UNIVERSITÀ DEGLI STUDI DI PADOVA

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Case study of HVAC system design with partial BIM integration

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Abstract

The reduction of greenhouse gas emissions and primary energy consumption have been among the most discussed topics in recent years. Within this context, the construction of new buildings, particularly the systems serving them, including Heating Ventilation and Air Conditioning (HVAC) systems, plays a significant role.

This paper presents a case study on the design of HVAC systems for a newly constructed building primarily dedicated to offices and meeting rooms. The objective was to combine the requirements for comfort and well-being within the indoor spaces with the goal of minimizing energy consumption and maximizing the efficiency of the developed systems.

The climate control is ensured by two versatile heat pumps capable of supplying the required thermal energy to various hydronic terminals, such as wall or floor-mounted fan coil units, as well as radiant floor and ceiling panels.

Regarding ventilation, three air handling units were designed to provide the necessary air volume for indoor air renewal and humidity control. Air volume regulators were integrated into the duct network to ensure the precise amount of air flow required.

In addition to these systems, a comprehensive control system was implemented to manage the numerous variables and diverse thermal demands that can occur within the building.

Simultaneously with advancements in machine technologies, there have been developments in software tools available to designers. In this project, the Building Information Modeling (BIM) approach was used. This tool was employed to create a three-dimensional model of the building and its systems, allowing for the association of parameters with objects, facilitating coordination among different workgroups, managing and resolving system interferences, extracting material quantities, and implementing a construction schedule.

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Introduction

In recent years, the impact of the built environment, specifically buildings, on the natural environment has been the subject of numerous studies and research efforts. It has also been at the center of debates, discussions, meetings, and conferences. The messages conveyed in this vast amount of data and information have not only sought to explain the nature of the problem but have also aimed to promote the concept of sustainability in various ways. These messages have encouraged initiatives, provided motivations, raised alarms about the consequences of ignoring the problem, and explained potential pathways to achieve sustainable projects.

Concerns regarding the building sector and its connection to energy-related issues are reflected in the numbers. Indeed, primary energy consumption has doubled since 1980 [1], and one-third of global energy consumption can be attributed to the building sector itself [2,3,4,5]. Without changes in design practices and approaches, there is a possibility that this share could rise to 50% [6].

Delving further into the topic and the statistics, it becomes evident that a significant portion of building-related energy consumption can be attributed to Heating Ventilation and Air Conditioning (HVAC) systems, which provide appropriate ventilation and climate control to buildings [7,8]. In particular, it has been estimated that HVAC systems are responsible for 40% of a building's energy usage [3], 50% of its electrical consumption [5], and approximately one-third of greenhouse gas emissions associated with building materials production and operational energy use [2,5].

In context of the aforementioned statistics, it becomes evident that there is a pressing need to reduce energy consumption and greenhouse gas emissions associated with buildings, particularly their subsystems, such as HVAC systems, given their significant contribution to energy consumption.

Improvements are needed for both existing buildings in need of renovations and new constructions. Existing buildings often require the replacement of certain components, such as generation devices or improvements in insulation, aimed at increasing the indoor comfort of occupants while simultaneously reducing the carbon footprint of the buildings [1]. Enhancing the energy efficiency of a building is undeniably a means to reduce emissions associated with it [9].

Concerning new construction, the need to design cutting-edge, technologically advanced systems is even more evident. There are typically no structural or systems constraints based on previously completed works, allowing for greater flexibility in design adjustments. This means that new buildings should be conceived with the latest available technological solutions in terms of energy efficiency from the very beginning of the design process.

In the last category, the case study of this work is located, in which it will be analyzed the design of the HVAC system of a newly constructed building located in Rosà, in the province of Vicenza.

The building in question will be spread over two underground levels and two above-ground levels, in addition to the roof, and will primarily be used to accommodate the company's offices and meeting rooms, as well as for organizing events, meetings, etc.

In relation to what was previously mentioned, the design choices have always aimed at minimizing energy waste and consumption, as well as selecting devices and components with a high level of energy efficiency chosen from the newest technologies available in the market, within the constraints of the budget and some strict requirements from the client.

Some examples of this include:

- Multifunction heat pumps for the production of hot and chilled water.
- Air handling units, inside which there is a rotary heat recovery unit.

- Heating and cooling of a large part of the building through radiant floor or ceiling systems.
- Ultrasonic VAV controllers for the regulation and control of ventilation airflow.
- Advanced electronic control systems.

In the following sections, these and other key components of the system will be presented in detail, along with the rationale for the design choices.

The technological development related to buildings doesn't stop at just reducing waste and energy consumption or designing highly efficient and high-performing systems. There's another aspect that has been gaining momentum in recent years, and that is the representation of buildings and their components in a 3D model capable of providing both a realistic graphical depiction and detailed characterization of the various elements. This technology is known as "Building Information Modeling" or BIM.

BIM is a tool that allows for the representation of a physical building as a comprehensive digital model [10], in which you can analyze the functional characteristics of the building. BIM is not merely a three-dimensional geometric representation; it also allows for the storage of a vast amount of data that is independent of the building's geometry. It enables the linking of various elements and the creation of useful documentation for project purposes [11].

From a practical point of view, BIM allows for the creation, management, and planning of projects, starting from the structure of a building down to the components of the systems that make up the building. These components could include things like air diffusers for ventilation systems or lighting fixtures for the lighting system.

The use of BIM becomes crucial in projects that involve multiple people from entirely different work teams because it facilitates better project sharing, streamlines coordination among various teams, reduces the chances of communication errors and misunderstandings, and minimizes potential conflicts [12,13,14].

In addition to these aspects, BIM enables constant updates regarding the building's structure and implemented systems, visible to all project stakeholders. This allows for the early detection of issues, such as clashes between the structure and the HVAC system [15], in the initial project phases, speeding up the design process and reducing costs and delays due to errors [14,16].

Other areas that make the use of BIM interesting include the ability to extract precise quantities of elements within the model, greatly simplifying cost estimation in subsequent phases and minimizing errors that could arise from manual counting on 2D files [10,14,17]. BIM also allows for the incorporation of specific parameters to manage the Work Breakdown Structure (WBS) of the project and the export of files in IFC (Industrial Foundation Classes) format for data and information exchange with various entities.

From an energy and sustainability perspective, BIM offers various facets for its use. It can range from calculating thermal loads once the structures and desired conditions within individual spaces are defined to providing information about the environmental impact of the building by implementing a series of parameters and metrics related to Life Cycle Assessment (LCA) [16,18] or LEED certifications [16,19]. BIM can also be used for cost-benefit analysis under varying fixed project conditions [20].

In relation to the previously analyzed case study, BIM files have been created for various disciplines (structural, architectural, hydraulic, HVAC, electrical) to facilitate better coordination among the various teams involved and all the other aspects mentioned earlier. This is done to simplify, as much as possible, the study and feasibility of the systems given the complexity of the building in question.

In this work, BIM has been primarily used for:

- Enhancing the project's graphics and layouts.
- Coordinating various workgroups.
- Facilitating the extraction of material quantities.

- Implementing the Work Breakdown Structure (WBS).
- Simplifying and expediting cost calculations.

What emerges from this work is, first and foremost, the presence of a multitude of design choices aimed at improving energy efficiency, optimizing system usage, and reducing consumption by simply selecting one element over another. However, it should be noted that some of these choices may be limited by economic considerations, given the current cost of certain equipment.

Secondly, it becomes evident that the use of a tool like BIM can assist in design from many perspectives, including graphical representation and numerous other opportunities that can arise once additional knowledge and skills are acquired in its use.

In conclusion, as mentioned earlier, the next step will be to employ this tool comprehensively, utilizing the additional possibilities it offers. There is still much to explore in its utilization by combining this resource with other specific software for energy and environmental analysis.

Chapter 1
Theoretical grounds

1.1 Basic concepts

HVAC (Heating, Ventilation, and Air Conditioning) systems are a fundamental part of the modern built environment, designed to ensure thermal comfort, air quality, and energy efficiency inside buildings.

Heating inside buildings is a vital process for the comfort of occupants during the winter season. An effective heating system utilizes various technologies, including boilers and various types of heat pumps, to transfer the necessary heat to the heat transfer fluid, which then powers the terminal units. These terminal units can include fan coil units, radiators, or heating through the perimeter surfaces of the structure. The primary goal is to ensure that the indoor temperature is maintained at comfortable levels, creating a welcoming and pleasant environment in which all planned activities can be carried out.

Ventilation is a fundamental aspect that concerns the quality of the air present in an environment. This process aims to replace stale air inside a building with fresh air from the outside. Additionally, ventilation helps manage humidity, control the presence of harmful gases for human health, and remove suspended particles in the air. Therefore, adequate ventilation is essential for the health and well-being of occupants.

The machines responsible for treating the air before introducing it into the environment are called AHUs, which stands for Air Handling Units. Inside these units, the air undergoes a series of transformations, including adjustments to temperature and humidity, before being discharged.

Air conditioning is responsible for controlling the temperature and humidity of the indoor air, especially during the summer season. This process involves cooling the air through either evaporation or the compression and expansion cycle of a refrigerant gas in split systems, or by using chilled water coils located in AHUs in air handling systems, or by using appropriate terminals as mentioned earlier for heating.

The distribution of heated and conditioned air is carried out through a network of ducts, which can be rectangular or circular in shape. It includes airflow regulators to maintain constant airflow or manage possible variations as needed, various types of diffusers, both in terms of shape and air distribution methods, and other devices that may be present, such as silencers.

This infrastructure is designed to ensure a uniform distribution of air in all areas of the building and to provide comfort for the occupants.

To determine the sizing of equipment and subsequently the distribution network for air and water, it is necessary, first and foremost, to understand the requirements of the structure for which an HVAC system will be developed.

To achieve this, there are various tools available in the market that can provide the load to be handled under various specified conditions, both internal and external. These tools are designed to facilitate the design process by helping engineers and designers understand the specific heating, cooling, and ventilation needs of the building or structure.

HVAC systems require control during their operation to adapt to the continuously changing conditions within indoor environments. The devices responsible for performing this control include thermostats, temperature and humidity sensors, CO_2 detectors, as well as occupancy sensors and control panels.

These instruments constantly monitor environmental conditions and adjust the system's operation based on the occupants' needs. There is an increasing trend toward the development of advanced automation that allows for optimized management of demands, adapting to climate variations, and aiming to minimize energy consumption and waste.

In connection with the last point mentioned, energy efficiency is crucial for reducing operating and management costs, as well as the environmental impact of HVAC systems. In recent years, there has been a growing development of systems and new machines aimed at increasing efficiency and reducing consumption. For example, the use of heat pumps instead of boilers or the installation of radiant floor or ceiling systems in place of traditional radiators are some of the advancements that have been made in pursuit of greater energy efficiency. These innovations not only help cut energy expenses but also contribute to reducing the environmental footprint of heating and cooling systems.

In conclusion, it can be stated that HVAC systems are among the fundamental components for ensuring the well-being of people in any environment, but they are also a source of energy consumption and environmental impact.

Therefore, it is evident that excellent system design, combined with the ongoing development of related technologies, is crucial to pursue the objectives of efficiency and sustainability that are now evident to all. This must be done without neglecting the comfort that needs to be provided to people.

1.2 Heat pumps and air handling units

A heat pump is a machine that allows the transfer of heat from a lower-temperature environment, known as the cold source, to a higher-temperature environment, known as the hot source, using a refrigerant fluid. From a functional perspective, a heat pump performs the same operation as a refrigeration machine, differing only in the fact that its primary purpose is to deliver heat to a higher-temperature environment, whereas in the case of a refrigeration machine, the desired effect is the removal of heat at a lower temperature.

According to the second law of thermodynamics, in order to perform this heat transfer, the machine requires a certain amount of external work. To make the working principle and the components of the machine as clear as possible, reference is made to Figure [1].

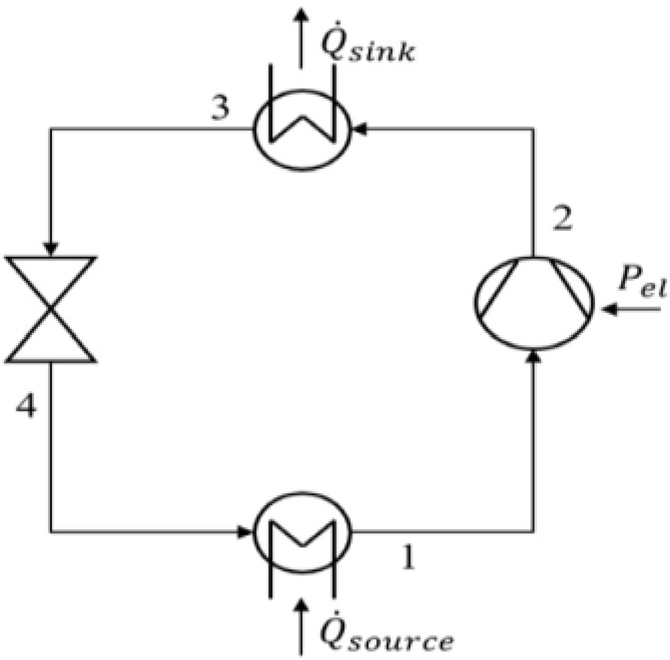


Figure 1 Operating cycle of a heat pump [21]

The useful effect of the heat pump will be the energy Qsink, which is equal to the sum of the energy extracted from the lower-temperature source, Qsource, and the work input, Pel, as represented by the following formula:

$$Q_{sink} = Q_{source} + P_{el}$$

The basic and main components required for the operation of a heat pump are the evaporator, the condenser, the compressor, and the expansion valve; additionally, refrigerant and connecting pipes are necessary. Heat pumps can typically operate in both heating and cooling modes, with the useful effect occurring at the condenser or evaporator, respectively; in this case, they are referred to as reversible heat pumps. In relation to the machine's performance, efficiency is defined as the ratio of the useful effect to the mechanical work at the compressor. Given the possibility of having two different operating modes, there are also two different ways to represent the efficiency, one for the winter case and one for the summer case: in the former, it is defined as the Coefficient of Performance (COP), calculated considering the heat supplied to the environment:

$$COP = \frac{Q_{sink}}{P_{el}}$$

while in the summer case, the parameter known as Energy Efficiency Ratio (EER) is defined, calculated considering the heat removed from the environment:

$$COP = \frac{Q_{source}}{P_{el}}$$

Both coefficients are strongly influenced by the temperature difference between the environment to be heated or cooled and the environment from which heat is extracted or released, respectively. As for the various existing types, these machines are classified according to the nature of the two sources, which can be air, water, and in some cases, even the ground.

The primary advantage of using air as an external source is that it is always naturally abundant and requires a lower initial investment compared to, for example, the ground, as it does not require a significant land area or excavation [22]. However, the variability of its temperature throughout the seasons can often reduce the efficiency of the heat pump.

In terms of energy performance, the heat pump stands as one of the most effective applications for achieving real energy savings, limiting air pollution and greenhouse gas emissions, as well as controlling the energy costs required for environmental conditioning. The increased efficiency of machines and systems that use electricity not only results in lower primary energy consumption but also leads to reduced greenhouse gas emissions [22,23].

The growing performance and advancements in technology over recent years provide further reasons to prefer heat pumps over gas boilers in heating and air conditioning systems.

An increasingly common type of heat pump, especially in the industrial sector, is the multifunctional heat pump, which is a machine that allows the simultaneous and independent production of hot and chilled water. The adoption of a single unit for both heating and cooling production helps overcome the complexities of traditional systems composed of chillers and boilers.

For buildings with a potential simultaneous demand for both heating and cooling, such as those with large glazed surfaces, especially during spring and autumn, it is reasonable to consider the idea of recovering the condensation heat from the refrigeration machine. This allows for the conservation of additional energy and, consequently, spending less and emitting fewer CO2 emissions into the atmosphere.

Multifunctional heat pumps are, therefore, very useful for meeting the needs of 4-pipe systems, as they involve combined production of hot and chilled water, with the unit operating as a chiller equipped with total heat condensation recovery. The transition from one configuration to the other occurs entirely automatically, thanks to an onboard microprocessor.

Another essential machine for air ventilation and conditioning systems is Air Handling Units (AHUs). Due to their great flexibility and capacity for ventilation and air conditioning, these devices are rarely standardized and are instead customized based on specific requirements. Their operation ensures high air quality, allowing control of both temperature and humidity, as well as air purification before it is introduced into the environment.

The integration of heat recovery systems into these devices makes them highly efficient, reducing energy consumption associated with ventilation. The ability to incorporate a precise and localized control system allows for complete machine control, integrating it with the building's overall system (Building Management System or BMS).

To further enhance the performance and efficiency of the machine compared to other air conditioning systems, it is possible to utilize free cooling, which involves taking advantage of naturally favorable outdoor air conditions for cooling without the need for mechanical refrigeration.

In Air Handling Units (AHUs), the correct selection of various components, their sizing, arrangement, and installation at the site of use are essential for the proper functioning of the unit. The main components include:

- Enclosure
- Fans
- Heat exchangers (heat recovery units)
- Filters
- Coils (heating and cooling coils)
- Humidifiers
- Control system

Each of these components plays a crucial role in ensuring efficient and effective air handling and conditioning within the unit, as well as maintaining air quality and comfort in the conditioned space.

The enclosure is the structural element that surrounds the Air Handling Unit (AHU). One of the most important factors is its airtightness, as it determines the quality of the indoor air within the AHU. The more airtight it is, the fewer unconditioned outdoor air infiltrations occur inside the unit.

The enclosure consists of three main elements: the panel, the profile, and the removable doors. The panel, typically constructed as a sandwich panel with an insulating layer (usually made of polyurethane or rock wool) sandwiched between two metal sheets, serves to seal the AHU and prevent energy losses through the enclosure. The profile, which is the structural framework of the unit, primarily prevents condensation from forming inside the AHU's framework. Lastly, the removable doors are necessary to provide access to various components of the unit, especially those requiring cleaning, maintenance, and periodic replacement.

The fans are responsible for conveying air through the unit and pushing it into the ducts and terminals for distribution into the environment. Proper sizing of fans is crucial to overcome the pressure losses that air experiences along its path. It's also important to consider that over time, these losses will increase due to wear and the accumulation of dirt in components like filters and coils. Therefore, it is advisable to apply a safety margin during the selection process to avoid problems with air distribution.

There are various types of fans. In the past, backward-curved centrifugal fans were commonly used, and occasionally forward-curved fans were employed. Backward-curved fans were preferred because they allowed for variable air volume, while forward-curved fans were less stable when pressure varied.

These traditional fan types have become practically obsolete and have been replaced by PlugFans, which are fans with an impeller mounted directly above a support and directly coupled to the motor. The motor can be either alternating current (AC) or electronically commutated (EC). In the case of AC motors, a variable frequency drive is needed to adjust the fan speed to match the installation's requirements. In contrast, EC motors do not require this equipment, as the speed can be easily adjusted using a 0-10V signal sent from the control system to the fan's electronic board, making them more versatile and efficient.

The primary element on which the energy efficiency of Air Handling Units (AHUs) relies is the heat recovery unit, responsible for recovering some of the energy from the previously conditioned indoor air and transferring it to the incoming untreated outdoor air. This enables ventilation while minimizing the energy loss associated with the process.

There are different types of heat recovery units: plate heat exchangers, rotary heat exchangers, and coil-based heat exchangers.

Plate heat exchangers recover only sensible heat, which can lead to drying of the indoor air in winter and introducing humidity from the outside in summer. They are suitable for applications where the building primarily has a sensible load.

Rotary heat exchangers consist of a rotating metal wheel that exchanges heat between the incoming and return air streams. They recover both sensible and latent heat, depending on the type of exchanger chosen. The existing types include condensation, enthalpy, and adsorption. In the first case, latent heat recovery occurs exclusively during the winter season. In the second case, the metal wheel is coated with a material capable of absorbing moisture, allowing latent heat recovery throughout the year. The third type is an improvement over the enthalpy exchanger, with a material on the wheel surface that captures moisture more effectively. This improvement often eliminates the need for a separate humidification section, particularly in most cases [9,24,25].

Special mention should also be made of the free cooling section, which involves using favorable external air conditions for air conditioning by introducing it directly into the indoor environment and bypassing the energy recovery unit, as its use is not necessary.

This operation can be performed by considering only temperature (thermal free cooling), only humidity (enthalpy free cooling), or by considering both (thermo-enthalpy free cooling).

The use of free cooling allows for energy savings and reduced reliance on mechanical cooling systems when outdoor conditions are suitable for cooling the indoor environment, ultimately contributing to improved energy efficiency and reduced operating costs in air handling units.

Essential elements to ensure air purity are the filters: they trap particles suspended in the air, reducing their concentration, and must always be present in the air intake section of the machine. The filtration required in the AHU is regulated by standards, depending on the quality of the outdoor air and the indoor air desired. There are different ways to classify filters, although all are based on the sizes of particles they can intercept. The most commonly used filters are those that use fiberglass as the filtering medium. There are also other types, such as activated carbon filters used to capture contaminating gases and odors, electrostatic filters, and filters with ultraviolet lamps for the elimination of biological contaminants.

Coils are the components responsible for transferring the thermal energy of the heat transfer fluid to the air through a heat exchanger consisting of pipes and fins. Typically, the tubes are made of copper, and the fins are made of aluminum.

Coils are classified into three types: water-based, direct expansion, or electric.

In the cooling coil, it is important to consider that if the air temperature drops below the dew point, condensation may occur. This potential occurrence necessitates the presence of a drip tray to collect the condensate in coils designed for this purpose.

To prevent water droplets from being entrained when condensation occurs, it is essential to size the section in such a way that the air velocity through the coil does not exceed 2.5 m/s.

The humidifier is the component, as the name suggests, responsible for increasing the water content in the air. There are different types of humidification devices, including the steam lance humidifier, which introduces high-pressure steam directly into the air handling unit (AHU), where water is atomized at high pressure inside the AHU. Another type is the adiabatic humidifier.

The steam lance humidifier primarily consists of a steam lance inside the machine and a device capable of producing steam, which can come from submerged electrodes, an electric resistance, or centralized steam production.

On the other hand, the adiabatic humidifier requires a longer module because the atomized water needs to evaporate before being absorbed by the air. Occasionally, the presence of a droplet separator at the end of the section may be necessary.

In the case of the adiabatic humidifier, the device consists of a panel, typically made of cellulose, into which water is introduced, and the air stream, passing through the section, absorbs the moisture from it.

In relation to the control system, given the continuous technological advancements, it is playing an increasingly important and central role in the proper functioning of machines. In particular, precise control is necessary here to adapt the operation of the various components of the HVAC system according to external conditions in order to achieve the desired comfort and hygiene conditions within the spaces.

To do this, a programmable controller is used to manage the operation of the machine, along with a series of peripheral elements whose number and type will depend on the configuration of the HVAC system and what needs to be measured and controlled (temperature, humidity, CO2, pressure, etc.).

What is particularly interesting is that the machine can be connected to the building's integrated control system (BMS), allowing for data management and monitoring during operation through a centralized system.

1.3 Overview of air conditioning units

Radiant heating is the oldest form of heating. With this type of system, heating of the spaces occurs differently from traditional methods as it modifies the thermal balance of the occupants. The operating temperature plays an important role and is adjusted to enhance the comfort of the occupants.

Panel-based heating systems experienced significant development in the 1970s due to advantages such as not taking up space in the rooms like other heating elements, low installation costs, and the ability to provide summer cooling as well. However, after a few years of success, the system was abandoned due to various design and implementation errors.

Fortunately, in recent years, thanks to a better understanding of the mechanisms that regulate human comfort and the introduction of new materials for the construction of the coils through which water flows, it has become possible to design and implement radiant heating systems more carefully. This has led to their increasing popularity, especially because they can also be used for summer cooling.

In the case of cooling, it is essential to pay close attention to the surface temperature of the panels, as it should not fall below the dew point temperature. Otherwise, condensation phenomena can occur, potentially causing damage to the environment where they are installed.

Among the main advantages of radiant heating and cooling systems compared to traditional convective air conditioning systems, can be found the recovery of space due to the absence of bulky heating elements, a reduction in technical space requirements compared to all-air systems, a lower indoor air temperature while maintaining the same level of comfort for people in the environment, as the mean radiant temperature increases at the same operating temperature. There is almost no noise and no air currents, and the water temperature for heating and cooling is respectively lower and higher, thereby offering energy savings [5,26,27].

