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Retro-commissioning and Energy Optimization: A Study of an advanced office Building in Milan

Tesi di Laurea Magistrale in
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Abstract

This thesis focuses on the retro-commissioning of a building located in Milan, characterized by a sophisticated Building Energy Management System (BEMS), with a particular emphasis on optimizing the air conditioning system. The study aims to demonstrate the importance of retro-commissioning as a crucial tool to maximize energy efficiency and address sustainability challenges in the built environment.

The work begins with an overview of the current context of buildings in Italy and Europe, examining energy consumption, current legislation, and anticipating future prospects in the industry. This context provides the necessary framework to understand the relevance of retro-commissioning in the perspective of a more sustainable use of resources. This is followed by a review of the state of the art of retro-commissioning, presenting a critical review of previous studies, focusing on retro-commissioning cases similar to the one under examination. This in-depth analysis provides a theoretical and practical foundation, identifying best practices and challenges faced by other researchers. Next, the Milanese case study is examined in detail, analyzing the building, its construction characteristics, and the air conditioning system. The data collection system, implemented through the Desigo software, is examined along with the problems encountered during the data acquisition phase. Subsequently, a detailed simulation model of the building is developed using SketchUp and DesignBuilder, incorporating corrected data collected on-site. The process of updating the initial model with corrected data from direct measurements on the building is outlined, highlighting the importance of an accurate model to guide improvement proposals.

The thesis then proposes specific improvements to the air conditioning system, including changes to temperature setpoints and nighttime shutdown of the system. A final improved case is presented, highlighting the energy savings achieved through these changes. The conclusions synthesize a checklist for the retro-commissioning procedure, identifying key points. Constructive criticisms are put forward, such as the improper collection of data despite LEED certification and the limited coverage of energy consumption by the photovoltaic system.

Keywords: Retro-commissioning, Building Energy Management System (BEMS), HVAC commissioning

Abstract in lingua italiana

La presente tesi si focalizza sul retro-commissioning di un edificio situato a Milano, caratterizzato da un sofisticato sistema di Building Energy Management System (BEMS), con particolare enfasi sull'ottimizzazione dell'impianto di climatizzazione. Questo studio mira a dimostrare l'importanza del retro-commissioning come strumento cruciale per massimizzare l'efficienza energetica e affrontare le sfide della sostenibilità nell'ambiente costruito.

Il lavoro inizia con una panoramica sul contesto attuale degli edifici in Italia ed Europa, esaminando i consumi energetici, la legislazione vigente e anticipando le prospettive future nel settore. Questo contesto fornirà il quadro necessario per comprendere la rilevanza del retro-commissioning nell'ottica di un uso più sostenibile delle risorse. A questo segue un resoconto dello stato dell'arte del retro-commissioning, che presenta una revisione critica degli studi precedenti, focalizzandosi su casi di retro-commissioning simili a quello in esame. Questo approfondimento fornisce una base teorica e pratica, identificando le migliori pratiche e le sfide affrontate da altri ricercatori. Successivamente, si esamina dettagliatamente il caso studio milanese, analizzando l'edificio, le sue caratteristiche costruttive e l'impianto di climatizzazione. Il sistema di raccolta dati, implementato attraverso il software Desigo, è esaminato insieme ai problemi incontrati durante la fase di acquisizione dati. In seguito, viene sviluppato un modello di simulazione dettagliato dell'edificio utilizzando SketchUp e DesignBuilder, incorporando dati corretti raccolti in loco. Viene delineato il processo di aggiornamento del modello iniziale con i dati provenienti da misurazioni dirette sull'edificio, evidenziando l'importanza di un modello accurato per guidare le proposte di miglioramento.

La tesi propone quindi miglioramenti specifici all'impianto di climatizzazione, tra cui la variazione dei setpoint di temperatura e lo spegnimento notturno dell'impianto. Viene presentato un caso finale migliorato, evidenziando il risparmio energetico ottenuto attraverso tali modifiche. Le conclusioni sintetizzano una check-list per la procedura di retro-commissioning, identificando i principali punti chiave. Critiche costruttive sono avanzate, come la mancata raccolta corretta dei dati nonostante la certificazione LEED e la limitata copertura del consumo energetico da parte dell'impianto fotovoltaico.

Parole chiave: Retro-commissioning, Building Energy Management System (BEMS), HVAC commissioning

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1 | Introduction

According to the International Energy Agency, the building sectors account for nearly 30% of global final energy consumption and this share jumps to 34% when including the final energy use associated with the production of cement, steel and aluminium for the construction of buildings. Moreover, during the past decade, energy demand in buildings has seen an average annual growth of just over 1% [1]. In Italy buildings are the largest energy consuming sector, accounting 44% of the total final energy consumption [2] and direct and indirect emissions from the buildings sector in Italy account for 19.8% and 11.4% of total energy-related CO2 emissions [3]. Despite the fact that this sector is the one where consumption has grown the most (+37% from 1990 to the present), one can see a contraction in consumption over the same time period of 6%, undoubtedly due to the strong change in the mix of energy sources (coal consumption has gone to zero and oil consumption has been greatly reduced, in the face of a strong growth in gas consumption and especially renewables energies) and the penetration of more efficient technologies. Buildings are the sector with the highest share of renewables (29%) and is the second largest sector in terms of electrification share (27%).

It is so clear that there is an urgent need for action to reduce the environmental impact of the building sector. In response to the aforementioned challenge within the framework of the Green Deal initiative, the European Parliament, on March 16, 2023, endorsed a series of proposals commonly referred to as "Fit for 55%." This comprehensive set of measures is designed to achieve a substantial reduction of net greenhouse gas emissions by 55% by the year 2030, in relation to the levels recorded in 1990. Notably, the initiative encompasses a significant revision of the European Directive 2010/31 pertaining to the energy efficiency and performance of buildings. Importantly, buildings contribute 40% of final energy consumption in the EU and 36% of energy-related greenhouse gas emissions, with 75% of them classified as energy inefficient, requiring large-scale renovations. The directive therefore includes more ambitious energy efficiency standards for both new and renovated buildings [4, 5].

Within the framework of building energy efficiency research, one point of particular relevance emerges: retro-commissioning. This phase, often underestimated but of crucial importance in the life cycle of buildings, is a crucial step on the path toward optimizing energy performance. Retro-commissioning goes beyond the mere conclusion of a building project. It constitutes an articulated and meticulous process that aims to verify, adjust, and optimize the components that influence a building's energy efficiency. It is a proactive practice that is inserted after the construction or renovation phase and aims to ensure that the building not only meets expected efficiency standards but also maintains that performance over time, thus contributing significantly to reducing the environmental impact of the building sector. Today, in a context where energy consumption in the building sector holds a significant percentage globally and nationally as shown above, retro-commissioning presents itself as an unavoidable answer. Through this verification and optimization phase, concrete opportunities arise to increase the energy efficiency of buildings and, consequently, to promote long-term sustainability. In this context, the details of how retro-commissioning can be implemented effectively and integrated within the framework of European directives and global sustainability and energy challenges will be explored, providing a solid foundation for the realization of a more efficient and sustainable building future.

2 | State of the Art

The first retro-commissioning analyses of buildings do not have a precise dating, but it is possible to trace the roots of this practice back to the 1970s. During that period, attention towards energy efficiency and sustainability began to grow in response to the "First Oil Shock" of 1973. The European Council responded to this crisis with a resolution promoting energy conservation in 1974, with the goal of reducing the growth rate of energy consumption and achieving by 1985 a level 15% lower than the estimates of January 1973 (Council Resolution of December 17, 1974, OJ C 153/2 [6]). However, it was necessary to wait until the 1990s, when the issue of climate change began to emerge, to witness the first European Union policies on the energy efficiency of buildings [7]. Among these, one can mention the "Boiler Directive" [8] of 1992 and the "SAVE Directive" [9] of 1993. At the national level, in 1991 Italy promptly responded with the promulgation of Law No. 10/91 [10] which established provisions for quality control in construction and energy efficiency. At the European level, the first significant directive on the energy efficiency of buildings was Directive 2002/91/EC, adopted in 2002. This directive set the minimum requirements for the energy performance of buildings, introducing the obligation of energy certificates for buildings. Subsequently, in 2010, Directive 2010/31/EU replaced the previous one, and as previously indicated, it was further updated on March 14, 2023.

In recent years, in response to the growing interest in these issues and the succession of numerous regulations along with an increase in energy prices, retro-commissioning analysis of buildings has taken on a primary role in the sustainable construction sector. This approach, born out of the need to optimise energy efficiency, has gained increasing relevance thanks to the growing awareness of environmental impact and the necessity to reduce resource consumption. In support of this practice, numerous case studies have concretely demonstrated the benefits achievable through in-depth analysis. Some of these studies focus, for example, on the "performance gap" which is the difference between the expected or predicted energy performance during design and the actual performance achieved during the real use of the building. Research of this kind has been conducted in various parts of the world, such as Spain [11, 12], South Korea [13], the United Kingdom [14] and Switzerland [15], highlighting how this discrepancy can range from -20% to 30%. Other studies have analyzed the possible causes of these discrepancies, which can include HVAC system malfunction [16], simulation errors [17], incorrect assessment of certain parameters [18] (such as COP and EER [19]) and incorrect occupancy evaluation [20].

Among all these cases, it is possible to identify a common process, which can be briefly summarized in three points [21]:

- Preliminary design, including parametric setting and system selection;
- Building modeling and performance simulation, involving modeling and analysis of various aspects of building performance (e.g., energy analysis, environmental analysis);
- Optimization, aimed at improving the building's performance.

During the preliminary design phase, the primary goal is to develop a reasonable initial design plan. In terms of the types of buildings being targeted, performance-driven design can be categorized into two main approaches: one focused on new construction and the other on retrofitting existing buildings. Each approach has its own applicable techniques. In the case of designing for building-retrofitting it can be described as a self referential process. This means that it centers on the existing buildings as the targets for retrofit. Data for modelling is determined and quantifiable, and the building's performance before retrofit serves as a standard for evaluating retrofit technologies (such as reducing heating and cooling demands, using energy-efficient equipment, and implementing energy-efficient technologies). The modelling data may encompass the definition of the building's shape and structure, including details about the materials used in each layer, their thermal properties, and thickness. It also involves information about all installations, including technical specifications of systems like HVAC - such as power capacity, performance characteristics, flow rates, and energy consumption. Additionally, it considers occupancy patterns and schedules to establish the building's operational profile.

In the second stage, the emphasis shifts towards constructing models and simulating performance. This critical step involves carefully transferring data from the initial design phase to specialized simulation software (such as Trnsys, IES VE, DesignBuilder) that enables a thorough analysis of various aspects of building performance, including energy usage patterns, environmental impacts, and overall operational efficiency. The accuracy of these simulation programs relies on the user's ability to input parameters that yield an accurate representation of the actual energy usage of the building, therefore it's essential to adjust the model's parameters to match the characteristics of the physical system, a process known as model calibration. Valuable insights into how the building operates under different circumstances and conditions are gained through precise modeling and simulation. This stage acts as a crucial link between the initial design concept and real-world performance, laying the groundwork for informed decision-making and targeted optimization efforts in the subsequent phases of the retro-commissioning process.

The third and final stage centers on optimization, representing a pivotal phase within the retro-commissioning process, directed towards augmenting the overall operational efficacy of the building. This phase entails a thorough assessment of the data amassed during the preliminary design and building modeling phases. The primary objective is to discern avenues for efficiency enhancements and to execute precise augmentations to vital systems. By means of meticulous adjustments and recalibrations, the objective is to harmonize the operational parameters of the building with its initial design specifications, thereby optimizing energy efficiency and enhancing occupant comfort.

The idea of the Thesis work is therefore to conduct a retro-commissioning analysis aimed at optimizing the efficiency of air conditioning systems in the context of a real building (CAP Group building, Via Rimini 16, Milan). By utilizing DESIGO software for the collection and analysis of operational data, areas for improvement are identified, and solutions are proposed to optimize performance. The conclusions drawn from this real case may provide insights applicable to other scenarios as well, emphasizing the importance of continuous supervision and adjustment of systems to ensure comfort and energy savings.

3 | Case Description

3.1. Building

As announced, the building taken into analysis as a real-life example is the new headquarters of CAP Group [22], an Italian utility that manages aqueduct, sewerage and purification services in the territory of the Metropolitan City of Milan. This futuristic building located at 34/36 Via Rimini, 20142 Milan, which can be described as a large ark inspired by the Dutch painter Mondrian, takes as its source of inspiration precisely water and the interconnection of its networks that give shape to a building without fences. It does not fail to consider more recent principles of energy, environmental and economic sustainability, having achieved Gold certification by the LEED (Leadership in Energy and Environmental Design) program and Class A3 instead in CENED (Certificazione Energetica Edifici della Regione Lombardia) certification.

Figure 3.1: Exterior view of the building [23]

The facility features 14'000 square meters of floor space, of which about 8'000 is air-conditioned, distributed over seven floors (one underground) and divided into different environments such as open space, offices, a cafeteria, a library, a non-exclusively corporate nursery, an auditorium and finally also an area dedicated to night events left to be managed by an outside company. This is complemented by an outdoor pool, which, surrounding the building, gives it the effect of floating on water and is intended to reference the group's network of services. The building, construction work on which began in October 2018, was scheduled to be completed by 2022. Although occupancy of the rooms began in late 2020 with the opening of the first offices, at the present time there remains a need to finish the basement, which is expected to include, in addition to the parking lots (some of which are also equipped with electric vehicle charging stations) that are already operational, various storage facilities and a gymnasium with attached locker rooms intended for the use of company employees.

3.2. Constructions

Once the building has been described, it is necessary to explore in detail the different components that constitute it by analysing the design choices that guide their construction that follow 'ex Legge 10' (Directive 2002/91/EC [24]), which is a crucial pillar in the Italian building legislative landscape. This body of regulations outlines the standards and procedures that must be followed during the design and execution of building works. In addition to ensuring structural safety, it promotes energy efficiency, sustainability and usability of spaces, thus contributing to safe and comfortable living environments. Moreover, all constructions are obviously performed in compliance with the transmittance limits imposed by Decree 2456/2017 of the Lombardy Region [25].

3.2.1. External Surfaces

As for the external surfaces, there are two types, one characterizing the lateral surfaces and another characterizing the roof.

External Wall

	Thickness [mm]	**Conductivity [$\frac{W}{m*K}$]**	**Resistance [$\frac{m^2*K}{W}$]**
Concrete Mortar	15	1,400	0,011
Concrete	350	1,650	0,212
Rock Wool	200	0,035	5,714
Concrete Slab	30	0,173	0,173
Artificial Stone	20	1,300	0,015

Table 3.1: Stratigraphy of the External Wall

Global Transmittance (U-value) : 0,159 $[\frac{W}{m^2*K}]$

Roof

	Thickness [mm]	Conductivity $[\frac{W}{m*K}]$	Resistance $[\frac{m^2*K}{W}]$
Lime and Sand	15	0,800	0,019
Concrete	300	1,650	0,182
Bitumen Membrane	5	0,170	0,029
Expanded Polystyrene	200	0,031	6,452
Concrete Screed	50	1,080	0,046

Table 3.2: Stratigraphy of the Roof

Global Transmittance (U-value) : 0,144 $[\frac{W}{m^2*K}]$

3.2.2. Horizontal Internal Partitions

As for the internal surfaces of horizontal separation, they come in two types. The first separates the internal levels from the ground floor to the fifth floor, while the second differs in that it separates the ground floor from the underground surfaces.

Interstory Floor

	Thickness [mm]	Conductivity $[\frac{W}{m*K}]$	Resistance $[\frac{m^2*K}{W}]$
Wood	15	0,180	0,083
Concrete Mortar	70	1,400	0,050
Cork	50	0,039	1,282
Concrete	250	1,650	0,152
Ventilated Cavity	800	1,250	0,640
Fiberboard	150	0,100	1,500

Table 3.3: Stratigraphy of the Interstory Floor

Global Transmittance (U-value) : 0,255 $[\frac{W}{m^2*K}]$

Interstory Floor over Box Area

	Thickness [mm]	Conductivity [$\frac{W}{m*K}$]	Resistance [$\frac{m^2*K}{W}$]
Wood	20	0,180	0,111
Concrete Mortar	70	1,400	0,050
Concrete Mortar	100	1,400	0,071
Expanded Polystyrene	150	0,036	4,167
Concrete	250	1,650	0,152
Lime and Sand	29	0,800	0,025

Table 3.4: Stratigraphy of the Interstory Floor over Box Area

Global Transmittance (U-value) : 0,209 [$\frac{W}{m^2*K}$]

3.2.3. Vertical Internal Partitions

Vertical internal partitions can be divided into four distinct categories. There are "solid" internal partitions, which do not have air layers inside and can separate air-conditioned from non-air-conditioned environments. Following are the "empty" partitions, which include air layers inside, designed to separate unoccupied spaces. Finally, glass walls are included, used to enclose specific offices.

Solid Inner Partition

	Thickness [mm]	Conductivity [$\frac{W}{m*K}$]	Resistance [$\frac{m^2*K}{W}$]
Concrete and Sand	20	1,000	0,020
Concrete	400	1,650	0,242
Concrete and Sand	20	1,000	0,020

Table 3.5: Stratigraphy of the Solid Inner Partition

Global Transmittance (U-value) : 2,210 [$\frac{W}{m^2*K}$]

Solid Inner Partition vs non-heated area

	Thickness [mm]	Conductivity [$\frac{W}{m*K}$]	Resistance [$\frac{m^2*K}{W}$]
Concrete and Sand	20	1,000	0,020
Concrete	300	1,650	0,182
Rock Wool	200	0,035	5,714
Concrete and Sand	20	1,000	0,020

Table 3.6: Stratigraphy of the Solid Inner Partition vs non-heated area

Global Transmittance (U-value) : 0,164 [$\frac{W}{m^2*K}$]

Empty Inner Partition

	Thickness [mm]	Conductivity [$\frac{W}{m*K}$]	Resistance [$\frac{m^2*K}{W}$]
Plasterboard	25	0,210	0,119
Air	100	0,560	0,179
Plasterboard	25	0,210	0,119

Table 3.7: Stratigraphy of the Empty Inner Partition

Global Transmittance (U-value) : 1,704 [$\frac{W}{m^2*K}$]

Glass Partition

	Thickness [mm]	Conductivity [$\frac{W}{m*K}$]	Resistance [$\frac{m^2*K}{W}$]
Glass	120	0,700	0,171

Table 3.8: Stratigraphy of the Glass Partition

Global Transmittance (U-value) : 2,318 [$\frac{W}{m^2*K}$]

3.2.4. Windows

Finally, there are non-opening windows characterized as follows:

	Transmittance [$\frac{W}{m^2*K}$]	Solar Transmission [-]	Emissivity [-]
Triple Glazed	0,600	0,187	0,020

Table 3.9: Window Glass

	Material	Thickness [mm]	Transmittance [$\frac{W}{m^2*K}$]
Frame	Metal	36	1,640

Table 3.10: Window Frame

3.3. HVAC system

The subject building is equipped with an air conditioning system that is distinguished by its complexity, designed with a vision in optimising thermal comfort and energy efficiency. Specifically, the mechanical systems are based on a high-efficiency generation subsystem consisting of a geothermal-type water-to-water heat pump, a ventilation and air handling subsystem equipped with enthalpy heat recovery units, and an all-air VAV (Variable Air Volume) distribution/emission subsystem, with timely control of air flow rate and temperature per individual room. The all-air system is capable of providing both room air changes and winter/summer heat load management. In fact, a dual-channel type air supply has been provided, with two air flows characterised by different temperature and relative humidity, in order to ensure maximum flexibility of management of each room by only varying the flow rates of each of the two flows. Air handling units (AHUs), dedicated to the different zones of the building and connected to the geothermal heat pump, will then treat the air taken from the outdoor environment and produce the supply flows at the required thermohygrometric conditions. Instead, the entirety of the air extracted from the rooms is conveyed to high-efficiency enthalpy heat recovery units, which will be able to recover the entirety of the sensible and latent heat energy contained in the exhaust air. This energy is used, again through AHUs, to treat the air, supplementing the input provided by the geothermal heat pump [26].

