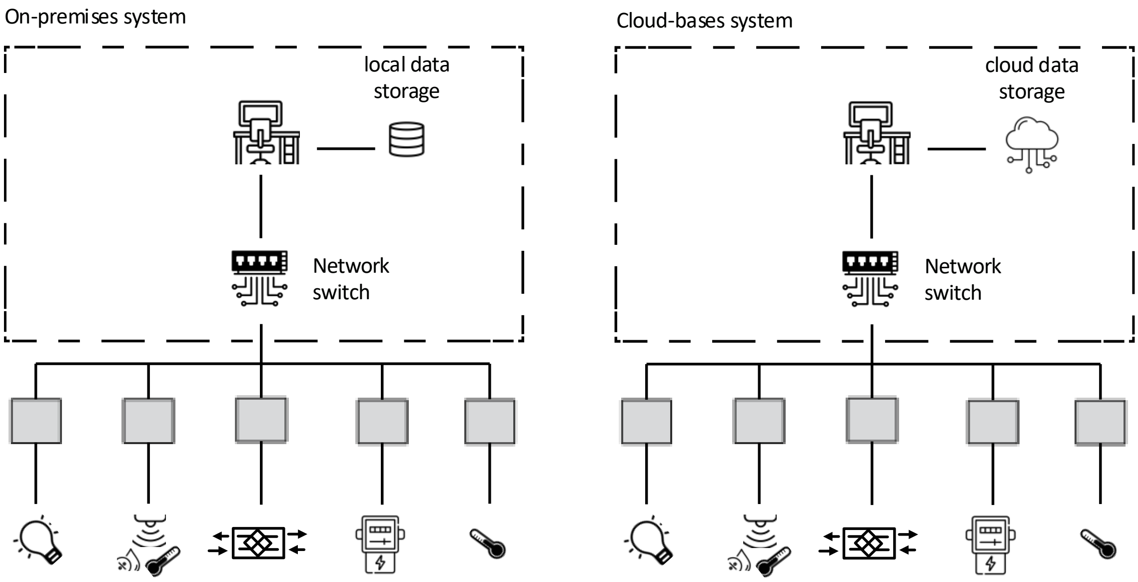


Figure 43: BMS classification: On-premises system (left) and Cloude-based system (right) – Source: author's elaboration

5.2.2.1.2 Classification according to architecture

BMSs can be distinguished based on their control architecture into centralized and decentralized. In centralized systems, all information from sensors and actuators flows into a single control point. This configuration is typical of small buildings or buildings with simple systems, which do not require elaborate systems, so management from a single control point is sufficient, even if it is a limited solution in terms of scalability. In decentralized systems, however, control is entrusted to multiple local units, each of which supervises a specific area or function of the building. This architecture improves flexibility and expansion capacity, making it suitable for large or complex buildings.

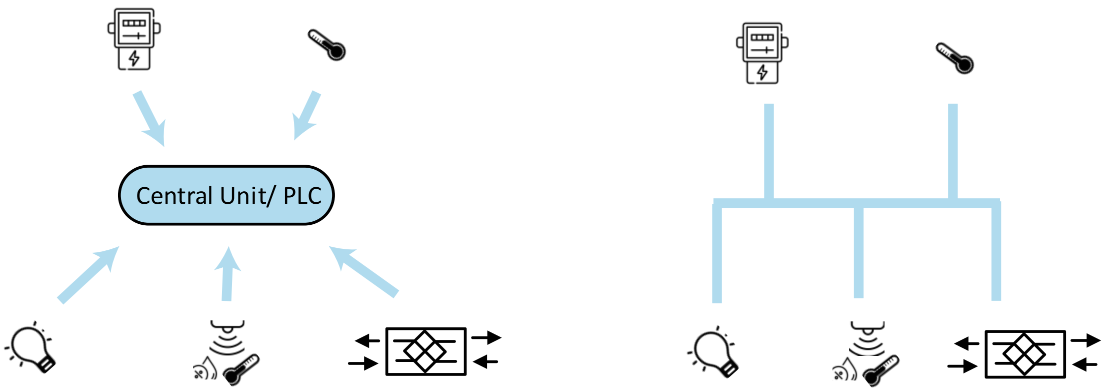


Figure 44: BMS classification: Centralized system (left) and Decentralized system (right) – Source: author's elaboration from Nýclt O. (2011)

In some cases, a hybrid solution can be found; you have local levels of automation with a central supervision and data analysis platform. So, the field level collects data from sensors, the local automation level manages the control of individual systems, while the central supervision level coordinates the entire building.

5.2.3 KPI

During the early design stages, it is essential to define the building performance objectives through the identification of appropriate Key Performance Indicators (KPIs). KPIs enable the management of building performance and support sustainable design strategies to reduce consumption and relative emissions by adopting a performance-based approach [64].
The benefits provided by KPIs in building management are numerous; in particular:

- Improved efficiency: KPIs enable the implementation of targeted corrective actions, reducing waste and optimizing the use of available resources by identifying inefficiency in building systems' behavior.
- Cost savings: the optimization of energy and water consumption, supported by KPI monitoring, can lead to significant reductions in utility costs over time.
- Enhanced occupant experience: maintaining good indoor air quality and comfortable temperatures can improve occupant health, productivity, and satisfaction.
- Sustainability: by tracking resource consumption and emissions, KPIs contribute to minimizing the environmental impact of buildings, fostering more sustainable operation and supporting long-term decarbonization strategies.

KPIs provide a measurable and comparable representation of building performance, enabling a clear understanding of how systems operate over time. Different types of KPIs can be defined depending on their purpose, addressing various aspects of building performance.

Key performance metrics in building systems can be broadly categorized into eight main areas:

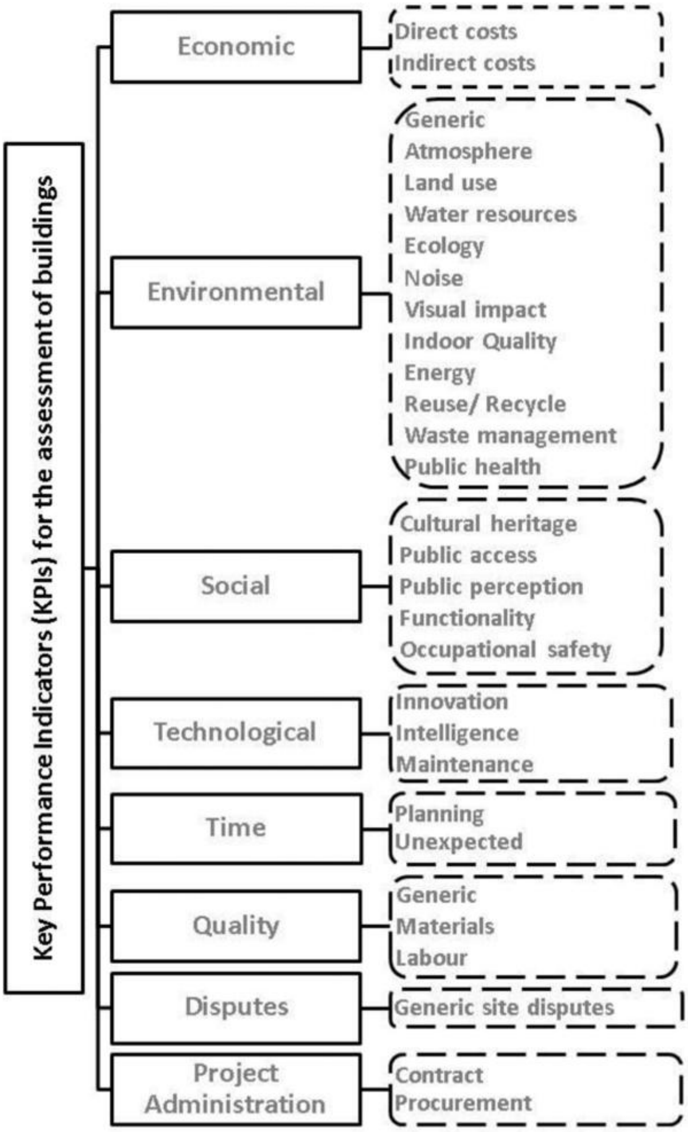


Figure 45: Categories and sub-categories of Key Performance Indicators (KPIs) on the performance of the buildings. – Source: Kylili, A; Fokaides, P.A.; Amparo Lopez Jimenez, P. (20126)

The decisions made during this stage have a significant impact on the building's management through its lifecycle. In fact, once KPIs are established, the tools and systems required to evaluate them are implicitly defined. Consequently, in the absence of a clear definition at this stage, it becomes difficult to implement such evaluation frameworks once the building is completed and operational.

Furthermore, KPIs determine which parameters must be monitored by the BMS, as well as which variables require trend logging over time. The identification of KPIs therefore directly influences the selection of data points, the structure of monitoring systems, and the overall ability to assess building performance during operation.

5.3 CONCEPT DESIGN

5.3.1 Energy classification: eu.bac method

Following the definition of the BMS architecture and functions in RIBA Stage 1, the efficiency class of the management system can be evaluated, , allowing an assessment of whether the objectives delineated in RIBA 0 have been met.

The EN ISO 52120 is a regulatory standard that defines the minimum functionalities of building automation and control systems. It specifies what an automation system must do, but it does not provide a method for evaluating its quality or for objectively comparing two or more different systems. This is where the eu.bac method comes in: it is a certification system that translates the functions outlined in EN ISO 52120 into an assessment model based on assigning scores to each function, with the total score allowing the classification of the entire system.

Each individual system function is rated according to a scale from A to D and is assigned a corresponding score:

- A = 3
- B = 2
- C = 1
- D = 0

Domestic hot water supply control			
Function	**Level of control**	**Residential buildings class**	**Non-residential buildings class**
Control of DHW storage charging with direct electric heating or integrated electric heat pump	Automatic on/off control	D (0)	D (0)
	Automatic on/off control and loading time start	C (1)	C (1)
	Automatic on/off control, timed loading start and multi-sensor storage management	A (3)	A (3)
Control of DHW storage charging using heating water generation	Automatic on/off control	D (0)	D (0)
	Automatic on/off control and loading time start	C (1)	C (1)C
	Automatic on/off control, timed loading start and	A (3)	A (3)

	multi-sensor storage management		
Control of DHW storage charging with solar collectors and supplementary heat generation	Manual control	D (0)	D (0)
	Automatic control of solar storage loading (priority 1) and storage supplementary (priority 2)	C (1)	C (1)C
	Automatic control of solar storage loading (priority 1) and storage supplementary (priority 2) with demand-based or multi-sensor management of accumulation	A (3)	A (3)
Control of the pump of domestic hot water recirculation	No control, continuous operation	D (0)	D (0)
	With timed program	A (3)	A (3)

Table 6 — BACS functions and efficiency classes – Source: author's elaboration from EN ISO 52120-1

As shown in the table, not all applications have four options classified from D to A.

The eu.bac in the classification calculations takes in consideration also different weights in function of the room/space intended use. In fact, a building consists of many spaces served by different equipment with different functions.

Another factor that influences the final score is the importance of the application in a group of functions. Each application group should be assessed based on their importance within the group. Each group of functions has to relate to another application, so a score is assigned based on the importance of the groups to each other.

Another factor of importance is related to the type of building. The eu.bac defined the following types of buildings:

- Office
- Data centre
- Education
- Hospital
- Hotel
- Retail
- Restaurant
- Apartment building

To better visualize the final result eu.bac standard adopt the following scheme:

Level	Points
A+	85-100
A	75-84
B	65-75
C	55-64
D	45-55
E	35-44
F	0-34

Table 7: eu.bac automation system classification – Source: author's rielaboration based on eu.bac (2012). Original image from eu.bac (2012)

The final output of the analysis should be presented as follows:

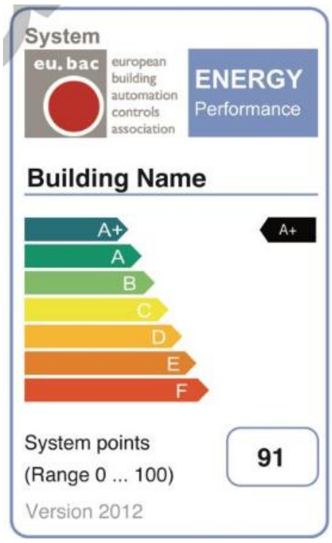


Figure 46: Energy performance label – Source: eu.bac (2012)

5.3.2 Points List

Once you have defined what the systems managed by the BMS will be, it is necessary to identify all the sensors, actuators and logic points connected to the system. Each controller has a limited number of inputs and outputs, so it is essential to define a list of all the necessary points that allows the designer to select the most suitable controller.

To define the number of points, you must first understand the difference between input and output, generically referred to as I/O. Inputs are the points that are not affected by the controller, they are simply read and used when necessary. Outputs, on the other hand, are the points that are influenced by the controller, which gives commands to the outputs whether or not they work, depending on the control logic.

Each input and output can be of a different nature: analogue or digital [65].

5.3.2.1 Analogue Input (AI)

These are inputs where the recorded value is not simply true or false but returns a variable value. For example, temperature sensors are analogue inputs in that the controller records a real temperature value. The greatest art of AIs are sensors, such as room temperature and humidity, channel pressure, etc.

Component	Measured/commanded variable	Functional meaning
Indoor temperature sensor	Temperature [°C]	Thermal comfort monitoring and HVAC control
Indoor CO_2 sensor	CO_2 concentration [ppm]	Indoor air quality indication and ventilation demand control
Supply air static pressure sensor	Air pressure [Pa]	Fan control feedback and ventilation diagnostics
Light level sensor	Illuminance [lux]	Daylight harvesting and lighting level monitoring
Indoor relative humidity sensor	Relative humidity [HR%]	Comfort control and condensation risk monitoring
Electrical voltage measurement	Voltage [V]	Power quality and supply monitoring

Table 8: Example of Analogic Inputs - Source: author's elaboration

5.3.2.2 Digital Input (DI)

Digital inputs are inputs that are intended to monitor the state of a function, so the controller reads one of two states: generally true or false, but other terminologies such as on/off, open/closed can be found. An example of a DI is the fire alarm, whose state is not described by a value but can only be deactivated or not. Other examples of functions with digital inputs are compressor and heat pump alarms, light switch controls, water flow switches.

Component	Measured/commanded variable	Functional meaning
Occupancy / presence sensor	Occupied/not occupied status	Lighting and HVAC control based on occupancy
Duct smoke detector	Smoke alarm status	Safety function: fan shutdown and alarm
Supply fan run status	ON/OFF status contact	Confirmation of actual fan operation
UPS alarm	Enable/disable status	Electrical continuity status

Table 9: Example of Digital Inputs - Source: author's elaboration

5.3.2.3 Analogue Output (AO)

AOs allow the controller to issue commands in a range of values. For example, the valves of the water circuit may have an opening percentage between two set values, between 0 and 100% but also in a reduced range when necessary for the proper operation of the circuit. The speed control of the UTA extraction/delivery fans, variable speed pumps, and the light intensity of an environment are also analogue outputs.