This last aspect is of considerable importance as it allows for the pairing of this type of solution with a versatile heat pump instead of traditional gas boilers, which are more energy-consuming and polluting. Radiant systems, whether in the ceiling or the floor, represent the best combination with a heat pump and are capable of making the system as effective and cost-efficient as possible.

Focusing briefly on radiant floor heating, it is a built-in surface conditioning system through which water flows under design conditions, becoming increasingly popular in modern buildings [28] due to its superior comfort and lower energy consumption.

From a regulatory perspective, UNI EN 1264-4-2021 sets the following maximum values for floor surface temperatures:

- In occupied areas: 29°C
- In bathrooms: 33°C
- In marginal areas: 35°C

The distribution of temperature on the heated floor surface depends on construction methods and control techniques and is influenced primarily by:

- Spacing between the pipes
- Thickness and conductivity of the topping screed
- Thermal resistivity of the surface covering

As for radiant ceiling panels, there are essentially two techniques for their implementation: embedded serpentine pipes directly in the concrete slab or prefabricated panels suspended from the ceiling. The latter, being more modern, offers reduced thermal inertia, ease of installation, and simplicity of construction.

Compared to all-air systems, radiant ceiling panels result in lower energy consumption, primarily due to the reduced electricity demand for fans. They also provide improved environmental comfort and reduce noise levels. Further studies [29] suggest that this system is particularly suitable for offices, open spaces, and meeting rooms.

The most important technical aspect to consider is the supply water temperature for cooling the environment, which must always be higher than the dew point temperature to prevent the possibility of condensation: typical values are around 15-16°C. It is essential to have a ventilation system in place to ensure air circulation and to mitigate any potential humidity buildup [5].

Another common component in ventilation and air conditioning systems is fan coil units (FCUs), which can take various forms depending on the situation and requirements, such as wall-mounted, ceiling-concealed, cassette, or floor-mounted units.

In FCU-based systems, the thermal and humidity conditions of indoor spaces are regulated, either partially or entirely, by these units installed in the conditioned rooms. They typically consist of a multi-speed centrifugal fan, a filter section, a coil, and a condensate collection tray.

The coil, depending on the season and the type of system, can be supplied with either hot or chilled water and is responsible for heating or cooling the air drawn in by the fan.

You can find FCU systems with 2-pipe, 3-pipe, or 4-pipe configurations, depending on the building's characteristics, climate zone, or specific customer requirements, such as cost considerations.

From a functional perspective, a 4-pipe system is typically considered for buildings with large shaded glass surfaces, where both heating and cooling are required whenever the outdoor temperature is below the desired indoor temperature. This type of system generally has a higher initial cost but lower operating costs compared to 2- or 3-pipe systems.

FCUs can have either two-coil configurations, with two regulating valves on the hot and cold circuits controlled sequentially, or a single-coil configuration with a three-way non-mixing valve at the coil's inlet and a two-position diverting valve at the outlet.

Regarding outdoor ventilation air introduced into the environment, it is typically introduced through a series of ducts after being treated in a dedicated central unit. This also depends on the type of FCU in use. For example, a floor-mounted unit would require a system of ducts and diffusers for air distribution, while ducted FCUs can mix the ventilation air in a plenum downstream of the FCU, thus blending ventilation air with conditioned air and using the same terminals for air distribution in the space.

From a design perspective, the choice of one device over another depends on both the structural characteristics of the building and the technical specifications of the fan coil unit itself. For space considerations, one type may be preferred over another, or it may be a matter of aesthetic preference. However, from a technical standpoint, it is crucial to ensure indoor comfort. Therefore, the unit must be able to meet thermal requirements, be relatively quiet, especially in environments such as offices or meeting rooms, and ideally, it should not create a hydraulic circuit with excessively high pressure drops.

1.4 Control system

A crucial aspect for the proper functioning of air conditioning systems is their correct regulation. As is well known, the system sizing is typically done to handle the most extreme conditions that may occur. However, under normal operating conditions, the requirements are lower and continually vary over time. To maintain the desired comfort conditions within the indoor spaces, it is necessary to modulate the system's operation using an appropriate control system.

In modern buildings, the management of HVAC (Heating, Ventilation, and Air Conditioning) systems plays a crucial role, and one of the keys to optimizing the balance between energy efficiency and thermal comfort is the proper regulation of the system itself.

Thermal comfort and exposure to indoor air pollutants have a direct impact on the productivity and health of occupants. An environment with high thermal satisfaction promotes work efficiency, psychological well-being, and physical health. Therefore, optimized management of HVAC systems contributes to creating ideal comfort conditions [30].

In line with the above, what needs to be prevented is the so-called "Sick Building Syndrome" (SBS), which refers to a set of discomfort situations that can occur inside a building, leading to occupants' discomfort. SBS develops when indoor air contaminants accumulate, resulting in poor health and low productivity [7]. Exposure to air pollutants such as suspended particles (PM) and NO2 is associated with a wide range of adverse health effects, including cardiorespiratory mortality and chronic bronchitis. Reduced thermal comfort or poor indoor air quality pose health risks and negatively impact work performance [2].

One of the key parameters in HVAC system management is the temperature set-point. This value determines the desired indoor temperature and directly affects energy consumption. Optimizing this parameter, considering external conditions and occupant preferences, can lead to significant energy savings without compromising comfort [31].

However, discrepancies between predicted and actual energy consumption often result from occupant behaviors, highlighting the importance of occupancy-based control. Therefore, HVAC system management should take into account the actual occupancy conditions of spaces, which is one of the most influential factors in determining the actual requirements of such a system [32].

The adoption of occupancy-based control strategies allows real-time adjustment of HVAC system operation in response to the presence or absence of people in the environment. This reactive approach not only saves energy but also considers occupants' preferences and behaviors, facilitating the achievement of comfort in the environment.

The evolution of technology has made advanced sensors and automated management systems available for controlling HVAC (Heating, Ventilation, and Air Conditioning) systems. The adoption of sensors for measuring CO2 concentration, humidity, and indoor temperature, along with intelligent control systems, allows for real-time optimization of HVAC system management [4].

These technologies enable the adaptation of ventilation, heating, and cooling based on actual environmental conditions, significantly improving energy efficiency. Regarding these tools, their placement has a significant impact on thermal comfort and is essential for proper regulation within the environment.

Often, thermostats are positioned on walls far from occupants or in non-representative locations, which can lead to one of the main sources of discomfort due to the difference in temperature recorded by the instrument compared to what occupants actually perceive. Studies demonstrate that placing thermostats near occupants, for example, above a table in the center of the room, can significantly improve perceived conditions within the environment compared to placing them on a wall opposite an external window [33].

This approach can reduce the need for constant manual adjustment of set points and, as a result, reduce energy consumption due to incorrect adjustments.

The control of an HVAC system faces a complex challenge, which is to minimize energy consumption while maintaining thermal comfort and indoor air quality. The use of advanced algorithms such as Model Predictive Control (MPC) allows for balancing these needs by making optimal decisions in real-time. This is because MPC can impose strict constraints on decision variables or use multi-objective optimization algorithms that can simultaneously evaluate energy and comfort goals[3,34].

Chapter 2

Case study

After discussing the basic concepts and fundamental components of an HVAC system in a general manner, it is now time to delve into the specific case study at hand, which is the design of the heating, ventilation, and air conditioning system for a new building located in Rosà, in the province of Vicenza.

This building consists of two basement levels and two elevated floors, in addition to the roof, and features facades made of glass with appropriate shading to prevent excessive energy consumption.

Regarding the HVAC system, the building includes 2 air-to-water heat pumps for simultaneous hot and chilled water production, 3 air handling units (AHUs) for building ventilation, each serving specific zones, and 5 heat recovery units for air treatment in the basement levels, which are used intermittently. Specifically, the basement levels house a kindergarten and the reception area, due to technical difficulties that would have arisen if one of the 3 AHUs had been used to serve the reception.

Going into more detail, in the two basement levels, there are heat recovery units with their respective air outlets directly connected to ducts. On the ground floor, you'll find the kindergarten, which has a heat recovery unit and an underfloor radiant heating system. There's also the Academy, characterized by linear diffusers for ventilation, with a dedicated AHU, and fan coil units for cooling. Finally, there's the Reception area, which also has a heat recovery unit and two different types of fan coil units, floor-mounted in the lobby and wall-mounted in the meeting rooms.

On the first floor, dedicated to offices and meeting rooms, the system consists of a radiant ceiling and 1 or 2-slot linear diffusers to ensure air exchange, with 2 AHUs sharing the task, one for the east side and one for the west side.

The rooftop is dedicated to housing the thermal-refrigeration plant and the AHUs, with a green space that can be used for events or leisure activities.

Special mention should be given to the ventilation system in the Academy and on the first floor, as it has been designed to accommodate variable air demand throughout the day, and as a result, variable air volume (VAV) controllers have been installed.

These systems differ from constant air volume (CAV) systems in that, as the environmental requirements change, the regulation involves adjusting the air volume supplied rather than the temperature at the point of supply. The main advantage of this approach is that air volume is directed only to the areas of the building that require it. Consequently, the system will circulate a lower air volume, and the sizing of the air handling unit (AHU) will also benefit from this flexibility.

In essence, VAV systems provide more precise control and energy efficiency by delivering the right amount of conditioned air to each zone as needed, rather than operating at a constant flow rate regardless of demand. This leads to improved comfort and reduced energy consumption.

All design criteria for the HVAC systems are aimed at ensuring adequate comfort for the occupants while also placing a strong emphasis on sustainability, environmental considerations, energy efficiency, and waste reduction. Additionally, there is a focus on leveraging the latest technological innovations available in the market to make the building as efficient and cutting-edge as possible.

This approach reflects a commitment to creating a building that not only meets the needs of its users but also minimizes its environmental impact and operates in an energy-efficient and forward-thinking manner.

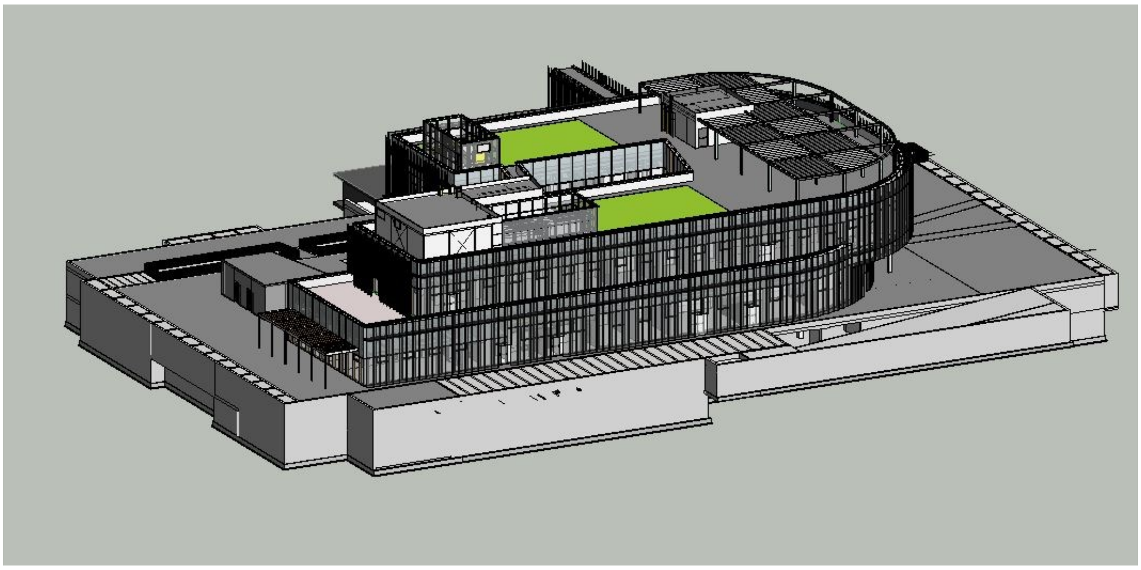


Figure 2 The building

2.1 Analysis of the thermal requirements of the building

The analysis of the thermal requirements of the building has been conducted using the MC4 Suite calculation software. This software is capable of determining the thermal demand of the structure throughout the year based on input parameters provided. It utilizes the TFM (Transfer Function Method) as per the ASHRAE Handbook from 1985.

First and foremost, it was necessary to create the building structure for which the thermal demand calculation would be performed, defining the building envelope to be considered.

Given the architectural complexity of the project, multiple building structures and openings (fenestrations) had to be defined.

Regarding the building structures, different structures were defined for various situations that could arise. This includes situations with different wall heights, different wall compositions, and the allocation of walls to specific zones within the building.

Similarly, for the floors, various types were created, taking into account factors such as the presence of raised or floating floors to accommodate plumbing or other requirements.

As for the fenestrations (windows and openings), different types were specified based on the size of the glazed areas, which could vary due to differences in floor heights (ground floor vs. first floor) and the presence or absence of specific solar shading devices.

Once the constituent components of the building envelope were defined, the actual structure was drawn in detail. This process allowed for the definition of the various spaces within the building, resulting in a total of 17 zones and 92 individual rooms.

Once the building structure was defined, the next step was to determine the possible internal loads within the spaces. This includes factors such as occupancy (both in terms of the number of individuals present and the amount of time spent), the presence of electronic devices that emit heat (such as PCs and monitors), lighting, and the building's orientation. All of these factors contribute to calculating the thermal loads in each room.

Expressing these concepts in numerical terms, here are the contributions considered for calculating the thermal requirements of the building:

- 65 W of sensible load per person present.
- 55 W of latent load per person present.
- 10-12 W/m^2 for lighting, depending on the type of lamp used.
- A variable contribution from equipment based on the presence of only PCs in the room or additional devices such as printers, projectors, etc.

The distribution of the hourly occupancy profile was created by hypothesizing possible occupancy schedules for the various spaces within the building. This involved creating different profiles for different room usages, with a predicted percentage of occupancy for each hour of the day.

As an example, in the office area, a 100% occupancy rate was assumed from 8 AM to 6 PM, indicating full occupancy of those spaces during regular working hours.

This approach to modeling occupancy profiles is crucial for accurately assessing the building's thermal and ventilation needs at different times of the day and week. It helps design an HVAC system that can adapt to varying occupancy patterns and maintain comfort and energy efficiency accordingly.

The same procedure has been carried out to account for the thermal load due to equipment and lighting. For example, in the office area, it was assumed that lighting would be at 100% only during the first hour of building usage and would then gradually decrease to 60% from 10 AM to 4 PM. Afterward, it would increase again and reach 100% only in the last hour. This approach takes into consideration the variations in lighting demand throughout the day, aligning it with expected external sunlight conditions.

Indeed, the goal was to simulate the building's behavior as closely as possible to reality to obtain accurate results. This approach avoids the error of over-sizing HVAC systems by considering situations of full occupancy and maximum use of lighting and equipment throughout the entire day. Each room is characterized by different hourly profiles for occupancy, lighting, and equipment based on its specific usage patterns.

For calculating the overall thermal requirements and subsequently sizing the HVAC terminals, it is necessary to define both the external environmental conditions and the internal conditions you want to maintain.

The project's external thermal and humidity conditions considered for the location in question are as follows:

- Summer: Dry bulb temperature of 35°C with a relative humidity of 50%.
- Winter: Dry bulb temperature of -7°C with a relative humidity of 80%.

Regarding the internal conditions, you have chosen to define temperature and humidity values for each zone based on its intended use.For example, in the basement-level storage areas, a dry bulb temperature of 29°C in summer and 15°C in winter has been set, while in the first-floor offices, the reference temperatures are 26°C and 21°C for summer and winter, respectively.

The humidity values are consistently 40% in winter but vary between 55% and 65% in summer, depending on the specific type of zone being considered.

Lastly, the software allows for the definition of the equipment used for air treatment and the production of hot and chilled water. You can specify these devices, indicating which zones they are intended to serve and providing other relevant technical input data. The software can then provide a form of sizing or capacity calculation based on the requirements it can assess.

Once the characteristics of the structure, the nature and quantity of thermal loads, the desired comfort conditions for each space, and the selected equipment have been defined, it is possible to initiate the calculation to determine the building's energy demand.

The software, based on the information provided, can calculate both the heating and cooling loads and provide the ventilation air flow rates for each zone, as well as more detailed calculations for each individual room.

The results are displayed in a report that presents all the geometric characteristics of each space, such as height, area, and volume, as well as its relationship with the surrounding areas, including the heat exchange surfaces and the magnitude of heat transfer. The report also includes internal loads and infiltrations. All of this information justifies the values of maximum summer and winter thermal loads, which are also specified based on the nature of each contributing factor.

Another representation of the results is available in an Excel file that can be exported from the software. This file provides key characteristics of each room and the summer and winter loads. It offers a convenient view for the designer who is primarily interested in the load values.

This mode is also very helpful for identifying and correcting errors. By quickly reviewing the values, anomalies can be spotted and subsequently addressed. For example, if there is an unusually high conduction load in a room located between two other conditioned rooms at the same temperature, it may indicate a potential error in the structural design.

Having this data in an easily accessible format in Excel allows for efficient troubleshooting and adjustment during the design process.

2.2 Design of HVAC system

The building in question, also referred to as "Corpo Q," will be a new construction project connected to the existing building structure. From an HVAC system perspective, it will be completely independent, meaning it will have its own system for generating thermal and refrigeration energy, typically in the form of a versatile heat pump.

The planned equipment will be of a leading brand and will rank at the top of their respective categories in terms of energy efficiency. The building's HVAC system design will allow for maximum operational flexibility, adapting air conditioning and ventilation services to the actual usage of the spaces and varying power demands.

For this reason, a 4-pipe system will be installed, capable of simultaneously producing hot and chilled water 365 days a year. This will enable the building to cool or heat spaces based on changing conditions such as solar radiation, occupancy levels, and more, particularly during transitional seasons.

Now, let's briefly analyze the HVAC design choices dedicated to each floor of the building and the respective macro areas into which they are divided.

2.2.1 Underground floors

The level -2 is primarily intended for a parking garage, but there will also be a room currently designated as storage and an archive space.

The storage room will be equipped with a mechanical ventilation system with heat recovery, featuring a hot water coil. Additionally, there will be provisions for heating through fan coil units in case the room's function changes in the future.

The archive space will only have a heat recovery unit with a hot water coil, and thus a hot water hydraulic line will be installed.

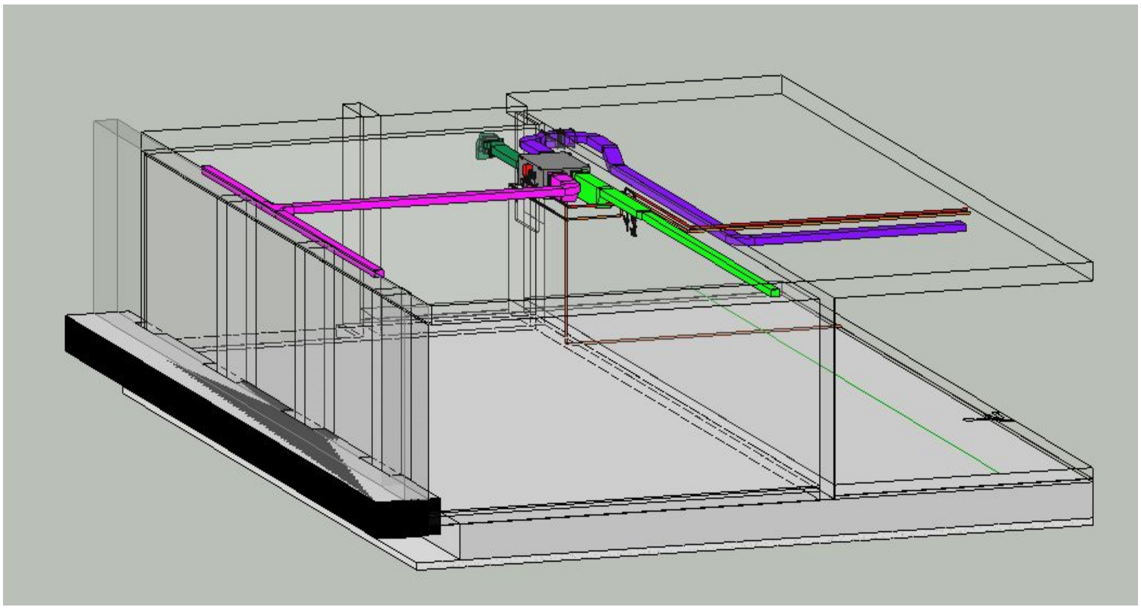


Figure 3 Level -2

The -1st floor, like the previous one, is primarily intended for a parking garage. It also includes technical rooms dedicated to the electrical systems within the building and a storage area. The technical rooms for electrical systems will be served by a standalone cooling system of the split type, with outdoor units positioned in the necessary ventilation openings for these spaces. The storage area will have the same HVAC setup as the corresponding room on the -2nd floor, including a heat recovery system with a hot water coil.

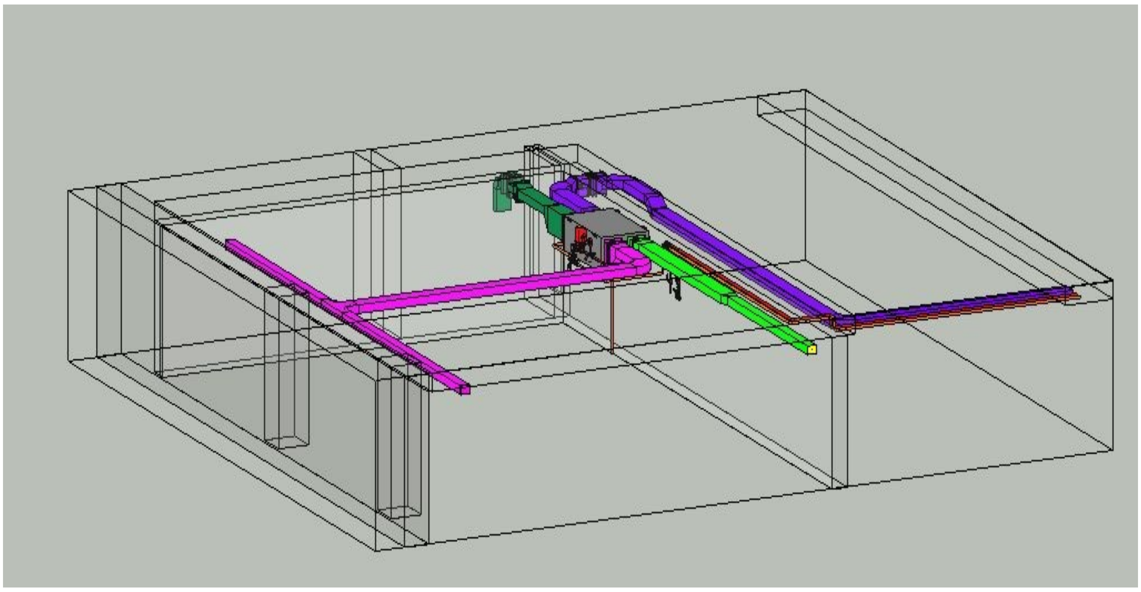


Figure 4 Level -1

Regarding the two described floors, the sizing of the heat recovery unit has been carried out based on the quantity of air required for proper ventilation of the space. The goal has been to select a product that ensures high heat recovery efficiency to minimize energy consumption. For the winter period, there is also provision for a hot air coil to maintain the indoor temperature not lower than 15°C.

The supply and exhaust of air will be managed by specific diffusers placed in the ducts, with their size and characteristics chosen to minimize pressure drop. In this case, given the functions of these spaces, the issue of noise generated by air movement in the ducts and terminals has been somewhat secondary in the selection of the equipment to be installed.

2.2.2 Ground floor

Moving up to the ground floor, lies the "Academy," consisting of multiple classrooms that can also be combined into a single large space capable of accommodating up to 600 people for major corporate events. The client's requirement is to dynamically manage the spaces, adjusting the system's output based on the actual occupancy levels to maximize energy savings.

For this purpose, a 4-pipe air handling system with primary air has been designed. The primary air system is divided into multiple modules, each equipped with Variable Air Volume (VAV) controllers on the supply and return, capable of adjusting the air exchange rate from 10 to 100% based on relative humidity and CO2 concentration measured by dedicated sensors. This ensures that even less crowded or unused areas have a minimum air exchange to maintain indoor air quality.

The fan coil system will be installed using recessed floor-mounted units, and these fan coil units will be positioned modularly to provide maximum flexibility in space usage, ensuring comfort whether room dividers are in place or removed.