To encapsulate what is described above, a simplified schematic of the complete air conditioning system is shown, where the connections between the various components can best be seen:

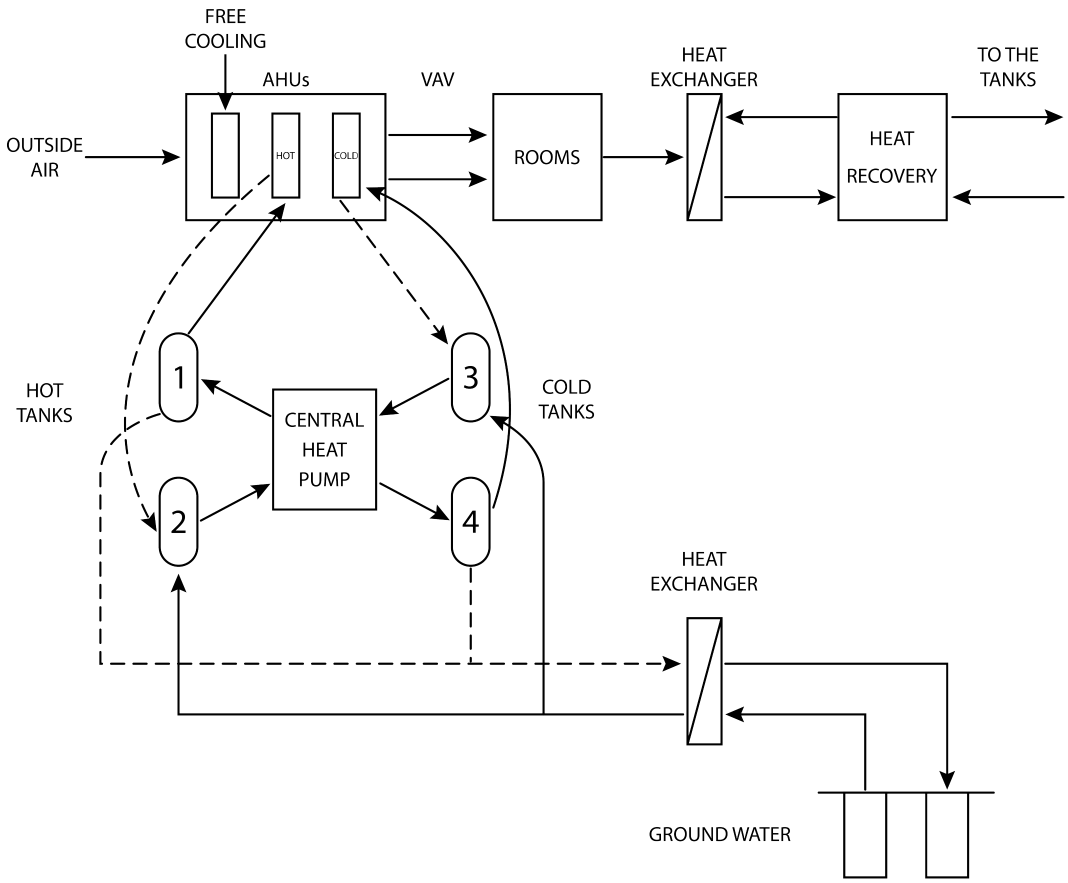

Figure 3.2: HVAC Global Schematic

3.3.1. Thermal Zoning

Before introducing the various components it is necessary to explain how the technological configuration of the system is based on the identification of thermal zones within which the regulation of room temperature and the amount of fresh air can be managed independently thanks to the presence of dedicated VAV controllers. Such thermal zones are constituted in confined rooms by the individual room, while in open-space in areas characterised by as homogeneous heat loads as possible. From a functional point of view, it was then chosen to group the different thermal zones into macrozones characterised as much as possible by similar uses. In fact, each macrozone will be served by a dedicated AHU and related distribution, emission and control equipment, as indicated below:

- Macrozones 1, 2 and 3: composed of the areas predominantly intended for offices and meeting rooms (floors 1 to 5). In particular, zones are envisaged resulting from the grouping of areas with the same exposure located on the various floors. In detail, macrozone 1 groups together the thermal zones located to the north on the various floors, where areas intended for open-space offices are located to a predominant degree; macrozone 2 groups together the zones to the south, where mostly closed offices are located; and macrozone 3 groups together the central thermal zones on the various floors, where mostly meeting rooms are located;

- Macrozone 4: consisting of the Auditorium spaces on the ground floor;
- Macrozone 5: consisting of the bar/restaurant area and other air-conditioned areas on the ground floor.

For each macrozone, it will then be possible to vary the thermohygrometric characteristics of the supply air independently of the other macrozones.

	Sensible & Latent Thermal Powers [kW]	Air Flow Rates [$\frac{m^3}{h}$]
Macrozone 1	253,1	25'167
Macrozone 2	165,0	17'111
Macrozone 3	88,0	6'535
Macrozone 4	55,0	5'356
Macrozone 5	115,5	10'482

Table 3.11: Macrozones Dimensioning Data

3.3.2. Heating and Cooling Unit

The heart of the system is the heating and cooling unit (model HiRef 30XSW-374DL) located in the basement, consisting of a water-to-water type heat pump with a heating capacity of 463 kW in heating and 382 kW in cooling. This unit is used to maintain the thermal imbalance between 2 storage volumes (1 and 4 reported in fig. 3.3), maintained at a temperature of 35°C and 7°C respectively, from which hot and chilled water is drawn for the utilities. Both hot and cold storage volumes consist of insulated inertial tanks with a capacity of 3'000 liters each characterized by total heat loss of less than 5 $\frac{W}{K}$. There are also 2 additional storage volumes (2 and 3 reported in fig. 3.3) having the same characteristics as the previous ones to which the returns from the utilities are connected. In addition to these, there is a plate heat exchanger, also located in the basement, having a thermal output of 550 kW to which groundwater taken from an extraction well is piped. Any excess thermal energy present in the hot storage return from the utilities or shortfall in the cold storage return from the utilities is transferred/withdrawn through this exchanger to the groundwater. Thermal/cooling energy from the enthalpy heat recovery units also flows into the storage volumes. Such energy thus reduces the building's air conditioning demand.

Thermal Power [kW]	463,4
Cooling Power [kW]	382,5
Nominal COP [-]	5,44
Nominal EER [-]	4,49
Electric Consumption [kW]	85,2
Inrush Current [A]	232
Weight [kg]	1'333
Sound Power [dB(A)]	79

Table 3.12: Heating and Cooling Unit Data

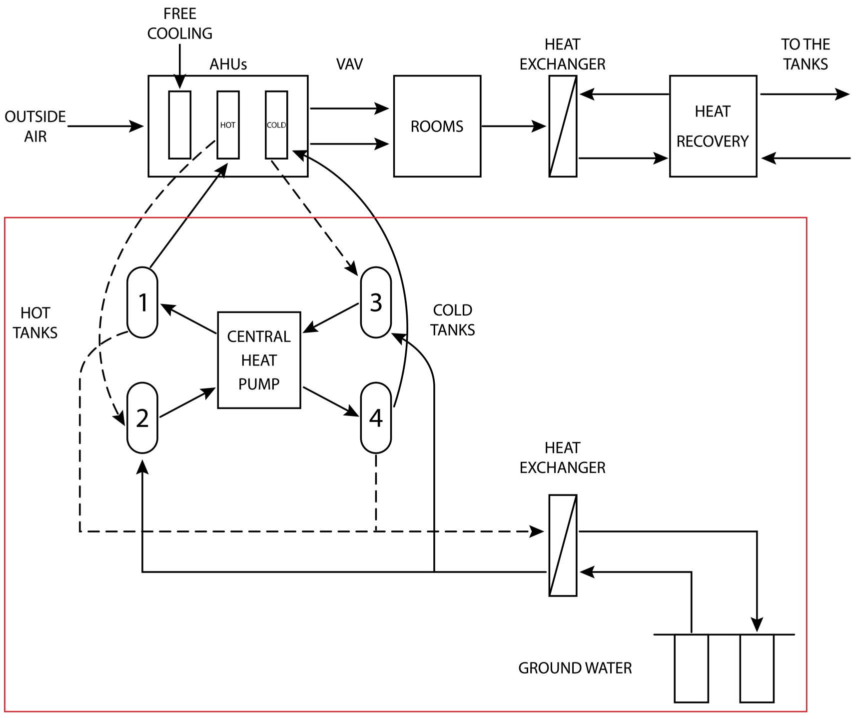

Figure 3.3: Heating and Cooling Unit Schematic

3.3.3. Central Air Treatment Unit

The central air handling unit consists of 5 AHUs (one for each macrozone) located in a special technical room on the 5th floor of the building, aimed at heating/cooling, humidification/dehumidification and filtration of the supply air in the rooms. Therefore the nominal capacity of each AHU was sized, considering the base air flow rates required by each macrozone. These units take outside air directly through the openings on the walls of that room that border to the outside, without ductwork. The total area of the openings was calculated to be approximately 50 m^2, thus allowing transit velocities through them of less than 1 $\frac{m}{s}$. All AHUs are equipped with the air supply section only, since the air being exhausted from the rooms is conveyed separately to the heat recovery units.

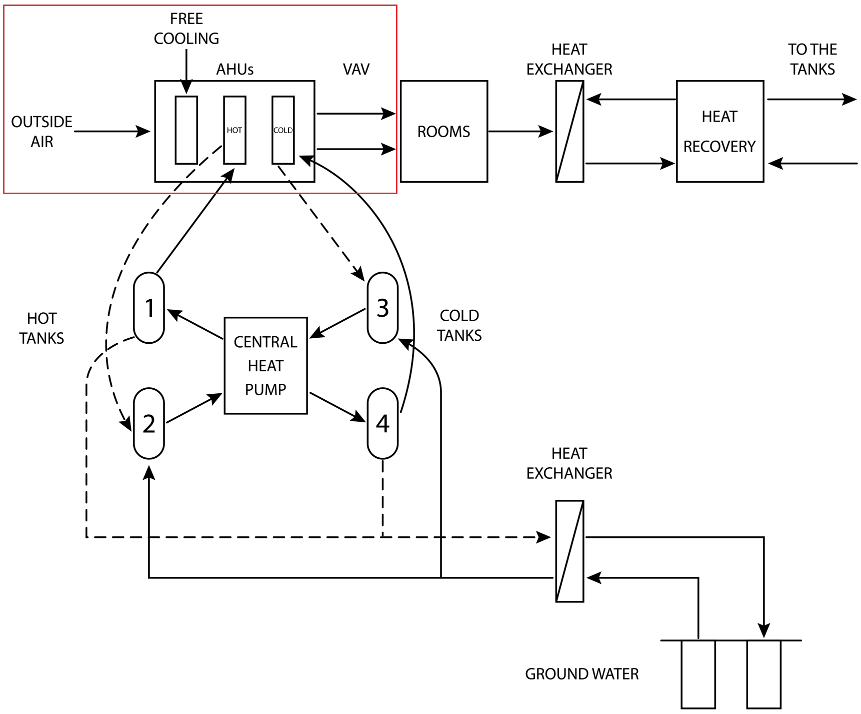

Figure 3.4: Central Air Treatment Unit Schematic

In accordance with the logic of the aeraulic system, AHUs are of the double supply duct type and are constructed as shown in the following diagram:

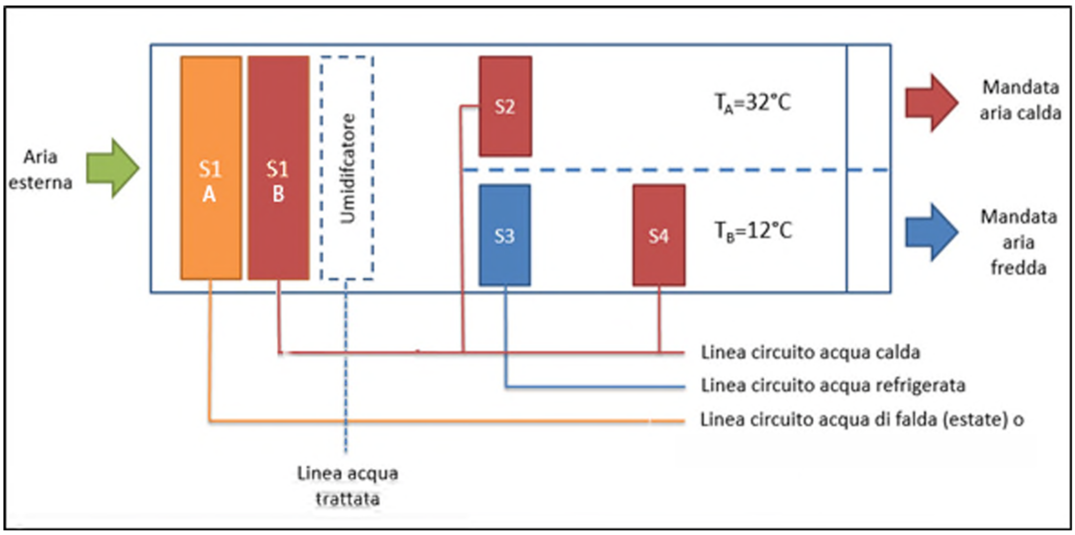

Figure 3.5: AHUs Schematic

- Exchanger S1A: fed by the hydronic line (glycol water) with indirect exchange with groundwater in both the cooling and heating periods, the exchanger provides the heat output needed to pre-heat (winter) or pre-cool (summer) the incoming air. Supply through the direct exchange circuit with groundwater allows free-cooling if environmental conditions permit. The electric pump supplying in circuit remains on with outdoor air temperatures below 10 °C and above 20 °C, with temperatures between 10 and 20 °C the said electric pump remains off;
- Exchanger S1B: fed by the hot hydronic line, it operates air preheating so as to enable air humidification with saturation temperature control;
- Humidifier: in the winter season it allows the absolute humidity of the supply air to be increased by high-pressure water vaporization;
- Exchanger S2: fed by the hot hydronic line, it operates the final heating of hot air;
- Exchanger S3: supplied by the chilled hydronic line, operates in the cooling period, if the air temperature downstream of exchanger S1 is higher than 10 °C, performing post-cooling of the air to be sent to the chilled ducts, completing dehumidification in the summer period;
- Exchanger S4: fed by the hot hydronic line, it operates post-heating of cold duct air in order not to send air with relative humidity close to saturation.

	Rated Flow Rate [$\frac{m^3}{h}$]	**Electric Consumption [kW]**	**Weight [kg]**
AHU 1	26'000	16,5	3'300
AHU 2	18'000	15,5	3'000
AHU 3	8'000	7,6	1'600
AHU 4	5'700	6,0	1'400
AHU 5	10'500	10,5	1'800

Table 3.13: AHUs Data

	S1a [kW]	**S1b [kW]**	**S2 [kW]**	**S3 [kW]**	**S4 [kW]**
AHU 1	179,0	63,2	84,1	174,0	12,5
AHU 2	116,0	44,0	58,2	120,0	8,6
AHU 3	56,0	19,5	25,9	53,5	4,3
AHU 4	40,0	13,8	18,4	38,5	3,0
AHU 5	73,6	25,4	34,0	69,5	6,0

Table 3.14: Heat Exchangers Data

3.3.4. Distribution and Emission System

The heat distribution/emission system comprises a VAV-type all-air distribution and emission system implemented in all air-conditioned zones of the building, with the exception of the kindergarten. This system enables temperature and humidity control in each thermal zone, while ensuring proper air renewal. As for the kindergarten, on the other hand, a radiant-type water emission system combined with a controlled mechanical ventilation system was designed. In fact, given the peculiarity of this intended use, it is believed that a radiant floor system provides greater comfort to the occupants than an all-air system.

Air distribution takes place for the entirety of the spaces by means of a multichannel system, whereby each thermal zone will be served by a pair of dedicated supply ducts and a return duct. The two supply ducts respectively convey air at two different levels of temperature and humidity, established in such a way that the different heat loads in individual zones can be met with maximum flexibility. In detail, for sizing purposes, the airflow temperature within each supply duct was assumed to be 12°C for the cold duct and 32°C for the hot duct. Each duct (hot and cold) was sized to provide a maximum total flow rate of 70% of the base flow rate of each thermal zone. Two opposing operating dampers equipped with a single electric servomotor, when conjugated, or dual electric servomotors, when single, are provided on the two supply ducts of each room. The two air flows are conveyed to a mixing plenum connected to the supply air VAV controller. From the latter, by means of flexible ducts, the air is channeled to diffusers placed in the ceiling. The mixing ratio of the two ducts is dictated by room temperature control requirements and is carried out in such a way as not to exceed the air supply temperature limits of a minimum value of 16°C and a maximum value of 26°C. These temperature values are those that allow the heat loads of each zone to be handled under the base conditions, based on which the required flow rates for each room were then calculated. The supply VAV adjusts the mixed air flow rate so that the required fresh air flow rate is always guaranteed based on the CO2 concentration. The adjustment is made on the basis of the data collected by the temperature and CO2 quantity sensors installed in each thermal zone. The minimum flow rate expected in each room, even in the absence of people, will still be the minimum flow rate required by ASHRAE 62.1 2010. On the other hand, the VAV controller placed on the return duct of each zone will act in order to maintain a flow rate of the exhaust air typically corresponding to that of the air fed into the room. In some cases, however, an expelled air flow rate will be provided to ensure a pressure difference with respect to adjacent rooms. In particular, the bar/restaurant area will be kept in a constant vacuum to limit odor propagation.