Component	Measured/commanded variable	Functional meaning
Cooling coil control valve	Valve position command 0–100%	Supply air temperature control (cooling mode)
Return air damper actuator	Damper position command 0–100%	Control of air mixing and recirculation
Supply fan VFD speed command	Speed setpoint 0–100%	Control of air flow or duct static pressure

Table 10: Example of Analogue Outputs - Source: author's elaboration

5.3.2.4 Digital Output (DO)

As with DIs you don't have a range of values, but the commands are simply on/off, true/false, closed/open etc.

Component	Measured/commanded variable	Functional meaning
AHU enable / supply fan start–stop	ON/OFF command	Unit or fan operation enable
Lighting ON/OFF relay command	ON/OFF command	Switching of lighting fixtures
Fire damper activation	Close/open	Fire damper closing command

Table 11: Example of Digital Outputs - Source: author's elaboration

5.3.2.5 BACnet standard

In addition to physical inputs and outputs, there are other points that can be implemented in the automation system. For example, BUS points are not physical I/O signals, but logical points or network variables read through digital protocols (e.g. Modbus, KNX, BACnet, etc.).

BACnet, in particular, defines a standard set of data points. Due to its object-oriented nomenclature (see section 3.5.1), the BACnet standard doesn't refer to inputs and outputs as points, but as *objects.* Each object is characterized by a set of standard *Properties*, which describe the object and its current status and allow it to be controlled by other BACnet devices [61].

BACnet defines a number of standard Object types (table 12) [66].

The BACnet standard does not require all Objects in all BACnet devices; rather, the selection of Object type should be determined by the device's function and capabilities of the device.

Object	Example of use
Analog Input	Sensor input
Analog Output	Control output
Analog Value	Setpoint or other analog control system parameter
Binary Input	Switch input
Binary Output	Relay output
Binary Value	Binary (digital) control system parameter
Calendar	Defines a list of dates, such as holidays or special events, for scheduling

Command	Writes multiple values to multiple objects in multiple devices to accomplish a specific purpose, such as day-mode to night-mode, or emergency mode
Device	Properties tell what objects and services the device supports, and other device-specific information such as vendor, firmware revision, etc.
Event Enrolment	Describes an event that might be an error condition (e.g., "Input out of range") or an alarm that other devices to know about. It can directly tell one device or use a Notification Class object to tell multiple devices
File	Allows read and write access to data files supported by the device
Group	Provides access to multiple properties of multiple objects in a read single operation
Loop	Provides standardized access to a "control loop"
Multi-state Input	Represents the status of a multiple-state process, such as a refrigerator's On, Off, and Defrost cycles
Multi-state Output	Represents the desired state of a multiple-state process (such as It's Time to Cool, It's Cold Enough and it's Time to Defrost)
Notification Class	Contains a list of devices to be informed if an Event Enrolment object determines that a warning or alarm message needs to be sent
Program	Allows a program running in the device to be started, stopped, loaded and unloaded, and reports the present status of the program
Schedule	Defines a weekly schedule of operations (performed by writing to specified list of objects with exceptions such as holidays. Can use a Calendar object for the exceptions

Table 12: Object types and example of use – Source: author's elaboration from Swan B. (2008)

BACnet standard does not define a list of Objects associated with each device, for example which points should be used for AHU, but provides a standardized object-oriented model to represent physical inputs, outputs and software variables.

6 SPATIAL COORDINATION AND TECHNICAL DESIGN (RIBA 3–4)

6.1 SPATIAL COORDINATION

The aim of the spatial coordination in RIBA 3 is to verify that architectural design and plant layout are spatially coordinated. Regarding the BMS, spatial coordination involves not only the identification of dedicated technical spaces for control panels, servers and workstation, but also the integration of field devices within the plant layout.

During the spatial coordination phase, it is necessary to define technical spaces which include rooms for control panels, BMS cabinets, servers, and supervision workstations, which must be located in accessible positions and be consistent with operation and maintenance requirements. The definition of these spaces during this stage is fundamental to verify the spatial feasibility of the system and helps prevent critical issues related to insufficient space or interference with other building services during the construction phase.

Spatial coordination also involves the integration of field devices within the overall plant layout. Even though control logics are not yet defined in detail at this stage, spatial coordination ensures that the strategic distribution of devices is compatible with the spatial organization of the building. To achieve this objective, sensors, actuators, local controllers, and interfaces must be positioned coherently in relation to the mechanical and electrical systems that the BMS is intended to monitor or control, without interfering with such systems.

6.1.1 Graphical representation

Spatial coordination activities are translated into graphical outputs, such as functional schematics and coordinated plans showing the location of equipment and devices.
This graphical documentation represents a fundamental tool for clash detection, interdisciplinary coordination, and the subsequent preparation of the Bill of Quantities, providing the information baseline for the technical design and tender stages.

6.2 TECHNICAL SPECIFICATIONS

The definition of technical specifications and functional logic of the BMS represents a fundamental step in the design process. This phase is essential both for the construction contractor, to ensure that all devices and system components are correctly installed, and for the BMS supplier, to guarantee that implemented control logics are fully consistent with the BMS design intent. Ensuring coherence between the designed BMS architecture and the specifications translated into the operational system is crucial to achieving an efficient and reliable building management system.
Technical specifications should describe not only the BMS architecture and the communication network between devices, but also the control logics, clarifying how the system operates under different operating conditions. The definition of control logics is crucial especially for systems whose functioning is closely linked to building efficiency, such as chilled beams, shading system, and groundwater well systems. For these systems, inadequate, inconsistent, or incomplete control logic definitions can significantly compromise the overall performance and efficiency of the building.

Table following table summarises the main contents that should be included within the BMS technical specifications, covering technical, functional, and organisational aspects necessary to guarantee an efficient, coordinated, and fully integrated system.

Content	Description
Reference drawings and documents	List of reference documents supporting the BMS design, such as coordinated layouts, system schematics, architectural and MEP drawings, control diagrams, relevant design reports and point list.
Roles and responsibilities	Definition of roles and responsibilities related to the development, implementation, and validation of BMS specifications and control logics (e.g. BMS designer, contractor, BMS supplier*). (see chapter 5.2)*
BMS architecture	Definition of the overall BMS architecture, including system levels (field, control, management) and main components. *(see chapter 2.4)*
Devices list	Detailed list of all BMS devices, including sensors, actuators, controllers, meters, and interfaces, with reference to their function and integration within the building systems.
Communication protocols	Specification of adopted communication protocols (e.g. BACnet, Modbus, KNX, DALI), network

	architecture, and interoperability requirements between systems. *(see chapter 3.5)*
System scope and BMS functions	Clear definition of systems monitored, controlled, or supervised by the BMS.
Control logics and operating sequences	Description of control strategies and operating sequences defining system behaviour under different operating conditions (e.g. normal operation, seasonal modes, fault conditions).
Performance and functional requirements	Definition of functional requirements and performance objectives related to energy efficiency, comfort, monitoring, and operational targets.
BMS interface requirements	Definition of the graphical user interface, including the structure of navigation pages, system layouts, and visualization principles. Specification of the parameters to be displayed, control setpoints, command statuses, and alarm indications, as well as identification of the variables for which trend logging is required.
Alarm and monitoring strategy	Specification of alarm types, priority levels, monitored parameters, data logging requirements, and notification rules.
Testing and commissioning requirements	Definition of functional tests, validation procedures, and commissioning activities required to verify compliance with the technical specifications and control logics.

Table 13: Technical specifications main contents – Source: author's elaboration

The BMS interface images presented in this section are derived from the selected case study and are used as illustrative support for the description of technical specifications and control logic. As such, they are not intended to represent a finalized or universally applicable design, but rather to provide a practical reference for the proposed methodology.

6.2.1 Control logics and operating sequences

The examples described in the following section are provided to illustrate possible approaches to system control and do not constitute an exhaustive list.
A Building Management System can integrate a wide range of additional systems and functionalities; therefore, only selected systems and representative functions are presented here, with the aim of clarifying how control strategies can be defined, as well as identifying the key parameters to be monitored and the variables for which trend logging should be implemented, as part of the technical specification of the BMS interface.
Consequently, the list remains open to future modifications, refinements, and integrations according to project-specific requirements.

6.2.1.1 Weather station

The weather station should measure parameters required for the effective management of building systems through the BMS. In general, it consists of an external air temperature sensor,

external air relative humidity sensor and a combined wind direction and wind velocity sensor. The temperature and relative humidity values shall be used to calculate the outside air enthalpy value in kJ/kg.
In order to determine which sensors should be included in the weather station, defining its purpose represents the key initial step. For example, external air temperature can be used to control AHU, while solar irradiance measurements can be employed for the regulation of shading systems such as blinds. In some cases, the weather station may also support the control of external lighting systems through a twilight setpoint, switching lights on or off based on measured illuminance levels.
To ensure effective management of building systems connected to the BMS, it is essential to define technical specifications as well as control logics governing sensors and the weather station. In addition, appropriate guidelines for the installation and positioning of these components shall be established, in order to guarantee accurate measurements and reliable system performance.
The following examples are provided to clarify these aspects.

- The temperature and humidity sensors shall be shielded from direct sunlight and shall be located away from any exhaust louver or any other source of heating or cooling effect. Covers shall also shield the sensors from contact with any snow and rain.
- The wind direction and velocity sensors shall be located at the top of a retractable mast to reduce the influence of building turbulence. The mast shall be capable of extending to a minimum of 3 metres above its retracted height. With the mast retracted, direct access to the wind direction and velocity instruments shall be possible to allow easy maintenance and calibration.
- The wind velocity value shall be filtered to produce an average wind speed value, and it is the filtered value which shall be transmitted (in steps of {0.5} m/s) unless a gust of greater than {10} m/s is detected when the gust value shall be transmitted directly.
- Pyranometer sensors shall be installed, to correspond to the vertical East, South and West facades of the building.
- The sensors shall be positioned so that they are not shaded when the sun is in the sector of the sky where it can affect that façade.

The main parameters to be displayed in the BMS interface and their trends are outlined in the table below*:

Parameter	Trend required
Dry bulb outdoor air temperature	X
Wet bulb outdoor air relative humidity	X
Outdoor relative humidity	X
Wind speed	X
Wind direction	X
Solar irradiance (by orientation if applicable)	X
Global solar irradiance	X
Calculated enthalpy (derived value)	X
Atmospheric pressure	
Geographic coordinates (longitude, latitude)	
Orientation (azimuth)	
Station elevation (installation height)	
Twilight setpoint (lux threshold)	
Lightning control status (on/off)	

Table 14: Weather station parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

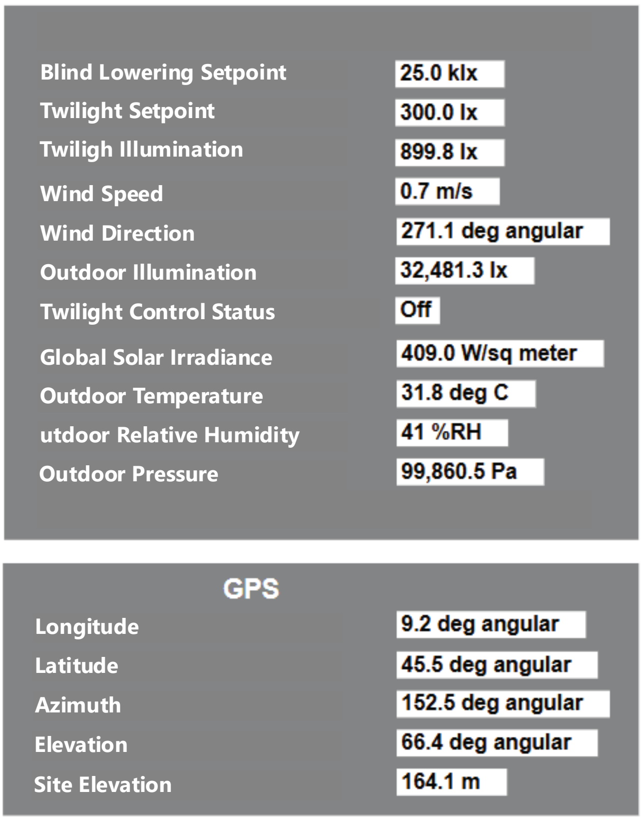


Figure 47: Example of weather station parameters displayed on the BMS interface – Source: case study documentation

6.2.1.2 Blinds control system

Solar shading system is not only an architectural element but actively contribute to the building's energy performance and indoor environmental quality. The control of blinds is typically based on the acquisition of environmental parameters such as solar radiation, indoor illuminance levels and temperature. Based on the inputs the BMS is able to adjust the position and tilt angle of the blinds in order to reduce glare phenomena, limit solar gains and optimize the natural daylight.

Radiation data can be obtained either from a weather station installed on the roof or from sensors located on the building façade. The use of distributed sensors is generally preferable, as it allows the control strategy to be differentiated according to the orientation of the building, resulting in a more accurate and responsive regulation. The use of a weather station typically provides global solar irradiance data, which enables a centralized but less detailed control strategy, as it does not account for façade orientation or local shading conditions. As a result, the control may be less accurate in responding to real solar exposure on specific building surfaces. This is particularly important in high-rise buildings, where solar irradiance can vary significantly depending on façade orientation and height.

Despite the implementation of automated control strategies, it may be useful to provide the possibility for manual override. In fact, occupants may have specific visual comfort requirements, temporary needs or individual preferences that are not captured by the automation system.

This dual approach introduces an additional layer of complexity, as the system must manage the interaction between automatic and manual command. In addition, allowing occupants to operate the blinds system without predefined criteria may negatively affect the overall energy performance of the building. For this reason, in most implementation, manual override is allowed only for a limited period of time.

The key parameters to be visualized in the BMS interface and trends are summarized in the following table*:

Parameter	Trend required
Wind speed	X
Wind direction	X
Solar irradiance (by orientation if applicable)	X
Calculated enthalpy (derived value)	X
Atmospheric pressure	
Geographic coordinates (longitude, latitude)	
Orientation (azimuth)	
Station elevation (installation height)	
Blind position (opening percentage)	
Slat angle	
Control mode (Auto/Manual)	

Table 15: Blinds control system parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

If the environmental parameters are already visualized within the weather station graphic page, it is not necessary to replicate all of them in the blind control section.