The supply air terminals in the rooms will consist of linear diffusers with multiple slots. Each slot will contain a pair of conjugate vanes that, when properly oriented, will allow for horizontal Coanda effect air distribution (either one-sided or two-sided) or vertical distribution. These terminals will be located near the glazed surfaces and in the center of various spaces.

The return air terminals, on the other hand, will also be linear in design, matching the aesthetics of the supply diffusers but without vanes. They will be placed along the internal partition walls.

As these spaces are dedicated to training courses, meetings, and assemblies, it was crucial to consider the issue of noise generated by the HVAC terminals, including both diffusers and fan coil units.

Regarding ventilation, as mentioned earlier, flow controllers have been designed to allow only the necessary amount of air for accurate ventilation. The sizing of these devices was done using manufacturer-provided charts while monitoring two critical parameters: noise and pressure drop, particularly at 50% partial load operation, which was chosen as the reference point among various possible scenarios.

The criteria for selecting linear diffusers were also based on noise and size considerations. The presence of partition walls in some cases led to adjustments in the length of these diffusers, requiring an increase in the number of slots to maintain the same performance.

Similar architectural challenges were encountered with the floor-mounted fan coil units, whose sizes were adjusted several times to accommodate the building's layout. Initially, fewer, larger fan coil units were chosen to reduce costs, but this led to high hydraulic pressure losses. Consequently, a decision was made to install a greater number of smaller fan coil units. Although smaller in size, they required a smaller water flow rate and resulted in significantly lower losses.

The goal was to ensure both thermal and acoustic comfort for the majority of the time. It was considered that during events with 600 attendees, the noise emitted by the terminals and devices would be relatively minimal and, to some extent, negligible.

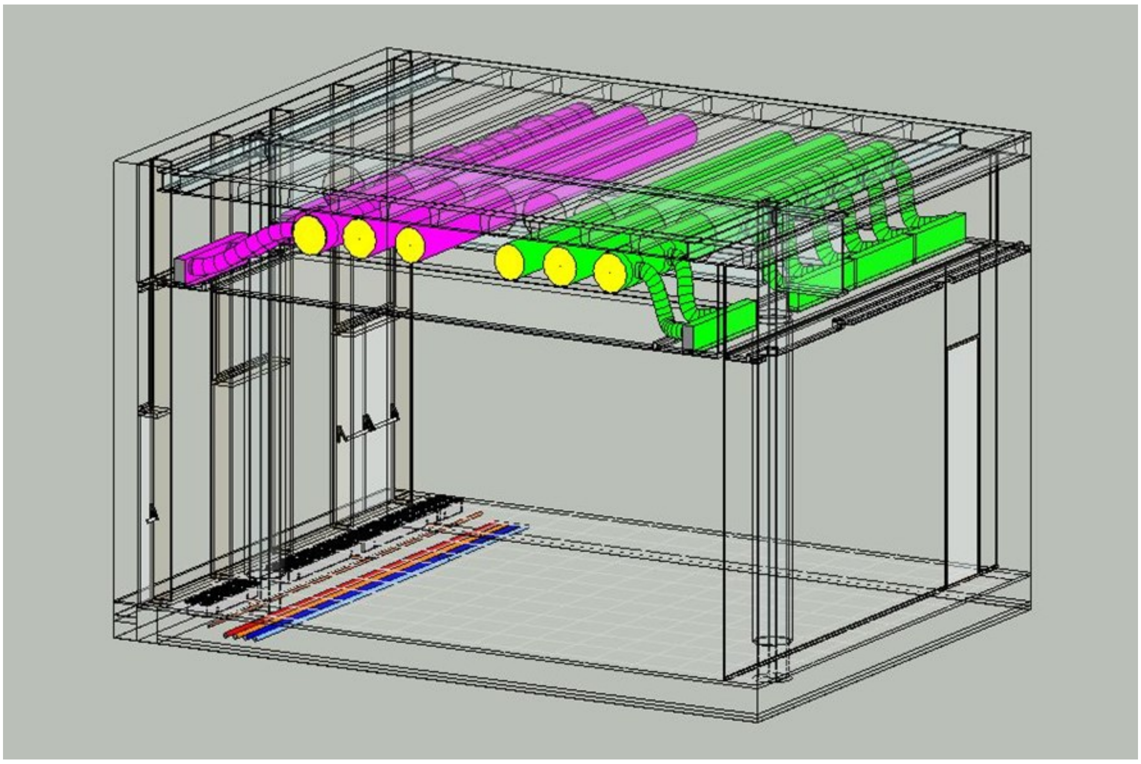


Figure 5 Academy

The second area on the first floor is the preschool, and its HVAC system is equipped with dedicated equipment, hydraulic and air circuits, making it easy to monitor energy consumption.

The system includes a low thermal inertia radiant floor heating system that operates in heating mode only, along with an air renewal system featuring heat recovery and hot and cold coils. During the summer, this air renewal system also serves the purpose of dehumidifying the spaces. Diffusers have been specifically designed to achieve uniform air distribution. In the event of potential future changes in space usage, the radiant floor system has been designed to operate in cooling mode as well. This cooling function can also be used in the scenario of the preschool, but with the chilled water temperature set to generate only a minimal sensible cooling effect to ensure the children's health and comfort.

The sizing of the radiant floor system was conducted using the MC4 software, utilizing an internal tool that requires only the position of the manifolds, the number of branches, and the design of the branch pipes to various spaces. The software then automatically creates the necessary coils to meet the thermal requirements.

The last area on the ground floor is the reception area, served by a 4-pipe fan coil unit system with primary air.

The primary air system is supplied by a heat recovery unit located in the ceiling of the service area. From there, ducts for supply, return, outdoor air intake, and exhaust are extended.

The fan coil units will be recessed in the floor (as in the Academy) in the main hall and surface-mounted in the meeting rooms. The diffusers will be linear, similar to those described for other areas.

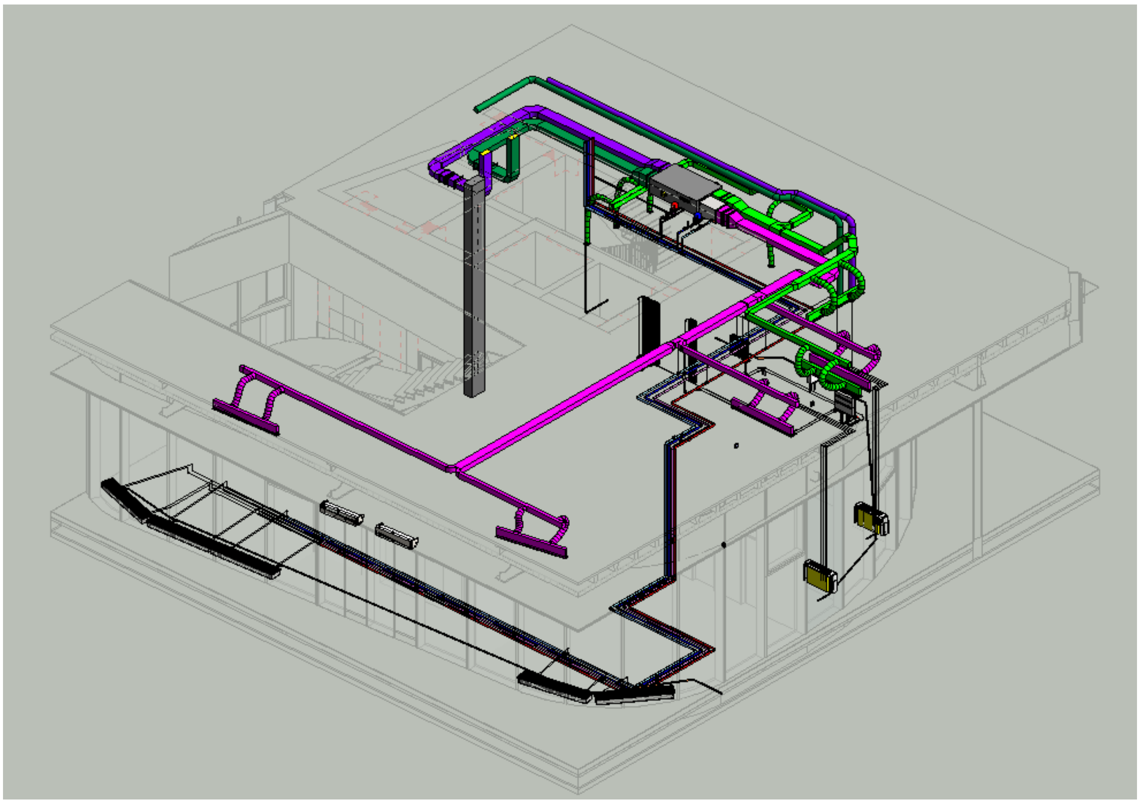


Figure 6 Reception

2.2.3 First floor

The first floor of the building is dedicated entirely to offices and meeting rooms. As with the Academy, the design philosophy here is to create modular heating, cooling, and ventilation systems, optimizing energy consumption and allowing for future layout changes.

The heating and cooling system will be a 4-pipe radiant ceiling system for both summer and winter conditions. Ventilation will be provided by linear diffusers, as previously described, with a constant airflow maintained for areas with a consistent number of occupants throughout the day. Variable airflow will be employed for the meeting rooms, using the same regulators as described for the Academy.

The placement of the linear diffusers, with one or two slots, will be near the glazed surfaces for supply and on the opposite side for return, with the length compatible with the size of the area to be ventilated.

Attention has been paid to diffuser selection to ensure low noise levels in the workspaces and to limit terminal pressure losses, given the significant losses due to the size and complexity of the distribution network.

The radiant panels have been defined by the architectural designer and consist of multiple radiant islands with integrated lighting fixtures. The distribution of the radiant areas will be modular, comprising multiple sub-modules that can be independently controlled based on the size of the area they serve.

Each sub-module can be supplied with hot or cold water throughout the year using a special 6-way valve. These valves can deliver either hot or cold water based on the actual needs of the room or zone. In the case of unoccupied rooms, especially meeting rooms, the 6-way valves will isolate the fluid in the relevant zone.

Additionally, the ventilation rate will be reduced while maintaining a minimum airflow to keep the environment healthy and dehumidified, making it available for potential spontaneous use.

Temperature and relative humidity sensors are placed in each room or at each radiant sub-module. Generally, it will be possible to adjust the internal temperature setpoint within a range of +/- 2°C from the value set by the centralized control system.

The temperature and humidity readings are necessary for the control system to calculate the dew point temperature in each space, ensuring that the supply water temperature remains above the dew point to prevent the risk of surface condensation on radiant surfaces.

The ventilation system, as described above, will also have the purpose of dehumidifying the spaces during the summer season.

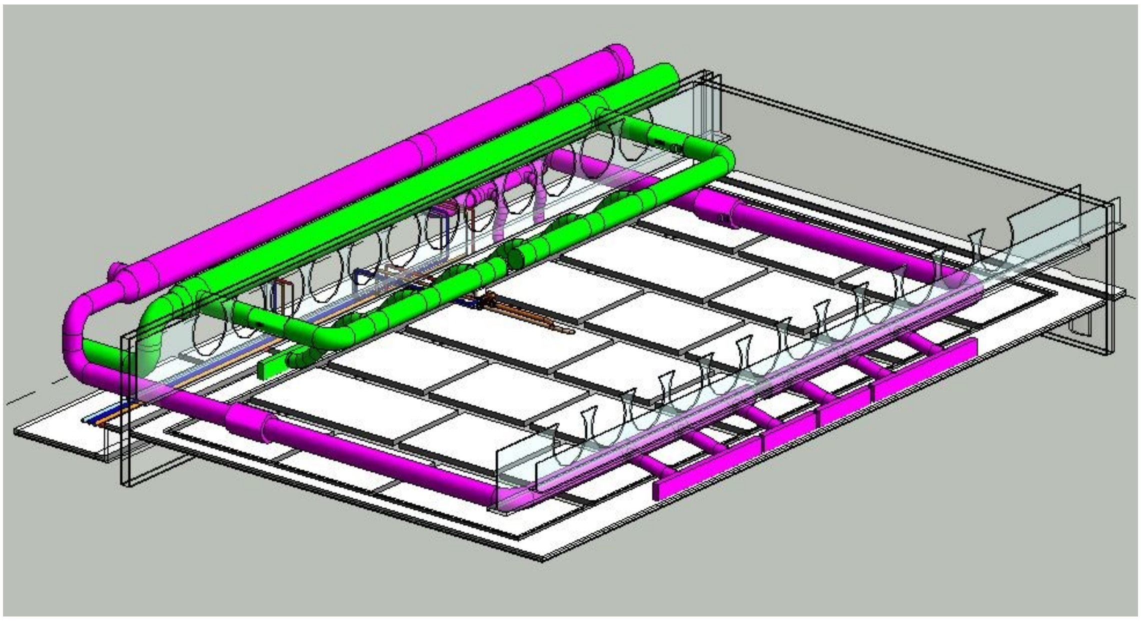


Figure 7 Office first floor

The sizing of the radiant system required a significant computational effort, as well as continuous interaction with architectural and structural designers. The layout of the ceiling was revised multiple times to achieve the largest possible radiant surface, and discussions were held with the panel manufacturer to find the best feasible configuration suitable for meeting the building's specific requirements.

First of all are defined the desired room air temperature, supply and return water temperatures circulating in the panel's coil, and then calculated their averages. This led to the calculation of an average temperature difference between the environment and the water, both for heating and cooling.

The chosen values are listed in the table below:

PARAMETERS	
COOLING	
AMBIENT TEMPERATURE	26
RETURN WATER TEMPERATURE	18
SUPPLY WATER TEMPERATURE	15,5
AVERAGE WATER TEMPERATURE	16,75
ΔT	9,25
HEATING	
AMBIENT TEMPERATURE	21
RETURN WATER TEMPERATURE	34,5
SUPPLY WATER TEMPERATURE	37
AVERAGE WATER TEMPERATURE	35,75
ΔT	14,75

Providing these values to the manufacturer allowed them to calculate the power per unit of surface area that the panel could emit. Furthermore, due to the unique nature of the structure and the specific conditions that needed to be met, it was necessary to implement a custom configuration of the panels. For the less favorable zones of the building, a panel with a larger exchange area, called "Convector Wings," had to be used.

DATA	
Heating supply air temperature [°C]	20
Cooling supply air temperature [°C]	18
Cooling panel yield [W/m^2]	110,6
Heating panel yield [W/m^2]	122,7
Cooling panel yield CW [W/m^2]	125,8
Heating panel yield CW [W/m^2]	128,2

At this point, knowing the available radiant area for each room and the panel output per square meter, it was possible to calculate the power they can emit, both in winter and in summer, while assessing which rooms meet the thermal requirements and which ones are still deficient.

In the latter case, given the impossibility of increasing the radiant surface, it was decided to introduce a greater quantity of primary air than strictly necessary for ventilation to reduce the remaining sensible load.

2.2.4 Rooftop

The last section of the building is the roof, an area where you can find two heat pumps in an open plant zone and three air handling units. Two of the air handling units are located in a covered area adjacent to the heat pumps, while one is placed on the uncovered west side, not adjacent to the central heating plant. This arrangement is solely due to space constraints, as can be seen in the following image [8]:

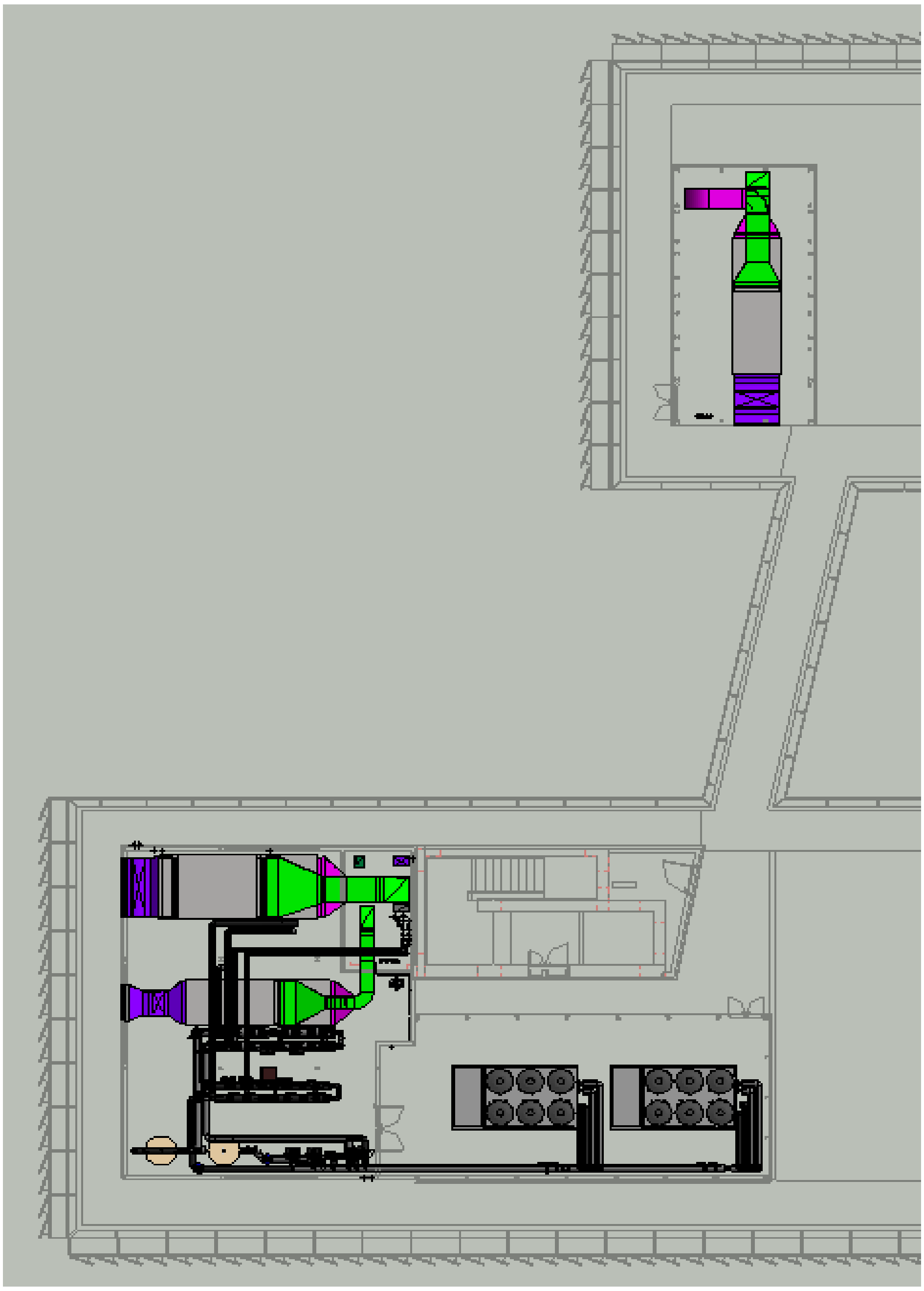


Figure 8 plan of the rooftop

The outdoor multifunctional units are capable of simultaneously meeting demands for hot and cold water without the need for seasonal switching. They consist of two independent circuits, each equipped with two dedicated hermetic rotary Scroll compressors for the use of the refrigerant gas R454B. R454B is one of the low global warming potential (GWP) gases used to replace the traditional R410A refrigerant, thanks to its 76% lower GWP.

The sizing of the two units was conducted based on the results obtained from the building analysis carried out using the MC4 software. The resulting values are 450 kW for cooling and 265 kW for heating, respectively. This difference in capacity is expected given the nature of the structure.

Focusing specifically on the cooling power requirement, it is important to note that this value represents the maximum simultaneous power demand from the building, assuming full occupancy of all zones.

However, it is known through the client that the building will never be fully occupied, as the Academy area will have sporadic occupancy and will reach its maximum capacity of 600 people only during company events, which are held at different times than regular working hours.

The design solution, developed with a focus on optimizing the HVAC and energy systems, assumes that all zones except the Academy can be fully occupied simultaneously. For the Academy, it is considered to be generally occupied at 35%, with approximately 200 people present.

Following this logic, the sizing of the thermal-refrigeration generators resulted in two machines with a cooling capacity of 192 kW and a heating capacity of 136 kW each, with the operating characteristics listed in the table below. This ensures that the building's needs are met both during normal occupancy of the spaces and during the rare occasions when all people are in the same environment.

HEAT PUMP DATA	
COOLING	
EXTERNAL TEMPERATURE [°C]	35
RETURN WATER TEMPERATURE [°C]	12
SUPPLY WATER TEMPERATURE [°C]	7
POWER [kW]	192
EER	2,4
HEATING	
EXTERNAL TEMPERATURE [°C]	-7
RETURN WATER TEMPERATURE [°C]	40
SUPPLY WATER TEMPERATURE [°C]	45
POWER [kW]	136
COP	2,34

Regarding the air handling units (AHUs), there is one for the ground floor (Academy) and two for the first floor, each serving half of the offices. The AHUs are designed for primary air ventilation and humidity control in the spaces, while air conditioning will be handled by the previously described terminals.

However, the two AHUs serving the first floor will not only handle the air required for ventilation but also a greater quantity. This is due to the difficulty of the radiant panels in reducing the expected thermal load in some rooms, contributing to the sensible heat load in those spaces.

In addition, the ground floor AHU (Academy) will have ventilating sections characterized by multiple fans to allow for a wide modulation of air volume, ranging from approximately 10% to 100%. This is to adapt to the significant variability in the load required in that area of the building.

Each AHU will be sized with an air velocity of approximately 2 m/s to reduce air flow resistance and optimize the power consumption of the fans. Furthermore, an additional advantage is provided by the presence of a rotary heat recovery wheel, which is capable of recovering latent heat for effective summer dehumidification.

The machines will be supplied in a plug-and-play version, complete with an electrical power and control panel.

The sizing of the air handling units (AHUs) was initially carried out based on the ventilation values prescribed by regulations and using the same calculation software. However, this software has limitations in this application. It cannot handle the presence of a rotary heat recovery wheel and can only consider sensible heat recovery using a specific coefficient. Additionally, the software assumes that the air leaving the heat recovery wheel reaches the dew point at the average temperature of the cold water coil, when in reality, considering the bypass factor, the system operates under different conditions with a higher temperature and lower relative humidity.

The consequence of this is that the cooling coil would be oversized, and consequently, the post-heating coil as well, leading to energy and economic wastage.

To address this issue, an Excel spreadsheet was implemented to manage all the transformations that the air undergoes during the treatment process, surpassing the limitations of the calculation software and ensuring an optimal sizing of all machine components.

In terms of calculations, the first step was to define the air flow rates to be processed for each unit, the incoming air temperature and humidity for both summer and winter conditions, the temperatures of the hot and cold water for the coils, and the efficiency of the heat recovery wheel. With these values and the implemented spreadsheet, it became possible to determine the operating points on the Mollier diagram and calculate the powers involved in various coils. These values are summarized in the table below, with a slight oversizing factor for safety:

RESULTS	
AHU EAST OFFICE	
AIR FLOW RATE [m^3/h]	5975
COOLING COIL POWER [kW]	64,2
POST-HEATING COIL POWER [kW]	30,1
HEATING COIL POWER [kW]	17,3
AHU WEST OFFICE	
AIR FLOW RATE [m^3/h]	5425
COOLING COIL POWER [kW]	58,3
POST-HEATING COIL POWER [kW]	27,4
HEATING COIL POWER [kW]	15,7
AHU ACADEMY	
AIR FLOW RATE [m^3/h]	14000
COOLING COIL POWER [kW]	163,9
POST-HEATING COIL POWER [kW]	61,5
HEATING COIL POWER [kW]	47,4

Regarding the sizing of the fans for the units, in the following section, calculations will be presented to determine the pressure losses that occur along the air distribution network due to straight ducts, bends, devices such as flow controllers, and terminals for air supply into the space.