For the vertical distribution of air from the 5th floor, where the AHUs are located, to the different floors, the placement of insulating galvanized sheet metal ducts, with a mainly rectangular cross-section, has been planned within the technical shafts. The horizontal supply distribution, on the other hand, takes place inside the false ceilings, by means of a main backbone and secondary branches, made with ducts consisting of sandwich panels made of embossed aluminum and expanded polysocyanate, while the return air is always in the false ceiling but has been made with uninsulated galvanized sheet metal ducts.

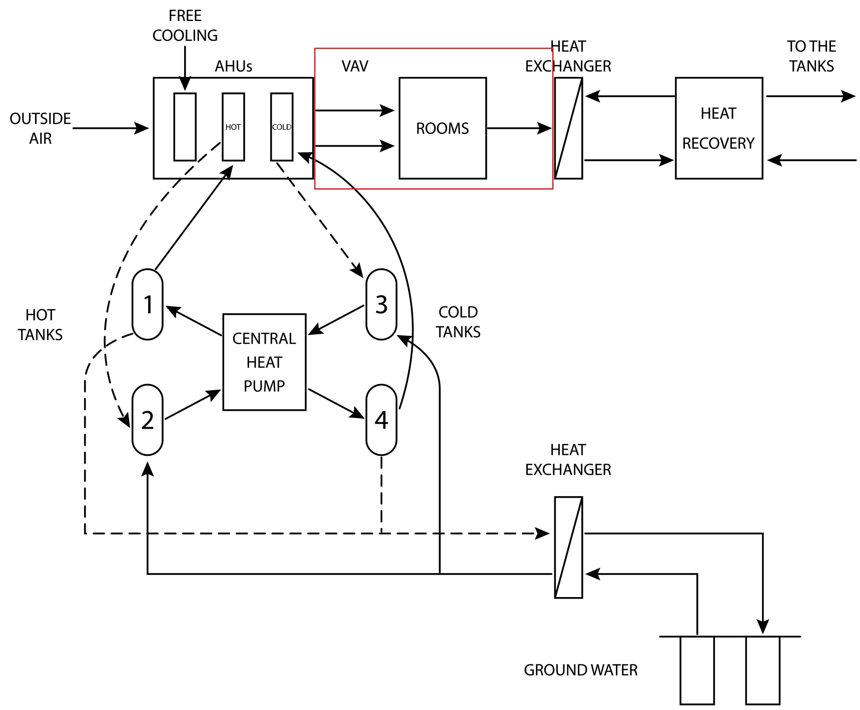

Figure 3.6: Distribution and Emission System Schematic

3.3.5. Heat Recovery System

Two heat recovery units located in the technical rooms of the 5th floor have been provided, which, through a vapor compression circuit, are able to recover both thermal and cooling energy from the air expelled from the rooms. All the expulsion ducts of the building's aeraulic system are in fact conveyed into two plenums, at the entrance of which motorized adjustable dampers are installed for each duct. The two plenums are connected to each other by a duct intercepted by a normally closed manual damper, said damper will be opened in case of emergency (failure of an extractor). The motorized dampers are of the ON-OFF type and each is slaved to its own AHU, with AHU ON the dampers slaved to it are open, with AHU OFF they are closed. Air entering the plenum is conveyed to two air-to-water exchangers equipped with air extractors, which, in turn, are connected to the two reversible water-to-water heat pumps. Each exchanger is thus able to transfer part of the thermal energy contained in the expelled air flow to the hydronic circuit, through the use of the two heat pumps. The heat exchanger coils of the air/water exchangers will cool/heat the airflow in the heating and cooling period, respectively.

The recuperators are always in operation transferring, in the winter period, the recovered fraction of heat to the system's hot hydronic network (Tank 1 and 2) while in the summer air conditioning period the maximum recoverable power is transferred to the system's cold hydronic network (Tank 3 and 4). The heat pumps, located in the basement, work to supplement the overall heat demand in both summer and winter. In this way groundwater can be used to a greater extent for free-heating and free-cooling. This solution achieves high thermal energy recovery efficiencies associated with air changes and avoids the need for recirculation of a fraction of the air extracted from rooms, thus ensuring high indoor air quality under all conditions. At the same time, the solution ensures that the footprint of the AHUs on the fifth floor is contained. The air exhausted by the two units is conveyed to the technical room where the two heat pumps are installed. This room, with the function of a plenum, is communicated with the outside through the openings located on the walls bordering the outside.

Maximum Heat Output in Winter Recovery [kW]	218
Maximum Cooling Capacity in Summer Recovery [kW]	164
Electric Consumption [kW]	57
Inrush Current [A]	150
Weight [kg]	825
Sound Power [dB(A)]	77

Table 3.15: Recovery Unit Heat Pumps Data

Maximum Air Flow Rate [$\frac{m^3}{h}$]	35’000
Useful Head on the Suction Side [Pa]	500
ΔT Hydronic Side (Summer) [°C]	5
ΔT Hydronic Side (Winter) [°C]	4
ΔT Aeraulic Side (Summer) [°C]	19
ΔT Aeraulic Side (Winter) [°C]	14
Maximum air crossing velocity [$\frac{m}{s}$]	2
Electric Consumption [kW]	15,5
Sound Power [dB(A)]	80

Table 3.16: Recovery Unit Heat Exchangers Data

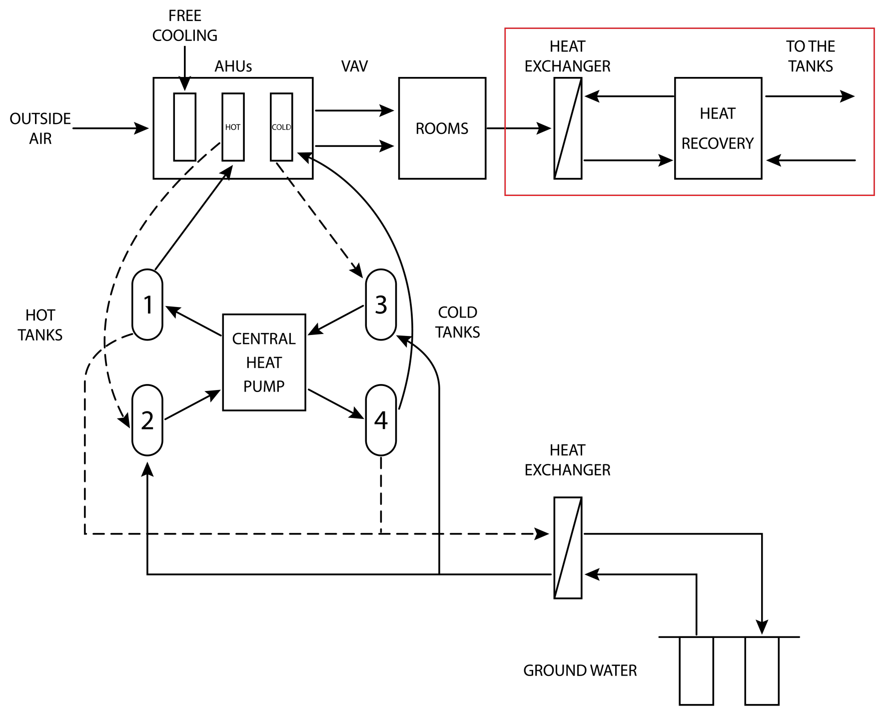

Figure 3.7: Heat Recovery Schematic

3.4. Bills

The electrical consumption in Italy is divided into three time slots, defined as follows:

- F1 - from Monday to Friday, from 8:00 AM to 7:00 PM;
- F2 - from Monday to Friday, from 7:00 AM to 8:00 AM and from 7:00 PM to 11:00 PM; Saturday, from 7:00 AM to 11:00 PM;
- F3 - from Monday to Saturday, from 12:00 AM to 7:00 AM and from 11:00 PM to 12:00 AM; all hours on Sunday and holidays.

The data collected over the past year by the electricity provider indicates the following distribution of energy consumption:

F1 [kWh]	**F2 [kWh]**	**F3 [kWh]**
554'458	409'344	727'765

Table 3.17: Electrical Consumption by Time Slot

The billing data, however, does not account for the output of the photovoltaic system, whose production is distributed across the various months as follows:

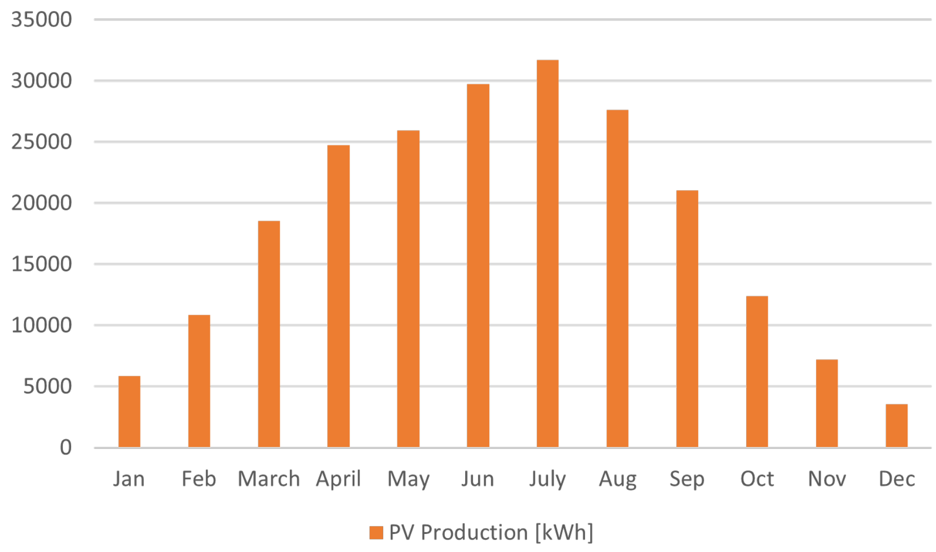

Figure 3.8: PV production

Given that such production primarily occurs during the central hours of the day, it can be asserted that from Monday to Friday, it falls within time slot F1, on Saturday within time slot F2, and on Sunday within time slot F3. Taking these considerations into account, the updated values are reported as follows:

F1 [kWh]	F2 [kWh]	F3 [kWh]
711'145	440'681	759'102

Table 3.18: Electrical Consumption by Time Slot (PV included)

Normalizing then consumption based on the annual hours for each time slot (2'860 hours for time slot F1, 2'132 for F2, and 3'744 for F3), the following power values are obtained:

F1 [kW]	F2 [kW]	F3 [kW]
248,65	206,70	201,46

Table 3.19: Power Consumption by Time Slot

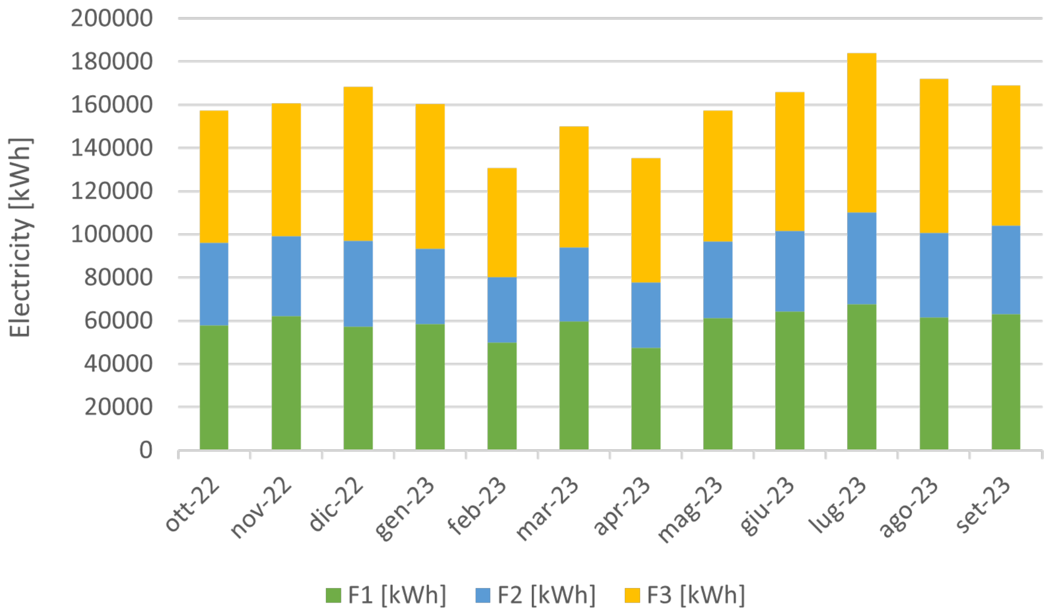

Figure 3.9: Electricity Monthly Bills Distribution

As evident, the power demand is higher during the F1 time slot, primarily due to the concentration of building occupancy hours within this period. Conversely, power requirements in the F2 and F3 slots are nearly identical, as both are characterized by periods when the building is predominantly unoccupied. The marginally higher power demand in the F2 slot is attributed to its inclusion of Saturday mornings, a regular working day. It is pertinent to highlight, however, that a significant portion of energy consumption corresponds to hours when the office is closed, mainly falling within time slots F2 and F3. This phenomenon can be attributed to various factors. For instance, the heating system is designed to operate continuously, 24/7, even during periods of office inactivity. Additionally, certain components, such as the data center, require continuous operation, contributing to nocturnal consumption.

3.5. Data Collection

In the context of this analysis, it is critical to note that the building under consideration is part of a new generation of state-of-the-art facilities equipped with a sophisticated Building Energy Management System (BEMS).

A BEMS is a computerized system that allows for the centralized management and control of air conditioning, lighting, electricity and other energy aspects within a building. Its primary objective is to optimize energy use, reducing consumption and associated costs. Key components of a BEMS include:

- **Sensors:** measure environmental parameters such as temperature, humidity, lighting, presence, and other factors affecting energy efficiency;

- **Actuators:** enable changes to control systems, such as opening and closing valves, activating energy-saving lighting devices, etc;
- **Controller:** processes data from sensors and issues commands to actuators to optimize energy systems.

Today, BEMS are critical to addressing global energy and environmental challenges. They provide an effective way to reduce energy consumption and greenhouse gas emissions, helping to meet sustainability goals and energy efficiency regulations. Looking to the future, however, BEMS will play an even more critical role, as urban populations increase and energy-efficient buildings expand, smart energy management will become essential to ensuring a sustainable urban environment. In addition, evolving IoT technologies and artificial intelligence promise to bring BEMS to an unprecedented level of sophistication, enabling even more predictive and responsive energy management, as well as playing a crucial role in Smart Grids and Smart Cities by overseeing the storage and distribution of excess electricity, especially from local renewable sources, helping to optimize the management of the power grid at the local level. According to Research&Markets [27] the global BEMS market, estimated at US $4.3 Billion in the year 2022, is projected to reach a revised size of US $12.3 Billion by 2030.

In this specific case, the system was managed through the powerful DESIGO software [28]. This platform enabled the collection and detailed analysis of a wide range of data, from ambient conditions to air handling unit performance parameters, from tank temperatures to thermal loads, ensuring intelligent and optimized management of the system.

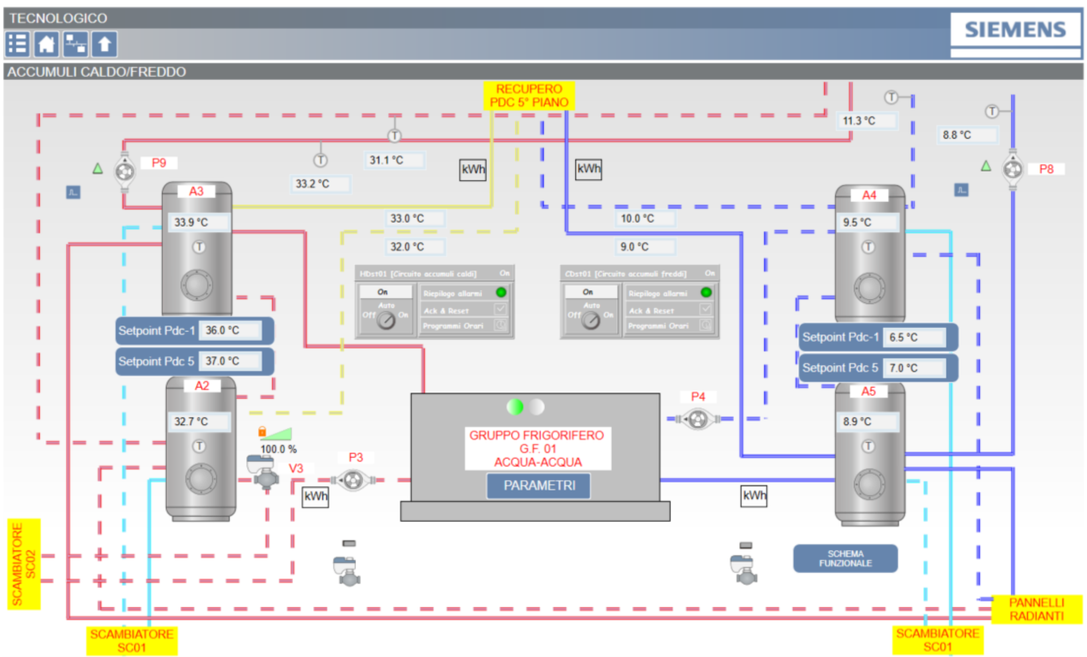

Figure 3.10: Central Heat Pump control interface

Figure 3.11: Floor control interface

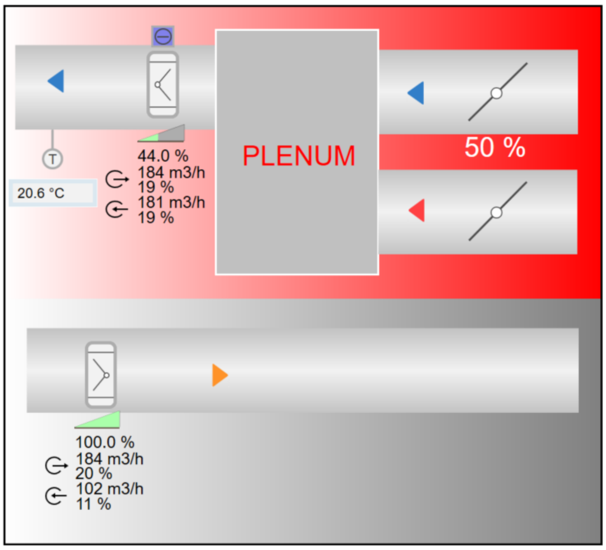

Figure 3.12: VAV control interface

3.5.1. Problems

During the analysis conducted on the building, several issues have emerged that require immediate intervention in order to optimize energy efficiency and the proper functioning of the systems.