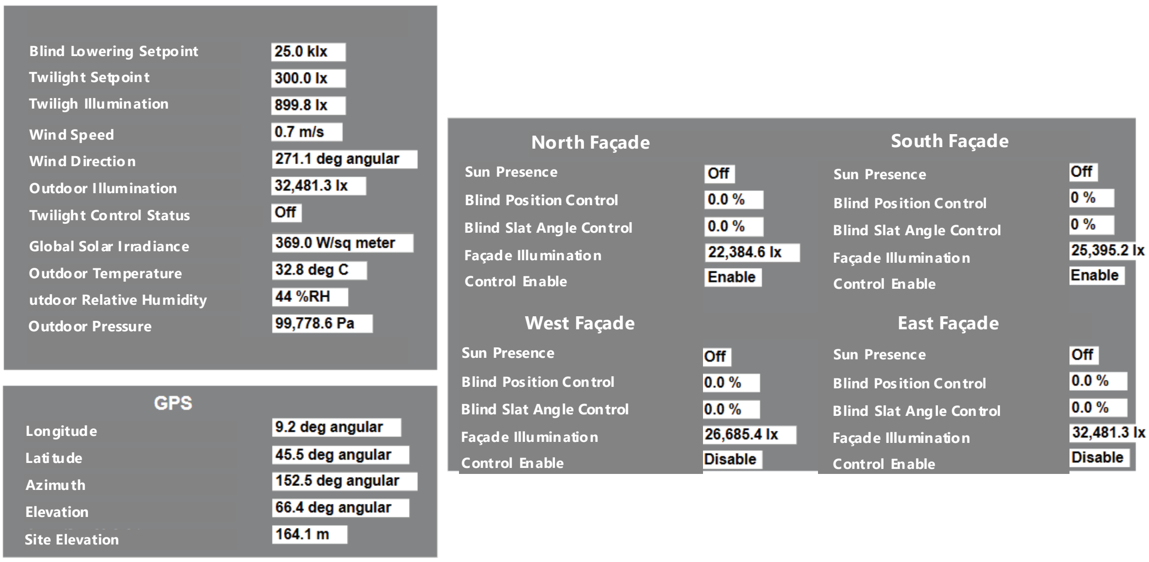


Figure 48: Weather station graphic with environmental parameters for blinds control – Source: Case study documentation

The blind control interface should instead focus on the representation of the blinds themselves and a limited set of key variables. These shall include the blind opening position (expressed as a percentage), the slat orientation angle, and the setpoint values associated with the control logic governing blind operation. In addition, the instantaneous values of the parameters that trigger the control logic (e.g. solar irradiance, wind speed, or illuminance) should be displayed. Furthermore, a clear indication shall be provided to distinguish whether the blind operation is manually overridden by the user or automatically controlled by the BMS.

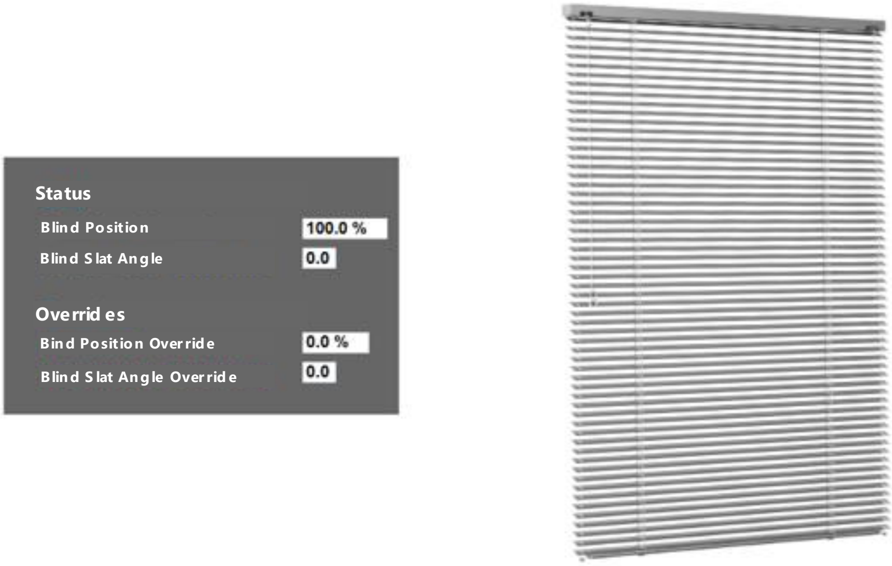


Figure 49: Example of blinds control system parameters displayed on the BMS interface – Source: case study documentation

In order to facilitate the identification and control of individual blinds, the interface should include an interactive floor plan.

This graphical representation shall allow the user to locate each blind within the building layout and interact with it directly, enabling intuitive monitoring and control of the system.

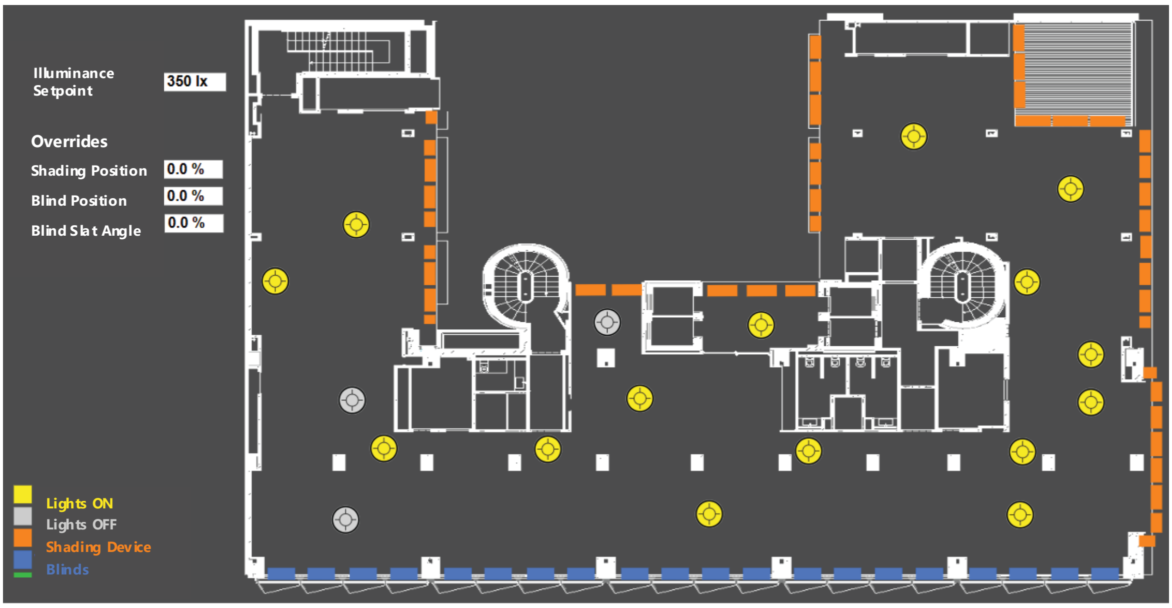


Figure 50: Example of interactive floor plan for blind control on the BMS interface – Source: case study documentation

6.2.1.3 *Lightning control system*

The control of artificial lightning systems enabling the regulation of indoor illuminance levels in accordance with both environmental conditions and occupancy requirements. Lightning control is typically based on the integration of multiple input variables, including indoor illuminance, occupancy status, time schedules, and, in some cases, daylight availability. To reduce unnecessary energy consumption, the presence of occupancy sensors enabling light to be switched off or dimmed when spaces are unoccupied, while illuminance sensors installed within the space provide real-time measurements of indoor light levels, allowing the BMS to modulate artificial lighting in order to maintain predefined illuminance setpoints.

To ensure the design lightning levels, it is essential that the installed equipment corresponds to the design specifications.

The key parameters to be visualized in the BMS interface and trends are summarized in the following table*:

Parameter	Trend required
Occupancy status	X
External illuminance (lux)	X
Indoor illuminance (lux)	X
Lux setpoint	
Occupancy status	X
Lightning command status (on/off)	
Control mode (auto/manual)	

Table 16: Lightning control system parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

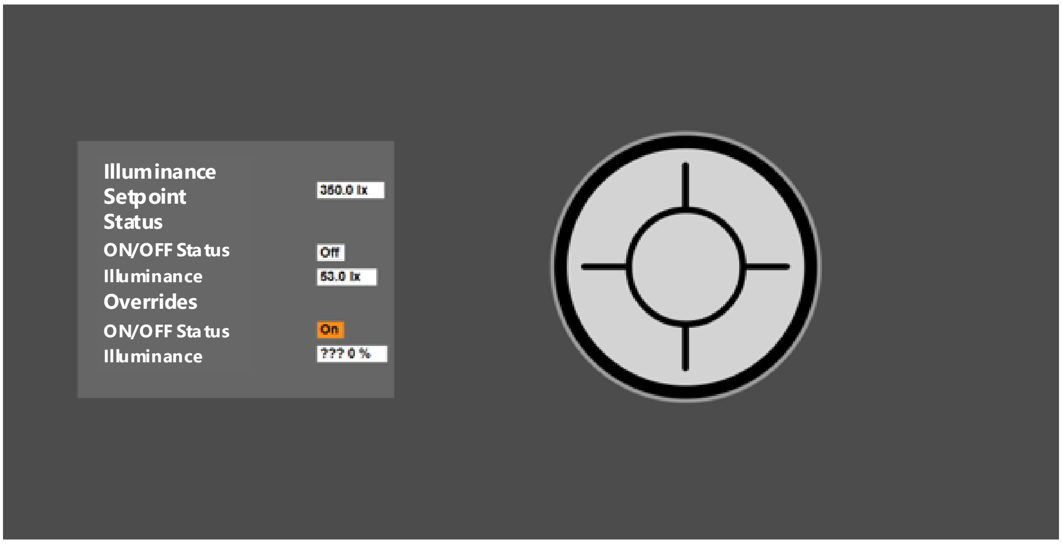


Figure 51: Example of lightning sensor parameters displayed on the BMS interface – Source: case study documentation

From an interface design perspective, the inclusion of a graphical floor layout is recommended for lighting control. This would allow users to identify lighting zones within the building and interact with them directly, providing a clearer understanding of system distribution and control.

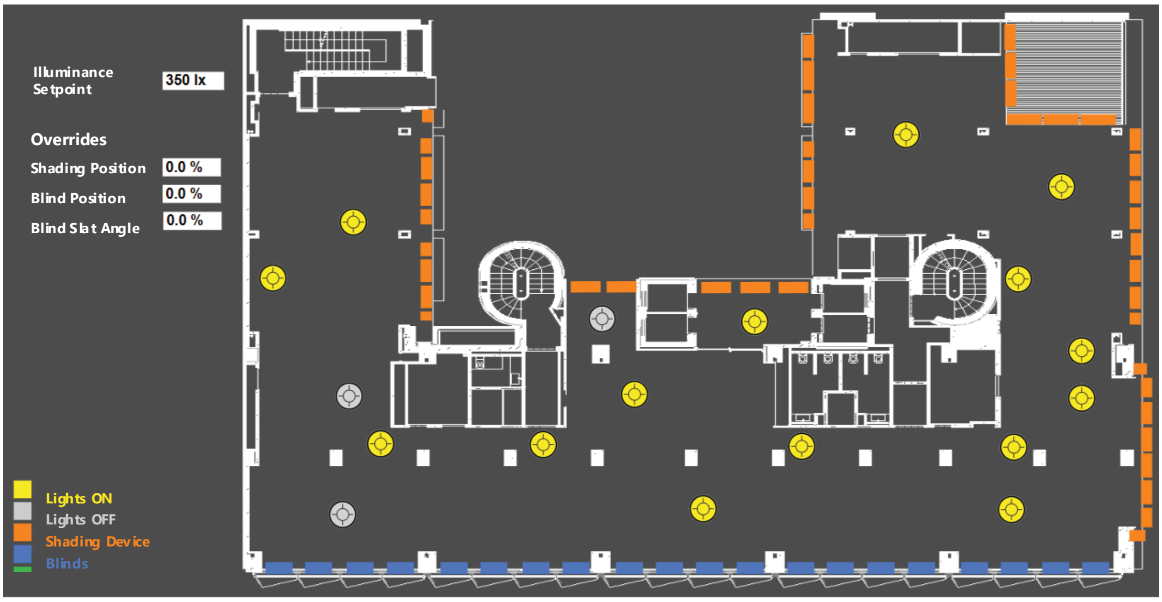


Figure 52: Example of interactive floor plan for lightning control on the BMS interface – Source: case study documentation

6.2.1.4 Ventilation and AHUs

Ventilation and air handling units (AHUs) control logic is based on automatic regulation systems, generally implemented via direct digital controls (DDCs) integrated into a Building Management System (BMS), with the aim of ensuring optimal indoor air quality, thermohydrometric comfort and energy efficiency.

The main components of an AHU represent the elements on which the BMS acts to implement the control logics previously described, modulating its operation in response to the values measured by the sensors. The main components are listed below:

- Supply air section
    - Fresh air intake
    - Supply fan
    - Outdoor and return air dampers
    - Heating coil
    - Cooling coil
    - Humidifier / dehumidification section
- Extract air section
    - Extract fan
    - Return air filters
    - Return and exhaust air dampers

The ventilation system requires the monitoring of a wide range of parameters. For this reason, the BMS interface shall include measured variables, setpoints, and system status indicators in

order to support the interpretation of system behaviour. Trend logging is required for most parameters, as it enables performance assessment and supports diagnostic activities.
In the following table, the key parameters to be visualized in the BMS interface and trends are summarized*:

Parameter	Trend required
AHU status (on/off)	X
Control mode (auto/manual)	
Supply air temperature	X
Return air temperature	X
Outdoor air temperature	X
Return air flow rate	X
Extract air flow rate	X
Fan status	
Fan speed	X
Damper position	
Filter status	
CO_2 concentration	X
Humidity (supply/ return)	X
Outdoor humidity	X
Supply ait temperature setpoint	
Air flow setpoint	
Alarm status	

Table 17: Ventilation and AHUs parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

Figure 53: Example of AHU on the BMS interface – Source: case study documentation

To define the control logic of AHUs and the ventilation system, it is essential to distinguish the type of system adopted, particularly whether it is an all-air or primary-air system. In the first case, the system is responsible for both controlling indoor air quality and regulating the thermohydrometric conditions of the spaces, while in the second case it is limited to ensuring air exchange, leaving the management of thermal comfort to other systems.
Starting from this distinction, it is possible to identify the main parameters adjustable through the BMS. The main relationships between the measured variables and the corresponding control actions, as reported in table xx, define the basis for the implementation of the control logic of the air handling unit (AHU) and the ventilation system.
Such correspondences establish the basis of the control logic of the plant, in which the combination of sensors, actuators and regulation algorithms allows to maintain the design conditions in a continuous and automatic manner.

Controlled parameter	Associated sensor	Control action	Control logic description
Indoor temperature	Room/duct temperature sensor	Heating and cooling coils	Temperature is maintained at the setpoint by modulating the thermal output of the coils
Relative humidity	Room/return air humidity sensor	Cooling coil (dehumidification) / humidifier	Humidity is controlled by removing or adding moisture to maintain the desired level
CO_2 (air quality)	Room/duct CO_2 sensor	Outdoor air fans	Outdoor air flow rate is modulated based on CO_2 concentration
Air flow (pressure)	Duct pressure or airflow sensor	Fans	Fan speed is regulated to maintain constant pressure or airflow

Table 18: AHUs control actions – Source: author's elaboration

The position of sensors within the ventilation system should be clearly defined in the construction drawings, as it directly affects the accuracy of measurements and the effectiveness of the implemented control strategies.