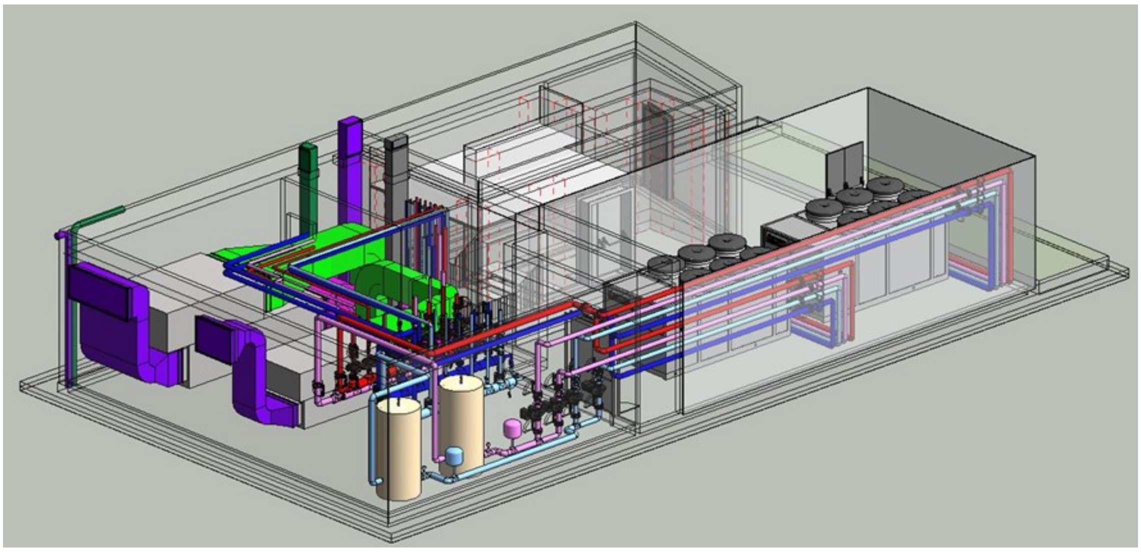


Figure 9 Central plant

2.2.5 Regulation system

An essential role in this project is played by the electronic control system, capable of supervising and managing the specified equipment, as well as controlling the internal thermal conditions of each room and, in general, the corresponding ventilation rates. It consists of programmable electronic controllers and field elements such as temperature sensors, humidity sensors, servo-controls for valves and dampers, thermostats, hygrostats, CO2 detectors, and occupancy sensors.

User interaction is facilitated through graphical pages that represent the architecture of the new systems, making it easy to read operating parameters and identify any anomalies. Through the graphical interface, accessible via any web browser on PCs or mobile devices, it will be possible to interact with the system by modifying setpoint parameters or operating schedules for the various serviced zones.

As mentioned above, the control system consists of multiple controllers serving specific zones, interconnected through signal electrical lines and connected to the building's LAN (Local Area Network), along with field elements such as sensors and actuators. Multiple access profiles will be established based on the needs, allowing the modification of only certain parameters depending on the level of credentials held by each user.

In relation to the operational logic, the multifunctional heat pumps will be responsible for maintaining the temperature of the primary hot and cold circuits to enable the rapid delivery of thermal fluids to the users. To achieve this, the operating schedule for the generators should be set broadly, considering, for example, 16-18 hours of continuous operation.

Regarding the internal systems, they may have operating intervals established by the company based on their specific needs. The operational logic is designed to condition only the occupied zones, while maintaining shutdown or reduced conditions in the remaining areas with minimal air exchange.

On the ground floor, the internal layout of the Academy can be modified by adjusting the movable walls according to the company's specific requirements. The air conditioning and ventilation system will be programmed to adapt to a maximum of 4 scenarios (i.e., 4 different layouts), keeping the unoccupied areas in shutdown or reduced operation. Occupied areas will undergo significant energy optimization through the following logic:

- During the startup phase, the internal system will operate at 100%, with fan coils at maximum speed and primary air supply at nominal values.

- As the set temperature approaches, the fan coils will gradually reduce their rotation speed, reducing the delivered power, and the valves associated with the devices will gradually close.

Regarding primary air, upon reaching the set relative humidity setpoint, the flow control regulator in each zone will start reducing the airflow based on the measured CO_2 levels in the environment. This reduction will be gradual until the relative humidity remains constant, allowing only the exact amount of air necessary to maintain comfort inside the space to be treated.

A similar logic will be applied to the first-floor offices, with the difference that there is no "dynamic" change in the internal layout. Open space zones, characterized by constant occupancy, will be ventilated with a fixed flow rate, while meeting rooms will be conditioned and ventilated "on-demand" using the same operating mode as used for the Academy.

The nursery will operate with a seasonal switch logic, with each room autonomously regulated and a constant primary air supply. In summer, this supply will also provide dehumidification. The reception area will also have a constant airflow ventilation system, with temperature regulation on a room-by-room basis.

2.3 Design of aeraulic and hydraulic networks

The sizing of the air and water distribution network follows a common principle, which is the containment of pressure and load losses, respectively. To achieve this, several additional factors come into play that affect this parameter, such as velocity, fluid density, viscosity, the size, and material of the duct or piping.

In addition to these technical aspects, economic considerations also need to be taken into account.

Pressure losses, also known as pressure drops, are losses of pressure with irreversible transformations of mechanical energy into heat. These losses occur due to resistance encountered by a fluid as it flows through a conduit or piping system. They can be either continuous or localized: in the first case, they occur along straight sections with a constant cross-sectional area or diameter, while in the second case, they occur at special components such as inlets, bends, branches, confluences, etc., and components that alter the direction or cross-sectional area of fluid flow.

In this project, the sizing of the air distribution network was heavily influenced by the structure of the building, due to the presence of steel beams with circular holes of a diameter of 600mm, through which air ducts, water pipes, and electrical distribution channels must pass. Therefore, the ducts were initially designed to be rectangular in shape as they exit the machines and in the chases, and then transitioned to a circular shape whenever structural considerations required it.

Of course, it would have been possible to maintain a rectangular shape throughout, but this would not have allowed for the optimization of available space. Additionally, the supply and return ducts were positioned side by side in adjacent holes, rather than one above the other, as is traditionally done, precisely due to the structure.

For the sizing of the air distribution network, an Excel spreadsheet was implemented to calculate the pressure losses along the air distribution line for each AHU (Air Handling Unit) and heat recovery unit. The chosen method for sizing the network is the static pressure regain method to balance the network without the need for throttling devices.

With this calculation method, once the velocity and dimensions of the first downstream section from the fan are chosen, all subsequent sections are determined in such a way that the velocity change resulting from a reduction in flow at a branching point is used to convert some of the dynamic pressure into static pressure. This compensates for the pressure losses in the next branch.

First, the initial data was set, including temperature, altitude, pressure, air density, air viscosity at the site of the structure, and the duct roughness. Then, the air flow rate in each section of the constructed network, along with the respective duct dimensions and length, was input.

At this point, using the specially designed spreadsheet, the parameters of interest for the distribution network, namely air velocity and unit losses, were immediately known. Analyzing each step of the procedure, the first calculation involves the equivalent diameter of the duct, a necessary parameter because the subsequent formulas for determining linear pressure losses are based on circular ducts. Hence, there is a need to establish a correlation between rectangular and circular ducts.

The formula in question, the Huebscher equation, is:

$$De = 1.30 * \frac{(a * b)^{0.625}}{(a + b)^{0.250}}$$

where De represents the equivalent circular duct diameter, while a and b are the sides of the rectangular section.

Subsequently, the velocity at which the air flows inside the considered section is calculated, and this value is crucial for determining the noise generated. In fact, the higher the velocity, the greater the noise produced by the flow of air [35].

Since these are primarily office environments, meeting rooms, and conference areas, it was chosen to size the ducts in a way that ensures the air velocity is always below 3 m/s, thus minimizing noise, except in sections within technical chases and where it is impossible to provide a larger cross-sectional area duct due to structural constraints.

The formula used for the calculation of velocity is:

$$v = \frac{Q}{A}$$

where Q is the air flow rate in m^3/s, and A is the cross-sectional area of the duct in m^2.

The same formula, in a circular duct, assumes the following form:

$$v = 278 * \frac{4 * Q}{\pi * D^2}$$

where D is the internal diameter in mm, and Q in this case is always the flow rate measured in m^3/h.

For the calculation of pressure losses, in circular ducts, the Darcy formula can be used:

$$r = \frac{Fa * \rho * v^2}{2 * D}$$

In this equation, the only unknown parameter is Fa, i.e. friction faction.
It can be determined by Altshul-Tsal relation:

$$Fa^* = 0.11 * \left(\frac{\varepsilon}{D} + 192.3 * \frac{D * v}{Q}\right)$$

imposing that, if Fa^* is greater or equal to 0.018, then $Fa = Fa^*$, otherwise$Fa = 0.85 * Fa^* + 0.0028$, where:

- Fa*= conventional friction factor, dimensionless
- Fa= friction factor, dimensionless
- ε= ruoghness, mm
- υ= kinematic viscosity, m^2/s
- G= flow rate, m^3/h
- D= inner diameter, mm

In this way is possibile to determine linear unit pressure drops measured in Pa/m, as:

$$r = 6.254 * 10^7 * Fa * \rho * \frac{Q^2}{D^5}$$

At this point, therefore, by multiplying the calculated unit loss by the length in meters of each section, it is possible to determine the individual losses, summing them together to determine the final total value for the entire network.

Now, it is possible to determine the concentrated losses for each type of special fitting present along the distribution network using the following formula:

$$z = \xi * \rho * \frac{v^2}{2}$$

where ξ represents the coefficient of localized loss and assumes a specific value for each type present. Finally, as for terminal losses, such as diffusers and flexible ducts, they were determined manually using the graphs provided by the manufacturers. With all these elements at hand, through an implemented spreadsheet, it was possible to determine the pressure losses in each distribution network within the facility.

In the figure below, you can see an example of the air distribution network sizing for the West AHU in the first-floor offices, where it is possible to quantify all the parameters mentioned earlier. It can be observed that the fan sizing for the unit has been done significantly oversized because we are still in a phase of the project that is not entirely defined. Therefore, without having to resize the AHUs, it was decided to use larger values than necessary.

Concentrated losses (Pa)		Code
Fan-channel coupling	5,6	
Curves	27,2	C
Section changes	6,8	CSa/b
Static derivations	2,7	DS
Dynamic derivations	0,0	DD
Static junctions	0,0	CS
Dynamic junctions	0,0	CD
Dampers	0,0	S
Sharp enlargement or shrinkage	0,0	BA / BR
Insect net	8,9	R
Inlet	5,6	IMB
Outlet	0,0	SB
Silencer		SIL
Flex duct	10,0	FL
Air diffuser	11,0	BM / BR
Iris damper	0,0	SE
TOTAL (Pa)	77,7	
Resume		
Total distributed losses (Pa)	25,1	
Pressure recovery (Pa)	-8,2	
Total concentrated losses (Pa)	77,7	
Useful static pressure required (Pa)	94,6	
Safety coefficient	1,15	
Useful static desing pressure (Pa)	**108,7**	

Regarding the hydraulic network sizing, it's important to clarify first that there are different circuits based on the terminal units to be supplied, which can be AHUs, floor-mounted fan coil units in the Academy or Reception areas, or the radiant system on the first floor. Therefore, exiting from the heat pumps, there are four manifolds: one for hot water supply, one for cold water supply, one for hot water return, and one for cold water return.

Subsequently, departing from the supply manifolds and exiting from the return manifolds, circulation pumps for each circuit can be found, as described above. This setup ensures differentiation for each zone to be served, preventing, first and foremost, the interruption of the supply to a large part of the building in case of a failure anywhere in the network. Secondly, it avoids the installation of pumps with excessive head pressure.

This division of the circuit is also necessary due to the different water temperatures required for the radiant ceiling panels, which cannot be supplied at the same temperatures as the floor-mounted fan coil units, for the reasons already described in the preceding paragraphs.

The sizing of each branch of the water distribution network was carried out taking into consideration the flow rate, the velocity for the respective diameter, and the resulting unit pressure losses. It was chosen not to exceed water velocities of 1.5 m/s to avoid unpleasant noise and to limit the linear pressure losses to a value of 22/24 mm of water column per meter of piping.

This choice was made to minimize linear losses as much as possible, given the already high losses due to the terminals present, which, in the case of radiant panels, are approximately 24 kPa, a value provided by the manufacturer.

As for the material of the pipes, stainless steel AISI 304 with a thickness of 3 mm was chosen for the pipes in the ceiling, 2 mm for the main distribution inside the building, transitioning to plastic material downstream of the 6-way valve in the first-floor radiant ceiling circuit. This choice is primarily due to corrosion resistance, longer lifespan, ease of maintenance compared to other materials on the market, as well as aesthetic and prestige considerations, given the quality of the project being undertaken.

On the other hand, this choice has led to relatively high costs for the construction of the circuits. Therefore, if cost reduction is considered in the subsequent project phase, this area may be one of the first to undergo changes.

The selection of diameters for each circuit branch was made using tables found in manuals, where it is possible to find the correlation between the three parameters mentioned earlier: velocity, flow rate, and pressure losses for each commercially available diameter.

As for the total calculation of pressure losses to which a circuit is subjected, and consequently, the sizing of the circulation pump, once again, an Excel spreadsheet was implemented to obtain the correct sizing of the circulation device.

In this case, tables were used, such as the one below, containing known values of diameter, flow rate, and the corresponding pressure loss for each specific material. Through an equivalence relationship, it was possible to determine the value relevant to the branch in question.

Multilayer pipe	DN	Di	Qn	rn
	(mm)	(mm)	(l/h)	(Pa/m)
	14/10	10,00	83	196,20
	16/12	12,00	121	196,20
	18/14	14,00	200	196,20
	20/16	16,00	249	196,20
	26/20	20,00	543	196,20
	32/26	26,00	1.106	196,20
	40/33	33,00	2.113	196,20
	50/42	42,00	4.066	196,20
	63/54	54,00	6.887	196,20

Starting from tables like this and choosing the diameter corresponding to the pipe, it was possible to determine the linear losses for each meter of pipe using the following formula:

$$r = \left(\frac{Q}{Q_n}\right)^2 * r_n$$

where:

- r= linear losses, Pa/m
- r_n= linear losses at rated flow rate, Pa/m
- Q= flow rate, l/h
- Q_n= rated flow rate, l/h

At this point, by multiplying this value by the length of the section, it is possible to obtain the value of linear pressure losses. Regarding the calculation of concentrated losses, the procedure is analogous to what was described earlier for the air distribution network, i.e., the same formula is used, and depending on the type of special fitting present, the appropriate ξ will be used.

Once the linear losses are added to the concentrated losses and the terminal losses, it is possible to obtain the total losses in the circuit, and with this value, the suitable circulation pump can be sized.

Using the example of the hot water circuit serving the coil of the Office AHU, the following results can be observed:

Circuit characteristics					
Branch		A		B	
Water flow rate (l/h)		7.196		3.425	
Type of pipe		Fe		Fe	
Nominal diameter (" o mm)		2		1 1/2	
Internal diameter (mm)		53,90		42,50	
Nominal flowa rate (l/h)		8.739		4.639	
Linear losses at Qn (Pa/m)		294,30		294,30	
Velocity (m/s)		0,88		0,67	
Linear losses (Pa/m)		199,6		160,4	
Branch's lenght supply+return (m)		20		120	
Distributed losses (Pa)			3.991		19.246,1
Concentrated losses (Pa)	z	n		n	
Simple T-branch (straight)	1,5		0,0		0,0
Simple T-branch (branch)	0,2		0,0		0,0
Simple T-junction (straight)	1,0		0,0		0,0
Simple T-confluence (branch)	0,5		0,0		0,0
Double T branch	3,0	1	1.151,5		0,0
Double T confluence	3,0	1	1.151,5		0,0
Curve (Di<18mm)	2,0		0,0		0,0
Curve (18mm<=Di<30mm)	1,5		0,0		0,0
Curve (30mm<=Di<=54mm)	1,0		0,0		0,0
Curve (Di>54mm)	1,0	10	3.838,3	10	2.224,9
Shrinkage	0,5	1	191,9		0,0
Enlaergement	1,0	1	383,8		0,0
Valve (Di<18mm)	10,0		0,0		0,0
Valve (18mm<=Di<30mm)	7,0		0,0		0,0
Valve (30mm<=Di<=54mm)	5,0	3	5.757,4	2	2.224,9
Valve (Di>54mm)	4,0		0,0		0,0
Gate	1,0		0,0		0,0
Non-returne valve	8,0	1	3.070,6		0,0
Anti-vibration	1,0		0,0		0,0
Y-strainer	16,0	1	6.141,2	1	3.559,9
Straight end valve	12,0		0,0		0,0
Square end valve	7,0		0,0		0,0
Straight holder	20,0		0,0		0,0
Square holder	8,0		0,0		0,0
Radiator	2,5		0,0		0,0
Known value (Pa)					
Thermal group			0,0		0,0
Chiller			0,0		0,0
Boiler			0,0		0,0
Device			0,0		30.000,0
Other known value			0,0		0,0
2 or 3 ways valve (Kvs)			0,0	10,0	11.727,9
Total branch loss (Pa)			25.677,6		68.983,8

With these obtained results, the final pump sizing is reached, which takes into account the flow rate to circulate and the head to overcome. This is achieved using the selection tools available on the manufacturer's website, providing the aforementioned data:

Circuit characteristics	
Head of calculation (kPa)	94,66
Safety coefficient (%)	15%
Increased head (kPa)	108,86
Calculated flow rate (mc/h)	7,20
Pump characteristics	
Brand	Grundfos
Model	MAGNA 3D 40-180F
Connection diameter (DN)	DN40
Supply ùvoltage (V)	230
Rated motor power (kW)	0,610
Number of poles	2

Chapter 3

BIM introduction

Technological innovation is constantly and continuously shaping the world we live in, revolutionizing numerous sectors. Among these, two of the fields that have undergone profound transformation are construction and engineering systems.

Construction activity is often a fragmented, complex, and inherently uncertain process. This often leads to limited productivity, largely caused by the loss of information between different project phases and stakeholders, making it difficult to establish efficient coordination and communication. These limitations affect both project profitability and the quality of the final result [14].

Therefore, efforts have been made to implement greater digitization in the design and administration process to accelerate and make operations and decisions more efficient, increasingly uncovering and eliminating any compatibility errors between various projects or other inconsistencies.

The current trend in building design involves a gradual shift away from CAD software in favor of design applications that have gained prominence in the industrial sector. One such tool, known as Building Information Modeling (BIM), has emerged as one of the cornerstones of this digital transformation in the Architecture, Engineering, Construction, and Operation (AECO) industry [16].

BIM represents a digital and intelligent approach to the design, construction, and management of buildings and infrastructure, and more and more people are realizing the benefits and opportunities it offers.

At present, its primary use in projects is for the faster development of 3D models and geometries, as well as for improved collaboration and coordination, with a usage frequency of 60%. For structural and energy-related applications, it accounts for usage frequencies of 27% and 25%, respectively [36].

Building Information Modeling (BIM) should be considered a comprehensive approach, not limited to a simple software tool, which allows for the creation of a digital model containing all information related to a building, not only during the design phase but throughout its entire lifecycle.

Compared to traditional 2D design, BIM is capable of storing a vast amount of data regarding the structure and systems. For this reason, it is considered a revolutionary innovation in the construction industry. Serving as a database, it can be used as a bridge to access external tools related to specific disciplines [37], such as energy performance or environmental impact assessments of the structure. It can also be used for conducting simulations or data analysis, leveraging interoperability with other software [16].

In more detail, BIM can be envisioned as a process of design, construction, management, maintenance, and scheduling of a construction project that utilizes an informative model, one that contains all information regarding its entire lifecycle, from design to construction, and ultimately to demolition and decommissioning [12,13]. It serves as a reliable source upon which to base certain design decisions and choices [10].

The fundamental goal of BIM is to provide a comprehensive representation of a construction project for every phase of its entire lifecycle, offering various information about the constituent elements of an infrastructure. This is achieved by specifying dimensional, qualitative, and quantitative data within the model or its individual elements. A BIM model contains information related to various aspects (geometric, energy-related, structural, etc.) and, due to its easy accessibility, enables all professionals involved in a project to collaborate more effectively. It also allows for data-driven decision-making throughout the entire lifespan of the construction in question [14].

A key feature of BIM is collaborative work among the various stakeholders, who have the ability, within their respective domains of expertise, to enrich the information model by inserting, extracting, updating, or modifying information.

BIM allows for the creation of 3D models and provides an overview to all interested

parties about the current state of the construction project from various perspectives, whether it's structural or related to systems.
This approach enables the early detection, in the initial phases of project development, of any potential errors or issues that might arise in subsequent stages, thus reducing future problems.

BIM, therefore, allows for the creation of a virtual model of a building that goes beyond a simple three-dimensional representation.
This model is dynamic and contains a vast amount of information, including details about shape, materials used, costs, systems, thermal characteristics, energy performance, lifecycle, and much more.
In essence, thanks to the BIM methodology, it is possible to 'construct' a building before its actual physical realization, using a virtual model, through the involvement and collaboration of all professionals involved in the project, such as architects, engineers, design consultants, energy analysts, who work together to develop the model, optimizing the final result.

3.1 Benefits of BIM

The adoption of BIM has brought numerous advantages to the construction industry, profoundly transforming it in both thinking and project implementation.

As previously highlighted, BIM should not be seen as software but as a methodology, a new way of operating through technology. Its main innovative value lies in the ability to share information among various stakeholders involved in a construction project. It is this new mode of information sharing that opens up a new collaborative operational scenario.
BIM represents a significant change from traditional work processes and offers opportunities to create value more efficiently throughout the entire production chain. In essence, it provides advantageous alternatives to traditional work methodologies.

In traditional design, which relies on 2D drawing software and separate applications for thermal calculations, lighting design, and cost estimates, there are many gaps and inefficiencies that lead to numerous issues both in the design phase and later in the actual construction of the project, resulting in significant delays and costs.

The fragmentation of work fields and teams often leads to suboptimal project management from the early stages, generating inefficiencies and typical value losses such as:

- Loss of accumulated knowledge at each step
- Occasional redundancy of information
- Frequent rework due to lack of sharing

In the subsequent construction phase, the most significant problems that arise include:

- Loss of information in data transmission from designer to contractor
- Lack of communication between site management and suppliers
- Verification of material presence and location on the construction site
- Monitoring of work progress

These are just some of the reasons why delays, issues, and inefficiencies occur in project execution, often necessitating a revision of established plans up to that point.

The need to adapt and manage project timelines flexibly, making decisions based on detailed analysis, can be addressed through the use of new methods and innovative tools, among which BIM is precisely one of them.

The numerous advantages associated with the use of BIM can be summarized as follows [12,13,14,16,38]:

1. Improved Coordination and Collaboration: Facilitated collaboration among all parties involved in a construction project, such as architects, engineers, etc., helping reduce conflicts and enhance coordination, thereby reducing unforeseen delays and costs.
2. Comprehensive Virtual Model: Enables the creation of a comprehensive model of the building containing detailed information on geometry, systems, materials, and more, providing a clear and accurate view of the project.
3. Visual Communication: Utilizes 3D visual representations, making it easier for all stakeholders, including clients and regulatory authorities, to understand the project.
4. Change Management Ease: Project changes can be easily managed through BIM, allowing for greater flexibility.
5. Reduction in Errors and Revisions: Thanks to real-time information sharing available to all involved users, communication errors and last-minute revisions are reduced, leading to significant time and cost savings.
6. Analysis and Optimization: BIM tools allow for detailed analysis, such as energy efficiency and structural safety, enabling the identification of potential issues before they occur and finding more efficient solutions.
7. Automated Documentation: BIM automates the generation of tables for calculating quantities of elements within the model, avoiding the problem of manual counting errors.

8. Lifecycle Management: Extending beyond the design phase, BIM allows for an analysis of the entire lifecycle of the project, including maintenance and facility management, helping optimize long-term operational efficiency.
9. Sustainability: BIM can be used to assess and improve the energy efficiency and environmental impact of a building, contributing to well-known sustainability goals.

In conclusion, the innovative aspects offered by BIM can be summarized as a more efficient, accurate, and collaborative approach to the design and construction of projects, with evident benefits in terms of quality, time, and costs.

3.2 Fields of application of BIM

BIM has a wide range of applications in various sectors, offering significant benefits in terms of efficiency, accuracy, and collaboration throughout the life cycle of construction and infrastructure projects. More specifically and in greater detail, its use is interesting and important for creating a three-dimensional geometric model, analyzing construction timelines, cost analysis, comprehensive and accurate project management, and finally, the sustainability of the structure to be built.

Regarding the creation of a three-dimensional model, the main purpose is to provide a clear and accurate representation of the actual dimensions of structures and systems, enabling the efficient management of potential interferences. It is especially advantageous, particularly in complex structures, to have a more detailed understanding of the available spaces for the placement of pipes, ducts, and terminal elements.