Initially, malfunctions were identified in different sensors and meters crucial for data collection compromising the accurate evaluation of the thermal system. Just to show an example, an error occurred in the measurements of groundwater temperature.

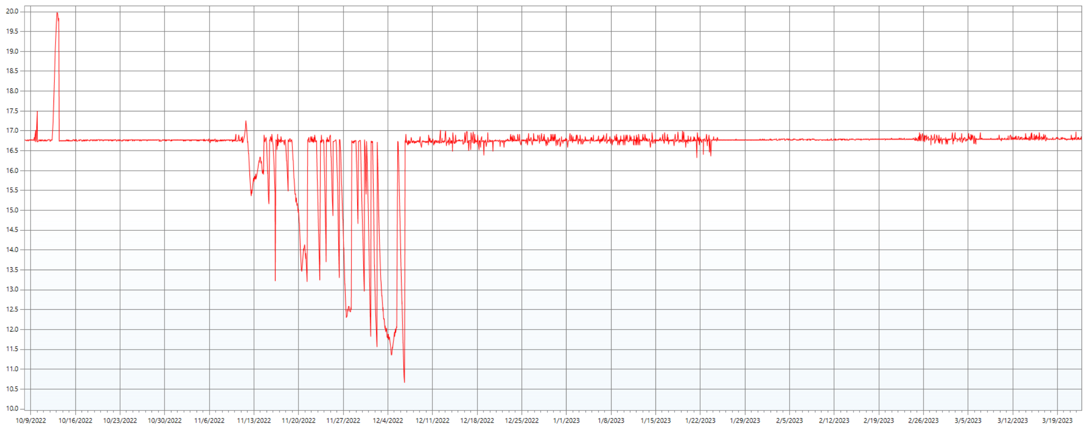

Figure 3.13: Groundwater temperature sensor error

Another significant issue concerns the dampers of the Variable Air Volume system, which, once the maximum opening limit is reached, remained stuck in position, preventing optimal airflow regulation. This leads to a significant waste of energy, as air is supplied in excessive or insufficient quantities, compromising the thermal comfort of occupants.

Furthermore, constrictions were identified in some air supply ducts. This problem hinders the uniform distribution of air inside the building, creating areas with uneven temperatures and thermal comfort. This situation not only negatively affects the well-being of users but also results in energy waste, as it becomes necessary to compensate for these differences through an increase in energy input.

Figure 3.14: Air supply ducts constrictions

Additionally, in the past, an incorrect initial operation of the heat recovery system was observed. This component plays a crucial role in maximizing the use of thermal energy within the building, and its past malfunctioning has affected data collection.

It is important to emphasize that, unfortunately, these critical issues cannot be accounted for in the simulation software. However, they hold fundamental importance as they directly impact the reliability and accuracy of the results obtained, underscoring the need for a careful on-site analysis to ensure the maximum performance and proper operation of the system.

3.6. Base Load Estimation

In light of the challenges encountered during the data collection phase, a decision has been made to estimate electricity consumption prior to conducting simulations. Temporarily setting aside considerations related to the air conditioning system, the primary sources of electrical consumption stem from the data processing center, various instruments connected to the power line, and the lighting system.

The data processing center is a dedicated computing infrastructure designed for the efficient processing, management, and storage of data, facilitating automation and enhancing business operations. It consumes approximately 90 kW of power and requires continuous operation 24 hours a day. The electrical systems connected to the power line primarily consist of electronic and computer equipment (PCs, monitors, printers, etc.). These devices are installed in an area of approximately 9'000 m^2 and are typically operational for an average of 10 hours per day, with exceptions for Sundays and holidays when the building is unoccupied. According to design data, the average load related to these elements is expected to be 6 $\frac{W}{m^2}$. However, estimates indicate a higher consumption, approximately 15 $\frac{W}{m^2}$. The lighting system comprises various elements distributed across the 6 floors of the building and the external square, covering an area of approximately 10'500 m^2. Similar to the electrical equipment, it is active for around 10 hours daily. According to design specifications, the load related to lighting should be 4,5 $\frac{W}{m^2}$. Nevertheless, estimates suggest a higher consumption, around 10 $\frac{W}{m^2}$.

The divergences identified between the actual electricity consumption data and the initial estimates have been the subject of thorough on-site inspections conducted directly at the location. The results of these verifications unequivocally confirmed the presence of significant discrepancies compared to the values hypothesized in the initial project. The detailed analyses carried out on-site have clearly highlighted a substantial surpassing of the initial projections, emphasizing the importance of a thorough and timely revision of the project estimates. The integration of these verified data into the simulation software is crucial to ensure precise and reflective modeling, enabling more informed design and effective optimization of resources within the realm of energy consumption.

	Power [kW]	Hours	Days	Energy [kWh]
Data Center	92	24	30	66’240
Equipment	35	10	26	27’300
Lighting	135	10	26	35’100

Table 3.20: Base Loads Monthly Energy Estimation

The total energy associated with these three loads is 128’640 kWh. As an additional validation of the calculations, it is noteworthy that this figure aligns closely with the energy consumption for the month of April (135’200 kWh). April, being a transitional month, typically exhibits lower demand on the air conditioning system compared to the summer and winter months. This correspondence serves as further affirmation of the accuracy of the calculations performed.

Having identified the baseline load, which can be considered nearly constant across all months, subtracting this value from the billing data allows for the estimation of air conditioning consumption. With the annual total from the billing amounting to 1’910’928 kWh, subtracting the baseline load consumption yields a value of 350’928 kWh, approximately corresponding to 18% of the total billing consumption.

4 | Simulation Model

4.0.1. Methodology

To evaluate the energy performance of the building in question, it is necessary to introduce an energy simulation model. Through the use of a three-dimensional model detailed analyses were performed in order to understand and quantify the expected energy consumption. The main objective of these simulations is to provide an accurate and reliable assessment of the building's thermal performance, as well as to identify opportunities for optimizing energy efficiency. In the course of this chapter, the details related to the model used, the considered input data, and the adopted simulation parameters will be presented.

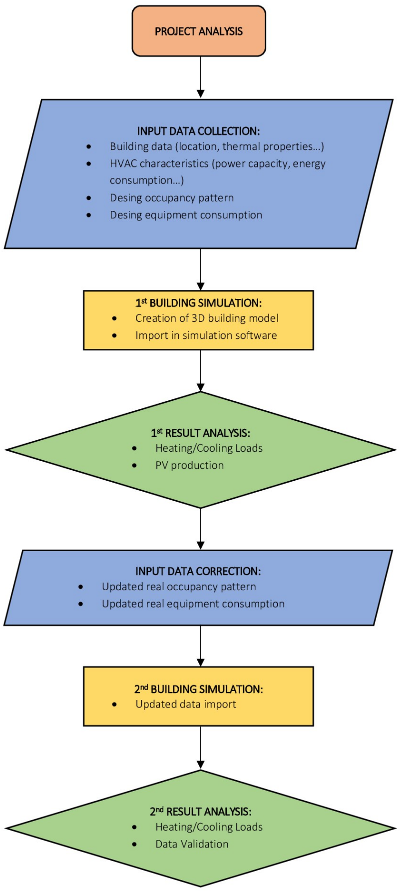

Figure 4.1: Simulation methodology flowchart

4.1. 3D Model

The meticulous modeling of a building stands as a crucial cornerstone in retro-commissioning analysis [29]. It delivers a precise and comprehensive virtual representation of the structure, allowing for a systematic and accurate evaluation of its energy efficiency, mechanical systems, and thermal performance. This representation empowers the simulation of the building's thermal dynamics across various operational scenarios, aiding in the pinpointing of critical areas like occupancy patterns or inefficiencies in heating and cooling systems. Furthermore, modeling enables the virtual testing of different HVAC and control system configurations, honing in on the most efficient solutions while optimizing occupant comfort. The detailed scrutiny of the model unveils specific energy efficiency measures that can be applied to curtail consumption, subsequently reducing the operational costs of the building. In addition, modeling facilitates the simulation of the potential impacts of proposed interventions prior to their actual implementation, enabling the assessment of their effectiveness and forecasting the benefits in terms of energy performance. The comprehensive documentation of the building and its performance, afforded by modelling, fosters effective communication among the professionals engaged in the retro-commissioning process. It also grants a clear visualization of the areas necessitating priority intervention. This holistic approach not only ensures a more sustainable and energy-efficient operation but also contributes to the overall longevity and resilience of the building's infrastructure. In essence, the thorough modelling process serves as a linchpin in the endeavour to enhance the environmental footprint and operational efficiency of the structure, ultimately aligning with broader sustainability goals.

In order to conduct a thorough analysis, a model of the building was generated using SketchUp software [30], with the objective of capturing the key architectural features of the subject building under study.

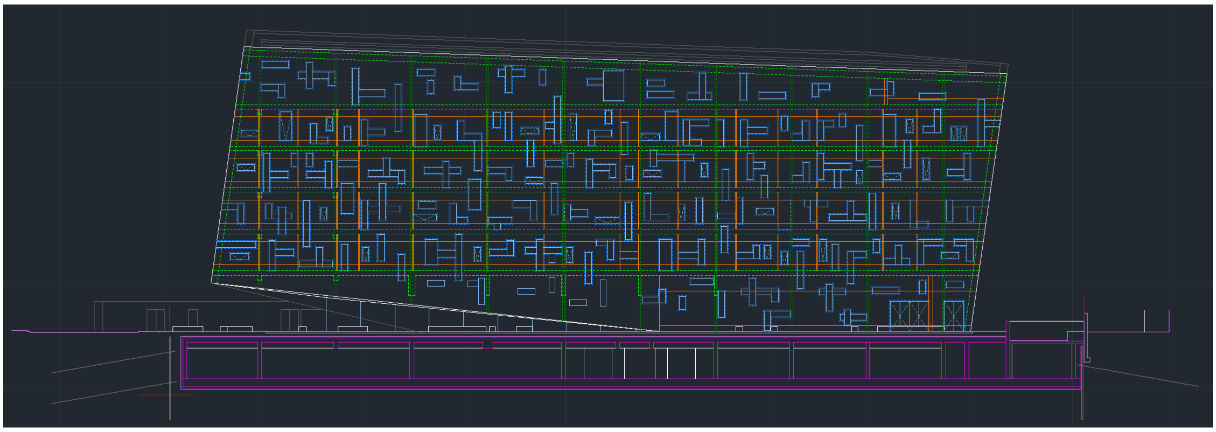

Figure 4.2: Example of a CAD drawing

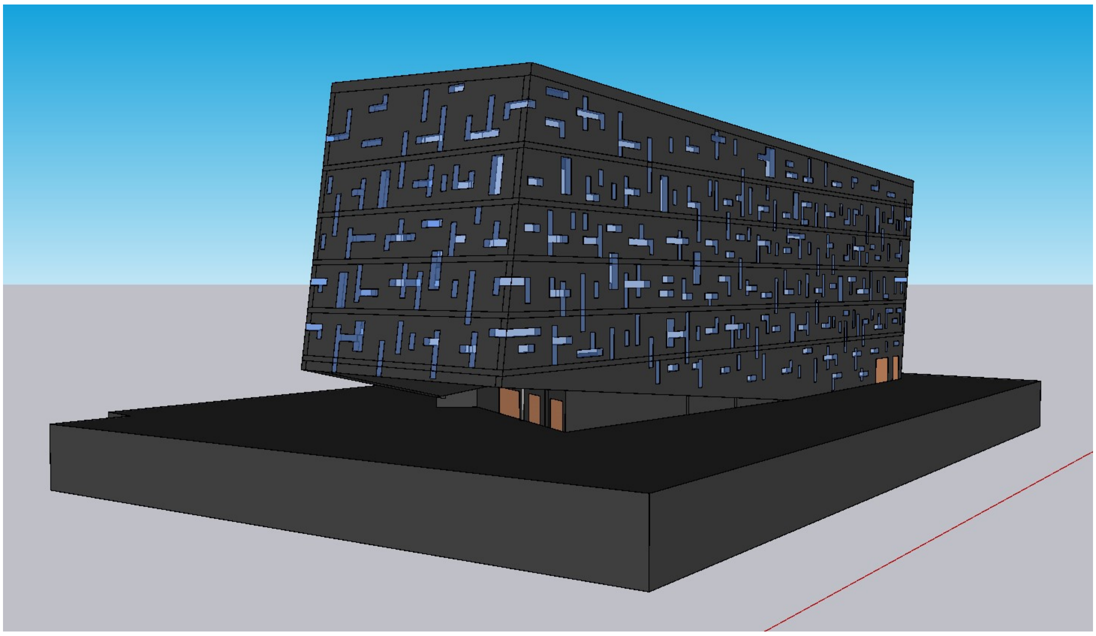

Figure 4.3: SketchUp 3D Building Model - Front View

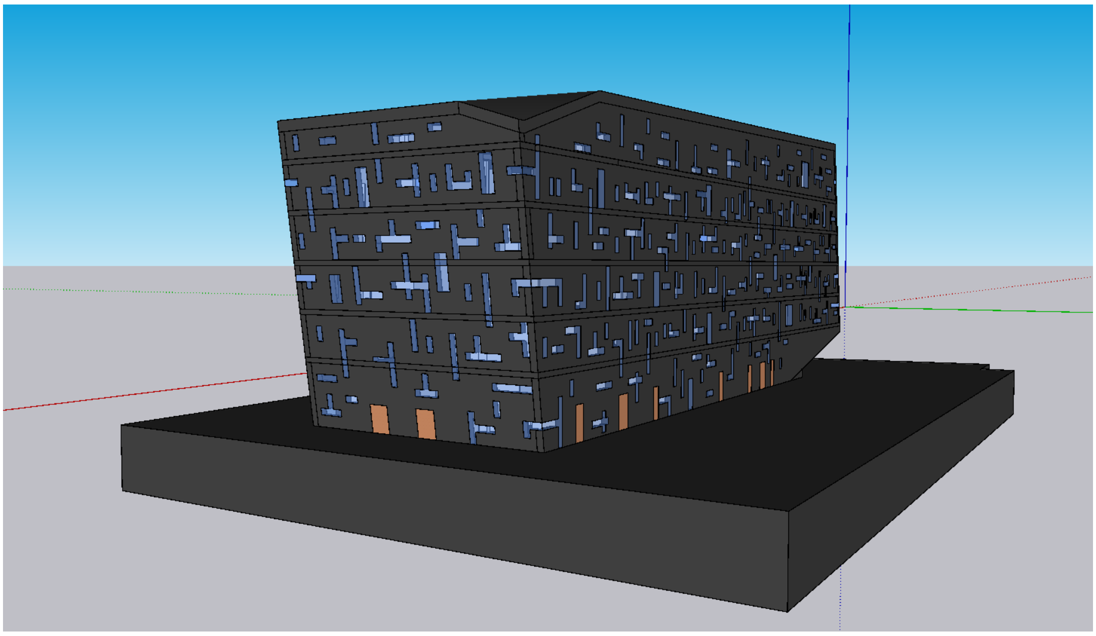

Figure 4.4: SketchUp 3D Building Model - Rear View

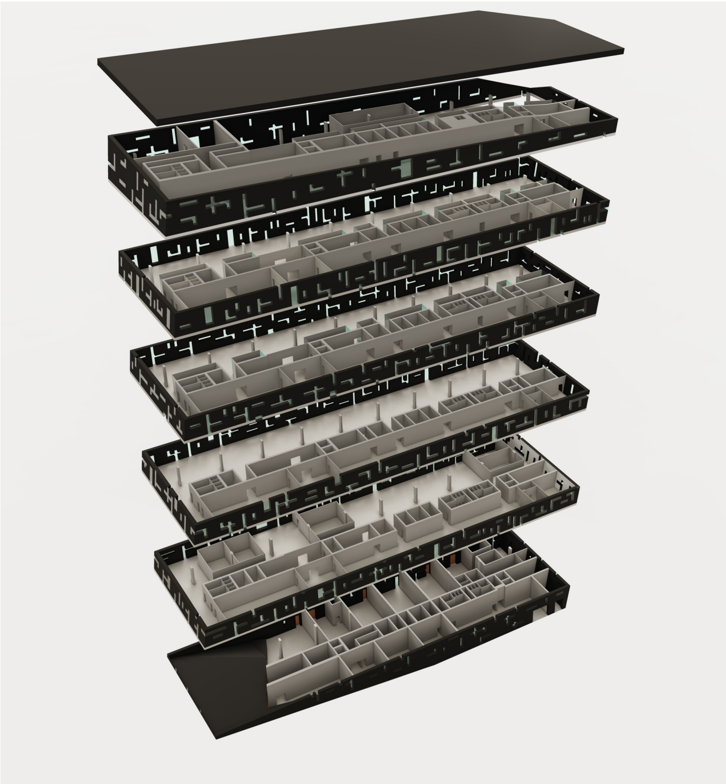

Figure 4.5: SketchUp 3D Building - Exploded View

Figure 4.6: SketchUp 3D Building Model - Section View

After completing the 3D modeling in SketchUp, the model was imported into Design-Builder software [31] as a .gbxml file for detailed energy analysis. During the process of creating the simulation model a simplification was undertaken pertaining to the intricate network of windows. In the original SketchUp model the windows were depicted in their full complexity, mirroring the real-world structure. However, for the purposes of simulation, a decision was made to represent the windows as uniform strips with equivalent total area. This simplification was implemented to streamline the computational process and enhance the efficiency of the simulation. By condensing the window representation to uniform strips, the model achieves a balance between accuracy and computational tractability. This approach ensures that the simulation results remain reliable and insightful, while significantly reducing the computational resources required.