It should be noted that the implementation of control logic may be limited by the capabilities of the BMS. In some cases, the range of adjustable setpoints are predefined at equipment level during the commissioning phase and therefore cannot be fully adjusted through the BMS, such as the maximum air flow.
The control logic of the supply air temperature depends on both the configuration of the AHU and the control strategy adopted, which may be based on internal conditions (e.g. return or room temperature) or external variables (e.g. outdoor air temperature). It is fundamental to

understand the limitations of both the BMS and the controlled equipment, in order to define a coherent and effective automation system control strategy.

The control logic of the supply air temperature should vary depending on seasonal operating conditions. Considering a primary air system, for example, and the indoor temperature defined as a function of the outdoor air temperature, different setpoints should be applied in summer and winter.

Following an example of temperature control logic is described:

- Winter: if outdoor temperature is under 20°C, the supply air temperature should be set at 21°C
- Summer: if outdoor temperature is above 24°C, the supply air temperature should be set at 18°C, implementing humidity control
- When the outdoor air temperature lies within the intermediate range between 20°C and 24°C, the supply air temperature set point is determined by interpolation

6.2.1.5 FCUs – Fan Coil Units

When there is a primary air system, the indoor thermal control can be delegated to Fan Coil Units (FCUs).

The BMS interface should provide a representation of both control variables and feedback parameters at unit or zone level. The graphical page of the FCU should show temperature measurements, valve positions, and fan operation. Trend logging is recommended for key variables to support performance analysis and optimization of control strategies.

The following table summarizes the main parameters to be displayed in the BMS interface for the FCU together with an indication of whether trend logging is required*:

Parameter	Trend required
FCU status (on/off)	X
Control mode (auto/manual)	
Indoor temperature	X
Temperature setpoint	
Fan speed	X
Valve position	
Alarm status	

Table 19: FCUs parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

Fan coil units' control is typically based on both local regulation and central supervision. Each unit has its own integrated unit controller (IUC), which is freely programmable and manages the local control loop, while the BMS provides supervisory functions such as enabling the unit, defining operating modes and setting temperature setpoints.

Supply and return sensors measure temperature and compared it with the desire setpoint. The resulting control action is implemented through modulating both water flow and air flow. In particular, the BMS modulates the opening of pressure-independent control valves (PICV) and the speed of the electronically commutated (EC) fan motor through analogue 0–10 V signals, enabling continuous and precise regulation of thermal output and airflow.

A key aspect in defining the control logic FCUs is the control architecture adopted, which determines how the units are managed within the system. In particular, fan coil units may be controlled individually at room level, grouped by zones, or organized in master–slave configurations, depending on the building layout and control objectives.

In the first case, the temperature measurement of a given area is used to control multiple units simultaneously, whereas in a master–slave configuration, the temperature sensor is typically connected to the master controller, which defines the control action and transmits the operating commands to the slave units.

As for the ventilation, the temperature control logic should depend on seasonal operating conditions. The switch between winter and summer modes is typically performed manually via the BMS by the facility management personnel.

In the following Figure, a graph is shown showing the trend of the opening of the heating and cooling valves and the fan speed as a function of indoor temperature.

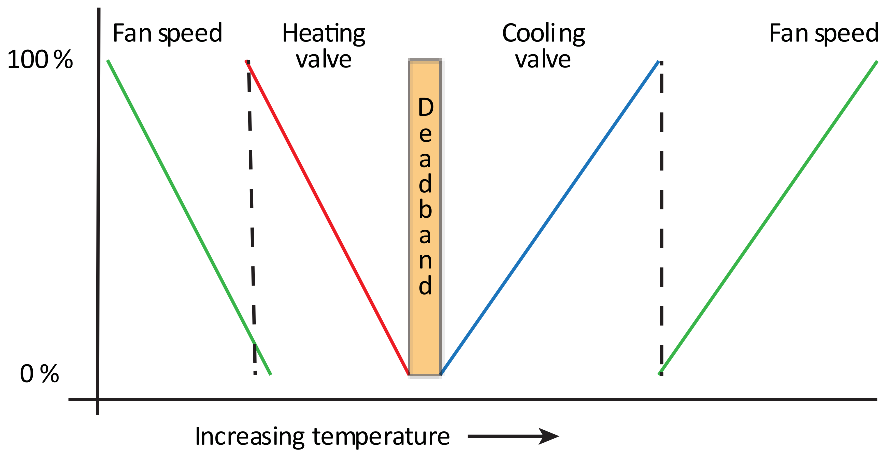


Figure 54: FCUs control logic – Source: author's elaboration

When the indoor sensor registers a temperature below the setpoint the heating valve is fully opened under the coldest conditions and progressively closes with as the temperature increases, until the neutral band (deadband) is reached. Within this range, both heating and cooling valves remain closed, and the fan speed is minimized. When the temperature exceeds the deadband, regulation shifts to the cooling system, with a progressive opening of the cooling valve and increase of the fan speed as the thermal load rises. The presence of the deadband prevents the simultaneous activation of heating and cooling systems, thereby avoiding overlapping control actions and improving overall energy efficiency.

6.2.1.6 Chilled beams

Another approach to integrating a primary air system is represented by chilled beams.
The BMS should allow the visualization of thermal conditions and control outputs such as room temperature, water flow and valve position. Considering the requirement for stable operation and the risk of condensation, trend logging of selected parameters is recommended to support continuous system monitoring and performance validation.
Key parameters and trends are listed in the following table*:

Parameter	Trend required
Chilled beams status (on/off)	X
Control mode (auto/manual)	
Indoor temperature	X
Indoor humidity	X
Temperature setpoint	
Water flow rate	X
Valve position	
Dew point temperature	X
Alarm status	

Table 20: Chilled beams parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

Unlike fan coil units, where airflow and thermal output can be directly modulated at terminal level, chilled beams rely on a decoupled control approach in which ventilation and latent loads are managed centrally, while only sensible heat exchange is regulated locally through water flow. This introduces a higher level of complexity in the BMS implementation, as temperature control cannot be defined independently but must be integrated with the management of indoor humidity and dew point conditions.
As for FCUs, the temperature control logic should depend on seasonal operating conditions. The switch between winter and summer modes is typically performed manually via the BMS by the facility management personnel.
In the following Figure, a graph is shown showing the trend of the opening of the heating and cooling valves as a function of indoor temperature.

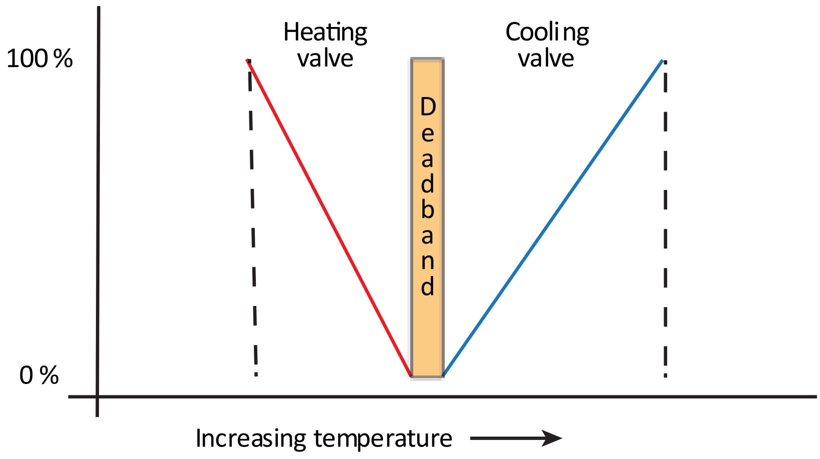


Figure 55: Chilled beams control logic – Source: author's elaboration

When the indoor sensor registers a temperature below the setpoint the heating valve is fully opened under the coldest conditions and progressively closes with as the temperature increases, until the neutral band (deadband) is reached. Within this range, both heating and cooling valves remain closed. When the temperature exceeds the deadband, regulation shifts to the cooling system, with a progressive opening of the cooling valve as the temperature rises. The presence of the deadband prevents the simultaneous activation of heating and cooling systems, thereby avoiding overlapping control actions and improving overall energy efficiency.

6.2.1.7 DHW

Regarding domestic hot water (DHW) control logics, it is important to emphasize that different production systems can be adopted, which significantly influence the regulation strategies implemented by the BMS. In particular, systems can be divided into centralized or decentralized production, as well as into storage or instantaneous production systems, each characterized by specific management methods of temperature, response times and energy consumption.
BMS control strategy for DHW significantly depends on the production configuration adopted. In centralized systems with storage tanks, the control logic is primarily based on maintaining the water temperature within the storage volume through on/off or modulating control of the heat source, combined with recirculation management to ensure temperature availability at distribution points. In this context, particular attention must be given to hygiene requirements, as the BMS must ensure that water temperatures are periodically raised to levels suitable for Legionella prevention, typically through thermal disinfection cycles.
In instantaneous production systems, the control is instead demand-driven and relies on real-time modulation of generators to match the required hot water flow, typically requiring stronger integration between flow, temperature sensors, and control valves.
In the figure below it is shown how the control logic can work in a centralized system. In this case the system is based on a high-temperature water-to-water heat pump supplying a storage

tank, integrated with an electric heater activated by the BMS only when the temperature drops below a threshold that prevents meeting the supply setpoint or hygiene requirements.

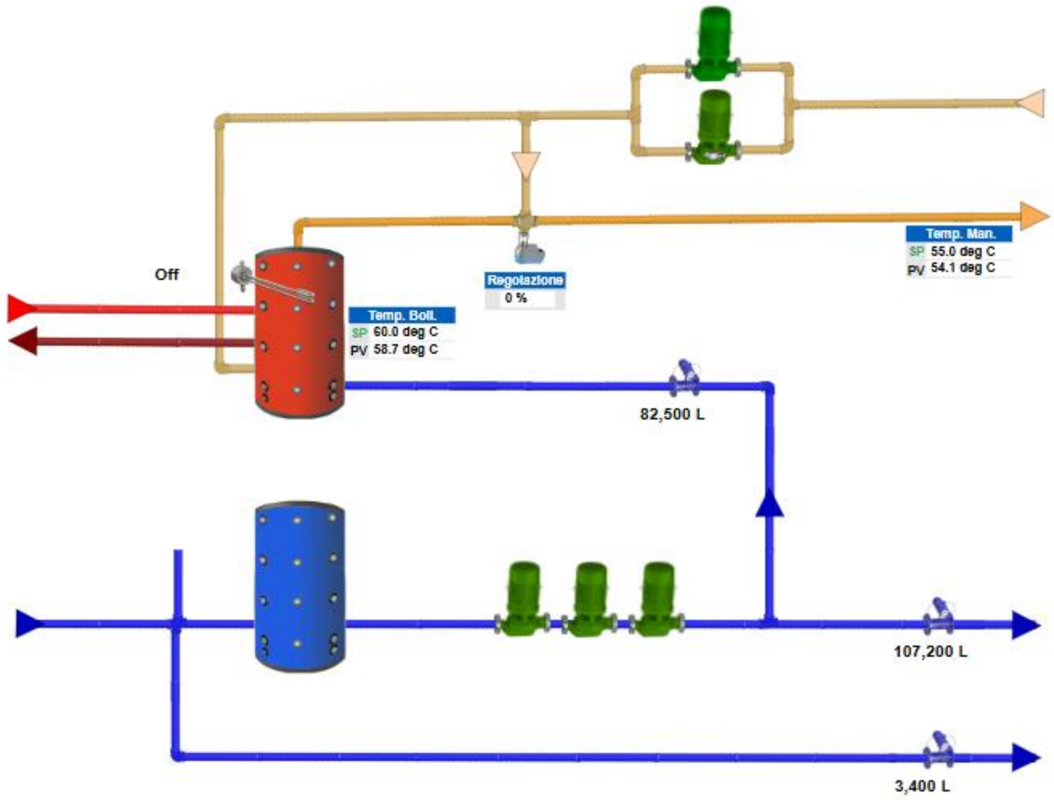


Figure 56: Example of DHW circuit on the BMS interface – Source: case study documentation

The key parameters to be displayed within the BMS interface, together with their requirement for trend logging, are summarized in the following table*:

Parameter	Trend required
Supply temperature	X
Return temperature	X
Storage tank temperature	X
Temperature setpoint	
Pump operating status (on/off)	X
Valve position and modulation	
Water flowrate	
Alarm	

Table 21: DHW parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

6.2.1.8 Heat pumps

The efficiency of heat pumps, expressed through the coefficient of performance (COP), varies continuously depending on external conditions and system setpoints. In this scenario the role of the BMS is not to directly control the refrigeration cycle, which is managed by the unit controller, but rather to define appropriate operating conditions, such as temperature setpoints and load requests, and to coordinate the interaction with distribution systems and auxiliary heat sources.

Heat pumps are managed through specific control logic implemented at the local controller level (DDC/PLC). These logics include the modulation of thermal power as a function of requirements, the management of start and stop sequences, as well as the activation of any backup or integration systems in the event of critical conditions or failure. Control is based on variables measured by sensors installed on the system, such as supply and return temperatures, internal and external environmental conditions, and energy parameters, allowing the design setpoints to be maintained and ensuring comfort and energy efficiency.

An example of a control logic implementable within a BMS is the use of heat pumps as backup system to a primary energy source, such as a geothermal plant. In this scenario, the control logic ensure that the secondary heat pump system remains inactive under normal operating conditions and is active only when the BMS detects abnormal conditions, such as the failure to reach the temperature setpoint within the circuit or the exceedance of a predefined load threshold. In this way, the heat pumps operate as an auxiliary or emergency system, ensuring service continuity and covering peak loads.

From an implementation perspective, the control logic relies on the availability of key operational data within the BMS interface. In particular, the system should provide real-time visualization of both primary heating and cooling circuits associated with heat pumps and the operating status of the individual heat pumps.