Furthermore, thanks to BIM, from simple parametric architectural object drawings such as beams, columns, walls, windows, etc., plans, elevations, sections, axonometric views, all consistently aligned and updated with the project are automatically generated. Any change in the virtual BIM model is reflected with automatic and dynamic updates to all project documents, ensuring consistent coherence across all parts of the project. This makes any changes to the building structure much more flexible and fluid, without the need to manually check and potentially modify individual drawings, reducing the risk of forgetting one or more changes.

In relation to the graphical aspect, the designer no longer needs to spend time manually drawing a vast number of lines, polylines, and various geometric shapes. Instead, they simply insert objects with specific information such as materials, dimensions, technical characteristics, etc., significantly reducing the time required for the graphical part of the project.

Additionally, by using three-dimensional representations for significant project elements, such as lamps, electrical panels, heat pumps, or ventilation units, a more realistic view is obtained, capturing aesthetic considerations made during the design phase.

Therefore, thanks to all these considerations, the structure will visually appear more captivating and closely aligned with reality [12].

The analysis of project completion times and its inherent structure can be implemented through the use of a Work Breakdown Structure (WBS). The WBS is a management methodology used in various sectors and involves the analytical division of a complex project into more manageable and detailed components, all designed specifically to extract, organize, and easily visualize the progress of the work.
Typically, it is designed using a top-down approach. The higher levels of the WBS are divided into logical groupings of work, and each subsequent level is further divided until the work has reached a easily manageable size, usually composed of individual elements with the same characteristics and belonging to the same work group [39].
Typical examples of how the breakdown of work can be developed in the construction and engineering field include, for instance, ownership floor plans, followed by room classifications, and then the system of ownership. From a practical standpoint, this could involve a lamp or a diffuser located on the first floor of the building, placed in meeting room A, belonging to the lighting or ventilation system, respectively.
Of course, depending on the type of project, the divisions can become even more detailed and specific.

Once you have defined how to divide the project into various categories and subcategories, interacting with BIM becomes very straightforward. All that is required is to define new parameters within the project and then populate them with the predefined values or codes.
At this point, every element in the model will be characterized by parameters associated with the WBS, clearly and precisely identifying its position within the project structure. When you export the model, it becomes possible to visualize which elements belong to a particular subcategory of work. This allows you to get an idea of how many and which objects are present and helps establish a timeline for the possible completion of that specific part of the project.

Another important, if not fundamental, aspect in the construction of buildings and facilities is the economic aspect. It is, therefore, of primary importance to have an idea of the costs from the very early stages of the project. This helps determine if the project is within budget, for example, or if a particular system is currently too expensive and needs to be downsized.

These operations are made possible through Quantity Take-Off, which involves extracting measurements from the project to define the quantities of materials needed for the construction of one or more elements. Once the quantity of a particular item is known, the next step is to select the items from the price list and assign them to the work, along with their respective unit prices, thereby determining the total cost.

The BIM advantage in this field lies in the fact that the virtual model provides a detailed view of how costs evolve in response to changes or adaptations in the project. This means that the model can be efficiently used to calculate resource requirements such as materials, labor, and time, both for individual processes and the entire project, from the early design phase.

Based on this multidimensional data model, BIM enables a level of cost, design, and scheduling certainty. Compared to traditional design, errors in quantity estimates are almost eliminated because this operation is not performed manually, does not depend on 2D drawings, and is not subject to subjective interpretations [10]. Instead, it is part of a process performed directly by the software, making cost calculations more accurate and faster, reducing the chances of significant financial estimation errors [14]. Most BIM tools include routines for calculating geometric properties of elements, presenting spatial quantities such as area in textual format [17]. Therefore, using BIM for cost estimation simplifies and simultaneously makes project evaluations more detailed and precise, reducing time and expenses associated with this process.

From a practical perspective, there are two ways to implement a quick and effective cost analysis: in the first case, quantities of various elements in the BIM model are extracted, and these collected data are then used in specialized software to calculate the expenses to be incurred. The alternative involves the possibility of obtaining a cost

estimate directly from the model without first extracting quantities and using another software.
This second method essentially involves importing the BIM model in IFC format into accounting software, and through pre-defined and managed parameterization, the elements are recognized, each associated with its respective cost based on a price list stored in the database. This way, the total cost calculation is automated to the maximum extent possible, and it is possible to obtain an economic estimate in a very short amount of time.

Managing a project of any kind requires a lot of collaboration and sharing of ideas and information among all the parties involved, especially when the teams collaborating in the project belong to different companies. Incorrect communication about a design choice or a change not shared with all the stakeholders can lead to errors of varying significance and can have significant impacts on both time and costs.

Through the use of BIM, the management mentioned earlier becomes much more streamlined and simplified, as well as effective from all perspectives, thanks to the inherent characteristics of BIM modeling. The physical functional characteristics of buildings can be shared on a resource platform, and project participants can integrate, extract, and update information at any time. Furthermore, by promoting collaboration among different teams, a more reliable construction is achieved. This requires effective coordination and communication among numerous multidisciplinary teams, proper cost and time management, as well as improved design and activity quality [12]. This process can clearly define the tasks and responsibilities of each individual and provide useful data and references to decision-makers, thus reducing disagreements and conflicts. Consequently, the use of BIM technology can significantly enhance work efficiency, increase the timeliness of information, and make project cost management more detailed and dynamic [13].

Another very important aspect in project management concerns the occurrence of interferences among various involved sectors, namely the possibility of geometric conflicts arising between different elements belonging to different disciplines. This operation is called Clash Detection and involves the verification of geometric interferences, which is the process of identifying elements that collide with each other. This operation is necessary and fundamental in the perspective of overall project coordination [14]. Clear examples can include a water pipe running through a structural pillar or an electrical conduit intersecting with an air duct. Clearly, in a 2D modeling, these types of issues remain somewhat hidden, often materializing during the actual construction phase, causing significant troubles and problems. By using a three-dimensional space for modeling, it becomes clear from the beginning what spaces are available and what the boundary areas are where a certain type of supply cannot be anticipated. Therefore, once again, it can be observed how the use of BIM in design can help prevent certain types of errors that can prove to be very costly both in terms of economics and timelines [20].

Sustainability has become a prominent theme in recent years, not only in construction but also in various other areas. In this regard, BIM can assist in the development of sustainable projects concerning energy consumption and emissions. It is possible to create a comprehensive virtual model of a building that contains not only the geometric information of the structure but also all energy-related details, such as systems, insulation type, building envelope, windows, climate data, internal inputs, and HVAC systems.

During the design and construction phases, it is essential that all data related to materials, technological components, decisions about systems, and geometric information are accessible to carefully assess the building's various energy performances. By using this data, it is possible to make an initial estimate of the environmental impact caused by the building even in the early stages of the project [19], allowing for initial considerations or even modifications if the client's requirements or regulatory standards are not met.

In a traditional system, each involved party would develop their models separately and later integrate them into a common platform, increasing the likelihood of information dispersion and errors during the unit sizing phase required for the project's operation.

The analysis and evaluation of the building's energy performance offer significant development opportunities. In particular, energy performance calculations are crucial for implementing the strategies necessary to minimize the building's energy consumption.

One of the primary advantages of BIM is its ability to directly export models to energy analysis software, thanks to interoperability among various applications. This eliminates the need to recreate models from scratch, saving valuable time and resources in the process of evaluating a building's energy performance.

The BIM model created can also be used for conducting other analyses and certifications in the energy sector:

- Cost Benefit Analysis (CBA)
- Life Cycle Assessment (LCA)
- LEED certification

Cost Benefit Analysis (CBA) allows associating a value with the project to quantify the benefits and costs of its implementation, thereby assisting the designer in making decisions when comparing different alternatives.

In a scheme proposed by Biancardo et al., the correlation between CBA and BIM is presented, which combines existing design and infrastructure planning tools with innovative process automation. Integrating CBA within a BIM model can be a powerful tool to support decision-makers as knowing the risks and benefits of a project is the best premise for deciding what and how to build.

It emerges that the integration between these two methodologies would contribute to:

- Ensuring maximum transparency of the reasons for project implementation.
- Simplifying and standardizing the decision-making process through automation of calculations.

•	Better understanding the potential impacts arising from infrastructure implementation.

In [20], an algorithm was created capable of calculating various indices of interest for cost-benefit analysis, leveraging the ability of BIM to input parameters as desired and have them interact with each other, ultimately creating metrics useful for project definition. The automatic input of parameter values and the various necessary calculation operations were once again implemented through the use of Dynamo, a software that allows, among other things, automatic input of values and parameters through visual programming, as can be seen in Figure [10], a tool that has now become essential for automating processes of this kind.

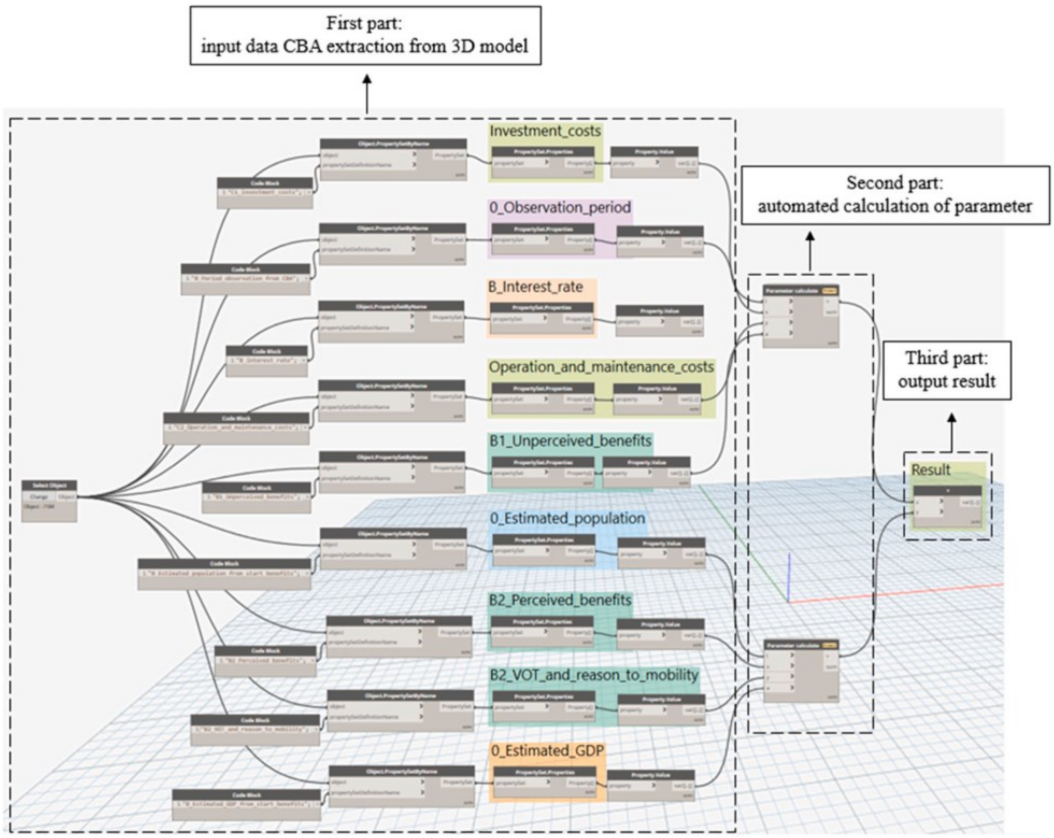


Figure 10 Algorithm overview

The primary goal is to improve LCA performance, allowing for analysis in the early stages of a project, thus guiding and optimizing the design process. Implementing BIM-LCA methodologies from the outset would provide insights into indices and metrics for a clear understanding of project sustainability and enable the selection of design solutions with lower environmental impacts.

Furthermore, the use of tools like Dynamo simplifies the automatic input of environmental data into BIM models, improving communication among various software systems. This enables the extraction of useful data and calculation of the overall environmental impact throughout the building's entire lifecycle, contributing to more informed decisions during the design phase.

LEED certification is based on an online assessment system to assign a score to the project under design, based on criteria such as site selection, waste reduction, energy, resources, materials, indoor environmental quality, location, and connections, among others.

BIM has evolved as a system that enables the more efficient use of existing design data for sustainable planning and performance analysis. Among the numerous advantages offered by this tool are pre-construction planning, digital collaboration, and cost analysis. Additionally, it can support the LEED certification process due to the wealth of data that can be derived from the BIM model, such as lighting and energy usage analysis, making the process fast and precise.

For example, it's possible to estimate the amount of recycled content or material recovery simply by using automated tables provided by the software, avoiding manual computational effort that could also be prone to errors. A method related to the possibility of automating the LEED credit allocation process by leveraging BIM capabilities has been proposed by Dubljevic et al. [16], and it can be seen in the figure [11] below:

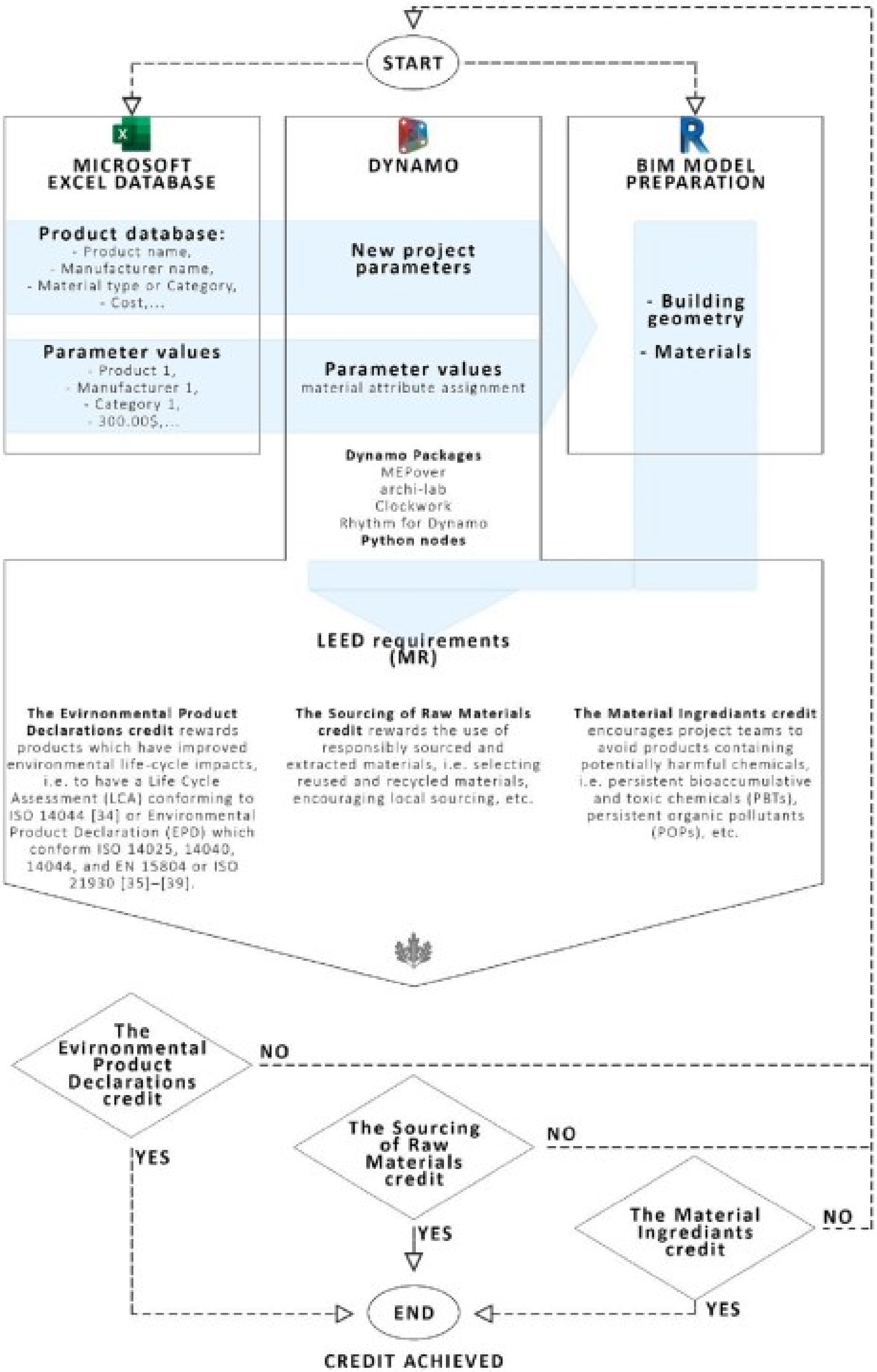


Figure 11 Overview of the computational BIM method

Similarly, Lean concepts can be used to eliminate waste that has a negative impact on the environment and optimize the construction process. To relate BIM to Lean methodology and LEED certification, the following points can be followed [19]:

1. Establish a residential site.
2. Create a BIM model.
3. Incorporate Lean methods.
4. Integrate LEED principles.
5. Analyze, adjust, and optimize.

The combined use of BIM, Lean methods, and LEED assessment tools can enable efficient and cost-effective construction of the project while improving its quality. The combination of these three methods can be an effective and powerful way to successfully execute structural and systems construction projects.

Chapter 4

BIM in the case study

As can be understood from the previous pages, the use of BIM in design is gaining increasing interest due to the significant advantages it can provide, greatly assisting designers in their tasks.

In the design of the HVAC system presented earlier, BIM methodology was used, particularly through the use of Revit 2023 software. However, the full potential of the software was not fully leveraged, and its use was primarily associated with:

- Coordination among various working groups involved
- Clash analysis between different systems
- Element parameterization
- Quantity takeoff
- Work Breakdown Structure (WBS)
- IFC export

The work did not involve using BIM for energy loss calculations, as a different application was used for this purpose, nor did it automate cost calculations.

Clearly, a further step in future design work will involve the ability to incorporate all the necessary considerations and calculations for the complete sizing of an HVAC system within a single software, without the need for additional steps through other applications.

Regarding the economic analysis of the building, quantities were clearly extracted from the BIM, but a fully automated cost calculation process was not implemented. Instead, quantities derived from the BIM were manually input into the appropriate software.

These two situations primarily arose due to the limited and less developed knowledge of the software by all parties involved and their preference for using well-known tools, thus limiting potential project delivery delays.

4.1 Coordination

Coordination and collaboration are two fundamental concepts when it comes to BIM design, and their advantages have been extensively discussed.

In particular, in a project like this, coordination among various working groups is crucial due to the presence of numerous fields of interest: structural, architectural, mechanical, and electrical. A lack of communication among the various teams could lead to various issues, such as the presence of electrical conduits overlapping with air ducts or the passage of pipes through walls containing iron within them.

In this project, it was decided to use a platform where each group would upload their model at the end of the working day, making it available for the next morning to all the other teams involved. This allowed for monitoring any changes or progress in the work. This way, everyone was aware of what was being done day by day, and any issues could be reported, presented, and discussed.

Clearly, this represents an improvement over traditional design because the continuous updating of the models eliminated the need to wait for the completion of 2D drawings, such as those by the architects, before receiving a file to work on for the building systems. This working methodology helped avoid numerous problems and subsequent discussions about the placement of structural elements that would have hindered or limited some system solutions. On the other hand, some requirements from the structural and architectural side led to changes in the HVAC network design.

4.2 Clash detection

Clash detection is the practical representation of how the BIM model, purely from a graphical perspective, is a step ahead of traditional two-dimensional design. In the latter, the creation of hydraulic and HVAC networks does not fully take into account available spaces or potential interferences with other systems or architectural elements, as it is based simply on plans or sections. Now, it is possible to know with certainty the technical spaces available for developing the networks of the systems involved, limiting or even eliminating problems that could arise during the construction phase, resulting in increased costs and completion times.

Some examples of interferences encountered during the project will now be presented, representing only a small part of those that were actually detected. In Figure [12], different types of interferences are shown:

- In the red circle, it is highlighted that the air duct was not passing through the designated hole.
- In the green circle, it can be seen that electrical conduits were passing through the air duct, which is clearly not permissible.

Furthermore, it can be noted that in this case, there was misalignment between the designated holes for the passage of the ducts. In the previous row, the air duct passed perfectly inside, while in the next row, despite a straight section of the duct, the same situation was no longer present. In this case, the ability for the HVAC system designer to view the 3D structure proved to be essential as it allowed the identification of an inconsistency that was subsequently corrected.

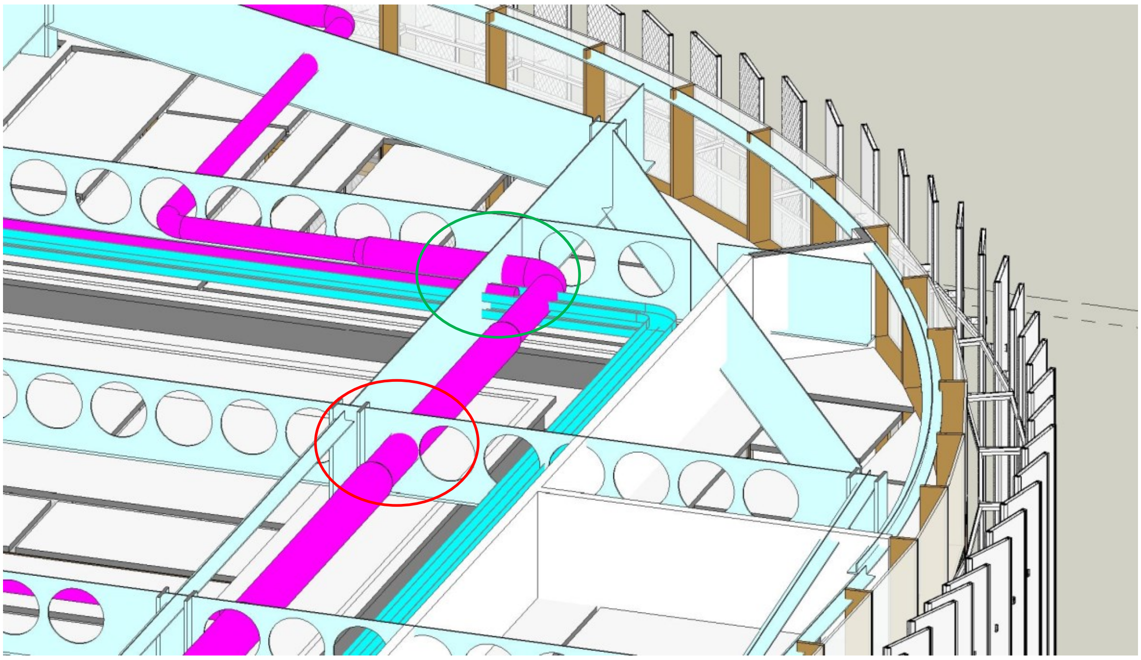


Figure 12 First clash detection

Continuing, in Figure [13], a different type of interference can be observed, which in this case was avoided thanks to the use of BIM. The air duct and electrical conduit are at the same level and passing through two adjacent holes. The problem arises when the electrical conduit needs to "turn" to the left. Since they are at the same height, the same error that occurred previously could have occurred.

As can be seen, thanks to the perfect knowledge of the available spaces, it is simply necessary to lower the electrical conduit below the air duct to avoid possible interference between the systems involved. Furthermore, it is important to note that the decision to create a change in elevation between the two systems fell on the electrical system rather than the HVAC system. This is because the presence of bends and changes in elevation required to avoid clash detection would have resulted in an increase in air circuit pressure losses, a factor that should not be overlooked and is crucial for fan sizing.

Just think about the consequences that could have occurred if it had been necessary to change the elevation of the HVAC circuit and perhaps even at high points in the distribution: much higher pressure losses and the fan's inability to deliver air to the most disadvantaged point in the network.