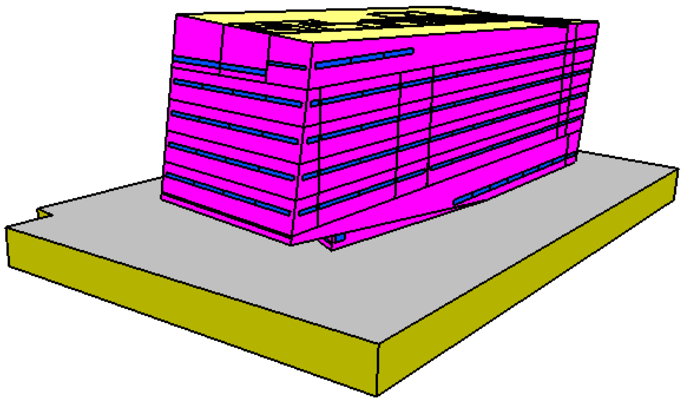

Figure 4.7: DesignBuilder - 3D Building Model

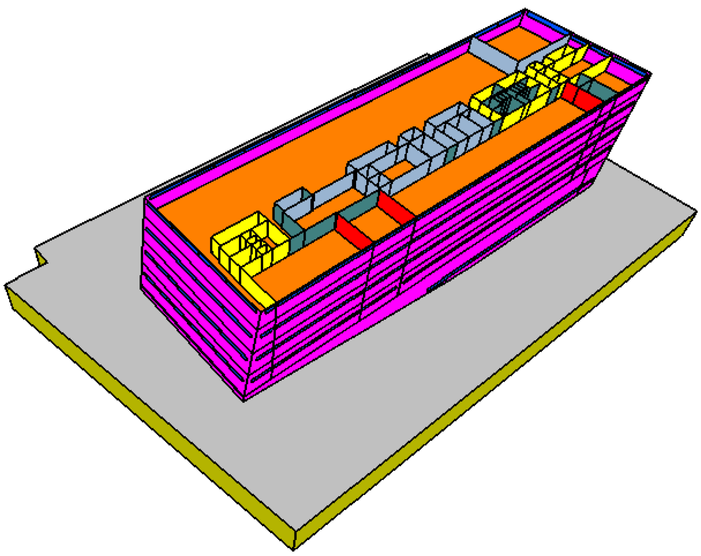

Figure 4.8: DesignBuilder - Floor section example

4.2. HVAC System

After modelling the building, it is then necessary to model the air conditioning system. However, in the process of integrating that plant into DesignBuilder, a significant challenge emerged arising from the inherent complexity of the plant itself. Such software allows detailed representation but has limitations in handling highly complex configurations. Consequently, some simplifications were made to ensure a balance between detail and modelling feasibility.

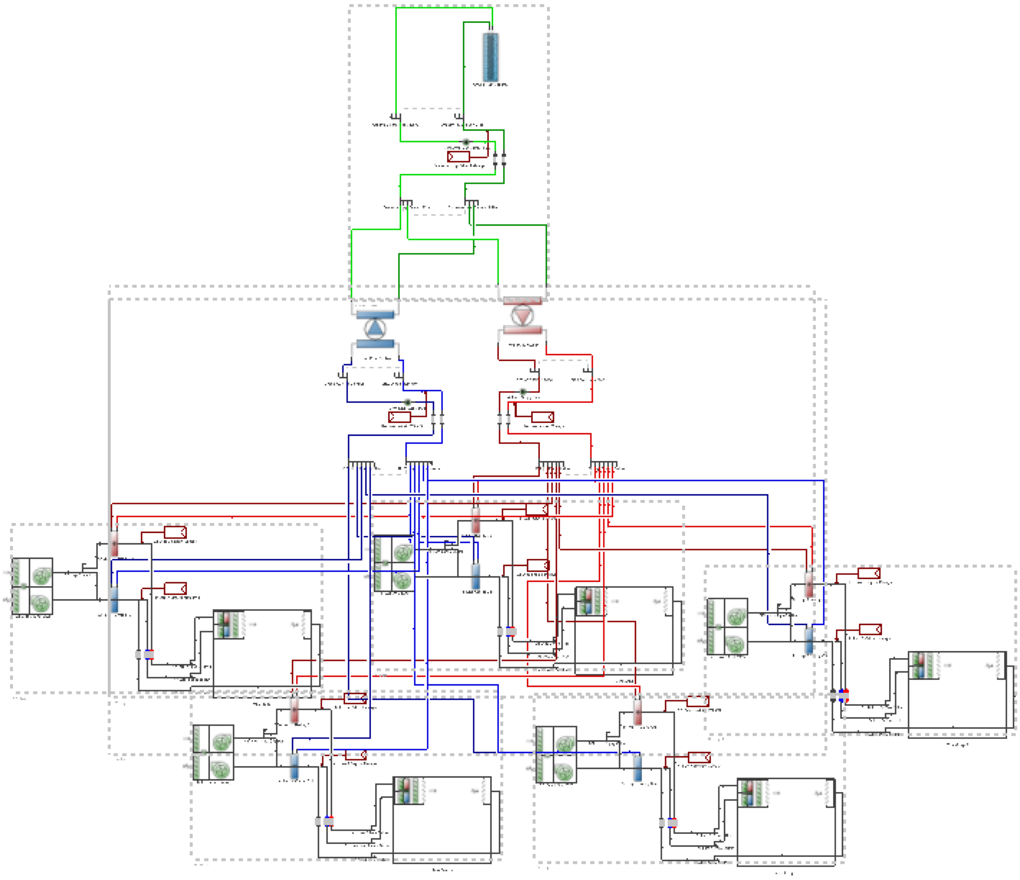

Figure 4.9: DesignBuilder HVAC Schematic

The simplifications in question, as can be seen from the simulation model, involve free cooling and heat recovery, two aspects that, if implemented, would have added positive value to the energy efficiency of the system. While certain aspects have been excluded, it is crucial to acknowledge that the conducted analysis still yields valuable insights into the energy-saving potential of the system. By prioritizing the AHUs, Central Heat Pump, and VAV system, targeted solutions can be identified that have a positive impact on energy consumption, thereby making a significant contribution to the overall efficiency of the HVAC system.

4.3. Weather File

Weather data, which includes information such as temperature, humidity, solar radiation and wind, provide the foundation for evaluating the energy performance of buildings under different environmental conditions. It is crucial that these data accurately reflect the current climate and recent climate trends. The use of outdated data or data not aligned with current climate changes could lead to inaccurate forecasts and a distorted assessment of the building's energy performance. In the specific case of energy simulations for buildings in Milan it is imperative to accurately consider the evolution of the climate, as the effects of climate change in recent years have resulted in significant variations in local weather conditions, impacting energy consumption and thermal requirements of the buildings.

For all these reasons, in order to ensure the most realistic simulation possible, it was necessary to replace the outdated weather data in the software with a dataset representing a collection from the period 2007 to 2021 [32].

4.4. Design Case

4.4.1. Input Data

Weather file location	Milano Linate
Average yearly temperature [°C]	14,6
Hottest yearly temperature (99%) [°C]	32
Coldest yearly temperature (1%) [°C]	-2
Annual cumulative horizontal solar radiation [$\frac{Wh}{m^2}$]	1'395
Heat Pump Hot Water Supply [°C]	35
Heat Pump Cold Water Supply [°C]	7
AHU Hot Air Supply [°C]	32
AHU Cold Air Supply [°C]	12
Occupancy Density [$\frac{people}{m^2}$]	0,1
Lighting [$\frac{W}{m^2}$]	4.5
Equipment Power Density [$\frac{W}{m^2}$]	6
Air Infiltration [$\frac{ac}{h}$]	0,7
Heating Setpoint Temperature [°C]	20
Cooling Setpoint Temperature [°C]	26

Table 4.1: Design Case Input Data

4.4.2. Heating and Cooling Loads

In the first phase of the project, a simulation of the Design Case was conducted by implementing the theoretical values calculated in the design phase in the simulation software. This simulation provided an essential initial framework for evaluating the system's behaviour under ideal conditions, allowing for the identification of fundamental dynamics and relationships among the various parameters involved.

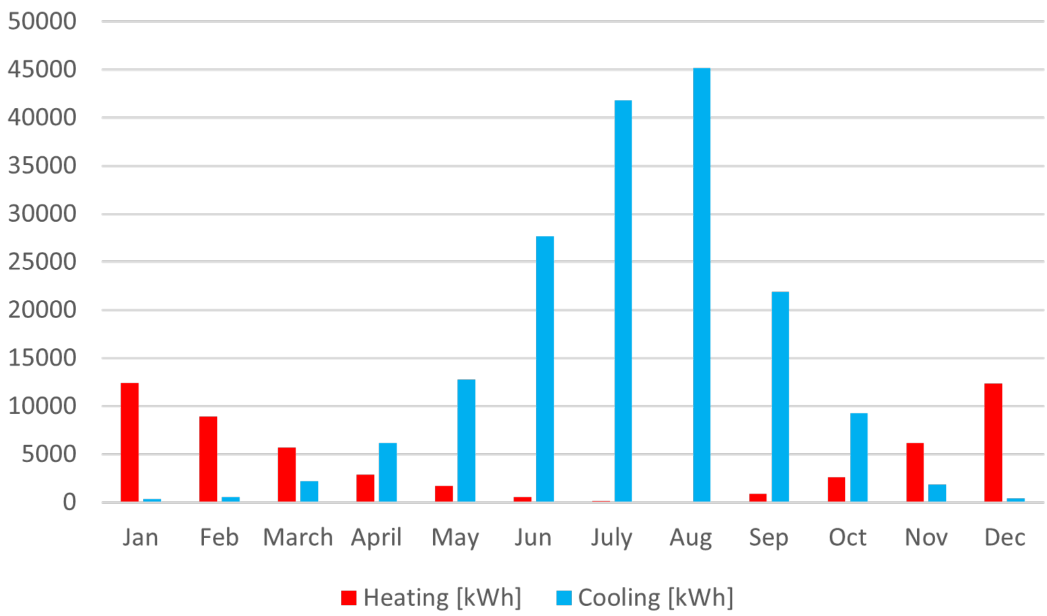

Figure 4.10: Heating and Cooling Load calculations - Design Case

It is evident that the energy consumption for heating experiences a marked increase during the winter months, with the peak registered in the coldest months. On the other hand, the energy consumption for cooling reaches its zenith during the summer months. It is noteworthy, however, that the peak cooling demand surpasses that of heating. This can be attributed to various factors, such as, in part, the sensible and latent internal loads, which contribute indirectly to heating indoor spaces in winter, but increase the need for cooling during the summer season. Another noteworthy detail is the demand for heating even during the summer months. This phenomenon can be attributed to the dehumidification process, which may lead to a decrease in air temperatures to levels that require heating intervention in order to ensure suitable conditions for supplying the VAVs.

4.4.3. PV Production

Regarding the annual electricity production of the photovoltaic system as projected, it had been estimated to be 198'728 kWh using the simplified formula:

$$E_{PV} = PR * P_{PV} * S \tag{4.1}$$

where E_{PV}, expressed in kWh, represents the amount of electric energy that can be produced annually, PR represents the performance ratio of the photovoltaic system, assumed to be 0.85 for the specific installation, P_{PV} represents the nominal power of the system (177,12 kW in our case) and S represents the value of solar radiation (approximately 1'320 $\frac{kWh}{m^2*year}$ for Milan).

From the simulation, however, a total value nearly 20% higher is obtained, precisely 237'866 kWh. This difference can be attributed to an inaccurate estimation of solar radiation. As indicated by the utilized weather file [33], the average solar radiation value in the period from 2007 to 2021 was 1395 $\frac{kWh}{m^2*year}$, which is 5.5% higher than the data used by the project. As illustrated in the chart below, the simulation closely approximates the actual trend of electrical production, which is estimated to be 219'361 kWh.

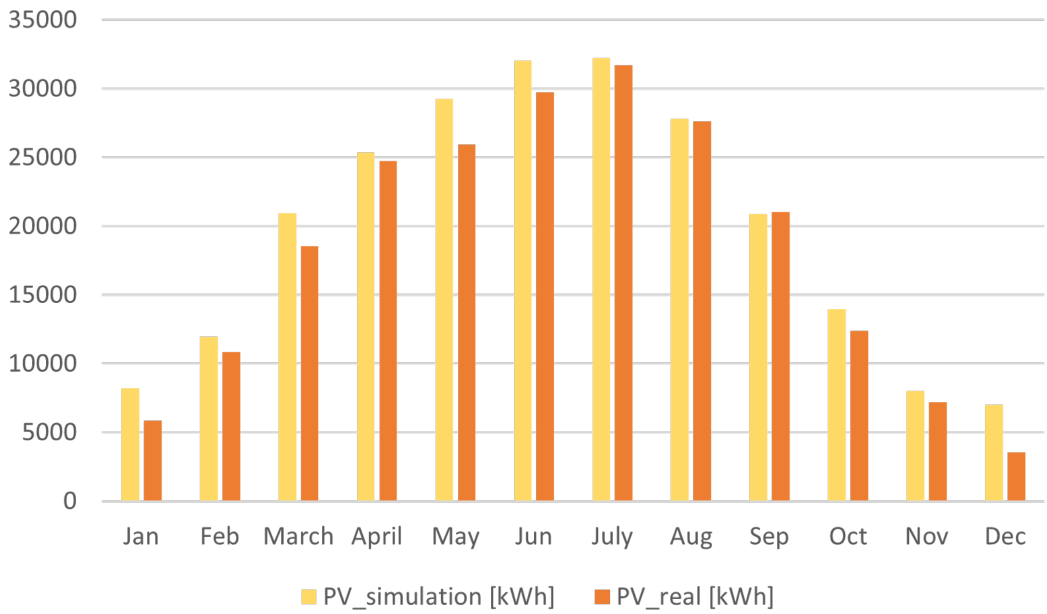

Figure 4.11: Photovoltaic monthly production - Comparison

4.5. Real Case

The building in question was conceived and constructed in a pre-Covid period, one year before the emergence of the pandemic that drastically changed the dynamics of work. In response to this global crisis, the management implemented an extensive smart-working program that led to a significant reduction in physical presence within the building. Originally designed to accommodate a workforce of around 500 employees, the current occupancy is approximately half of the initial projection. This significant shift in space utilization has necessitated a reevaluation of occupancy density assessments. The building, originally designed with an occupancy density of 0,1 individuals per square meter, can now be said to have an occupancy density of approximately 0,06 individuals per square meter. This value was chosen considering not only the internal employees, for whom a presence at half of the initial projection (0,05) can be assumed, but also the flow of external people entering the building throughout the day, to which an additional factor of 0,01 has been attributed. Furthermore, the analytical study of loads within the spaces has shown an exceedance of the assumed design values. In particular, the project-specified values for equipment power density are 5 $\frac{W}{m^2}$, while the actually installed values are higher, reaching up to 25 $\frac{W}{m^2}$ for some areas.

Occupancy Density $[\frac{people}{m^2}]$	0,06
Lighting $[\frac{W}{m^2}]$	10
Equipment Power Density $[\frac{W}{m^2}]$	15

Table 4.2: Real Case Updated Parameters

After reviewing these elements, the analyses are updated, taking into account the two new values (while the others remain unchanged).

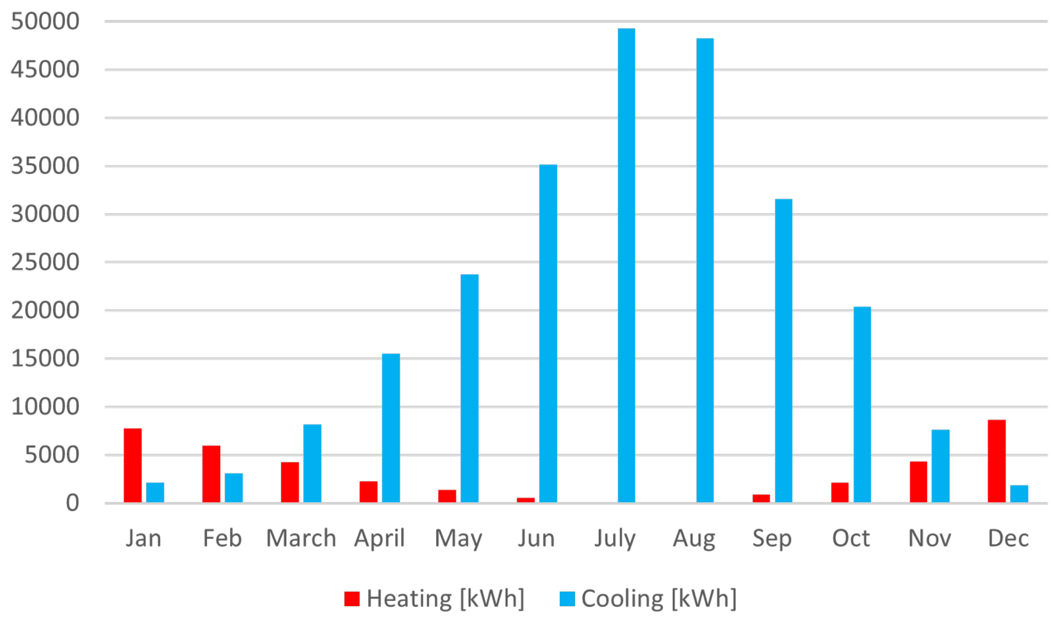

Figure 4.12: Heating and Cooling Load calculations - Real Case

As can be observed from the graph, the peaks reached during the heating phase are lower compared to the Design Case, whereas conversely, the peaks reached during the cooling phase are higher. This is a consequence of the greater internal loads, which help meet the heat demand during winter months but are at the same time more challenging to dissipate in the summer period.

In more detail, comparing the two phases in the two different cases, it can be concluded that annually the heating demand is 30% lower, while the cooling demand is 45% higher.