Primary circuit page should include following parameters and trends*:

Parameter	Trend required
Supply temperature	X
Return temperature	X
Heat pump status (on/off)	X
Temperature setpoint	
Flow rates	
Secondary circuit end users (AHUs, chilled beams, fan coil units, etc.)	
Pump operating status (on/off)	X
Set point valves	
Valve position and modulation	
Alarm	

Table 22: Primar pay circuit parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

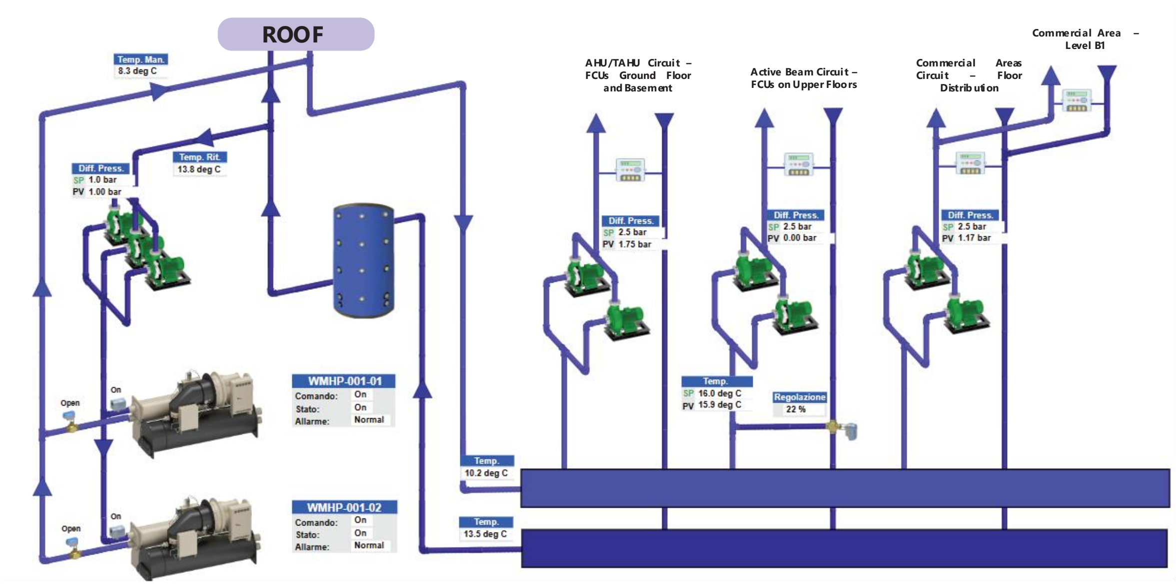


Figure 57: Example of primary circuit on the BMS interface – Source: case study documentation

The BMS interface should provide the following parameters and trends for each individual heat pump*:

Parameter	Trend required
Supply temperature	X
Return temperature	X
Heat pump status (on/off)	X
Temperature setpoint	
Mode of operation (heating/cooling)	
Compressor**s** status	
Alarm status and fault conditions	

Table 23: Heat pumps parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

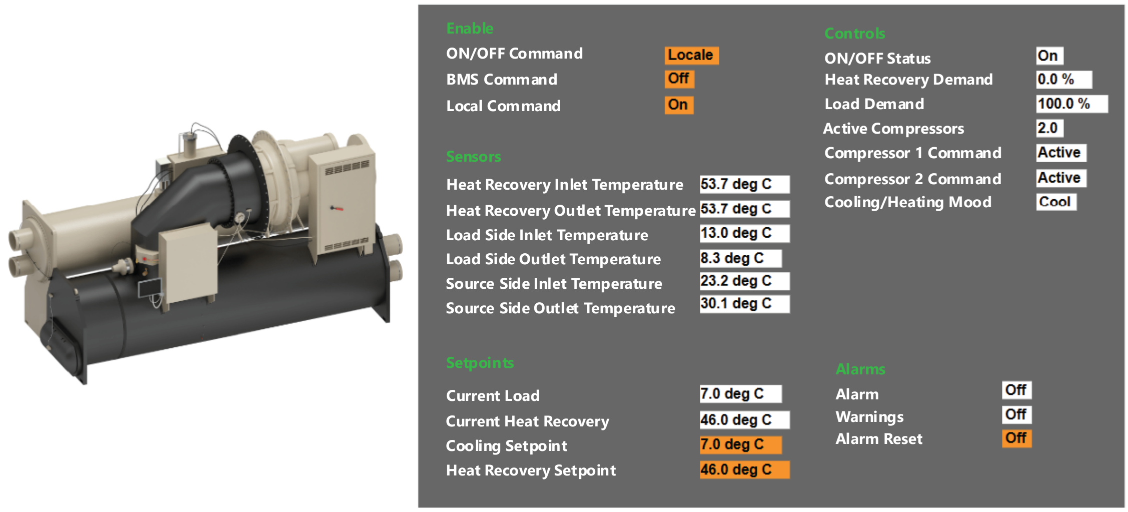


Figure 58: Example of Heat Pump on the BMS interface – Source: case study documentation

6.2.1.9 Groundwater system

The groundwater system, which provides both heating and cooling, is typically composed of a hydraulic circuit with a heat exchanger that separates the groundwater loop from the secondary circuit serving the heat pumps.Based on the heat exchanger load demand, the control system drives the groundwater abstraction pumps by modulating their flow rate. The supply water temperature is a function of the heating and cooling load demand and is regulated through the control of the heat exchanger operation.

Temperature sensors should be installed on both the abstraction and reinjection circuits to ensure that the discharge temperature remains below the maximum value permitted by local regulations. If the system detects an abnormal discharge temperature, an alarm should be generated and corrective actions should be implemented to reduce temperature.

These actions may include increasing heat exchange by further opening the heat exchanger control valves or activating auxiliary heat pump systems to support the load demand. High discharge temperatures may occur either due to excessive system load or elevated groundwater temperatures, particularly during periods of high external ambient temperatures.

Within the groundwater circuit page, the following parameters and trends should be visualized*:

Parameter	Trend required
Groundwater supply temperature	X
Groundwater reinjection temperature	X
Heat exchanger supply and return temperature	X
Heat exchanger status (duty/standby)	
Heat exchanger valves position	
Temperature setpoint	
Groundwater flow rate	X
Groundwater circuit pressure	X
Alarm status	

Table 24: Groundwater circuit parameters to be displayed in the BMS interface and associated trends – Source author's elaboration

* It should be noted that the parameters requiring trend logging may vary depending on project-specific requirements, operational strategies, and monitoring needs.

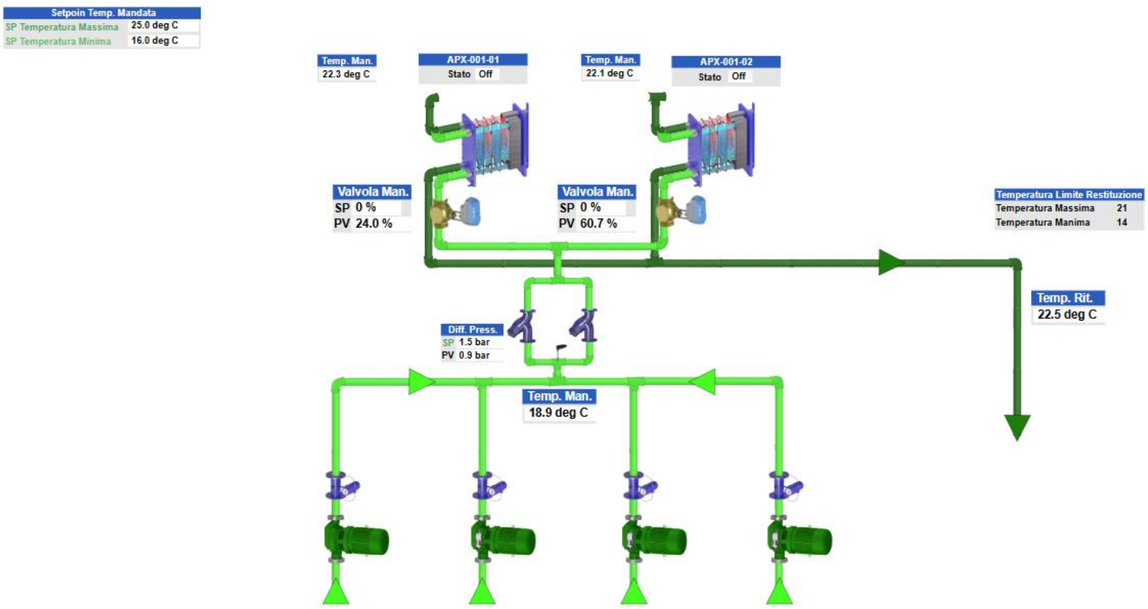


Figure 59: Example of Groundwater circuit on the BMS interface – Source: case study documentation

6.2.1.10 Meters

Regarding meters, appropriate measurement devices must be installed to monitor energy consumption, water usage and system performance. Metering data should be integrated into the BMS to enable real-time monitoring, trend analysis, supporting energy efficiency and system optimization through the calculation of key performance indicators (KPI).

Typical meters include:

- Thermal energy meters, used to measure heating and cooling energy exchange.
- Electrical meters, used to measure electrical consumption associated not only with lightning and occupants' activities, but also with equipment such as heat pumps, chillers, and other building systems.
- Water flow maters, used to monitor water consumption and flow rates in hydraulic circuits.

The selection of metering devices depends on the specific characteristics of the project and on the monitoring and control objectives defined during the design phase. At this stage, the requirements should focus on ensuring proper integration with the BMS, including data acquisition, visualization, and trend logging.

As an example, at floor level, the metering strategy may include electrical meters (e.g. main distribution boards and lighting circuits), thermal energy meters for air handling units, and water meters to monitor domestic water consumption, including cold water, hot water, recirculation loops, and dual water networks.

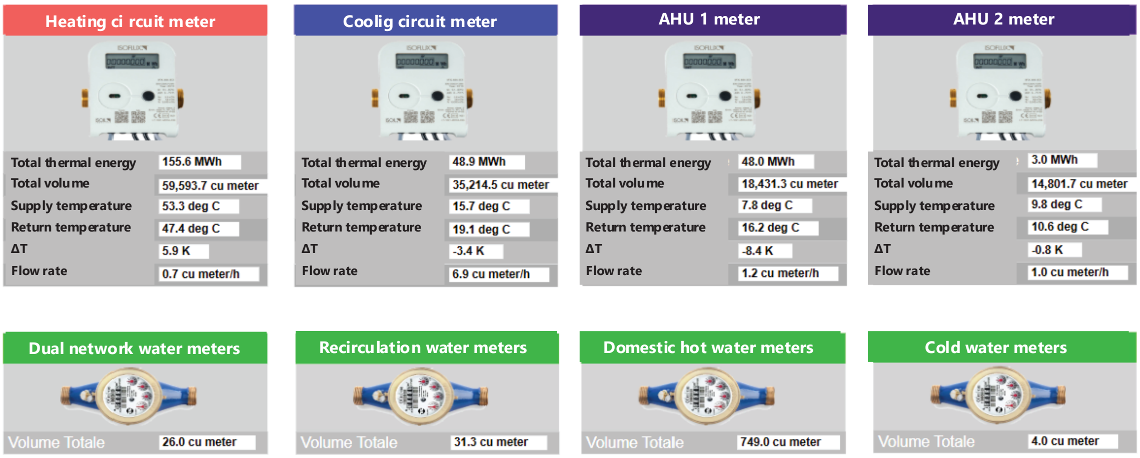


Figure 60: Example of energy and water meters on the BMS interface – Source: case study documentation

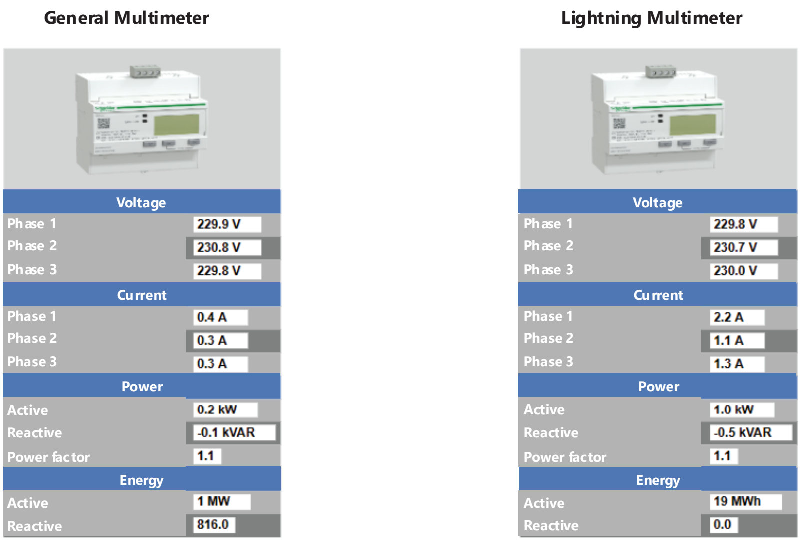


Figure 61: Example of electrical meters on the BMS interface – Source: case study documentation

6.3 TENDER

The tender documentation developed during the technical design stage represents the basis for supplier selection and typically includes project specifications, drawings and the Bill of Quantities. These documents together define the project scope and enable consistent bid comparison, supporting the tender process. In particular, for BMS, the tender documentation plays a critical role, as, in addition to quantitative aspects, it must include a clear definition of control logic, integration requirements, and operational functionalities of the system. For this reason, documents such as the point list and the technical specifications are essential in translating monitoring and control requirements, supporting both technical definition and cost estimation.

Document type	Purpose in Tender Phase
Technical specifications	They establish the qualitative and functional expectations that the client expects the BMS to meet, guiding both system design and supplier proposals.
Point list	It translates system requirements into measurable signals, supporting both technical definition and cost estimation.
Drawings and technical reports	Represent the system layout, architecture, and connections between devices. They support spatial coordination and provide the basis for quantity take-off and system understanding.
Bill of Quantities - BoQ	Provide a detailed quantification of components, materials, and works derived from drawings and specifications. It enables suppliers to prepare comparable financial offers and ensures transparency in bid evaluation.

Table 25: Tender list of documents – Source: author's elaboration

6.3.1 Evaluation of tender proposal

Just as there is no single type of tender, there are no universal criteria for evaluating proposals. Evaluation parameters are typically defined based on the client's technical requirements, including aspects such as data storage solutions, availability of technical support, and economic constraints. Furthermore, the profile of the supplier may also represent a key factor for the client, including previous experience, level of specialization in BMS solutions, technical expertise, and ability to provide long-term support services.

In general, tender evaluation can be structured into two main categories: technical criteria and economic criteria:

- **Technical criteria**: typically include compliance with technical specifications and the capability to integrate with other building systems. These criteria can also comprise other aspects such as the scalability, the availability of technical support, ease of maintenance, cybersecurity considerations, and the use of open communication protocols.

- **Economic criteria**: are essential to ensure the feasibility of the proposed solution within the project budget. The total cost of the BMS should include supply, installation, engineering and commissioning. A comprehensive evaluation may also consider lifecycle costs, including maintenance, software licenses, and future upgrade requirements. This approach allows the client to assess not only the initial investment but also the long-term economic impact of the selected BMS solution.

A balanced evaluation between these two aspects is essential to ensure the selection of a solution that is both cost-effective and aligned with the performance and operational objectives of the project.

To support the comparison of tender proposal evaluation criteria can be formalized within a scoring matrix. This approach not only facilitates a balanced evaluation process, but also enables the client, who may not have a technical background, to clearly understand the extent to which each proposal complies with their requirements.

The following table presents an example of how the evaluation matrix could be structured.

	Supplier 1	**Supplier 2**	**Supplier …**
Company profile			
Financial information	Notes ……..	……………..	……………..
Relevant experiences	……………..	……………..	……………..
……..	……………..	……………..	……………..
Technical specification on BMS			
Data storage, trending, and reporting capabilities	Notes ……..	……………..	……………..
Compatibility with other systems	……………..	……………..	……………..
User interface and ease of operation	……………..	……………..	……………..
Availability of technical support and maintenance services	……………..	……………..	……………..
Economic evaluation			
Capital cost	……………..	……………..	……………..
Lifecycle cost (maintenance, licences, upgrades)	……………..	……………..	……………..