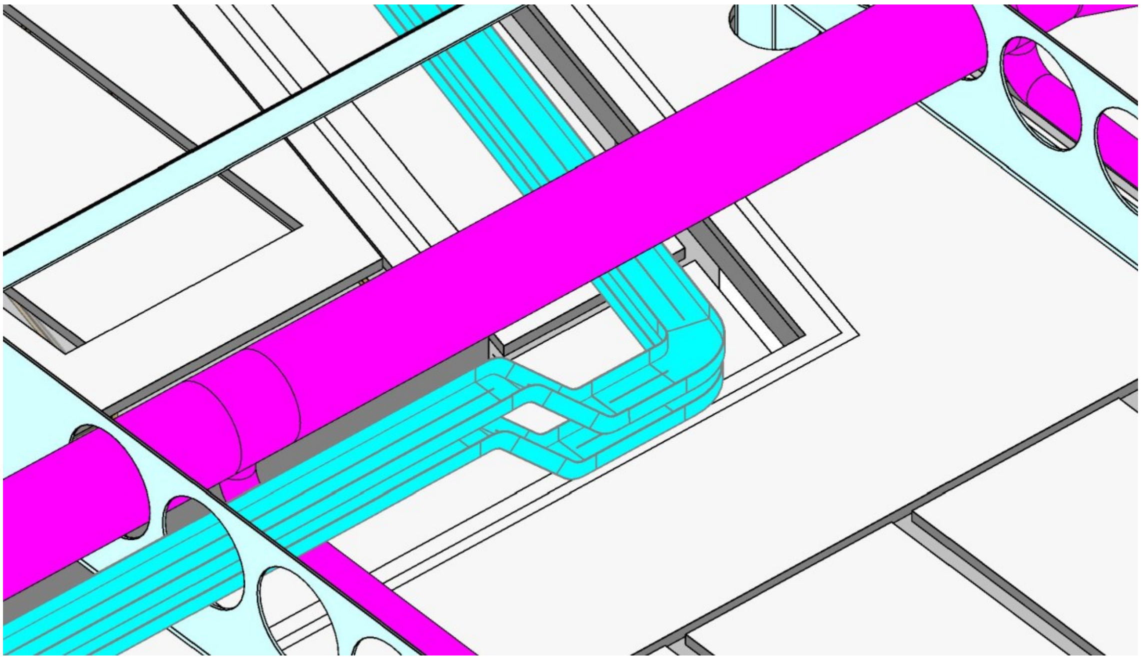


Figure 13 Second clash detection

In a very similar manner to the previous case, in the last one represented by Figure [14], it can be seen that the water pipes (in black) have to pass over the air circuit and then return to the same starting elevation. In this situation as well, it is crucial to know precisely the number of bends and changes in elevation along the water distribution network in order to correctly size the circulation pump.

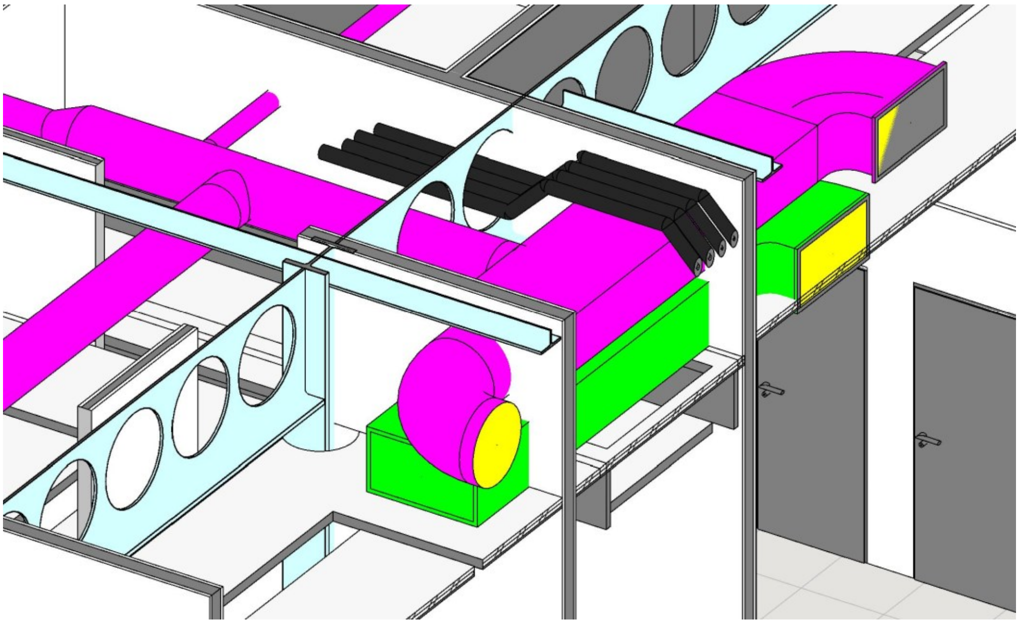


Figure 14 Third clash detection

4.3 Parameterisation and properties of element

The inclusion of parameters associated with each element in the model is what sets BIM design apart from traditional design. In BIM, every represented object is not just a collection of lines or polylines but is characterized by a set of parameters that provide specific characteristics.

These parameters can include wattage and dimensions of a lamp, the composition of a wall, the thermal capacity of a radiator, and so on. Therefore, a simple object becomes a collection of geometric and technical parameters that are very useful for immediately understanding its characteristics and whether it is suitable for its intended purpose. For instance, consider a radiator placed in a room. By clicking on the object, you can immediately see if its thermal capacity can meet the room's requirements, and if not, you can replace it with a different object.

In addition to the purely technical and intrinsic characteristics of an element, BIM allows for the creation of new parameters associated with defined categories of objects, making what is present in the model even more specific and characteristic. In this work, for example, new parameters were created and associated with objects to:

- Facilitate and improve the final layout of the documents.
- Ease the location of objects.
- Implement the Work Breakdown Structure (WBS).
- Create an IFC file compliant with project directives.

All these possibilities offered by the use of BIM were used to make the work more streamlined and precise compared to traditional design, particularly regarding the presentation of documents, quantity calculations, and ultimately exporting the model in a format visible to all stakeholders without the need for the specific BIM software in question.

Now i twill be presented some examples related to the specific characteristics of BIM objects and the custom parameters used in this project. Starting with Figure [15], which relates to a piece of ductwork, you can immediately understand its dimensions, the material it is made of, the distribution system to which it belongs (in this case, supply air), and the insulation specified by the designer.

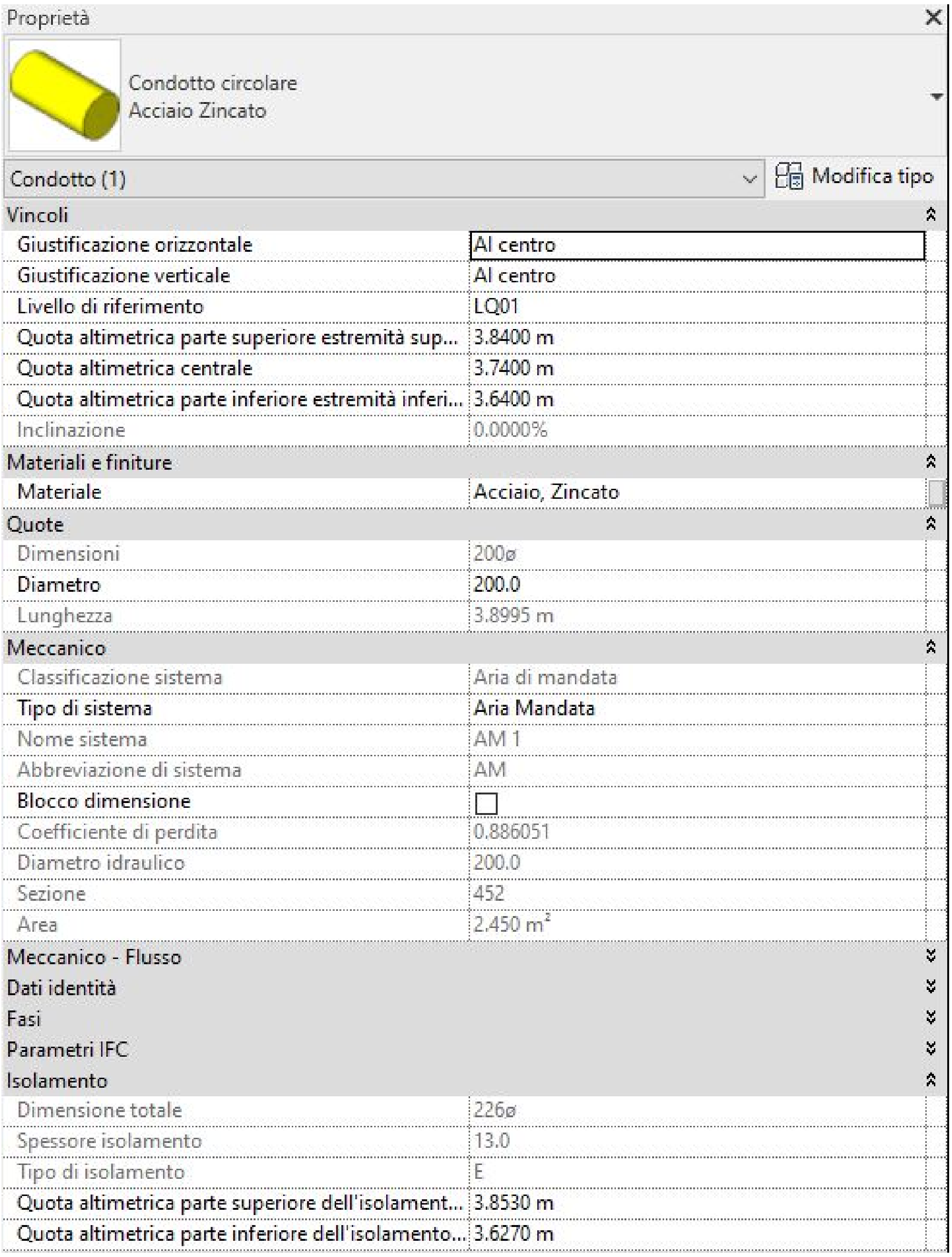
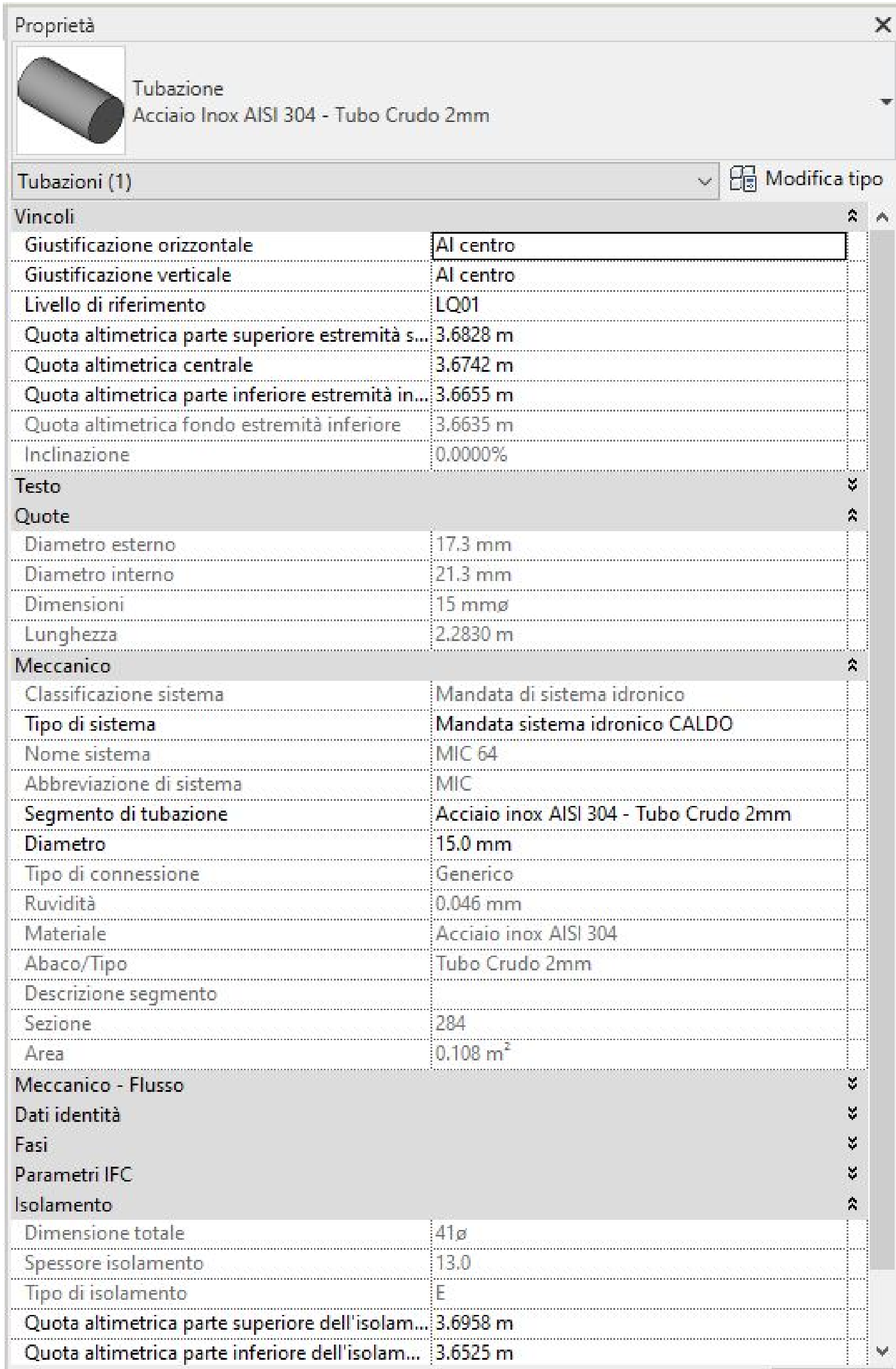


Figure 15 Duct characteristics

Another example can be seen in Figure [16], representing the characteristics of a water pipe. As in the previous case, the geometric properties of the pipe are immediately visible, as well as some technical aspects.



Proprietà

Tubazione
Acciaio Inox AISI 304 - Tubo Crudo 2mm

Tubazioni (1) — Modifica tipo

Vincoli	
Giustificazione orizzontale	Al centro
Giustificazione verticale	Al centro
Livello di riferimento	LQ01
Quota altimetrica parte superiore estremità s...	3.6828 m
Quota altimetrica centrale	3.6742 m
Quota altimetrica parte inferiore estremità in...	3.6655 m
Quota altimetrica fondo estremità inferiore	3.6635 m
Inclinazione	0.0000%
Testo	
Quote	
Diametro esterno	17.3 mm
Diametro interno	21.3 mm
Dimensioni	15 mmø
Lunghezza	2.2830 m
Meccanico	
Classificazione sistema	Mandata di sistema idronico
Tipo di sistema	Mandata sistema idronico CALDO
Nome sistema	MIC 64
Abbreviazione di sistema	MIC
Segmento di tubazione	Acciaio inox AISI 304 - Tubo Crudo 2mm
Diametro	15.0 mm
Tipo di connessione	Generico
Ruvidità	0.046 mm
Materiale	Acciaio inox AISI 304
Abaco/Tipo	Tubo Crudo 2mm
Descrizione segmento	
Sezione	284
Area	0.108 m^2
Meccanico - Flusso	
Dati identità	
Fasi	
Parametri IFC	
Isolamento	
Dimensione totale	41ø
Spessore isolamento	13.0
Tipo di isolamento	E
Quota altimetrica parte superiore dell'isolam...	3.6958 m
Quota altimetrica parte inferiore dell'isolam...	3.6525 m

Figure 16 Pipe characteristics

From these first two figures related to an air duct and a water pipe, it is immediately evident how, simply by clicking on the object of interest, the knowledge of the object's properties is available to anyone. Additionally, this makes it easier for project coordinators to check for any errors or omissions by the modelers.

Continuing, in Figures [17] and [18], the characteristics related to the linear diffuser and the heat pump are shown, respectively. In the first case, it is immediately possible to determine if the element is suitable for its task, given the lower and upper limits of air flow rate. As for the second object, there are more extensive technical and informational characteristics, including subcomponents that make up the heat pump, such as the compressor, evaporator, fan, and refrigerant. In addition to this, thermal and cooling capacity values are provided, as well as information about the machine's noise levels.

Since these two BIM objects are provided by their respective manufacturers, the level of detail depends on internal company choices.

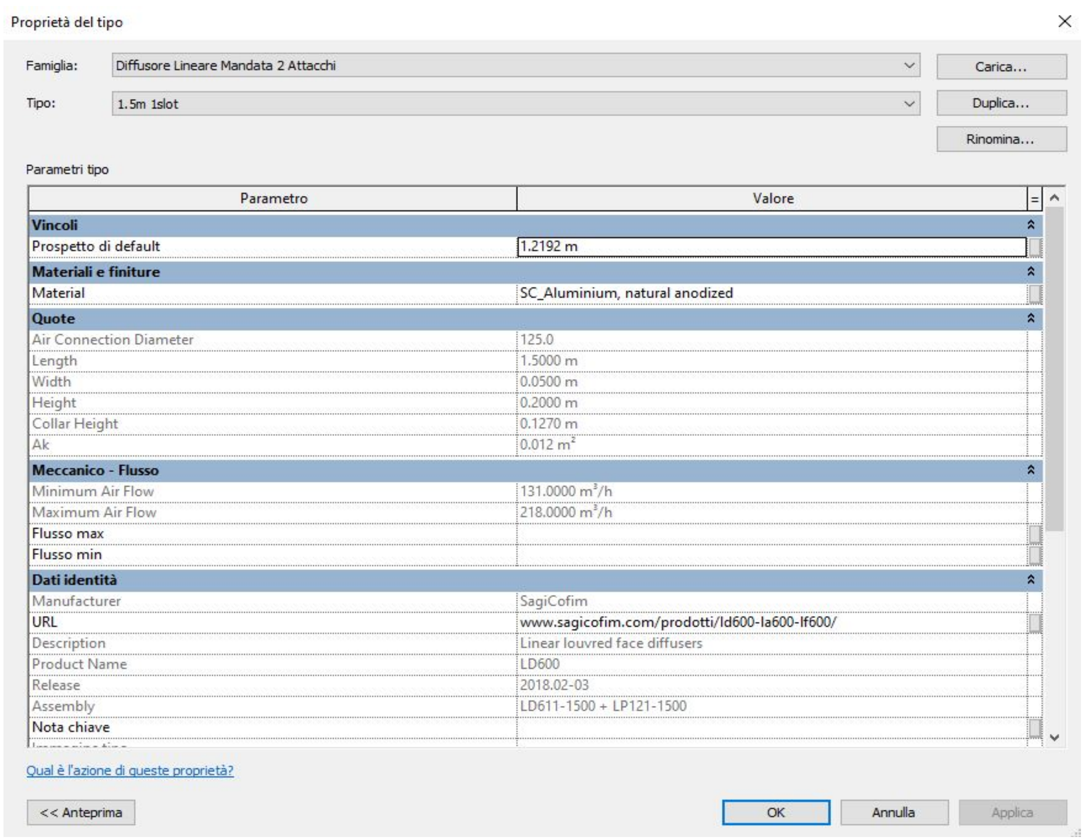


Figure 17 Air diffuser

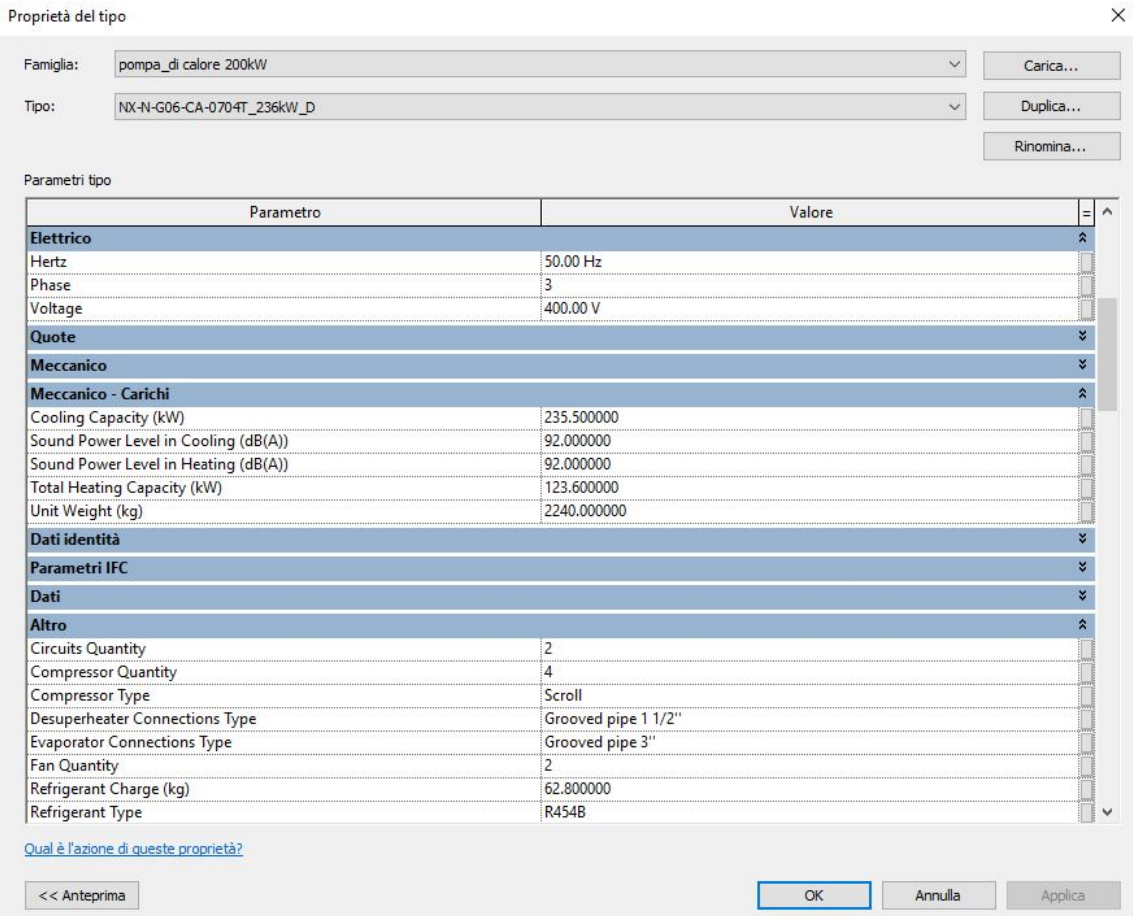


Figure 18 Heat pump

Additional parameters related to quantity extraction, WBS creation, and IFC export will be presented on the following pages.

4.4 Quantity take off

Calculating quantities in a project is a fundamental part of providing an accurate cost estimate for the work. In fact, significant errors related to incorrect counting can lead to overestimating or underestimating the project, subsequently resulting in unnecessary decisions.

In the first case, an excessive calculation of costs can lead to considering cheaper materials for pipelines, or lower-quality and consequently less efficient terminal units, and in extreme cases, even abandoning the project due to being out of budget.

In the other situation, considering a much lower expense than what will prove to be the reality can be a source of numerous problems and conflicts, especially with clients who had budgeted for a significantly different cost, perhaps finding it difficult to complete the project and having to abandon it.

With the use of BIM (Building Information Modeling), quantities are automatically calculated by the software, clearly taking into account what has been input into the model. Therefore, precise information about the numbers of objects present will be available.

In the subject of study, there is a large number of diverse elements, belonging to different systems and located in various spaces. The calculation of the total costs required by the client necessitates a clear and distinct separation by zones and system types. Therefore, it is essential to categorize all types of elements in the model based on their location and the circuit to which they belong.

To further clarify this concept, it's not enough to simply count the number of 1-meter linear diffusers in the entire model; rather, it is necessary to know how many belong to the supply or return system and which area of the building they pertain to. This way, it will be possible to have a clear and precise understanding of the costs associated with each segmented area of the project, making it easier to manage any changes or reconsiderations by focusing directly on the relevant aspect of interest.

A representation of this concept can be seen in the following image, Figure [19], depicting how this segmentation has been implemented: for each type of element, the quantity present in a specific area of the building is known based on the distribution system to which it belongs.

It is immediately evident that the number of 1-meter linear diffusers with 1 slot, belonging to the supply air system located in the nursery school, is 10.

This clearly simplifies the calculation for each area since the segmentation has already been done and does not contain errors, as it has been implemented automatically by the software and not through manual counting, as is done in traditional design.