Heating Load - Design Case [kWh]	54'414
Heating Load - Real Case [kWh]	38'255

Table 4.3: Heating Loads Data

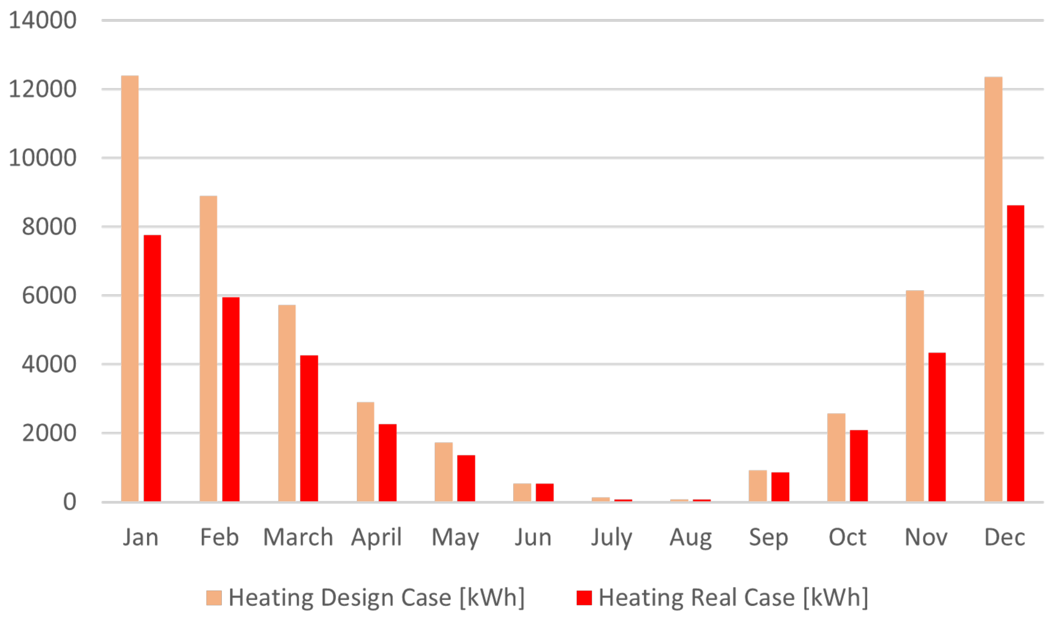

Figure 4.13: Heating Loads Monthly Comparison

Cooling Load - Design Case [kWh]	170'067
Cooling Load - Real Case [kWh]	246'788

Table 4.4: Cooling Loads Data

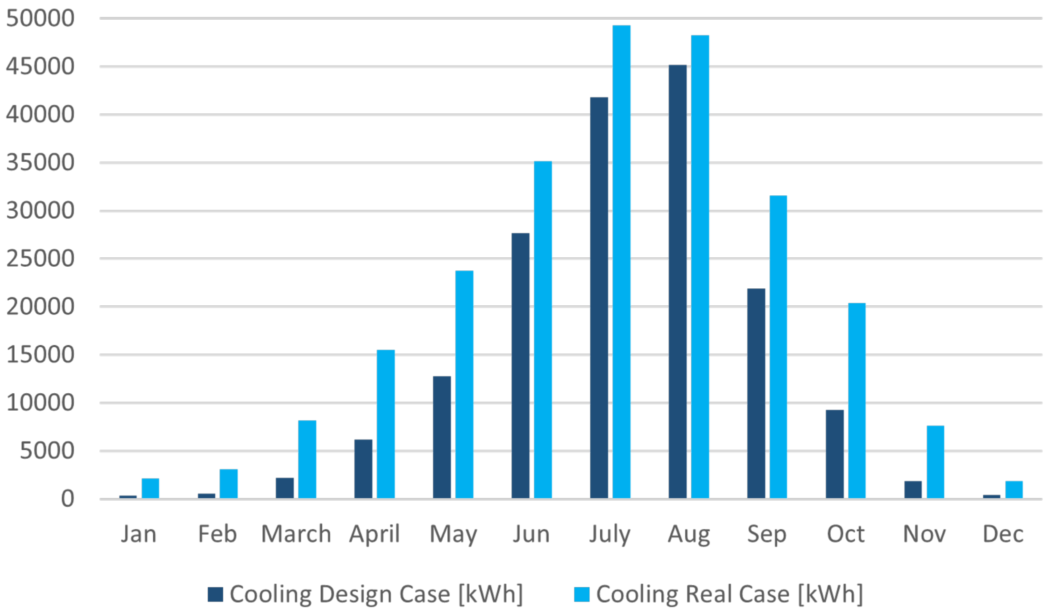

Figure 4.14: Cooling Loads Monthly Comparison

4.5.1. Data Validation

Comparing the results obtained through the simulation software with the data recorded by the Desigo software in this case proves to be complex due to issues related to sensor accuracy that have hindered precise monitoring. Additionally, a malfunction of some components of the air conditioning system has been identified, which would have nevertheless affected the reliability of the acquired data. These issues have only recently been reported. Therefore, to ensure the validity of the results obtained from the simulations, a comparison is made between the total consumption derived from the simulation and the data reported in the bills.

DesignBuilder Results [kWh]	2'074'278
Electric Bills + PV Production [kWh]	1'919'631

Table 4.5: Annual Building Load Comparison

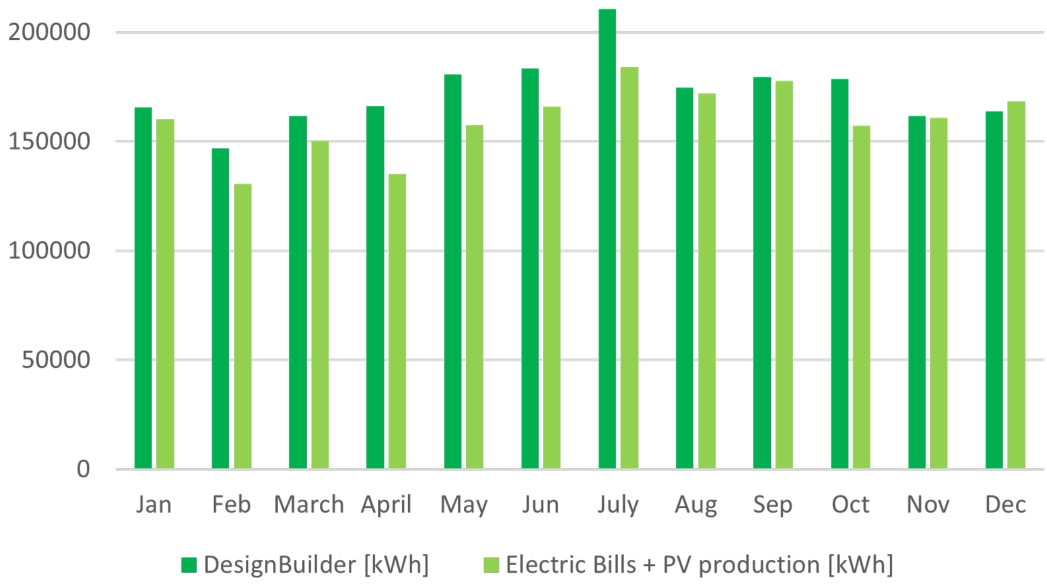

Figure 4.15: Monthly Building Load Comparison

As can be observed, the monthly trend from the simulation consistently follows the real data, showing an overall discrepancy of 7% in excess. This result aligns with the expectations, as the simulation takes into account a simplified version of the air conditioning system which does not account for free cooling and heat recovery, two elements that contribute to reducing the building's energy load. Additionally, factors mentioned in the *State of the Art* should also be taken into consideration, as they may cause differences between the simulation and the real-world case.
In addition to the aforementioned, as an additional validation of the data, the simulated consumption of the HVAC system is 447'550 kWh, equivalent to 21% of the total energy consumption. This figure aligns closely with the estimate made in the preceding chapters, which projected the air conditioning system's consumption to be around 18%.

Taking these considerations into account, the obtained data is deemed suitable for analysis and will serve as the basis for formulating improvement proposals in the subsequent chapters.

5 | Proposed Improvements

5.0.1. Methodology

Before analyzing the situation, it is crucial to acknowledge that within the context of the building in question, the HVAC system constitutes only a fraction of the total energy consumption, amounting to approximately 20%. Therefore, as the focus is directed towards conducting a detailed analysis and proposing targeted improvements to optimize the efficiency of this specific system, it is essential to bear in mind that other areas significantly contribute to the overall building energy consumption (primarily lighting and various appliances). Implementing advanced solutions for the HVAC system will be a significant step towards a more sustainable energy management, but additional strategies may be required to address other sectors and maximize the overall benefit in terms of energy efficiency.

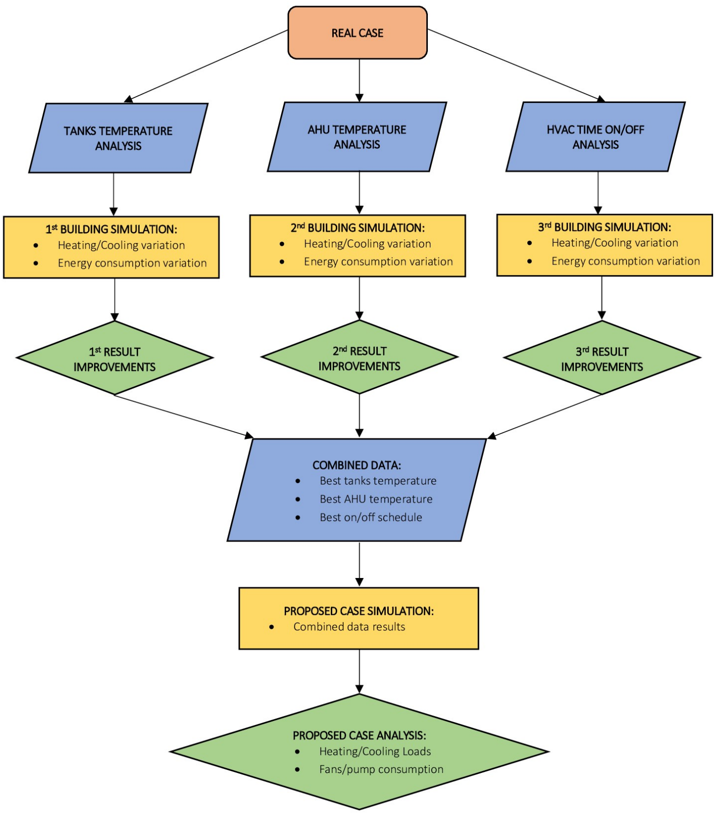

Figure 5.1: Improvements methodology flowchart

5.1. Storage Tanks

The first conducted simulation aims to analyze the temperatures of the storage volumes from which hot and chilled water is extracted for the utilities. These temperatures were initially set arbitrarily during the design phase or based on standard reference data. It is crucial therefore to understand how these initial conditions affect the overall performance of the HVAC system and what their impact is on energy consumption.

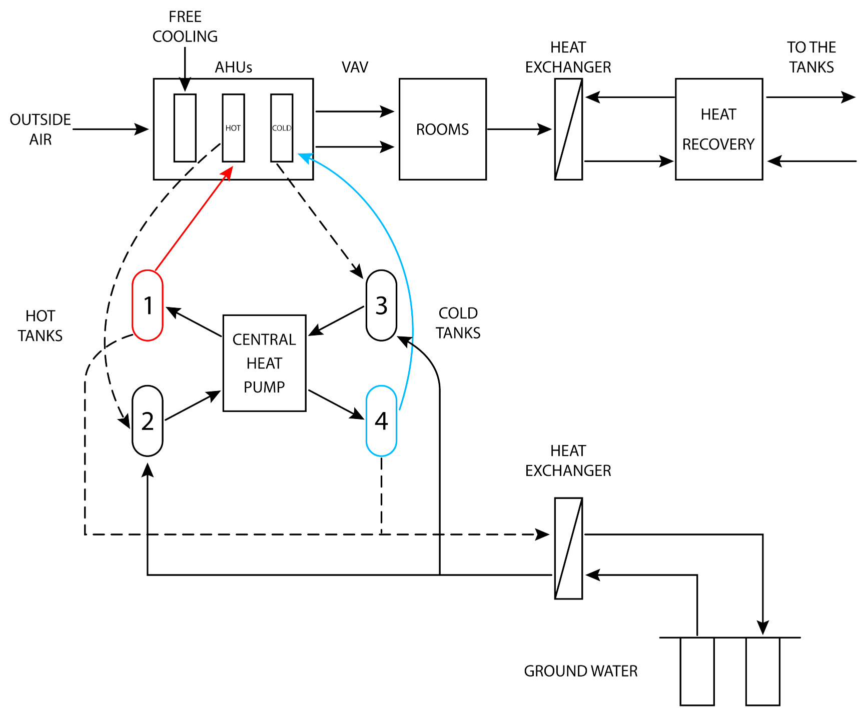

Figure 5.2: Tanks under analysis

In order to conduct an initial assessment of the impact of these temperatures on the air conditioning system, cases are considered in which a change occurs in the temperature differential of the storage volumes (i.e., the supply temperature to the coils of the AHUs), transitioning from 35 °C for warm storage and 7 °C for cold storage to 34 °C and 8 °C respectively, or increasing to 36 °C and 6 °C.

	Real Case (35/7)	ΔT higher (36/6)	ΔT lower (34/8)
Heating [kWh]	38’255	40’425	35’908
Cooling [kWh]	246’798	255’651	242’772

Table 5.1: Heating and Cooling Loads - Comparison

Changing the temperatures leads to variations in energy consumption for the heating and cooling system. In the case of an increased thermal gap as to be expected the consumption will rise, as the tanks must be maintained at temperatures further apart. Conversely, reducing the thermal gap leads to energy consumption reduction due to the lower energy required to maintain the smaller temperature difference. Indeed, recalling the formula for calculating the COP and EER of machines operating at maximum theoretical efficiency

$$COP = \frac{T_{HOT}}{T_{HOT} - T_{COLD}} \tag{5.1}$$

$$EER = \frac{T_{COLD}}{T_{HOT} - T_{COLD}} \tag{5.2}$$

it can be seen that as the denominator decreases, the efficiency of the heat pump increases.

	Real Case (35/7)	**ΔT higher (36/6)**	**ΔT lower (34/8)**
Fans [kWh]	145’252	147’584	143’562
Pumps [kWh]	17’145	17’048	18’296

Table 5.2: Fans and Pumps Loads - Comparison

As can be observed, the demand for pumps varies significantly with temperature changes. Specifically, higher thermal differentials result in lower consumption due to the reduced water flow required to cool/heat the incoming air to AHUs. Conversely, when the thermal differential decreases, the water flow required by the AHUs increases, consequently leading to higher pump consumption.

5.2. AHUs

The second simulation focuses on analyzing the range of operation of the AHUs within the HVAC system. These devices play a crucial role in controlling the distribution of air inside the building, regulating the airflow in response to thermal conditions and comfort requirements of the spaces. As in the previous case, this temperature range (32 °C for the hot flow and 12 °C for the cold flow) has been chosen arbitrarily, so it is necessary to conduct an analysis to understand its impact on energy consumption.

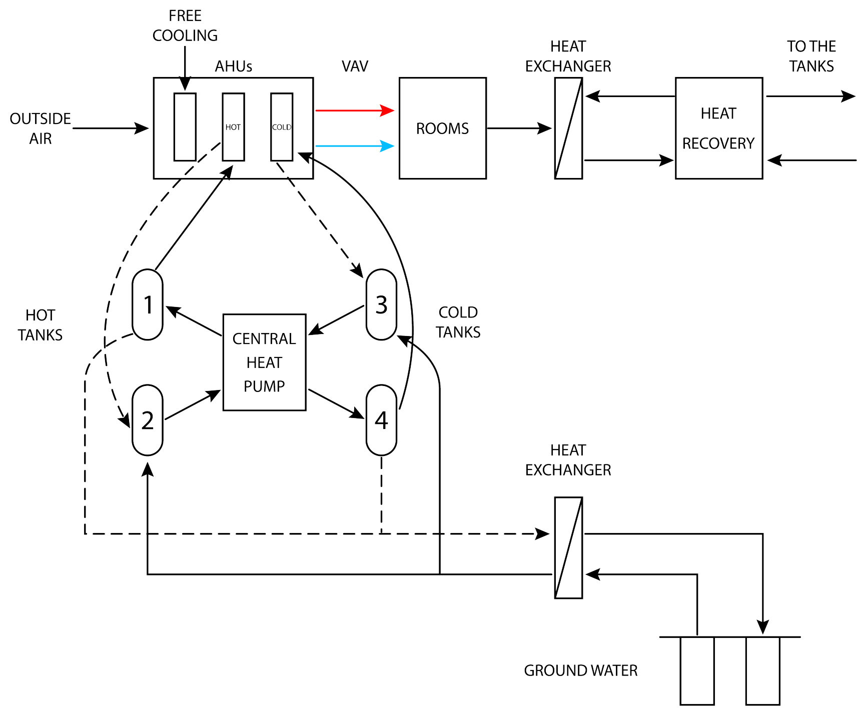

Figure 5.3: VAV under analysis

To conduct a preliminary assessment of the impact of these temperatures on the air conditioning system, an analysis is performed on how individually manipulating the two flows can affect consumption.

	Real Case (32/12)	**Higher T (33/12)**	**Lower T (31/12)**
Heating [kWh]	38'255	37'989	37'225
Cooling [kWh]	246'798	250'324	250'355
Fans [kWh]	145'252	145'668	145'695
Pumps [kWh]	17'145	18'726	16'708

Table 5.3: AHU Hot Flow - Comparison

An increase in the temperature of the hot channel, going from 32°C to 33°C, results in an elevation of the pumping demand. This occurs because, in order to maintain the ambient air supply temperature at desired levels, it is necessary to augment the supply of cold water to the coils. Conversely, when a decrease in temperature from 32°C to 31°C occurs, there is a corresponding reduction in the demand for pumping cold water. This phenomenon is attributable to the diminished need for cooling the incoming airflow.

	Real Case (32/12)	Higher T (32/13)	Lower T (32/11)
Heating [kWh]	38’255	36’847	39’458
Cooling [kWh]	246’798	235’777	258’066
Fans [kWh]	145’252	149’343	142’107
Pumps [kWh]	17’145	16’310	18’137

Table 5.4: AHU Cold Flow - Comparison

In the same way as described above, when the supply temperature of the cold channel increases from 12 °C to 13 °C, the pumping demand will decrease to maintain the desired air inlet temperature. Conversely, when it decreases from 12 °C to 11 °C, the pumping demand will increase. Additionally, it is worth noting a significant different in cooling consumption in this two cases, attributable to the great importance of the cooling system given the high internal loads.

5.3. Night Switch-off

The third simulation concerns the analysis of the nighttime shutdown logic in the HVAC system, which has not been implemented in the base case. Currently, the system operates continuously 24 hours a day, regardless of the specific thermal comfort needs of the occupants. Considering the nature of the structure, consisting of several buildings occupied from 8 AM to 7 PM, there arose the need to adopt a more targeted and efficient management strategy. The proposal involves implementing a regulation that allows for turning off the air conditioning system at the end of the working day and reactivating it shortly before the start of the next day. This approach avoids energy waste during periods of non-use of the building without sacrificing comfort for the occupants.

The study of the nighttime shutdown logic has highlighted a specific characterization of the building. The energy situation allows for the identification of two distinct periods. The first, consisting of the months from January to June and from September to December, is characterized by low heating demands but more pronounced cooling demands, while the second, which includes the remaining months of July and August, is distinguished by the highest cooling demands. The adoption of a single annual shutdown logic would not be feasible, therefore two differentiated solutions are proposed, one for each period. In the first one, a suggested operating mode involves shutdown at 7:00 PM and restart at 6:30 AM. In the second period however due to the very high daily cooling demands the application of the aforementioned logic is not feasible.