 High compliance

 Medium compliance

 Low compliance

Table 26: Example of evaluation matrix – Source: author's elaboration

7 From BMS installation to lifecycle feedback (RIBA Stages 5–7)

7.1 Execution phase

The execution phase of the BMS should commence in alignment with the construction stages of the building systems. In this context, effective coordination among subcontractors is essential to ensure the proper delivery and integration of the automation system. For example, the control subcontractor can typically operate only at the end of the project, because much of his work cannot be performed util after the mechanical and electrical work has been substantially completed in a particular area or system.

The amount of effort required to coordinate these activities will vary depending on the scope and complexity of the project.

7.1.1 Quality control and snag list

A key requirement during the execution phase is that all aspects of the installation are monitored for compliance with project specifications and applicable codes. This is achieved through a structured set of inspections, tests, and verification procedures, typically defined within the project quality management framework. This framework typically involves the client, consultants, and, where applicable, independent testing bodies, in addition to the contractor. Within the quality framework, the contractor is responsible for implementing and documenting quality control procedures. The contractor’s responsibilities can be summarized as follow:

- Identify, investigate, and analyse the occurrence of nonconforming products or installation
- Act to avoid recurrence of a problem
- Apply quality controls to ensure corrective actions are taken and are effective
- Implement and record changes in procedures resulting from corrective actions

For example, checks may include ensuring that temperature sensors are correctly positioned and calibrated, verifying that control valves respond properly to command signals, or testing alarm generation within the BMS interface.

The outcomes of these controls enable the identification of deviations from project requirements, which are then managed through appropriate tracking tools. In particular, significant non-conformities are addressed through the Non-Conformance Report (NCR) workflow, ensuring formal review, corrective actions, and traceability within the overall quality management system.

7.1.2 Snag list

Once the execution begins, one of the most effective ways to supervise the progress of the work is through regular site visits aimed to monitoring on site activities. The outcome of these inspections should be formalized in a snag list, in which all discrepancies with respect to the project specifications are recorded, enabling both the identification of deviations and the tracking of the overall progress of the execution phase.

Unlike the NCR process, snag lists are used to manage less critical issues that nonetheless require resolution before project completion or handover. Typical snag items may include incorrect graphical representations on the user interface, missing trend logs for key parameters, incomplete implementation of control logic, or incorrect sequencing of equipment operation. As an example, issues such as simultaneous operation of duty/standby equipment or absence of required monitoring parameters may be identified during snagging activities.

They provide a clear and continuously updated overview of works, supporting coordination among subcontractors and enabling the tracking of corrective actions until closure.

The snag list can be structured as a table in which each identified issue is recorded together with the corresponding corrective action required for its resolution and the party responsible for addressing it. Additionally, assigning a level of urgency or priority to each issue can be useful in order to define an effective strategy for their timely closure.

Issue	Responsible party	Corrective action	Priority	Status
………	BMS contractor / system integrator	e.g. Modify set point parameters	High / Medium / Low	Solved / Not solved / To be Monitored

Table 27: Snag list structure example - Source: author's elaboration

7.1.3 Testing activities: FAT and SAT

To verify component functionality and system integration, Factory Acceptance Tests (FATs) and Site Acceptance Tests (SATs), should be carried out during the installation phase.

FATs are executed at the manufacturer's premises to verify that equipment and control components meet the required technical and functional specifications before delivery. These tests are typically performed by the vendor's engineers in the presence of a client or consultant representative acting as witness. The outcomes of the verification process are formally documented, and the successful completion of the tests is certified through official test reports and approval documentation. Before the installation, all BMS components should be provided with a valid FAT certification, confirming that they have successfully met the required technical and functional specifications.

SATs are performed on site, after the equipment installation, before the handover. These tests are typically performed by the vendor, in coordination with the system integrator, and in the presence of the client, consultant, and, where applicable, commissioning agent representatives, who act as witnesses to the verification process [67].

7.1.4 Pre-commissioning

The aim of the pre-commission phase is to ensure systems and equipment are installed correctly, functioning as intended, and ready for the final commissioning stage. This phase includes tests to verify the installation and functionality of equipment, focusing on comparing the results to those obtained during Factory Acceptance Tests. For BMS, and generically in automation systems, pre-commissioning may involve the testing of a distributed control system (DCS) or similar control platforms. This includes verifying the correct communication between sensors, actuators, and the control system, as well as ensuring that control loops are properly configured and operating as intended. In addition, alarm functions and safety interlocks must be tested to confirm compliance with the design requirements. The control logic is typically validated under simulated or real operational scenarios to assess system behaviour, and any discrepancies identified with respect to FAT results are carefully analysed and resolved before commissioning.

7.2 HANDOVER AND CLOSE OUT

The stage 6 represents the final phase of the construction process. This stage is characterized by the validation of system performance under real operating conditions. The objective is not to verify individual components, but to demonstrate that the building functions as an integrated operational system.

The key activities carried out in Stage 6 can be structured into the following phases:

- Completion of commissioning activities
- Closure of snagging items and resolution of outstanding defects
- Preparation and delivery of handover documentation
- Training of client personnel
- Final handover and project close-out

Stage 6 may partially overlap with stage 7 (Use) as certain performance tests can only be carried out only once the building is operating under full-load, real-use conditions. This overlap is particularly relevant for systems such as the BMS, whose behaviour and control strategies can only be validated when the building is running at full capacity an interacting with actual occupancy patterns.

7.2.1 Commissioning and Snagging Closure

The commissioning phase marking the transition from construction to operation. In automation systems commissioning involves control systems, software, and instrumentation that must be integrated with mechanical and electrical systems.

Checkout and testing activities shall be carried out by the controls subcontractor, who shall be responsible for the following [27]:

- Observe and make adjustments, calibrations, and measurements
- Perform tests of the BAS
- Tune the controllers
- Set schedules
- Make any necessary BAS corrections to ensure that the systems function as described in the sequences of operation

To ensure that each control device is operating properly and is calibrated, point-to-point verification is required. Checking a sample of points is insufficient.

After checking all input and output points, he start-up and testing

of the sequences of operation will occur. Testing of the sequences of operation should be performed methodically, from simple start/stop through all control routines.
For example, testing for a VAV AHU may include the following steps [27]:

1. Start/stop of equipment, including morning warm-up, night override, and shutdown
2. Duct static pressure control
3. Ventilation/economizer control
4. Cooling control
5. Heating control
6. Alarms
7. Reports

Commissioning tests shall demonstrate that the system meets the requirements defined in the contract documents. In the event of non-compliance, the snag list shall be updated accordingly, and the identified issues shall be rectified.
Until all items included in the snag list have been properly resolved, the list cannot be considered closed, and the commissioning process cannot be deemed complete.

7.2.2 Handover Documentation

One of the outputs of the stage 6 is also the handover documentation, which ensure continuity of building operation after project completion. The list of documents includes all the necessary information for the client and facility management team to operate and maintain the BMS effectively.
This documentation typically includes:

- As-built drawings reflecting the final installation
- Operation and maintenance (O&M) manuals
- Commissioning reports and test results
- Equipment certificates, warranty and technical data sheets

7.2.2.1 O&M Manual

To support facility manager and maintenance contractors an Operation and Maintenance (O&M) Manual should be included in the handover documentation. The O&M should be provided by the BMS contractor and must include drawings of all subsystems, equipment interactions, network architecture, sequence of operations, data sheets, users manuals, maintenance manuals, spare-parts list, system access (login credentials and URLs), training agenda, etc. [27]

7.2.3 Training

Training of the client personnel ensure that the system operators are able to effectively operate the equipment for the BMS are different for each owner and depend on the experience background of users. The BMS designer is responsible for identifying the proper training in function off the client's staff needs and adapt the specifications to their requirements.

The length of training class depends on both the experience level of the user and the BMS user's job function [27]:

- Monitoring and operation
- Maintenance and troubleshooting
- Administrative and system management

Staff can be distinguished into three main functions: day-to-day operator, advanced operator and system manager/administrator. The primary user of the BMS is the day-to-day BAS operator, so most of the training should be oriented to these individuals. He needs to know how to use the system for daily activities, including checking system tatus using graphics or point reports, adjusting set points, and acknowledging and responding to alarms.

It is also recommended that refresher courses be conducted at appropriate intervals following system turnover or BMS acceptance.

Training costs will affect bid price, so it may be limited by budget constraints and should be tailored to meet the owner's requirements.

7.2.4 Final Handover and Project Close Out

The construction phase reaches its final stage with the final handover and the project close-out. This process includes final inspections, resolution of outstanding issues, and the delivery of comprehensive documentation, such as as-built drawings, operation and maintenance manuals, and commissioning reports.

The close-out package formally closes the construction process, but it also facilitates the client's formal acceptance of the project and minimizes the risk of future disputes.

7.3 USE

The primary objective of the stage 7 is to ensure that the building continues to operate in accordance with the design intent under real conditions of use. This is achieved through continuous monitoring, post-occupancy evaluation and performance analysis. In this context, the BMS play a key role. The system both enabling the collection and analysis of operational data and ensuring that building performance is maintained and improved over time.

During the design stage, KPIs are defined and, through technical specifications, the corresponding trends can be implemented. This process becomes essential to monitor building performance and support further optimization during operation.

In this phase, BMS trend data can also support post-occupancy evaluation (POE) activities, in order to determine how the building is performing. Occupant behaviour (OB) affects building energy use and is recognized as one of the main sources of discrepancy between expected and actual building performance [68].

The outcomes and performance feedback collected during RIBA Stage 7 play a crucial role in informing the subsequent RIBA Stage, effectively creating a feedback loop that supports continuous improvement and evidence-based decision-making in future projects.

8 CYBER SECURITY

8.1 CYBER SECURITY IN BUILDING AUTOMATION

The increasing technological developments in building technology, such as smart buildings and automation systems, are leading to an increasingly higher cyber security risk, particularly in relation to the growing convergence between IT (Information Technology) and OT (Operational Technology) networks. In buildings automation IT systems include data networks, servers, clouds, enterprise information systems, while OT incorporates automation systems, such as BMS, BACS. Given IT/OT convergence an attack can propagate to the OT, i.e. the BMS (or BAC). The digital evolution is characterized by the growing interconnection of traditional systems such as programmable logic controllers (PLCs), sensors and supervisory control and data acquisition (SCADA) systems with IT platforms, including cloud infrastructure, enterprise resource planning (ERP) systems, and data analytics platforms [69]. Even if this progress leads to increased automation, real-time data-driven decision-making, and improved operational efficiency, it also introduces new risks and vulnerabilities.

Cyber-attacks on building systems can take various forms: phishing, malware, zero-day exploits, and more [70]. For example, Building Automation Systems (BACS) are vulnerable to *Siegeware*. The hacker can take control of operations and disable some functionalities, such as ventilation, heating and fire suppression systems. The control is given back only upon payment of a ransom.

Software and hardware are vulnerable to not only common malware, but also to *Zero-Day Exploit*. This kind of attack involves exploiting a vulnerability in software or hardware that is unknown to the vendor or can't be fixed instantly at the time of the attack. In this way hackers can affect computer programs, data or a network.

Not all cyber-attacks have the scope of causing damage to the network organization, but sometimes the intention is to steal data. An example of this kind of cyber-attack is *phishing*. It consists of a fraudulent attempt to obtain sensitive information, pretending to be a trustworthy entity in digital communication. This technique is common: the hacker sends an email that seems to be reliable to trick people into divulging personal intimations, like passwords and credit cards number. *The Advanced Persistent Threats* is a prolonged and targeted attack to steal data. The hacker infiltrates a network and remains undetected for an extended period during which he can steal information unnoticed.

Attacks such as these in buildings have potential drastic consequences. For example, in a hospital, if a hacker has access control of it, his actions can compromise life-threatening system. In a data centre a cyber-attack could disable normal operation, causing a shutdown.

Clearly, it is essential to comprehend the risks associated with cyber-attacks and comprehend how to prevent and combat them at every stage of the building's life, from design to use.

8.1.1 IT/OT convergence

In the field of computer science, the issue translates into the need to establish governance that can manage both Information Technology (IT) and Operational Technology (OT) systems in an integrated way.

IT and OT have different roles and scope in the organization: the IT is the set of servers, computers and devices and its aim is to manage, achieve and process data; the OT must control and monitor physical processes and equipment, with the scope of guaranteeing efficiency and security of the organization. The two technologies also operate in different settings. While the IT works in a general informatics field and can manage standard operational systems, the OT is specifically designed for industrial environments and uses specialized systems to fulfil specific operational requests.

IT and OT have historically been technically and organizationally separated. As the digital era has transformed, IT and OT are coming closer together IT is integrating with OT using independent systems and machine visualization [71].

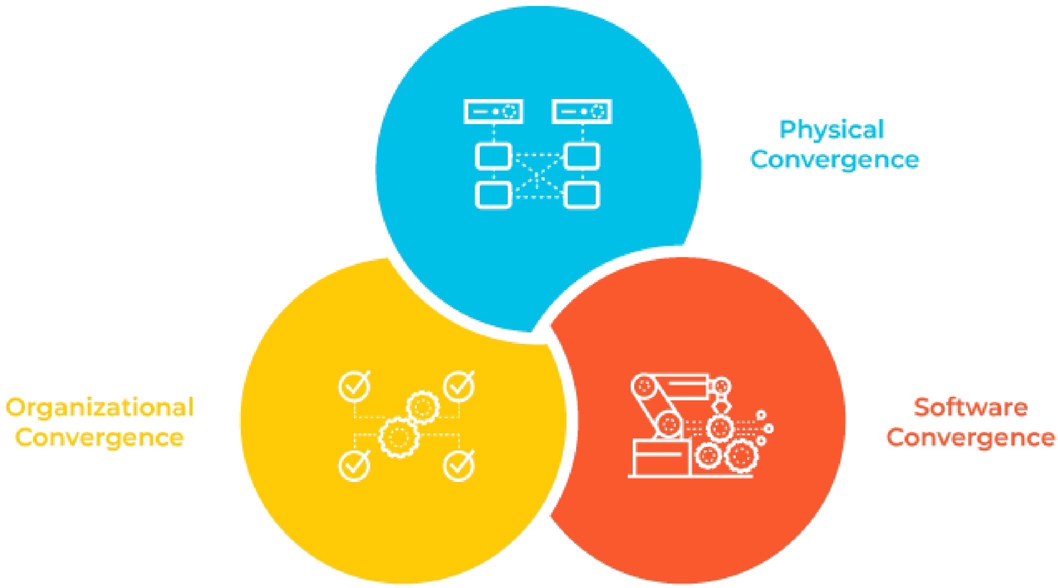


Figure 62: Types of IT/OT convergence – Source: Palo Alto Networks (2023).

The IT/OT convergence can be seen by many points of view; it's not a monolithic concept. Physical, Organizational and Software convergence can manage different aspects of the integration process, managing specific objectives and requests.

8.1.1.1 Physical convergence

With physical convergence OT devices and IT networks are directly connected. This configuration allows the direct transfer of data from the OT device to the IT system.

8.1.1.2 Software convergence

The integration between OT and IT makes communication more efficient. This convergence finds its scope in an optimization of the operational control and the decision process, because of the real time acquisition of data from devices.