<DIFFUSERS' COUNT>

A	B	C	D	E
Famiglia e tipo	Codice categoria	Tipo di sistema	Zona	Livello
Diffusore Lineare Mandata 1 Attacco: 1m 1slot	BOC	Aria Mandata	Scuola Infanzia	LQ00
Scuola Infanzia: 10				
Diffusore Lineare Mandata 1 Attacco: 1m 1slot	BOC	Aria Mandata	Uffici (P1)	LQ01
Uffici (P1): 14				
Diffusore Lineare Mandata 1 Attacco: 1m 2slot	BOC	Aria Mandata	Uffici (P1)	LQ01
Uffici (P1): 6				
Diffusore Lineare Mandata 1 Attacco: 1m 4slot	BOC	Aria Mandata	Academy	LQ00
Academy: 4				
Diffusore Lineare Mandata 2 Attacchi: 1.5m 1slot	BOC	Aria Mandata	Uffici (P1)	LQ01
Uffici (P1): 16				
Diffusore Lineare Mandata 2 Attacchi: 1.5m 2slot	BOC	Aria Mandata	Uffici (P1)	LQ01
Uffici (P1): 3				
Diffusore Lineare Mandata 2 Attacchi: 1.5m 4slot	BOC	Aria Mandata	Academy	LQ00
Academy: 22				
Diffusore Lineare Mandata 2 Attacchi: 2m 1slot	BOC	Aria Mandata	Uffici (P1)	LQ01
Uffici (P1): 39				
Diffusore Lineare Mandata 2 Attacchi: 2m 2slot	BOC	Aria Mandata	Reception	LQ00
Reception: 4				
Diffusore Lineare Mandata 2 Attacchi: 2m 2slot	BOC	Aria Mandata	Uffici (P1)	LQ01
Uffici (P1): 3				
Diffusore Lineare Mandata 2 Attacchi: 2m 4slot	BOC	Aria Mandata	Academy	LQ00
Academy: 5				
Diffusore Lineare Mandata 2 Attacchi: 2m 4slot	BOC	Aria Ripresa	Academy	LQ00
Academy: 1				
Diffusore Lineare Ritorno 1 Attaccho: 1m 1slot	BOC	Aria Ripresa	Scuola Infanzia	LQ00
Scuola Infanzia: 1				
Diffusore Lineare Ritorno 1 Attaccho: 1m 1slot	BOC	Aria Ripresa	Uffici (P1)	LQ01
Uffici (P1): 8				
Diffusore Lineare Ritorno 1 Attaccho: 1m 2slot	BOC	Aria Ripresa	Uffici (P1)	LQ01
Uffici (P1): 6				
Diffusore Lineare Ritorno 1 Attaccho: 1m 4slot	BOC	Aria Ripresa	Academy	LQ00
Academy: 4				
Diffusore Lineare Ritorno 2 Attacchi: 1.5m 1slot	BOC	Aria Ripresa	Uffici (P1)	LQ01
Uffici (P1): 20				
Diffusore Lineare Ritorno 2 Attacchi: 1.5m 2slot	BOC	Aria Ripresa	Uffici (P1)	LQ01
Uffici (P1): 1				

Figure 19 Diffusers' quantity

All the concepts just discussed regarding the precise calculation of quantities by zone clearly apply to every type of element present in the model. However, it's worth delving into the calculation of water pipes and air ducts implemented with BIM.

In addition to differentiation by zone and system membership, here it is necessary to calculate the total length of various branches and the area of insulation required. This is done to facilitate and expedite the subsequent cost calculation for the project.

Therefore, a function has been implemented to perform the summation of various pipe branches with the same physical (material) and geometric (diameter) characteristics, belonging to the same zone and system.

A	B	C	D	E	F	G	H	I
Famiglia e tipo	Zona	Livello di riferimento	Diametro	Lunghezza	Tipo di sistema	Tipo di isolamento	Spessore isolamento	Area isolante
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	20.0 mm	0.158	Mandata sistema idronico CALDO	E	13	0.02 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	20.0 mm	4.932	Mandata sistema idronico CALDO	E	13	0.71 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	20.0 mm	2.736	Mandata sistema idronico CALDO	E	13	0.40 m²
Mandata sistema idronico CALDO				7.826				1.13 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	20.0 mm	0.158	Ritorno sistema idronico CALDO	E	13	0.02 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	20.0 mm	4.932	Ritorno sistema idronico CALDO	E	13	0.71 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	20.0 mm	2.679	Ritorno sistema idronico CALDO	E	13	0.39 m²
Ritorno sistema idronico CALDO				7.769				1.12 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	2.388	Mandata sistema idronico CALDO	E	13	0.38 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	3.491	Mandata sistema idronico CALDO	E	13	0.56 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	2.849	Mandata sistema idronico CALDO	E	13	0.46 m²
Mandata sistema idronico CALDO				8.728				1.40 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	3.408	Mandata sistema idronico FREDDO	E	13	0.55 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	1.892	Mandata sistema idronico FREDDO	E	13	0.30 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	3.511	Mandata sistema idronico FREDDO	E	13	0.56 m²
Mandata sistema idronico FREDDO				8.812				1.41 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	2.208	Ritorno sistema idronico CALDO	E	13	0.35 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	3.383	Ritorno sistema idronico CALDO	E	13	0.54 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	2.834	Ritorno sistema idronico CALDO	E	13	0.45 m²
Ritorno sistema idronico CALDO				8.425				1.35 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	3.288	Ritorno sistema idronico FREDDO	E	13	0.53 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	1.744	Ritorno sistema idronico FREDDO	E	13	0.28 m²
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	LQ00	25.0 mm	3.473	Ritorno sistema idronico FREDDO	E	13	0.56 m²
Ritorno sistema idronico FREDDO				8.505				1.36 m²

Figure 20 Pipes' quantity

The same approach has been applied to calculate the insulation area, naturally using the appropriate mathematical function, taking into account the pipe diameter and the specified insulation thickness. In the event that the pipe diameter or the specified thickness of insulation is modified, the table will update automatically, thereby avoiding additional computational efforts for the operator.

<PIPES' COUNT>						
A	B	C	D	E	F	G
Famiglia e tipo	Zona	Diametro	Tipo di sistema	Tipo di isolamento	Spessore isolamento	Area isolante
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	20.0 mm	Mandata sistema idronico CALDO	E	13	1.13 m^2
Mandata sistema idronico CALDO						1.13 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	20.0 mm	Ritorno sistema idronico CALDO	E	13	1.12 m^2
Ritorno sistema idronico CALDO						1.12 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	25.0 mm	Mandata sistema idronico CALDO	E	13	1.40 m^2
Mandata sistema idronico CALDO						1.40 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	25.0 mm	Mandata sistema idronico FREDDO	E	13	1.41 m^2
Mandata sistema idronico FREDDO						1.41 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	25.0 mm	Ritorno sistema idronico CALDO	E	13	1.35 m^2
Ritorno sistema idronico CALDO						1.35 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	25.0 mm	Ritorno sistema idronico FREDDO	E	13	1.36 m^2
Ritorno sistema idronico FREDDO						1.36 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	32.0 mm	Mandata sistema idronico CALDO	E	13	3.56 m^2
Mandata sistema idronico CALDO						3.56 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	32.0 mm	Mandata sistema idronico FREDDO	E	13	3.56 m^2
Mandata sistema idronico FREDDO						3.56 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	32.0 mm	Ritorno sistema idronico CALDO	E	13	3.53 m^2
Ritorno sistema idronico CALDO						3.53 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	32.0 mm	Ritorno sistema idronico FREDDO	E	13	3.58 m^2
Ritorno sistema idronico FREDDO						3.58 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	40.0 mm	Mandata sistema idronico CALDO	E	19	6.64 m^2
Mandata sistema idronico CALDO						6.64 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	40.0 mm	Mandata sistema idronico FREDDO	E	19	6.41 m^2
Mandata sistema idronico FREDDO						6.41 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	40.0 mm	Ritorno sistema idronico CALDO	E	19	6.64 m^2
Ritorno sistema idronico CALDO						6.64 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	40.0 mm	Ritorno sistema idronico FREDDO	E	19	6.41 m^2
Ritorno sistema idronico FREDDO						6.41 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	50.0 mm	Mandata sistema idronico CALDO	E	19	9.80 m^2
Mandata sistema idronico CALDO						9.80 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	50.0 mm	Mandata sistema idronico FREDDO	E	19	9.31 m^2
Mandata sistema idronico FREDDO						9.31 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	50.0 mm	Ritorno sistema idronico CALDO	E	19	9.65 m^2
Ritorno sistema idronico CALDO						9.65 m^2
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	50.0 mm	Ritorno sistema idronico FREDDO	E	19	9.15 m^2
Ritorno sistema idronico FREDDO						9.15 m^2

Figure 21 Insulation

It is evident from these small examples how the use of automated tables makes the calculation of quantities very simple and quick, ensuring a certain level of accuracy, given the almost negligible possibility of making errors, unless they were made upstream by the modeler. However, individual designers still have the option to add an additional margin of safety when performing the cost calculation, as the extracted measurements are not obligatory to follow to the letter, especially if they wish to exercise caution, especially in estimating the required meters of piping or ductwork.

4.5 Work Breakdown Structure

As previously discussed, the WBS represents a methodology for breaking down the work into various subprocesses and elements in order to create a structure that defines the work itself. Such division is crucial for quantifying quantities, expenses, and the completion times of each individual part into which the infrastructure has been decomposed.

In the case at hand, a three-level structure has been conceived, each level becoming increasingly distinctive and specific.

Level 1 refers to the different intended uses of the various areas into which the building is divided:

- "Blocco Q"
- "Edificio Q, Parcheggio interrato"
- "Edificio Q, Scuola d'infanzia"
- "Edificio Q, Academy"
- "Edificio Q, Reception"
- "Edificio Q, Uffici"
- "Attrezzeria"
- "Attrezzeria esistente"
- "Aree esterne"

The entries "Attrezzeria" ed "Attrezzeria esistente" belong to a different building that is not relevant to the current project and will therefore be set aside.

The WBS Level 2 refers to the position in the space of the objects, that is to the various planes present:

- "Fondazione"
- "Interrato -2"
- "Interrato -1"

- "Piano Terra"
- "Piano Primo"
- "Piano Copertura"
- "Tutti I Piani"
- "Aree Esterne"

With the category "Tutti i piani", reference is made to those objects present in different planes at the same time, that is mainly those pipes or those ducts that descend along the system and therefore are not associated exclusively with a single floor.

With the WBS Level 3 it goes finally to specify which is the use of the represented element, that is the system to which it belongs.

Without mentioning them all, those of interest in this work are reported:

- "Termici – Centrali Termiche O Frigorifere"
- "Termici – Climatizzazione Invernale O Estiva"
- "Termici – Reti Aerauliche"
- "Regolazione"

Each of the fields described here, for each level of the WBS hierarchy, is represented by a code that uniquely describes the characteristics of the element. To implement this coding in BIM, three specific parameters were created: WBS01, WBS02, and WBS03.Code, and each element was manually inputted by the user. Clearly, a process like this could also have been automated using Dynamo for even greater efficiency. However, given the ability to manage tables through specific and customized filters and sorting, it was decided to implement it manually due to the speed of completing the procedure. As can be seen in the image below, Figure [22], the use of specific filters and groupings for elements with the same characteristics, particularly the "Zone" parameter, makes it straightforward to assign the correct WBS to a large number of objects, making the process very fast.

<WBS DUCTS>							
A	B	C	D	E	F	G	H
Famiglia e tipo	Zona	Tipo di sistema	Lunghezza	Diametro	WBS01	WBS02	WBS03.Codice
Condotto circolare: Giunti/Raggio stretto	Academy	Aria Aspirazione Esterna	0.761 m	140	QA	PT	gd
Condotto circolare: Giunti/Raggio stretto	Academy	Aria Espulsione	0.759 m	140	QA	PT	gd
Condotto circolare: Giunti/Raggio stretto	Copertura	Aria Aspirazione Esterna	0.226 m	160	Q	CP	gc
Condotto circolare: Giunti/Raggio stretto	Copertura	Aria Espulsione	1.460 m	160	Q	CP	gc
Condotto circolare: Giunti/Raggio stretto	Reception	Aria Aspirazione Esterna	11.859 m	160	QR	PT	gd
Condotto circolare: Giunti/Raggio stretto	Reception	Aria Espulsione	13.736 m	160	QR	PT	gd
Condotto circolare: Giunti/Raggio stretto	Scuola Infanzia	Aria Aspirazione Esterna	6.808 m	200	QS	PT	gd
Condotto circolare: Giunti/Raggio stretto	Scuola Infanzia	Aria Espulsione	6.297 m	200	QS	PT	gd
Condotto circolare: Giunti/Raggio stretto	Tutti Piani	Aria Aspirazione Esterna	10.873 m	160	Q	PP	gd
Condotto circolare: Giunti/Raggio stretto	Tutti Piani	Aria Espulsione	10.997 m	160	Q	PP	gd
Condotto circolare: Giunti/Raggio stretto	Uffici P1	Aria Aspirazione Esterna	6.588 m	160	QU	P1	gd
Condotto circolare: Giunti/Raggio stretto	Uffici P1	Aria Espulsione	7.335 m	160	QU	P1	gd

Figure 22 WBS duct

With regard to the individual elements, as an example, a linear speaker located in the Offices area on the first floor belonging to the supply air system will be characterized by the coding visible in Figure [23] below.

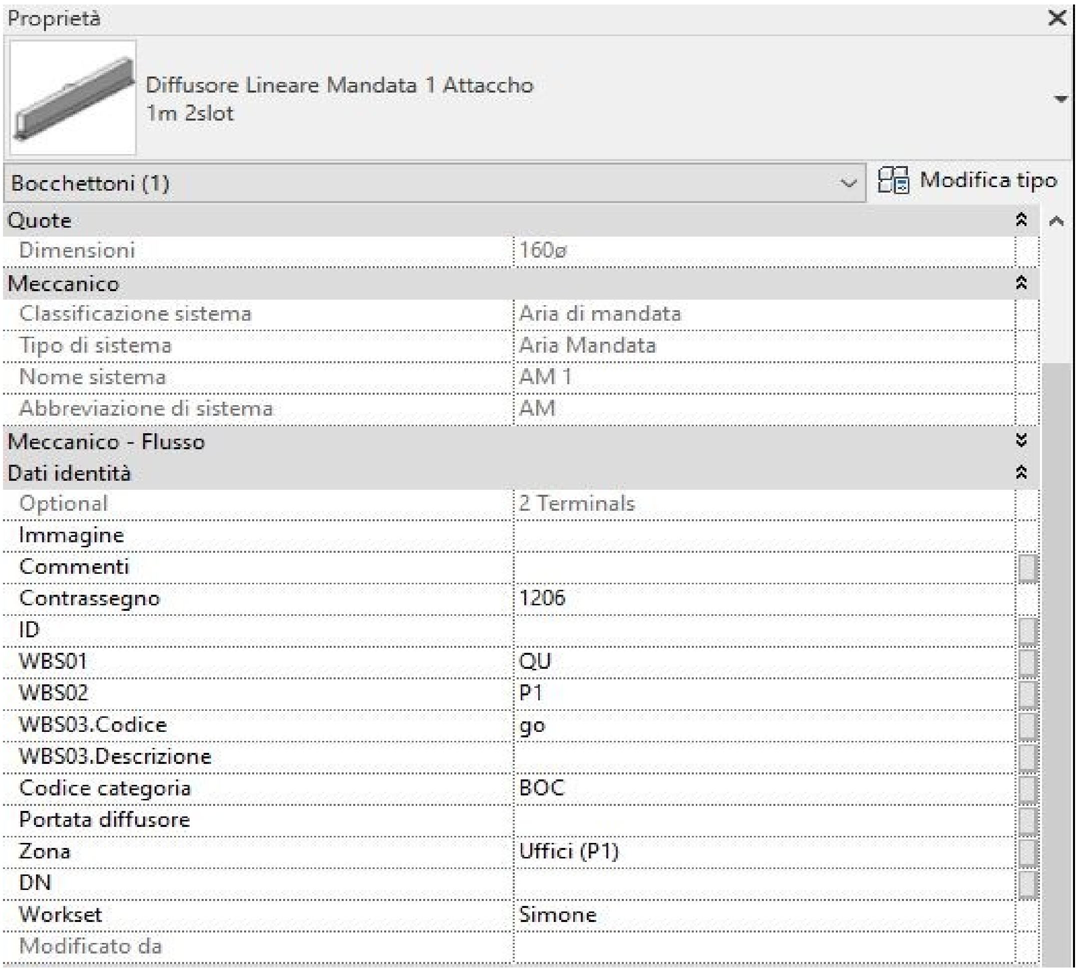


Figure 23 Diffuser’s code

For a larger number of elements, the final table for linear speakers is represented by figure [24]where you can see how each individual element is characterized by the 3 WBS parameters described before going to describe uniquely their place in the work.

<WBS DIFFUSER>				
A	B	C	D	E
Famiglia e tipo	Codice categoria	WBS01	WBS02	WBS03.Codice
Diffusore Lineare Mandata 1 Attaccho: 1m 1slot	BOC	QS	PT	go
Diffusore Lineare Mandata 1 Attaccho: 1m 1slot	BOC	QU	P1	go
Diffusore Lineare Mandata 1 Attaccho: 1m 2slot	BOC	QU	P1	go
Diffusore Lineare Mandata 1 Attaccho: 1m 4slot	BOC	QA	PT	go
Diffusore Lineare Mandata 2 Attacchi: 1.5m 1slot	BOC	QU	P1	go
Diffusore Lineare Mandata 2 Attacchi: 1.5m 2slot	BOC	QU	P1	go
Diffusore Lineare Mandata 2 Attacchi: 1.5m 4slot	BOC	QA	PT	go
Diffusore Lineare Mandata 2 Attacchi: 2m 1slot	BOC	QU	P1	go
Diffusore Lineare Mandata 2 Attacchi: 2m 2slot	BOC	QR	PT	go
Diffusore Lineare Mandata 2 Attacchi: 2m 2slot	BOC	QU	P1	go
Diffusore Lineare Mandata 2 Attacchi: 2m 4slot	BOC	QA	PT	go
Diffusore Lineare Ritorno 1 Attaccho: 1m 1slot	BOC	QS	PT	go
Diffusore Lineare Ritorno 1 Attaccho: 1m 1slot	BOC	QU	P1	go
Diffusore Lineare Ritorno 1 Attaccho: 1m 2slot	BOC	QU	P1	go
Diffusore Lineare Ritorno 1 Attaccho: 1m 4slot	BOC	QA	PT	go
Diffusore Lineare Ritorno 2 Attacchi: 1.5m 1slot	BOC	QU	P1	go
Diffusore Lineare Ritorno 2 Attacchi: 1.5m 2slot	BOC	QU	P1	go
Diffusore Lineare Ritorno 2 Attacchi: 1.5m 4slot	BOC	QA	PT	go
Diffusore Lineare Ritorno 2 Attacchi: 2m 1slot	BOC	QU	P1	go
Diffusore Lineare Ritorno 2 Attacchi: 2m 2slot	BOC	QR	PT	go
Diffusore Lineare Ritorno 2 Attacchi: 2m 2slot	BOC	QU	P1	go
Diffusore Lineare Ritorno 2 Attacchi: 2m 4slot	BOC	QA	PT	go

Figure 24 WBS diffuser

In relation to elements such as piping, figure [25], the same coding has always been applied, but in the table has been added the column length, representing the total amount in meters of each type of pipe for each room and for each system, so you immediately at first glance know how many meters of pipe are needed.

<WBS PIPES>

A	B	C	D	E	F
Famiglia e tipo	Zona	Lunghezza	WBS01	WBS02	WBS03.Codice
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Copertura	74.867	Q	CP	ge
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Tutti Piani	13.945	Q	PP	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Tutti Piani	283.581	Q	PP	gf
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Copertura	239.271	QA	CP	ge
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Academy	423.347	QA	PT	gf
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Interrato -1	11.528	QP	B1	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Interrato -1	113.893	QP	B1	gf
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Interrato -2	172.542	QP	B2	gf
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Reception	302.224	QR	PT	gf
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Scuola Infanzia	4.196	QS	PT	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Scuola Infanzia	118.894	QS	PT	gf
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Uffici P1	8.081	QU	P1	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 2mm	Uffici P1	1356.982	QU	P1	gf
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 3mm	Tutti Piani	31.625	Q	PP	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 3mm	Academy	23.920	QA	PT	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 3mm	Interrato -1	200.440	QP	B1	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 3mm	Reception	22.158	QR	PT	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 3mm	Scuola Infanzia	38.762	QS	PT	gb
Tubazione: Acciaio Inox AISI 304 - Tubo Crudo 3mm	Uffici P1	241.272	QU	P1	gb

Figure 25 WBS pipes

4.6 IFC

The Industry Foundation Classes (IFC) is an open and non-controlled data format created to facilitate communication and cooperation among various stakeholders in the industry. Its primary purpose is to enable the exchange of an informative model related to a building without any loss or alteration of data and information [15].

As extensively presented earlier, the BIM methodology relies on close collaboration among different professionals involved in various phases of a structure's lifecycle, making it necessary to continuously and accurately input, extract, modify, or update information within the model.

To support such collaboration, it is essential to have access to a standard data exchange format that ensures interoperability and information security. This is precisely the fundamental role of the IFC format, created with the objective of facilitating communication and cooperation among various professionals.

In this work, as in other cases, specific parameters have been implemented to characterize the objects present in the model, using standards suggested by international platforms. In the figures below, [26] and [27], you can see the parameters used to standardize the elements and make them clearly understandable to all users involved in the project. The goal is particularly to define the object's macro-group of belonging and subsequently the specific typology.

Thanks to this coding, once the BIM file is exported in IFC format, the objects and their classification are automatically recognized, making it possible to share information without the risk of losing anything.

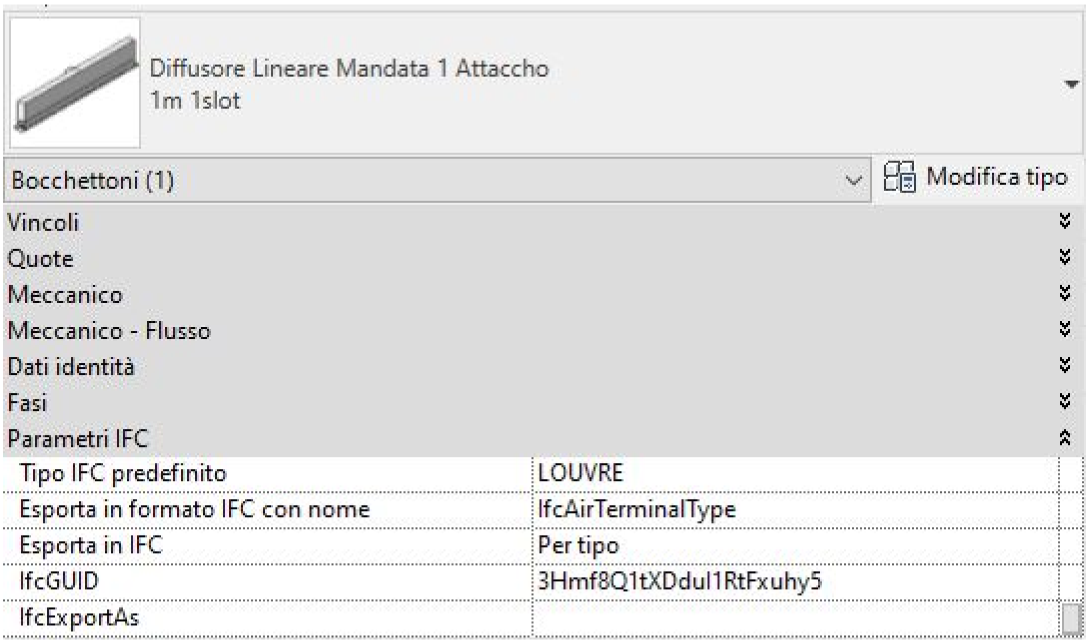


Figure 26 Ifc Diffuser

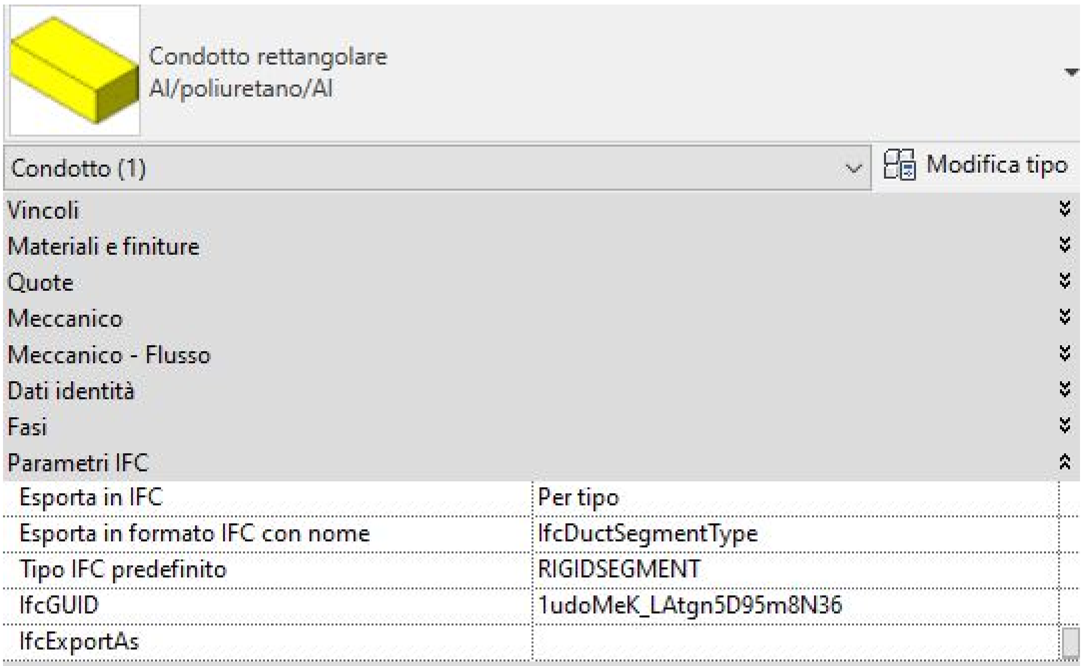


Figure 27 Ifc Duct

Chapter 5

Results and discussions

5.1 General results of HVAC system

Following the presentation, it is possible to summarize the key aspects that distinguish this project. The upcoming construction building, as emphasized multiple times, is set to be the company's flagship, serving as the headquarters for offices, meeting rooms, reception areas, as well as a venue for both internal and external events and conferences.