	Real Case	Night switch-off
Heating [kWh]	38’255	10’560
Cooling [kWh]	246’798	199’686
Fans [kWh]	145’252	107’601
Pumps [kWh]	17’145	12’082

Table 5.5: Night switch-off/on - Comparison

The results obtained demonstrate a significant improvement compared to the real case in every aspect, and overall, the consumption is reduced by 26%.

Implementing the "night purge" technique, which uses outdoor air to cool indoor spaces during the night hours by capitalizing on the thermal inertia of the building, could potentially lead to further improvements in the results. Unfortunately, the simulation software currently being used does not support this type of analysis. However, adopting this methodology could result in a significant reduction in the daily energy consumption of the system, even though it would lead to an increase in consumption due to the use of fans required for air circulation. To be more specific, this strategy could yield particularly optimal results in the months of June and September when the building’s cooling demand is particularly high, and historical data indicates that nighttime outdoor temperatures range between 16 and 18 degrees Celsius. On the other hand, it would be less advantageous to apply this technique in the months of July and August, as even during the night, temperatures exceed 21-22 degrees Celsius, making this technology less cost-effective.

5.4. Combined Results

In conclusion, after reviewing the characteristic parameters of the system, a possible improvement solution is proposed, resulting from a combination of the considerations drawn from the preceding chapters. It is suggested to adjust the setpoint temperature of the hot tank from 35 °C to 32 °C, and the cold tank from 7 °C to 11 °C. As for the VAV (Variable Air Volume) units, it is proposed to adjust the temperature of the hot channel from 32 °C to 31 °C and the temperature of the cold channel from 12 °C to 14 °C.

	Real Case	Tank, AHUs Improvements
Heating [kWh]	38’255	29’159
Cooling [kWh]	246’798	197’455
Fans [kWh]	145’252	148’273
Pumps [kWh]	17’145	18’355

Table 5.6: Improvements - 1st Comparison

The implementation of these parameters alone would result in a decrease in performance of about 12% compared to the current real case. However, in order to further enhance this improvement, it is also necessary to implement the nighttime shutdown logic. Specifically, it is proposed to shut down the system at 7:00 PM and restart it at 6:30 AM for the months from January to June and from September to December.

	Real Case	Tank, AHUs, Night switch-off Improvements
Heating [kWh]	38'255	7'622
Cooling [kWh]	246'798	173'854
Fans [kWh]	145'252	98'539
Pumps [kWh]	17'145	9'008

Table 5.7: Improvements - 2nd Comparison

A decrease of 80% in heating consumption can be observed, a result primarily attributed to the implementation of night shutdown logic. The latter alone contributes to a big improvement, without which the overall benefit would be limited to 23%. In this specific context, with a relatively minor participation, there is also a reduction in both the temperature of the thermal storage tank and the supply temperature to the VAV. This observation is consistent with our findings. As highlighted in the 'Bills' chapter, the system exhibited elevated nighttime consumption even during periods of building vacancy. Consequently, anticipating significant improvements during these intervals (F2 and F3) is a logical expectation.

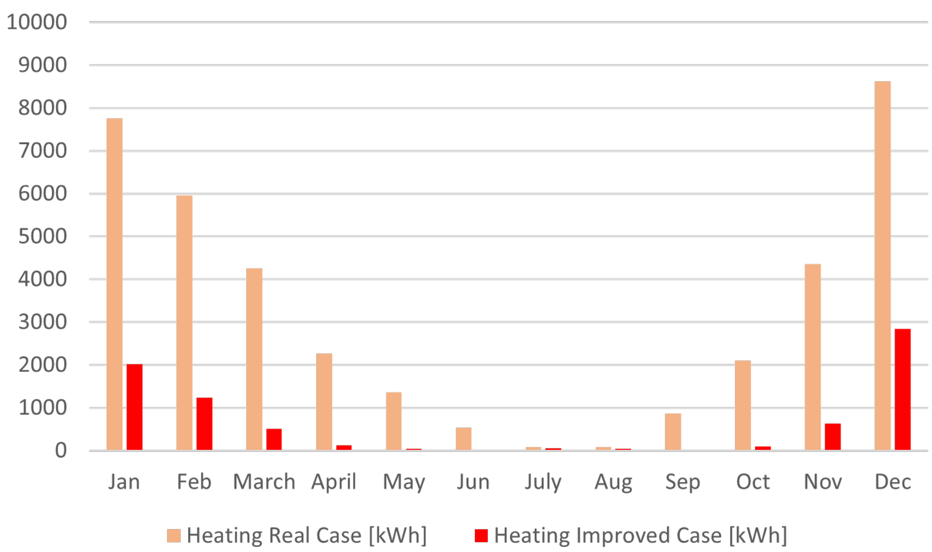

Figure 5.4: Heating Loads Real Case vs Improved Case

As for cooling, the improvement is primarily attributable to the increase in the cold tank temperature from 7 to 11 °C, leading to a 20% reduction in energy consumption. The nighttime shutdown programming, unalterable during the months of July and August (peak periods of cooling demand), further contributes to raising the percentage improvement to 30%.

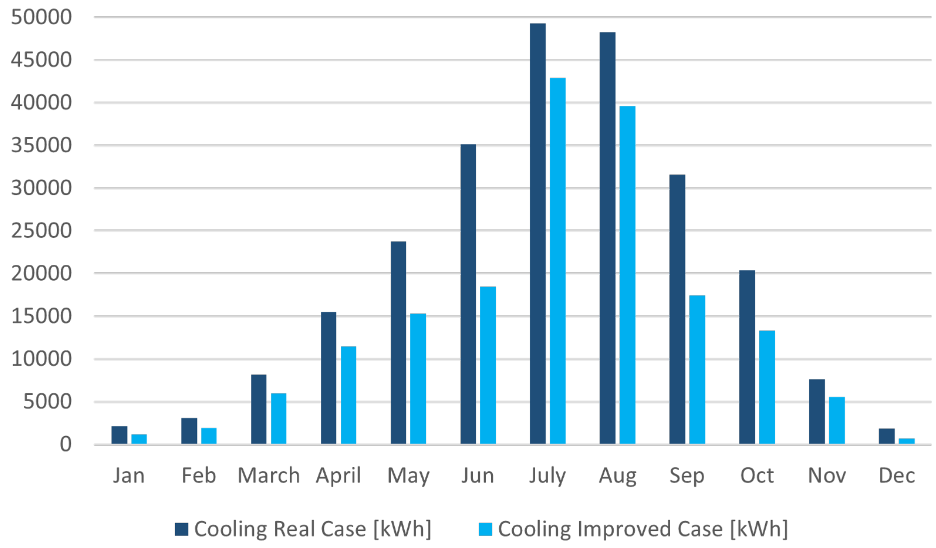

Figure 5.5: Cooling Loads Real Case vs Improved Case

The continuous use of fans would result in practically constant energy consumption, as the amount of treated air remains unchanged. On the other hand, by introducing a night shutdown logic, an improvement in performance of up to 32% can be achieved.

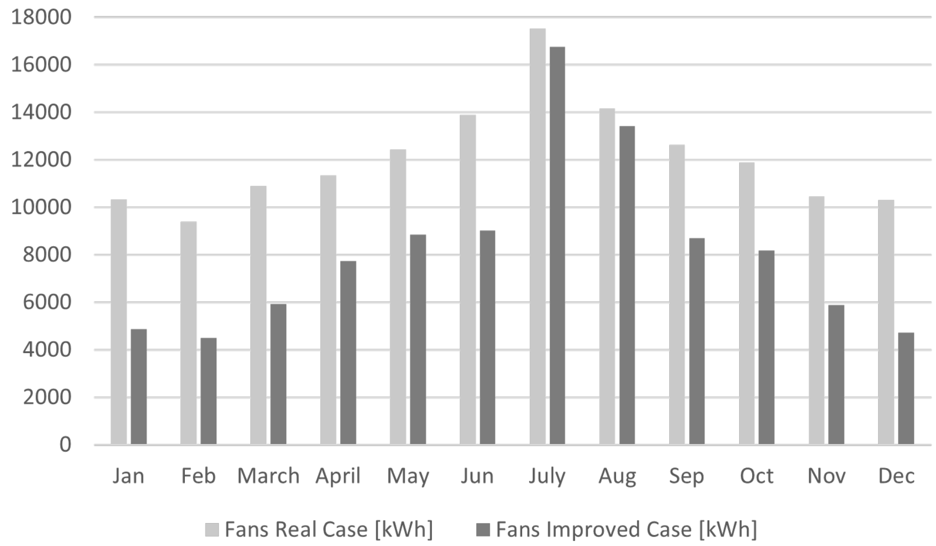

Figure 5.6: Fans Consumption Real Case vs Improved Case

The consumption of pumps, due to the lower temperatures of the tanks, would show an increase of 8%, as the water flow required by the coils is higher, without the application of the nighttime shutdown logic. In the presence of the aforementioned operational logic, on the other hand, a reduction of 48% is observed compared to the original scenario.

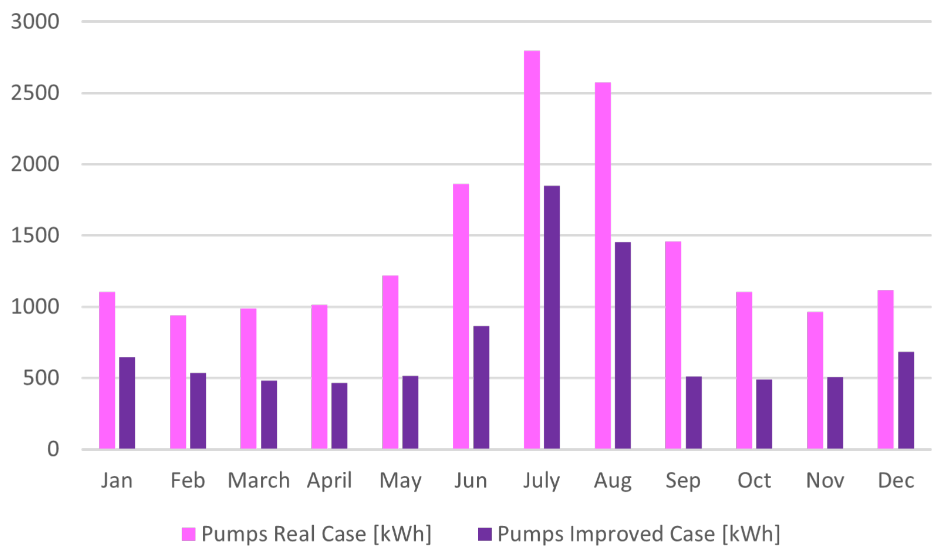

Figure 5.7: Pumps Consumption Real Case vs Improved Case

In summary, the integration of these improvements results in an annual energy savings of **158'427** kWh exclusively for the air conditioning system, with a **35%** reduction in consumption compared to the Real case.

6 | Conclusions

6.1. Project Feasibility

The conducted analysis aims primarily to assess the feasibility and effectiveness of the proposed intervention, ensuring that it is not only valid from a theoretical standpoint but can also be successfully and advantageously applied in practice. It is crucial to ensure that any improvement suggestions resulting from retro-commissioning are not merely theoretical but can be effectively implemented, producing tangible results. The effectiveness of this intervention is not limited to a significant reduction in the energy consumption of the HVAC system, amounting to 35%, but also extends to its implementation without requiring structural modifications. The key to success lies in the ability to make significant improvements through optimal adjustment of operational parameters, avoiding the need for massive investments or component replacements. It should be emphasized that, despite the HVAC system representing only 20% of the total building energy consumption, optimizing it constitutes a strategic element in holistic energy management. The sustainability of a building requires careful and targeted management of all its systems, and retro-commissioning presents itself as the ideal approach to achieve this goal. The relevance of this project further emerges considering its potential to be extended to other sectors, such as lighting, without requiring substantial modifications to the existing infrastructure. This non-invasive approach not only simplifies implementation but also promotes the replicability of the project in different contexts, thereby contributing to the dissemination of best practices in the field of building energy efficiency.

6.2. BEMS Data Collection Critique

One of the crucial aspects in assessing the energy efficiency of a building is the accuracy of data collected through the Building Energy Management System. This system plays a fundamental role in monitoring and controlling the energy consumption of the building, providing crucial data for evaluating performance in terms of sustainability. However, during retro-commissioning analysis, a significant issue has arisen regarding the fidelity of recorded data. Some sensors appear to be afflicted by anomalies that compromise the accuracy of the data recorded by the DESIGO software. This has significant impacts on energy performance assessments, leading to potential overestimation or underestimation of the actual efficiency of the building. Such errors in data recording not only introduce uncertainties in the overall assessment of energy performance but can also influence strategic decisions regarding energy consumption optimization. Relying on unreliable data can result in suboptimal investments and ineffective resource management.

To address this issue, a thorough analysis of the affected sensors is recommended, along with the implementation of regular maintenance procedures to ensure their proper functionality over time. It is also advisable to periodically monitor the quality of the collected data. Additionally, it is important to note that initially, the BEMS system was expected to meticulously record and archive data from its launch three years ago. However, due to unforeseen technical issues and obstacles encountered along the way, data from only the last year has been obtained. It is equally important to emphasize that assigning the management of such a complex and technologically advanced building to staff without prior experience with these types of structures can lead to operational inefficiencies and a limited ability to fully exploit the potential of BEMS systems. Before assigning the management of such a complex building, it is advisable to provide staff with specific, both theoretical and practical, training focused on understanding and using the BEMS systems employed in the building in question. In addition to initial training, periodic update sessions and a direct communication channel with system experts would be necessary.

6.3. nZEB Critique

In recent years, there has been a growing interest in the energy efficiency of buildings, with the aim of reducing consumption and greenhouse gas emissions. In this context, there is increasing reference to NZEB buildings, or near-zero energy buildings, which have very low or no energy requirements, covered to a significant extent by energy from renewable sources. As of January 1, 2021, the near-zero energy buildings (NZEB) requirement has been established in Italy for all new construction or work involving demolition and subsequent reconstruction. In some regions, such as Lombardy, this obligation has been brought forward and as early as 2016 all new buildings must be NZEB [34]. Reading the definition of a "nearly zero-energy building" in the European Directive 2010/31/EU [35], also called EPBD, one can understand how it is defined as a *"building with very high energy performance...* whose *...very low or nearly zero energy requirements should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on site or nearby"*. It is therefore clear that the achievement of this goal is directly dependent on the incorporation of renewable energy sources within buildings.

However, despite the good will and efforts to achieve the standards imposed, some concrete cases highlight the inherent challenges of this ambitious perspective [36]. A prime example is the case under review, which, despite the installation of as many as 656 solar panels on its roof, manages to cover only a small percentage of the facility's total energy consumption. This circumstance, although emblematic, raises important questions about the real impact and economic and environmental sustainability of nZEB buildings.

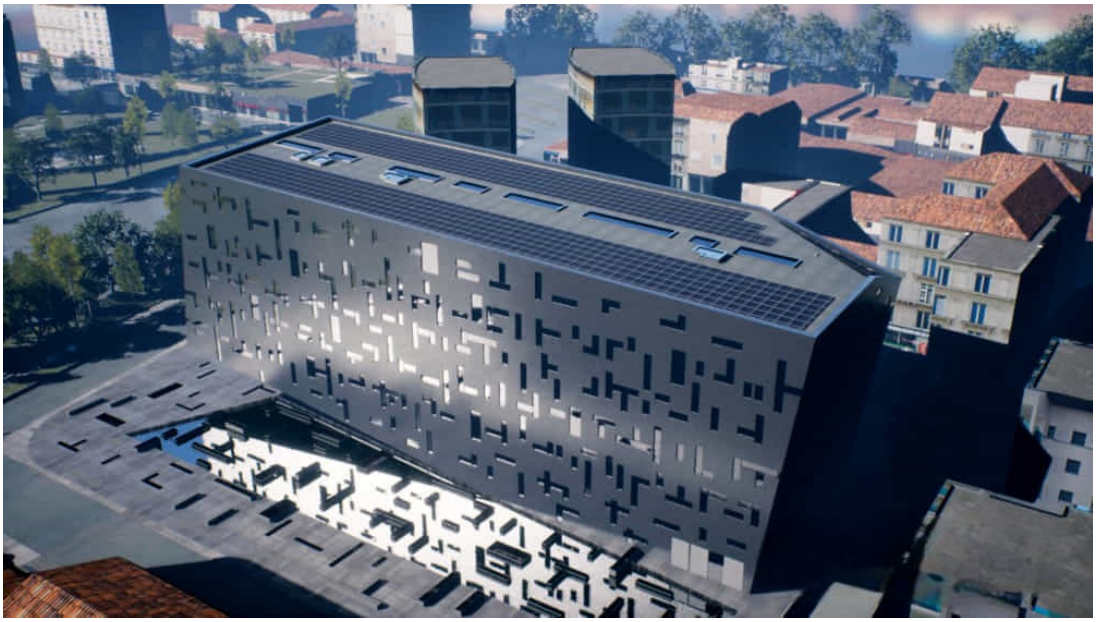

Figure 6.1: Roof View of the building

	Electric Bills [kWh]	PV Production [kWh]	PV Production [%]
Jan.	160'317	5'878	3,67
Feb.	130'580	10'878	8,33
March	150'097	18'556	12,36
April	135'200	24'766	18,32
May	157'380	25'970	16,50
June	165'971	29'736	17,92
July	184'080	31'698	17,22
Aug.	171'964	27'652	16,08
Sep.	177'597	21'055	11,86
Oct.	157'327	12'420	7,89
Nov.	160'738	7'204	4,48
Dec.	168'382	3'549	2,11

Table 6.1: Percentage of Photovoltaic Production to Global Electricity Consumption

When comparing the photovoltaic production to the annual estimate of consumption for air conditioning it would only cover 62,5%.

HVAC Consumption [kWh]	PV Production [kWh]	PV Production [%]
350'928	219'361	62,5

Table 6.2: Percentage of Photovoltaic Production to HVAC Electricity Consumption

One possible approach to addressing critical issues of this kind could be to take a broader view, considering the building not as an isolated entity but as part of an interconnected system. This is where solutions such as "district heating" for example, a centralized thermal energy distribution system that allows heat to be supplied to different buildings and utilities through a shared network, come into play. Milan's neighborhoods would be ideal candidates for the implementation of such a system, whether 4 or 5 generation [37]. Building density, combined with high heating requirements during the winter months, creates a fertile environment for the success of this technology. However, this technology has advantages and disadvantages [38]. Its main virtue lies in its superior energy efficiency compared to decentralized systems. By centralizing heat production, resource use is optimized, making the most of the thermal potential of primary sources such as biomass, geothermal, or thermal power plants. This results in a significant reduction in carbon emissions, thus contributing to efforts to combat climate change. In addition, because district heating systems serve a larger area, the cost of the energy source can be spread out among more users, resulting in lower individual costs. However, its implementation and maintenance is not without challenges. It requires considerable initial investment, involving the construction of central facilities and the laying of a distribution network. Logistical complexity is another critical consideration: coordinating the installation of a district heating network in a densely populated urban area may require detailed planning and close cooperation between public and private entities. Involving and educating the local community is a critical step, but it can require significant time and effort.