8.1.1.3 Organizational convergence

The organizational convergence implies the physical interconnection between IT and OT teams. The two divisions can operate separately, but the sharing of information between them is the key to better results.

8.1.1.4 Security convergence

In the past, OT security strategy was the “air gap”, this meant that systems were not connected to a large network or the world wide web, so they could not be exposed to cyber-attacks. IT/OT convergence implies that OT systems are no longer isolated from external computer world, so new security challenges arise.

A study made by ENISA (European Union’s Cybersecurity Agency) analyzed about 4900 accidents that happened between July 2024 and June 2025. The data shows that 18.2% [72] of all threats have involved OT systems.

8.2 REGULATORY REFERENCES

From a regulatory point of view, the subject of cybersecurity applied to building management systems is addressed within a set of standards that concerns the security of automation and control systems. The BMS is not indeed treated as a computer system, but rather as an operational component of the building. The relevant regulations do not provide specific design solutions but define general principles and areas of responsibility useful for framing the topic of cybersecurity of BMS systems within the building life cycle.

The following table summarises the main regulations and standards regarding cybersecurity in building automation systems. Even if they are not specifically dedicated to the BMS, such documents are a useful tool to define the frame of reference within which to place the topic of information security of automation systems.

	Scope	Relevance for BMS
IEC 62443 (series) [73]	Cybersecurity of industrial automation and control systems (OT)	Provides a general framework of security controls that can also be applied to OT systems
ISO/IEC 27001 [74]	Information security management systems (ISMS)	ISMS requirements can be applied to BMS
ISO/IEC 27002 [75]	Information security controls	Provides a general framework of security controls supporting ISO/IEC 27001
ISO/IEC 27005 [76]	Information security risk management	Relevant for risk analysis and risk management at organisational level
ISO 16484-5:2022 [77]	Building automation and control systems – BACnet protocol	International reference standard for communication and interoperability of BMS
Directive (EU) 2022/2555 – NIS 2 [78]	Security of network and information systems	Governance-level regulation with indirect implications for BMS in critical or strategic contexts

Table 28:Cyber security regulatory references – Source: author's elaboration

8.3 CYBER SECURITY GUIDELINES

The regulatory scenario is flanked by guidelines that have the objective of supporting designers and consultants in integrating aspects related to information security within the project choices. Even if they are not prescriptive, the guidelines are an important reference to recognize the role of cybersecurity as a requirement to be considered from the definition and system specification stages.

Among the guidance the most relevant are the ASHRAE Guideline 13 and the BACnet cybersecurity guideline.

8.3.1 BACnet cyber security Guideline

The vulnerability of BMS lies in the interconnection between devices and their openness to cloud networks. Therefore, the presence of open protocols poses a security management risk. The 77% [79] of all commercial building automation uses BACnet protocol. BACnet was born in 1987 as an open and neutral protocol for networking buildings.

With the growth of digitalization also BACnet expanded communications among OT systems, introducing new risks of cyber-attacks. Traditional BACnet security relied on physical separation, virtual separation and proprietary protocol solutions. However, these solutions are not so efficient. For example, virtual separation methods can be expensive and complex, without increasing the security level of the device. Physical separation can limit some functionalities and the use of proprietary protocol prevent the interoperability between hardware.

BACnet has develop his own standard about security in automation building, but it had also defined a guideline, whose objective is to guarantee the safety, reliability, and continuity of building automation systems. The BACnet Interest Group Europe (BIG-EU) drawn up a roadmap to define how manage cyber security in Automation Buildings, focusing on tasks and requirements in the IT/OT-RMP [80].

RMP stands for Risk Management Plan, in fact, the guideline is a structured document that defines the methods for identifying, assessing, mitigating, and monitoring cyber risks. The plan identifies tasks and roles required for all life cycle phases, which are defined according to European and National legislation.

At the European level there are two main directives:

- NIS 2 Directive – *Network and Information System Directive 2* (EU 2022/2555)
- Cyber Resilience Act (CRA- EU 2022/0272)

To be juridically applicable, the NIS 2 directive must be transposed by each European member state. As an example, the BACnet guideline uses the German regulation. In particular, the HOAI - *Honorarordnung für Architekten und Ingenieure,* defines phases of the design process as follows:

Figure 63: Overview of the service phases according to HOAI – Source: ASHRAE BACnet (2024)

Identifying responsible individuals and defining their roles is essential to achieve security requirements. In the BACnet guideline the BSI and the "INF.14 Building automation" are considered for this purpose. The BSI - *Bundesamt für Sicherheit in der Informationstechnik,* is the

federal office in Germany for cybersecurity, which define guidelines and standard for cybersecurity of IT/OT systems and building automation. BSI drafted the "INF.14 Building Automation", an official document concerning Building Automation Systems in which security requirements, organizational, technical and procedural measures and roles and responsibilities are defined.
The "INF.14 Building Automation", identifies 4 roles:

1. Building services
2. Planner
3. Administrator
4. IT operations

BACnet guideline implements these roles with additional figures:

- Building users or demand organizations, e.g. tenants;
- Internal or external operator organizations who ensure operational management of automation systems, e.g. building services;
- External service providers, e.g. for maintenance or servicing;
- Facility managers who are responsible for management functions, e.g. commercial management or the optimization of life cycle costs;
- System administrators who take care of system maintenance, e.g. backup and restore, user support, etc.;
- Installers, e.g. when it's necessary installing new firmware.

Using the 4 roles defined in the "INF.14 Building Automation", BACnet specifies role requirements in each service phase of the HOAI, building up a structured map.

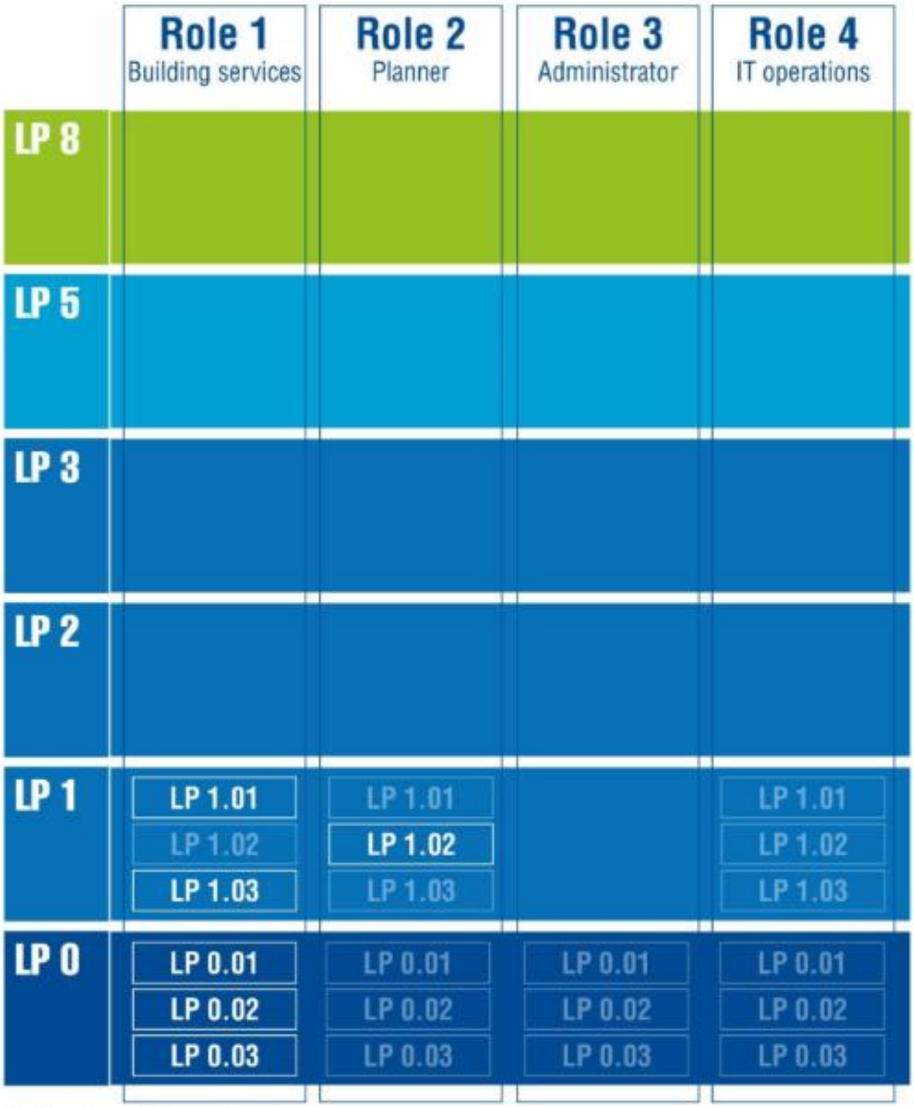


Fig. 8: Overview of the role cards

Figure 64: Overview of the role cards - Source: ASHRAE BACnet (2024)

This structure of the "role cards" provides an overview of which must be responsibilities and expertise of each stakeholder involved in a phase.

BACnet cybersecurity guideline currently doesn't cover the full range of project phase. As can be seen from the map image above, fields L2 to L8 are empty, and recommendations and processes on these stages are still in progress.

8.3.2 Cyber security in the ASHRAE Guideline 13

ASHRAE Guideline 13 - *Specifying Building Automation System* has a dedicated section about cybersecurity. The guide highlights that the best practice for helping secure building systems is the real time monitoring and alerting of anomalies, which might include unauthorized access request/denial, network variable change requests that are out of range, too many messages from one source (typical of denial-of-service attacks) that attempt to compromise the system by overloading the network.

This document defines roles that should be involved in the BMS cybersecurity and their responsibilities, such as [27]:

- Owner: the facility owner is responsible for many elements of BAS cyber/physical security. He should be part of the discussion about cybersecurity to ensure that the issue is port of the project design.
- System designer: he should design the system to ensure that it will ensure the right level of security for the project.
- Information Technology (IT) group: has a critical role as the gate-keeper between internal and external data and control system protection.
- Facility Operations/Maintenance Group: his role is to maintain and monitoring the system. This can be through the security system, the building management system (BMS) front end, or a variety of other avenues depending on the nature of the facility.
- Legal/human resources: the legal team can assess value, importance, and risk mitigation plans, particularly in the event of an incident. They also collaborate with human resources to manage access privileges during onboarding and offboarding.
- Audit team: an internal team periodically reviews the current BAS cybersecurity implementations, establishes any new or revised requirements, and makes adjustments to the plan.

ASHRAE focuses on the design phase of the automation system, defining design principles and giving advices about security levels and network architecture.

It also highlights the importance of ongoing monitoring and management of the system and for this reason good system alarming and alerting and a real-time monitoring should be specified as a requirement of the BMS. Even if the importance of cybersecurity during the life cycle of the system is acknowledged, the guideline focuses on aims to ensure that these needs are correctly anticipated and integrated into initial design choices, without providing operational guidance for the phases following the implementation of the BMS.

8.4 CYBERSECURITY IN BMS DESIGN

The BACnet guideline is an excellent tool for integrating the topic of cybersecurity into the BMS workflow. Furthermore, HOAI phases are compatible with RIBA ones. But, as already seen, the BACnet guideline has some gaps in phases after LP1, not yet filled.

The ASHRAE Guideline 13 is a valid instrument to implement the theme of cybersecurity in the life stages of the BMS, but he too has his gaps to fill.

In conclusion, there is currently no guideline that systematically integrates the subject of cybersecurity within the building design phases.
The available framework shows that the tools to address this integration are already in place, both in terms of official standards and sector-specific guidelines. International standards provide principles, requirements and conceptual models for cybersecurity in IT and OT systems, while guidelines developed by bodies such as ASHRAE, together with documentation related to BACnet, contribute to translating these principles into the specific context of Building Management System design.
The scope of this thesis is not to fill the existing gap implementing the cybersecurity theme in the current developed framework, but rather to highlight the importance of implementing it within the BMS design process in each phase.
As such, the topic of a fully structured integration of cybersecurity throughout the entire RIBA workflow remains open and represents a relevant area for further research.

CONCLUSIONS

The analysed case study represents only one example of the potential challenges associated with the design and implementation of a Building Management System (BMS), and the consequent impact on its operational performance. These findings demonstrate how the absence of clear, structured and consistent design guidelines can hinder designers in developing effective and consistent BMS strategies.

To address this gap, this thesis has proposed a workflow aimed at supporting the BMS design process through a structured approach. However, the proposed methodology should be considered as a foundational framework rather than a complete solution. The guideline is intentionally designed to be adaptable to the specific requirements of different projects and therefore cannot be considered exhaustive.

Future developments should focus on incorporating lessons learned and operational feedback collected gathered at the end of the project lifecycle (RIBA Stage 7). This would enable the establishment of a continuous improvement process, strengthening the connection between building performance during operation and decision-making during future design stages. Such an approach would contribute to the progressive refinement of the guideline and help ensure its long-term relevance and effectiveness.

From an organizational perspective, a key opportunity for Arup lies in promoting greater knowledge sharing and collaboration across offices and technical disciplines. This will support the further development, validation and consolidation of the proposed methodology, fostering a more consistent approach to BMS design across the organisation.

In this context, the guideline is intended to remain open to continuous improvement and future enhancements, allowing for iterative development based on project feedback. A particularly valuable development would be the expansion of sections related to technical specifications and control logic, enabling a more robust and detailed definition of system requirements and operational strategies.

Smart building sector continues to evolve, driven by the increasing adoption of advanced digital technologies including Artificial Intelligence. In this scenario, increasing system complexity represents a critical challenge: the more sophisticated and interconnected the systems become, the more difficult it is to identify, manage, and mitigate performance gaps, ultimately increasing the likelihood of operational issues during the building use phase. This also

introduces additional risks related to cyber security given the growing exposure of building systems to networked and cloud-based environments.
These emerging challenges reinforce the need for structured methodologies that support the Automation System design process and remain flexible and capable of evolving over time in response to emerging technologies and project feedback. Such guidelines should take into account the fact that building systems must follow the full lifecycle of the assets they serve, from design and construction through operation, maintenance, and future adaptation.

Equally important is the promotion of effective collaboration among all stakeholders involved in the process. By enabling a coordinated and transparent approach, these guidelines can contribute to the delivery of systems that are functionally reliable, operationally efficient, and easily understandable and manageable by end users.

APPENDIX A

The following page provides a tabulated summary of the proposed workflow, detailing for each RIBA Stage the core tasks, expected outcomes, and associated roles and responsibilities.

BMS workflow across RIBA Plan of Work Stages

Design Principles

BMS design should bebased on a set of principles:

- **Demand-based control:** systems should respond to actual building demand, avoiding overproduction and conflicting operations
- **Efficient supply:** the most suitable and energy-efficient systems should be selected and operated in optimal conditions to maximise performance.
- **Intuitive interface:** control and monitoring tools should be clear and user-oriented, supporting effective interaction and management by operators.