In line with this, the client's requirements for the building systems were high, both in terms of aesthetics and functionality. Additionally, some of the system choices were influenced by architectural considerations or the structure's layout.

To recap, the HVAC system designed consists of two versatile heat pumps for simultaneous hot and chilled water production and three air handling units to meet the thermal and ventilation requirements determined through calculation software, with the following key features:

HEAT PUMP DATA	
COOLING	
POWER [kW]	192
EER	2,4
HEATING	
POWER [kW]	136
COP	2,34
AHU DATA	
AHU EAST OFFICE	
AIR FLOW RATE [m^3/h]	5975
AHU WEST OFFICE	
AIR FLOW RATE [m^3/h]	5425
AHU ACADEMY	
AIR FLOW RATE [m^3/h]	14000

Furthermore, it is important to highlight the presence of five heat recovery units serving the basement levels, the nursery school, and the reception area. Given the uniqueness of the building and its predominantly glass structure, it is clear that throughout the day, there may be a demand for heating or cooling depending on the location of the space in question and external weather conditions.

For this reason, the designed system is of the 4-pipe type, primarily constructed using stainless steel, to accommodate all possible user needs that may arise during the workday. The heat pumps are responsible for producing technical water at 45°C for heating and 7°C for cooling. This water is used to supply the 4-pipe system intended to serve all the hydronic terminals within the building, including wall-mounted fan coil units, floor-mounted units, and radiant ceiling panels.

For the latter, the water supply temperatures are different from those of the other terminals, so the inclusion of specific mixing valves has been planned to bring the hot water supply temperature to 37°C and the cold water supply temperature to 15.5°C, a temperature that prevents condensation from forming inside the spaces.

Regarding the selected terminals, machines with low noise levels, low energy consumption, and high efficiency have been chosen, particularly for the ceiling radiant panels, considered among the best available in the market.

Ventilation, as previously mentioned, is managed by three units located on the roof with the aim of ensuring proper air circulation and dehumidification of the spaces. Additionally, concerning the two air handling units (AHUs) serving the first floor, they also play a role in part of the summer sensible heat load reduction. This is because the radiant panels alone, provided in certain areas, are not capable of fulfilling this task, not due to their efficiency but rather due to the lack of additional radiant surface and the south-facing orientation of the spaces themselves.

The chosen air distribution terminals, supplied through circular ducts due to the presence of perforated beams, are linear diffusers with one or more slots, and their airflow is controlled by specific devices such as CAV (Constant Air Volume) and VAV

(Variable Air Volume). This choice was driven by architectural requirements given their aesthetic design and the need to install them along the perimeter edges of the spaces, particularly on the first floor, given the presence of radiant panels in the rest of the ceiling.

Furthermore, the selected diffusers ensure low pressure drop and minimal noise, considering the nature of the spaces in which they are installed.

From an economic standpoint, the building's systems prove to be particularly costly, a result that was anticipated given both the client's demands and the uniqueness of the structure. There was a need to provide highly efficient devices, as well as an increase in general prices that occurred in the last year. In the following table, are reported the total costs relatively to the HVAC plant divided by area:

LOCATION	COST [€]
Underground -2	31.941,20
Underground -1	40.929,15
Roofing	545.859,78
All floors	295.178,95
Kindergarten	42.420,86
Academy	188.611,52
Reception	51.500,00
Offices	515.789,70
Total	1.712.231,16

It should be specified that the electronic regulation of the system has been computed under the heading "All floors", and weighs for a value of 233985,97€.

Carrying out a relative analysis regarding the total, in the following diagram it is possible to visualize how much every item weights inside the total cost of the structure:

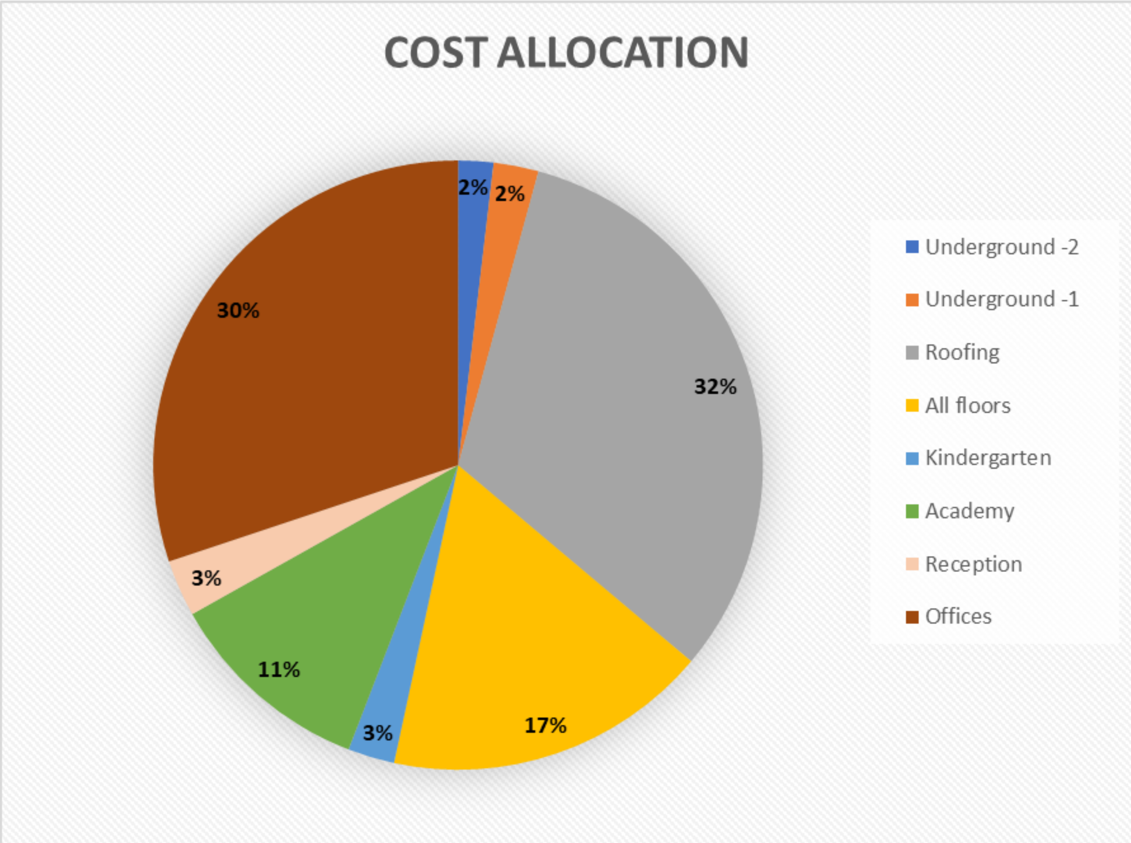


Figure 28 Cost allocation

It can be seen that what is present in the rooftop, gives the greatest contribution to the expenditure, this clearly due to the presence of heat pumps and air handling units; secondly, the air conditioning and ventilation of the office floor are also particularly expensive, due both to the presence of numerous regulating and diffusion devices, and to the considerable amount of pipes and air ducts compared to the other floors; Finally, the most "economical" spaces turn out to be the basement floors as they provide for the presence of a few elements.

5.2 Search for efficiency

As presented at the beginning of this project, one of the most significant topics of interest in recent times is sustainability, which clearly extends to the construction of new buildings, given their significant contribution to greenhouse gas emissions and energy consumption.

It is evident, therefore, that a design comprised of numerous sustainable choices is fundamental to addressing the present problem, aiming to limit consumption and waste while providing the opportunity to ensure comfort and well-being for the people inside an environment.

The decision to use versatile heat pumps instead of boilers and refrigeration units is directly linked to the aspects just described, due to their higher efficiency and lower energy consumption for proper machine operation.

Related to this, the choice to include radiant ceilings and floors, which require hot water at significantly lower temperatures than traditional radiators to provide heating, thus pairs perfectly with heat pumps.

Staying on topic, the presence of innovative 6-way valves in the hydraulic circuit supplying the ceiling panels, represented in the figure [29] below, ensures modulation of water flow based on user demands, limiting unnecessary resource consumption and also providing the option to completely exclude a branch if the supply of fluid for the conditioning of a specific area is not required.

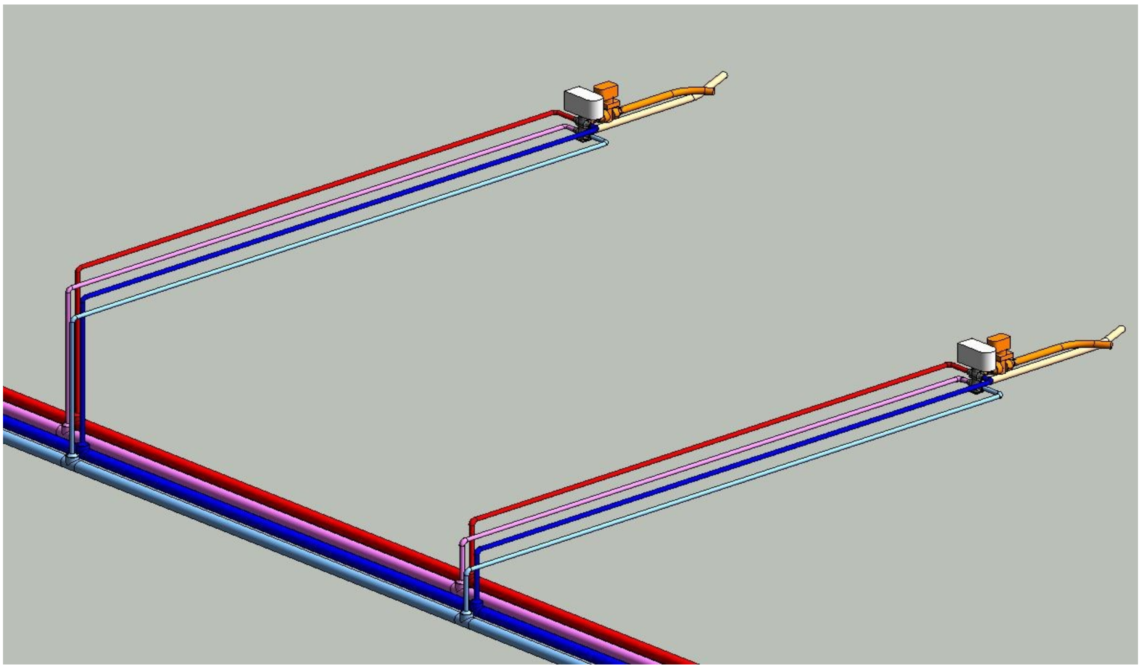


Figure 29 Six-ways valve

The AHUs are characterized by the presence of a rotary heat recovery wheel, capable of recovering both sensible and latent heat through a metal wheel.

Initially, there was a tendency to consider the use of a cross-flow heat exchanger, which recovers only sensible heat, but the decision was made to switch to this solution to ensure dual heat recovery in both seasons. Thanks to the presence of this device, it was possible to reduce the sizing of the cold water circuit serving the cooling coil and the hot water circuit serving the heating coil.

Indeed, due to the reduced need to add or remove heat from the incoming air stream, the flow rates of hot and cold water for the coils decreased, along with the pipe diameter, valves, and pump required to complete the circuit.

A further element that highlights the energy efficiency and the reduction of waste are the variable flow regulators designed to serve the Academy and environments with a presence of people not constant during the time at the office floor.

The installed regulators differ from the traditional ones in that they regulate the air flow and extraction without a physical sensor, since they exploit a new ultrasonic technology, eliminating possible turbulence, noise and consequently operating silently.

In addition, in these devices, flow measurement is carried out without any pressure drop, have minimal sensitivity to dust and interference, and do not require any maintenance.

As for the basement floors, the Reception and the Kindergarten, were provided for heat recovery units operating with countercurrent flows, allowing an effective heat exchange between the air flow of expulsion from the environment and the renewal, exploiting in this way the energy contained in the spoiled air, which would also be lost, for preheating or pre-cooling depending on the season.

Finally, all that manages the adjustment of the various accessories and devices is the control system, studied in detail with the manufacturer given the complexity of the case in question.

The presence of particular probes in the environment aimed at measuring not only the temperature, but also other parameters such as CO_2 or crowding, allow a precise and precise regulation of the air flow for ventilation and water supply to the terminals to ensure comfort and well-being to the people present.

In addition to this, the presence of an accurate control system allows the containment and reduction of waste of primary resources and energy consumption, given the ability to limit the flow rates of fluids if their input is not necessary at the nominal value of the project.

5.3 Current use and future role of BIM

In parallel with the design of the HVAC system, the BIM model of the building and facilities was also implemented in this work.

BIM, Building Information Modelling, is one of the key turning points in modern design techniques, as it allows you to create a three-dimensional representation of everything a work is made of.

This tool, however, is not only an improvement of the design, but also presents many other possible uses that make it very interesting and attractive for all design studios but also for the customers themselves.

In the presented and discussed work, BIM has been used for various purposes: three-dimensional modeling to generate a visually enhanced layout and provide a better perception of available spaces, ensuring coordination among different working groups from various firms, identifying and eliminating interferences among different systems, thereby reducing potential issues that traditionally arise during construction, characterizing and parameterizing the represented elements, extracting quantities to facilitate cost estimation, building the WBS (Work Breakdown Structure) of the project to estimate project completion times, and finally, creating an IFC file to make the model accessible to anyone interested with all the contained information.

What emerges as a result of this work, are the great potential present in this tool and having been able to confirm the improvements described in the texts and manuals made compared to traditional design.

As for the graphic layout, obviously through the BIM you were able to present and deliver a project visually more attractive and that best represented the size and appearance of the inserted appliances, pipes and pipes present:

In addition, the production of the drawings of the project has been made much faster and free of possible errors related to the structures or position of the objects, since they too are the result of a simple "photograph" of what is present in the model.

Continuing, there was a greater and more efficient ease of interfacing with the other designers involved given the possibility of having continuous updates on the development of the model; this has resulted in immediate resolution of some problems or errors present, rather than comparing additional new solutions to be expected to improve the project.

Related to this aspect of continuous coordination among different systems, the use of BIM has been essential for identifying and analyzing interferences that may occur, such as between air ducts and electrical conduits or with the building's structure. It has allowed for both changing the route or dimensions of the affected elements and introducing different strategies for the construction of certain components, whether they are related to building systems or structural elements.

Resolving issues like the ones described during this phase of the detailed design will reduce time wastage during the construction of the project due to errors or inaccuracies that were not considered during the initial design phase.

The most striking aspect and for which the use of BIM has been more successful, is related to the extraction of quantities from the model.

This function, which is automatically implemented by the software, has made it possible to determine with absolute precision the number of objects of any type, diffusers or piping meters that are, considerably reducing the time that this procedure requires if done manually, but also the risks arising from having it carried out by an operator, given the greater possibility of incurring counting errors, rather than forgetfulness.

As mentioned above, BIM not only offers the possibility to represent in three dimensions a structure and the plants present in it, but it allows the opportunity to create parameters to be associated with the elements.

This parameterization extends to each field, as in addition to the native parameters present, you can create additional parameters belonging to any field of interest.

Leveraging this aspect, it was possible to create a list of parameters related to the creation of a Work Breakdown Structure (WBS) and the implementation of an Ifc file. The project was divided into three levels, and for each of them, categories were created, encoded in a specific way to uniquely represent objects within the spaces.

With BIM, three parameters corresponding to the various levels were created, and each of them was specifically encoded following the guidelines provided and known to all parties involved.

Regarding the parameters for the Ifc file in native BIM software, they were simply used, and by filling them out, it enables the transfer and maintenance of information during export. The Ifc file, being a standard and accessible format, is very convenient if you want to take a look at the project but don't have access to BIM software. This is precisely how the Ifc file was used, to give all involved parties the opportunity to review and revise what had been produced, allowing them to report errors or suggest changes without the need for the actual BIM software and the necessary knowledge to use it.

The role of BIM presented in these pages clearly does not take advantage of all the possibilities and performance that it can offer to the design.

The additional steps that can be done depend on the use that you want to do and what may be the needs for each job you face.

For a company whose core business is the design of HVAC systems, the next step is to use the software also for energy simulations of the building, that is to calculate dispersions and thermal demands so as to have in a single platform both the graphic representation and the technical one: in this way, in fact, the risk of making different changes to the graphic part but not to that of calculation is reduced, as the model is unique and can be used for multiple purposes.

In addition, BIM also allows the calculation of pressure losses of air ducts and water pipes, being able to immediately find any values that are not convincing, and once the necessary changes have been made, you can immediately get an idea if the implemented solution is sufficient or not.

Therefore, in a single software, with the help of dedicated external tools, you can find everything that is necessary for the complete design of this type of systems, starting from the graphic layout up to the necessary calculations for the correct sizing of the machines and devices to be provided in the system.

If you want to perform different analyses or studies, such as the environmental impact of a building, then the drafting of the Life Cycle Assessment, or the energy certification of the same, through Energy Performance Certificates or LEED certification, the use of Bim is once again recommended and it is very useful to create custom parameters by the user to carry out the above analysis.

Through the use of external tools such as Dynamo for the automated assignment of parameters and Excel files for the management and encoding of the same, but also of dedicated tools, you can implement calculation routines aimed at providing information and results related to the scope of interest and that you are evaluating.

By widening the look towards other disciplines, BIM also allows the calculation of structures, or lighting environments, etc.

In essence, the vast majority of engineering disciplines could make use of it and the idea of incorporating all of the calculations, layouts and so on into a single platform would really be a breakthrough for the industry, allowing to streamline many laborious processes, reduce design errors and information transfer, since in the model are present all the features of the work in question and are accessible to anyone who is part of the working group.

Conclusions

This work presents the analysis of the design of an HVAC system dedicated to a new building whose use is for offices, meeting rooms and events. In parallel, this design was carried out using the so-called BIM, a new tool available for plant modeling.

The purpose of the following work was to present the various design criteria taken into account, trying to justify as much as possible the choices made, remaining in the perspective that the primary objective was to ensure conditions of well-being and comfort within the spaces without neglecting the search for high efficiency of the systems to contain consumption and costs associated with the plant itself.

The HVAC (Heating, Ventilation, and Air Conditioning) system designed features two multi-purpose heat pumps for the simultaneous production of hot and chilled water, with a thermal output of 136 kW and a cooling capacity of 192 kW, respectively.

Ventilation is provided by 3 AHUs (Air Handling Units), one dedicated to the area called the Academy with a nominal airflow of 14,000 m3/h, while the other two serve the first floor, which includes offices and meeting rooms, with a combined airflow of 11,400 m3/h.

The hydronic terminals used include fan coil units, floor-mounted or wall-mounted, as well as radiant surfaces, floor-mounted in the Nursery School area and ceiling-mounted in the Office area. All of these elements are supplied with water produced by the heat pumps at various design temperatures through a hydraulic network consisting of stainless steel pipes.

Ventilation is distributed throughout the entire building through a network of rectangular or circular ducts, which then distribute air into the spaces through linear diffusers with one or more slots.

Given the nature of the spaces in the building, their occupancy is not constant. Therefore, renewing the air in the same way all the time would lead to significant waste and energy consumption. For this reason, variable air volume controllers have been installed along the distribution network, allowing for the modulation of fluid flow based on the needs of the environment.

Given the complexity of the structure and associated facilities, An articulated control system has been designed to monitor the correct functioning of the various devices to ensure that all those measures taken to make the system as efficient as possible, are carried out in the established way.

Concurrently, the design process did not take place in a traditional two-dimensional environment but rather utilized Building Information Modeling (BIM) software to create a 3D model of the building and its systems.

This tool not only allowed for a more detailed and accurate representation of the project but also facilitated continuous and effective coordination and collaboration among the various working groups. It highlighted critical issues and provided solutions quickly. Subsequently, it enabled the monitoring of model development and the identification of any anomalies, errors, or interferences, with the ability to address them almost instantly.

Another valuable aspect of using this tool was the extraction of quantities of objects present in the model, a task performed automatically by the software, resulting in time savings and the elimination of counting errors. Finally, the creation of customized parameters focused on, in this case, developing a Work Breakdown Structure (WBS) and generating a standard Ifc file, made it possible to produce these instruments.

In conclusion, what emerges from this work are the numerous possibilities within the field of HVAC system design, both in terms of the choice of generators and terminals, as well as the different ways to connect utilities together. In essence, for the same project, there are endless possibilities for execution, depending on the knowledge and preferences of the designer.

Regarding BIM, it has proven to be a very useful and effective tool. It has allowed for the resolution of many issues in this initial design phase and an understanding of the spaces and challenges that may arise during system installation. Additionally, it has accelerated many processes compared to traditional design methods.

Certainly, the next step involves even more extensive use of this tool during the design phase, to fully harness its potential.

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ABSTRACT

La riduzione delle emissioni di gas ad effetto serra e del consumo di energia primaria sono tra i temi di cui si parla maggiormente negli ultimi anni. In questo tema trova spazio quella che è la costruzione di nuovi edifici ed in particolare gli impianti a servizio di essi, tra i quali i cosiddetti sistemi HVAC, Heating Ventilation and Air Conditioning.

Nel presente lavoro viene presentato un caso di progettazione dei sistemi HVAC di un edificio di nuova realizzazione dedicato principalmente ad uffici e sale riunioni, nel quale si è cercato di combinare quelle che sono le richieste di benessere e comfort da garantire all'interno degli spazi con i requisiti di minor consumo energetico possibile e massima efficienza degli impianti sviluppati.

La climatizzazione viene garantita da due pompe di calore polivalenti in grado di alimentare i terminali idronici presenti, ovvero ventilconvettori a parete o a pavimento, soffitto e pavimento radiante. Per quanto riguarda la ventilazione sono state previse tre macchine di trattamento aria in grado di fornire la portata di fluido necessaria a garantire il rinnovo dell'aria e la deumidificazione degli ambienti. Lungo la rete di condotti progettata sono stati inseriti dei regolatori di portata in modo da far fluire solo la quantità d'aria necessaria. A corredo di tutto ciò, è stato implementato un articolato sistema di controllo per gestire le numerose variabili e differenti possibili richieste termiche che possono verificarsi nell'edificio.

Di pari passo con il progresso delle tecnologie a disposizione per le macchine, vi è stato uno sviluppo anche per quel che riguarda i software a disposizione dei progettisti e tra questi trova spazio il cosiddetto BIM (Building Information Modeling), utilizzato nel suddetto progetto. Tale strumento è stato utilizzato per la realizzazione di un modello tridimensionale di edificio ed impianti dando anche la possibilità di creare parametri da associare agli oggetti presenti, favorire il coordinamento tra differenti gruppi di lavoro, gestire e risolvere interferenze tra i vari sistemi, estrarre le quantità dei materiali, implementare un cronoprogramma.