To draw a conclusion, it is critical to recognize that the success of near-zero energy buildings cannot be achieved without a holistic view of the context in which they are embedded. The integration of district-level solutions is a significant step toward energy efficiency and long-term sustainability, allowing us to overcome the limitations that can arise in the individual building approach. Only through careful analysis and judicious design at the district level can the goal of near-zero energy buildings that are sustainable, efficient, and cost-effective for the local community truly be realized.

6.4. LEED Critique

LEED (Leadership in Energy and Environmental Design) certification [39] represents a prestigious achievement in the field of sustainable building and energy efficiency. This international certification system was developed by the U.S. Green Building Council (USGBC) and has established itself as one of the most globally recognized standards for assessing the environmental performance of buildings. Its main objective is to promote the design, construction and operation of sustainable buildings that have minimal impact on the environment. The importance and universal recognition of this certification is amply evident from the fact that in 2022 it passed the significant threshold of 100'000 certifications worldwide. In Italy there is a total of 592 certifications obtained, including 96 in 2022 alone, placing it ninth in the annual ranking [40]. As mentioned earlier the building studied can claim to have achieved Gold certification by the LEED program. This is an achievement of great significance, as only 372 buildings in Italy can boast such an achievement [41].

Obtaining the prestigious LEED Gold certification is a significant milestone in a building's commitment to sustainability and energy efficiency. However, it is critical to recognize that the path to sustainability does not end with the seal of approval. It is necessary to ensure that the high standards set by the certification are actually met over time. During the retro-commissioning analysis, a number of errors emerged that deserve special attention (see the problems found in *Data Collection* [42]), hence the importance of implementing a post-certification monitoring system allows early identification of any deviations from the established standards and prompt action to correct them. Only then can the standards of efficiency and sustainability represented by LEED Gold certification be ensured for the building.

It is crucial at the same time to recognize how the burden of ensuring compliance with certification standards should not fall solely on the end user who very often does not have the expertise or resources necessary to accurately assess the detailed operation of a building and detect any deviations from established standards. Certifiers, with their specialized expertise, are in a privileged position to assess and monitor a building's adherence to LEED requirements. It is they who, through careful oversight, can ensure that the building maintains sustainability standards over time, thereby protecting the initial investment and promoting long-term sustainable operation.

6.5. Retro-Commissioning Checklist

The implementation of a retro-commissioning process is a crucial phase that requires a methodical and detailed approach. This process serves as the cornerstone of an effort to ensure that the building achieves and maintains optimal performance, fully leveraging its potential. Therefore, to provide comprehensive and efficiency-oriented guidance, a set of fundamental points has been developed as a basis for conducting a retro-commissioning analysis. These parameters, derived from a synthesis of practical experience and the analysis of example cases, serve as guiding pillars for a thorough and in-depth investigation. This carefully balanced plurality of focuses allows for the attainment of a comprehensive framework that meets the specific needs of the building and, simultaneously, contributes to a sustainable optimization of energy resources.

- **Staff Training:** A fundamental element for the success of retro-commissioning is the training of involved personnel. A thorough understanding of the implemented changes and new strategies is crucial. The goal is to ensure that the staff can effectively manage the Building Energy Management System and respond promptly to any operational issues. Training should be ongoing, keeping the staff up-to-date with new technologies and industry best practices.

- **Verification of Proper Operation:** Before delving into detailed analysis, it is imperative to ensure that all system components are functioning optimally. This verification phase represents an essential starting point for the success of retro-commissioning. Any malfunction or inefficiency must be addressed before proceeding further, ensuring that the entire system operates at its maximum potential. For example, in the cited case study, a previous issue with the ventilation system dampers was identified. Timely correction of such issues is essential to ensure the accuracy of the conducted analysis.

- **Sensor Validation:** In a BEMS, data reliability is of crucial importance. Sensor validation ensures that real-time recorded data accurately reflects the actual building performance. This is a critical step to ensure a reliable database for energy management decisions. Regular sensor maintenance and calibration are additional key elements in this phase. However, as previously highlighted, it is not uncommon for some data to be missing or incorrect, so engineering judgment is necessary to verify the accuracy of monitored data through sensor and recorded data analysis.

- **On-Site Verification:** Before proceeding with the modeling phase, it is essential to verify that theoretical parameters align with those measured on-site. This on-site analysis provides further verification of consistency between theory and reality, identifying any deviations to be corrected. On-site verification not only represents an essential checkpoint to ensure the reliability of collected information but also an opportunity to identify any unforeseen issues or variations, allowing for a refined customization of plant optimization strategies.

- **Modeling:** With the confirmation of the operational efficiency of the real system, the construction of an energy simulation model is undertaken. This model represents a virtual replica of the building and its system, enabling detailed simulations. Modeling provides valuable predictive insight, allowing for the assessment of the potential impact of proposed changes before they are physically implemented.

- **Analysis:** Finally, the analysis phase is the point where all collected information and actions taken are evaluated in terms of success and impact. The central question to answer is: has everything done led to significant improvements? The analysis should consider both technical and economic aspects, ensuring that retro-commissioning not only optimizes energy performance but is also financially sustainable.

In conclusion, the implementation of a retro-commissioning process emerges as a crucial step in the optimized management of buildings, ensuring that energy performance is maximized sustainably. Through a detailed methodology encompassing staff training, operational verification, sensor validation, on-site verification, modeling, and analysis, a comprehensive and efficiency-oriented approach is created. The interconnection of these phases provides comprehensive guidance, allowing for the identification and resolution of inefficiencies, contributing not only to improving building performance but also ensuring long-term economic sustainability. Investing in retro-commissioning proves to be not only an advanced technical strategy but also a financially wise decision, positioning the building on the path of continuous energy optimization and responsible resource management.

6.5.1. Non-BEMS Building

While the Building Energy Management System is a resource of fundamental importance for monitoring and advanced management of energy consumption in many modern buildings, it is equally essential to apply highly effective analysis methods even in contexts where such a system is not implemented. A crucial element that undoubtedly distinguishes a building equipped with a BEMS from one without such a system lies in the ability to conduct a detailed analysis of the operational data of various components. Unlike a non-BEMS environment, BEMS provides an advanced platform that allows real-time monitoring and in-depth analysis of energy consumption, providing an unprecedented level of granularity in understanding and optimizing resource use. However, it is important to emphasize that even in the absence of a BEMS, highly satisfactory results can be obtained in the analysis of energy consumption.

Initially, staff training remains a cornerstone, although the focus should shift towards understanding traditional control systems, such as individual thermostats and manual controls of heating, ventilation, and air conditioning systems. Verifying proper operation, the first crucial step in retro-commissioning, assumes an even more significant role in a context without a centralized BEMS. In this scenario, it is crucial to ensure that each component operates efficiently, identifying and addressing any malfunctions or inefficiencies. Maximum attention should be devoted to the calibration and regular maintenance of systems since the centralized control provided by a BEMS is not available.

The validation of sensors continues to be a critical step, although the approach may vary. In a building without a BEMS, data collection may be based on manual measurements and independent monitoring tools. A first solution could be, for example, the simple estimation of consumption. Using common tools like Excel, it is possible to estimate and record when specific electrical components are turned on or off throughout the day, taking into account consumption variations during different time periods. This method, if applied with precision and systematicity, can provide a solid starting point for optimizing energy performance. A second solution could be the use of devices such as the Shelly EM [43], a cutting-edge tool that proves particularly effective in the analysis and monitoring of the energy performance of a building. It can precisely measure the current and voltage of an electrical network, providing reliable data on electricity consumption in various settings, from home management to in-depth analysis of the energy needs of more complex structures.

On-site verification also assumes a more relevant role in a building without a BEMS, as it represents the only means to ensure that actual parameters align with theories and reference standards. Field analysis becomes crucial to identify critical issues and variations, providing an accurate basis for customizing optimization strategies. Modeling, while inherently more complex in the absence of a BEMS, and subsequent comprehensive analysis can be considered substantially analogous to the previous context.

Bibliography

[1] International Energy Agency. Buildings. 2023. https://www.iea.org/energy-system/buildings.

[2] Italy for Climate. Gli edifici in italia sono i primi consumatori di energia, 2022. https://italyforclimate.org/gli-edifici-in-italia-sono-i-primi-consumatori-di-energia/.

[3] Climate Transparency. Climate transparency report 2022. https://www.climate-transparency.org/media/italy-country-profile-2022.

[4] Council of the European Union. Fit for 55, 2023. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/.

[5] European Union Parliament. European directive 2010/31/ue, 14/03/2023 modified version. https://www.europarl.europa.eu/doceo/document/TA-9-2023-0068_EN.html.

[6] Council of the European Communities. Council resolution of 17 december 1974. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A31975Y0709%2802%29.

[7] M. Economidou, V. Todeschi, P. Bertoldi, D. D'Agostino, P. Zangheri, and L. Castellazzi. Review of 50 years of eu energy efficiency policies for buildings. *Energy and Buildings*, 225:110322, 2020. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2020.110322. URL https://www.sciencedirect.com/science/article/pii/S0378778820317229.

[8] Council of the European Communities. Council directive 92/42/eec, 1992. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=celex%3A31992L0042.

[9] Council of the European Communities. Council directive 93/76/eec, 1993. https://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A31993L0076.

[10] Italian Republic. Legge 9 gennaio 1991, n. 10, 1991. https://www.gazzettaufficiale.it/eli/id/1991/01/16/091G0015/sg.

[11] María Herrando, David Cambra, Marcos Navarro, Lucio de la Cruz, Gema Millán, and Ignacio Zabalza. Energy performance certification of faculty buildings in spain: The gap between estimated and real energy consumption. *Energy Conversion and Management*, 125:141–153, 2016. ISSN 0196-8904. doi: https://doi.org/10.1016/j.enconman.2016.04.037. URL https://www.sciencedirect.com/science/ar

ticle/pii/S0196890416302783. Sustainable development of energy, water and environment systems for future energy technologies and concepts.

[12] T. Magraner, Á. Montero, S. Quilis, and J.F. Urchueguía. Comparison between design and actual energy performance of a hvac-ground coupled heat pump system in cooling and heating operation. *Energy and Buildings*, 42(9):1394–1401, 2010. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2010.03.008. URL https://www.sciencedirect.com/science/article/pii/S037877881000085X.

[13] Dong-Bae Kim, Daeung Danny Kim, and Taeyeon Kim. Energy performance assessment of hvac commissioning using long-term monitoring data: A case study of the newly built office building in south korea. *Energy and Buildings*, 204:109465, 2019. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2019.109465. URL https://www.sciencedirect.com/science/article/pii/S0378778819315609.

[14] Pieter de Wilde. The gap between predicted and measured energy performance of buildings: A framework for investigation. *Automation in Construction*, 41:40–49, 2014. ISSN 0926-5805. doi: https://doi.org/10.1016/j.autcon.2014.02.009. URL https://www.sciencedirect.com/science/article/pii/S092658051400034X.

[15] Stefano Cozza, Jonathan Chambers, Chirag Deb, Jean-Louis Scartezzini, Arno Schlüter, and Martin K. Patel. Do energy performance certificates allow reliable predictions of actual energy consumption and savings? learning from the swiss national database. *Energy and Buildings*, 224:110235, 2020. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2020.110235. URL https://www.sciencedirect.com/science/article/pii/S0378778820303315.

[16] Liping Wang, Steve Greenberg, John Fiegel, Alma Rubalcava, Shankar Earni, Xiufeng Pang, Rongxin Yin, Spencer Woodworth, and Jorge Hernandez-Maldonado. Monitoring-based hvac commissioning of an existing office building for energy efficiency. *Applied Energy*, 102:1382–1390, 2013. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2012.09.005. URL https://www.sciencedirect.com/science/article/pii/S0306261912006459. Special Issue on Advances in sustainable biofuel production and use - XIX International Symposium on Alcohol Fuels - ISAF.

[17] Daniel Coakley, Paul Raftery, and Marcus Keane. A review of methods to match building energy simulation models to measured data. *Renewable and Sustainable Energy Reviews*, 37:123–141, 2014. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2014.05.007. URL https://www.sciencedirect.com/science/article/pii/S1364032114003232.

[18] E.H. Borgstein, R. Lamberts, and J.L.M. Hensen. Mapping failures in energy and environmental performance of buildings. *Energy and Buildings*, 158:476–485, 2018. ISSN 0378-7788. doi: https://doi.org/10.1016/j.enbuild.2017.10.038. URL https://www.sciencedirect.com/science/article/pii/S0378778817322132.

[19] M. Miara, D. Günther, R. Langner, S. Helmling. Efficiency of heat pumps in real operating conditions – results of three monitoring campaigns in germany. https://www.researchgate.net/publication/265241583_Efficiency_of_Heat_Pump

s_in_Real_Operating_Conditions_-_Results_of_three_Monitoring_Campaigns_in_Germany.

[20] Mohamed Elsayed, Sofie Pelsmakers, Lorenza Pistore, Raúl Castaño-Rosa, and Piercarlo Romagnoni. Post-occupancy evaluation in residential buildings: A systematic literature review of current practices in the eu. *Building and Environment*, 236: 110307, 2023. ISSN 0360-1323. doi: https://doi.org/10.1016/j.buildenv.2023.110307. URL https://www.sciencedirect.com/science/article/pii/S0360132323003347.

[21] Yiqun Pan, Mingya Zhu, Yan Lv, Yikun Yang, Yumin Liang, Ruxin Yin, Yiting Yang, Xiaoyu Jia, Xi Wang, Fei Zeng, Seng Huang, Danlin Hou, Lei Xu, Rongxin Yin, and Xiaolei Yuan. Building energy simulation and its application for building performance optimization: A review of methods, tools, and case studies. *Advances in Applied Energy*, 10:100135, 2023. ISSN 2666-7924. doi: https://doi.org/10.1016/j.adapen.2023.100135. URL https://www.sciencedirect.com/science/article/pii/S2666792423000148.

[22] CAP Group. https://www.gruppocap.it/it/il-gruppo/chi-siamo/headquarters.

[23] Photo by "duepiedisbagliati". https://blog.urbanfile.org/2023/02/17/milano-barona-moncucco-cantiere-arca-di-via-rimini-febbraio-2023/.

[24] Gazzetta Ufficiale della Repubblica Italiana. Decreto Legislativo 19 agosto 2005, n. 192. https://www.gazzettaufficiale.it/eli/id/2005/09/23/005G0219/sg.

[25] Regione Lombardia. Decreto 2456/2017, . https://www.regione.lombardia.it/wps/portal/istituzionale/HP/DettaglioAvviso/servizi-e-informazioni/cittadini/Tutela-ambientale/impianti-termici-edilizia-sostenibile-e-certificazione-energetica/integrazioni-alle-disposizioni-per-efficienza-energetica-degli-edifici/integrazioni-alle-disposizioni-per-efficienza-energetica-degli-edifici.

[26] Technical-illustrative and calculation report of the mechanical, plumbing, electrical systems realized in the new headquarters of CAP Holding, Milan.

[27] Research Markets. Building Energy Management Systems (BEMS) - Global Strategic Business Report. https://www.researchandmarkets.com/report/building-energy-management-system?gclid=Cj0KCQjwpc-oBhCGARIsAH6ote-.

[28] Desigo Software, . https://www.siemens.com/it/it/prodotti/buildingtechnologies/automation/desigo/building-management.html.

[29] Hao Gao, Christian Koch, and Yupeng Wu. Building information modelling based building energy modelling: A review. *Applied Energy*, 238:320–343, 2019. ISSN 0306-2619. doi: https://doi.org/10.1016/j.apenergy.2019.01.032. URL https://www.sciencedirect.com/science/article/pii/S0306261919300327.

[30] Sketchup software. https://www.sketchup.com.

[31] Designbuilder software, . https://designbuilder.co.uk.

[32] Repository of free climate data for building performance simulation. https://climate.onebuilding.org/default.html.

[33] Center for the built environment (CBE) clima tool. https://clima.cbe.berkeley.edu/.

[34] Regione Lombardia. DGR n. 3868, 17/07/2015, . https://www.regione.lombardia.it/wps/portal/istituzionale/HP/DettaglioRedazionale/servizi-e-informazioni/Imprese/Imprese-edili-ed-estrattive/edilizia-sostenibile-e-certificazione-energetica/disciplina-regionale-efficienza-energetica-edifici/disciplina-regionale-efficienza-energetica-edifici.

[35] European Union. EU Directive 2010/31/EU. https://eur-lex.europa.eu/IT/legal-content/summary/energy-performance-of-buildings.html.

[36] N. Aste, C. Del Pero, F. Leonforte, R. S. Adhikari . Pv ratio for deep renovation.

[37] Francesco Calise, Francesco Liberato Cappiello, Luca Cimmino, Massimo Dentice d'Accadia, and Maria Vicidomini. A comparative thermoeconomic analysis of fourth generation and fifth generation district heating and cooling networks. *Energy*, 284: 128561, 2023. ISSN 0360-5442. doi: https://doi.org/10.1016/j.energy.2023.128561. URL https://www.sciencedirect.com/science/article/pii/S0360544223019552.

[38] Andrew Lake, Behnaz Rezaie, and Steven Beyerlein. Review of district heating and cooling systems for a sustainable future. *Renewable and Sustainable Energy Reviews*, 67:417–425, 2017. ISSN 1364-0321. doi: https://doi.org/10.1016/j.rser.2016.09.061. URL https://www.sciencedirect.com/science/article/pii/S1364032116305585.

[39] LEED Rating System. https://www.usgbc.org/leed.

[40] U.S. Green Building Council. The top 10 countries for leed demonstrate that green building is a truly global movement, . https://www.usgbc.org/articles/top-10-countries-leed-demonstrate-green-building-truly-global-movement.

[41] U.S. Green Building Council. Country market brief report, . https://www.usgbc.org/resources/country-market-brief.

[42] U.S. Green Building Council. Leed advanced energy metering, . https://www.usgbc.org/credits/commercial-interiors-retail-commercial-interiors-hospitality-commercial-interiors/v4-draft/e.

[43] Shelly Italia. https://www.shellyitalia.com/.

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