The aim of this guideline is to support BMS design in alignment with the building design process, ensuring consistency across all project stages.	0 Strategic Definition	1 Preparation and Briefing	2 Concept Design	3 Spatial Coordination	4 Technical Design	5 Manufacturing and Construction	6 Handover	7 Use
		The outcome of Sage 0 may be the decision to initiate a project; Satges from 1 to 6: project delivery; STage 7 covers the ongoing use of the building						
Core tasks during the stage	• Prepare client requirements • Review feedback from previous projects • Definition of objectives (comfort, energy, reporting); first choices on level of automation/monitoring and indicators to be tracked	• Define roles and responsibilities • Define functional requirements • Define metering/monitoring philosophy and control strategy principles	• Define preliminary BMS architecture • Define main integrations (HVAC, meters, lightning)	• Coordination between disciplines (dimension of electrical panels, positioning of sensors, etc.) • Defining graphic user interface	• Detailed point list • Define BMS technical specifications and operating logics	• Supplier submittal review • Site visits and coordination meetings • Product quality control • Factory Acceptance Tests (FATs) • Site Acceptance Tests (SATs) • Point to point testing / point checkout procedure • Snag list and non conformities	• Verification of functional and performance requirements • User and Facility Management training • Final documentation handover	• Monitoring of real operational performance • Analysis of trend data and energy consumption • Monitoring of KPIs • Lessons learned feedback
Stage outcome at the end of the phase	The best means of achieving the client requirements confirmed	Project Brief approved by the client	Preliminary point list	• Coordinated drawings • Updated point list • Confirmation of integration criteria • Consistency check of drawings/implants with BMS requirements	• BMS specification and detailed drawings • Technical package for tendering/procurement/ construction		• As built documentation • O&M manuals • BMS trend data handover • Commissioning and functional test records	• Performance reports • Updated asset and system documentation
Roles and Responsabilities	**Building owner/client** • Define the intended role of the BMS in the building and the level of control and automation • Approve the target BMS efficiency level **BMS designer** • Translate client ambitions into a BMS scope of work • Identify which building systems are included in the BMS **Facility management** • Provide operational needs and fu-ture expectations	**Building owner/client** • Confirm alignment with project objectives **BMS designer** • Formalise BMS functional requirements • Define preliminary BMS architecture **Consulting/MEP Engineer** • Assess feasibility with building sys-tems	**BMS designer** • Define control philosophy • Draft preliminary point list **Consulting/MEP Engineer** • Ensure integration with HVAC and other systems	**BMS designer** • Verify consistency with BMS design intent **Consulting/MEP Engineer** • Coordinate BMS with spatial and system layouts	**BMS designer** • Review control logic and configurations **Consulting/MEP Engineer** • Define logic control and finalize point list • Support technical coordination with other disciplines **Controls Contractor** • Develop detailed BMS technical solutions	**BMS designer** • Clarify design intent when required • Supervise BMS implementation in the building **Controls Contractor** • Install BMS hardware and software • Configure and program the BMS • Perform testing and commissioning	**Controls Contractor** • Deliver BMS documentation and training **Building owner/client** • Accept the BMS at handover **Facility management** • Take over system operation	**Building owner/client** • Define long term optimisation objectives **Facility management** • Operate and maintain the BMS • Monitor performance and energy use

How to use the guideline

The workfloww proposed wants to support the design and implementation of the BMS by aligning its development with the overall building design and construction process. The guideline follows the porhgression of porject stages, , ensuring that BMS-related activities evolve in parallel with architectural, mechanical, and electrical design decisions. It is conceived as a structured design reference rather than a rigid procedure so it should not be applied prescriptively; instead, it must be tailored to the specific requirements, scale, and complexity of each individual project.

BIBLIOGRAPHY

[1] IEA – International Energy Agency (2025) - Global Energy Review 2024, Paris.

[2] IEA – International Energy Agency (2022), Technology and Innovation Pathways for Zero-carbon-ready Buildings by 2030, IEA, Paris.

[3] IEA – International Energy Agency (2023) – Energy efficiency 2022., Paris.

[4] European Parliament and Council 2024 - Official Journal of the European Union. – Directive (EU) 2024/1275 on the energy performance of buildings (recast) (EPBD).

[5] CEN (2017) - EN 15232-1:2017 Energy performance of buildings – Impact of Building Automation, Controls and Building Management – Part 1

[6] Upadhyay, L., Singh Chani, A., Khan, B.R. and Bhatt, K. (2024) "Smart Building Technologies: A Review of Building Management Systems for Enhanced Efficiency and Sustainability".

[7] Eagle Technology (2021) - A Guide to Building Automation Systems and CMMS Integration.

[8] Johnson Controls, Make your Buildings Work (2026) "Empire state building: case study".

[9] Marston A. (2023) "Back in control: making savings with BMS optimisation." CIBSE Journal, November 2023.

[10] Wang S., Li Y., Cui Y., Yu J., Zhou C., Ametefe D. S., Dah J., Darboe T. (2025) "Integrating renewable energy into building energy systems: a systematic review of strategies, barriers, and policy interfaces." Discover Sustanability.

[11] Siemens (n.d.) "The Crystal – A sustainable cities initiative

[12] Hello energy (2024) "Gioia 22: redefining Milan's skyline."

[13] Randall T. (2020) "Unlocking the secrets of the black box: control strategies for engineers." CIBSE Journal, February 2020

[14] van Roosmale S, Audenaert A, Meysman J (2024) "Understanding the opportunities and challenges of building automation and control systems to support facility management – an extensive literature review". Facilities, Vol. 42 No. 7-8 pp. 677–693.

[15] Clauß J., Caetano L., Svinndal B. Å. (2024) "Impact of practical challenges on the implementation of data-driven services for building operation: Insights from a real-life case study" Volume 316.

[16] Jradi M., Boel N., Madsen B. E., Jacobsen J., Strandensen Hooge J., Kildelund L (2021) "BuildCOM: automated auditing and continuous commissioning of next generation building management systems" Volume 4, article 2.

[17] Van Roosmale S., Vandenbogaerde L., Verbeke S., Audenaert A., Meysman J. (2023) "Building Automation and Control Systems: A Facility Manager's secret weapon?" The 22nd EuroFM Research Symposium (November 2023).

[18] Li Y., Im P., Lee S., Bae Y., Yoon Y.; Lee, S. (2023) "Sensor Incipient Fault Impacts on Building Energy Performance: A Case Study on a Multi-Zone Commercial Building. Buildings" 2023, 13, 520.

[19] Gilbert S.W. (2013) "Benefits and Costs of Commissioning: A Case Study Analysis" - NIST.

[20] Zeng, Q.; Shagar, M.; Fatemifar, K.; Pishdad, P.; Yang, E. (2026) "Utilizing Building Automation Systems for Indoor Environmental Quality Optimization: A Review of the Current Literature, Challenges, and Opportunities. Buildings" 2026, 16, 1267.

[21] Li, G., Ren, L., Fu, Y., Yang, Z., Adetola, V., Wen, J., Zhu, Q., Wu, T., Candan, K.S. and O'Neill, Z. (2023) "A Critical Review of Cyber-Physical Security for Building Automation Systems". Annual Reviews in Control, 55, pp. 237–254.

[22] Mesa Jimenez, Jose & Stokes, Lee & Yang, Qingping & Livina, Valerie. (2021). "Early warning signals of failures in building management systems." - International Journal of Metrology and Quality Engineering.

[23] Tronchin L., Fabbri K., (2010) "A Round Robin Test for buildings energy performance in Italy - Energy and Buildings, Volume 42, Issue 10, 2010.

[24] Petersen S., Hviid C.A. (2012) "The European Energy Performance of Buildings Directive - Comparison of calculated and actual energy use in a Danish office building".

[25] European Committee for Standardization (CEN), 2022. UNI EN ISO 52120-1:2022, Energy performance of buildings – Contribution of building automation, controls and building management – Part 1: General framework and procedures.

[26] Ente Nazionale Italiano di Unificazione (UNI), 2024. UNI EN ISO 16484:2024, Building automation and control systems (BACS)

[27] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta – ASHRAE (2024) "ASHRAE Guideline 13 – Specifying Building Automation System

[28] Chartered Institution of Building Services Engineers, London – CIBSE (2009) "Guide H: Building control systems".

[29] Chartered Institution of Building Services Engineers, London – CIBSE (2001) "Commissioning Code C: Automatic controls".

[30] Chartered Institution of Building Services Engineers, London – CIBSE (2023) "Guide M: Maintenance engineering and management."

[31] Chartered Institution of Building Services Engineers, London – CIBSE (n.d.) “Digital Engineering Series (DE1-DE9)”.

[32] Chartered Institution of Building Services Engineers, London – CIBSE (n.d.) “Technical Memoranda (TM series)”

[33] BSRIA (2014) “Design framework for building services”.

[34] BSRIA (2010) “Commissioning job book: a framework for managing the commissioning process”.

[35] BSRIA (2012) “Effective BMS”.

[36] BSRIA (2015) “Building performance evaluation”.

[37] European Building Automation and Controls Association – eu.bac (2012) “Certifying energy efficiency of building automation and control systems, at first delivery and during the lifetime – Part 5: Classification system”.

[38] University of British Columbia Vancouver (2023) “Building Management system (BMS) – Design Guidelines”.

[39] University of Sidney (2020) “Building Management and Control Systems Standard - Design, Engineering, Planning & Sustainability”.

[40] Australian National University (2024) “Campus and Buildings Requirements Manual – Section 06: Building Management Systems”.

[41] University of Auckland (2019) “Property Services Design Standards and Guidelines – Section 7: Building Management System (BMS)”.

[42] Bosh Building Technology (n.d.) “The history of building automation - milestones from 1600 to tomorrow”.

[43] Tyrrell Analytics (2024) “The Evolution of Building Automation System: From Simple Rules to Smart Systems”.

[44] ASHRAE Terminology.

[45] Department of the Environment and Energy (2013). “HVAC factsheet: Building management systems”.

[46] Ente Nazionale Italiano di Unificazione (UNI), 2024. UNI EN ISO 16484-1:2024, “Building automation and control systems (BACS) – Project specification and implementation”

[47] Kensby J.; Olsson R. (2012) Department of Energy and Environment Division of Building Services Engineering - CHALMERS UNIVERSITY OF TECHNOLOGY “Building Automation Systems Design Guidelines for Systems with Complex Requirements”

[48] Franco, A.; Crisostomi, E.; Leccese, F.; Mugnani, A.; Suin, S. (2025) “Energy Savings in University Buildings: The Potential Role of Smart Monitoring and IoT Technologies. Sustainability” 2025, 17, 111.

[49] Abuimara, T.; Hobson, B.W.; Gunay, B.; O'Brien, W.; Kane, M. (2021) "Current state and future challenges in building management: Practitioner interviews and a literature review"
[50] UNFCCC (2015). Paris Agreement. United Nations Framework Convention on Climate Change.
[51] Gazzetta Ufficiale della Repubblica Italiana (2020). Decreto Legislativo 10 giugno 2020, n. 48 – Attuazione della direttiva (UE) 2018/844 sulla prestazione energetica nell'edilizia.
[52] République Française (2020). Décret n° 2020-887 du 20 juillet 2020 relatif à la performance énergétique des bâtiments.
[53] Bundesministerium / Gesetze im Internet (2020). Gebäudeenergiegesetz (GEG) – Gesetz zur Einsparung von Energie und zur Nutzung erneuerbarer Energien zur Wärme- und Kälteerzeugung in Gebäuden.
[54] Gobierno de España (2021). Real Decreto 390/2021, de 1 de junio, por el que se regula la certificación de la eficiencia energética de los edificios.
[55] Government of the Netherlands (2026), Besluit bouwwerken leefomgeving (Bbl).
[56] Government of Ireland (2024). S.I. No. 749/2024 – European Union (Energy Performance of Buildings) Regulations 2024.
[57] Government of Poland (2021). Act on Energy Performance of Buildings.
[58] Government of Portugal (2020). Decree-Law No. 101-D/2020 establishing the energy performance of buildings framework.
[59] Sahu, R. (2019) "DALI Protocol and Interface with DALI Devices from External Master Controller"
[60] RIBA Architecture London (2020) "RIBA Plan of Work 2020 Overview".
[61] ASHRAE. (2024). ANSI/ASHRAE Standard 135-2024: BACnet – A Data Communication Protocol for Building Automation and Control Networks.
[62] Angeliki Kylili, Paris A. Fokaides, Petra Amparo Lopez Jimenez (2016) "Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built environment: A review" Renewable and Sustainable Energy Reviews Volume 56, 2016.
[63] Operational Intelligence (2025) "Types of Building Management Systems: Features & Comparisons"
[64] Kylili, A; Fokaides, P.A.; Amparo Lopez Jimenez, P. (20126) "Key Performance Indicators (KPIs) approach in buildings renovation for the sustainability of the built

environment: A review." Renewable and Sustainable Energy Reviews, Volume 56, 2016.

[65] Project BMS (2020) "BMS inputs & outputs"

[66] Swan, B. (2008) The Language of BACnet: Objects, Properties and Services. Alerton Technologies

[67] EnSmart – Technical guide "Catching BMS Controller Failures Before They Reach Your Site"

[68] Gaetani dell'Aquila d'Aragona (2019) "A strategy for fit-for-purpose occupant behavior modelling in building energy and comfort performance simulation"

[69] Uutela, K. (2025) "Cybersecurity Standard-Based Model for IT/OT - Converged Environments" University of Turku

[70] Vermeer, T. (2024). Smart Buildings and Cybersecurity. Arizona State University Energy Efficiency Center.

[71] Palo Alto Networks (2023). What is IT/OT convergence?

[72] Kovacs, E. (2025). Many Attacks Aimed at EU Targeted OT, Says Cybersecurity Agency. Security Week, 2 October 2025.

[73] International Electrotechnical Commission (IEC) (various years), IEC 62443 series – Industrial communication networks – Network and system security. IEC.

[74] International Organization for Standardization and International Electrotechnical Commission (ISO/IEC) (2022), Information security, cybersecurity and privacy protection – Information security management systems – Requirements (ISO/IEC 27001:2022). ISO.

[75] International Organization for Standardization and International Electrotechnical Commission (ISO/IEC) (2022), Information security, cybersecurity and privacy protection – Information security controls (ISO/IEC 27002:2022). ISO

[76] International Organization for Standardization and International Electrotechnical Commission (ISO/IEC) (2022), Information security, cybersecurity and privacy protection – Guidance on managing information security risks (ISO/IEC 27005:2022). ISO.

[77] International Organization for Standardization (ISO) (2022), Building automation and control systems (BACS) – Part 5: Data communication protocol (ISO 16484-5:2022). ISO.

[78] European Parliament and Council of the European Union (2022), Directive (EU) 2022/2555 of 14 December 2022 on measures for a high common level of cybersecurity across the Union (NIS 2 Directive). Official Journal of the European Union, L 333, 27 December 2022.

[79] Siemens (2024) “Cybersecurity in Building Automation: The time to act is now!”
[80] ASHRAE BACnet – Interest Grupo Europe (2024) “Guideline Cyber Security in Building Automation”