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Use of IoT technology and artificial intelligence in energy management and control

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Abstract

The objective of the work is **the application of Evogy's IoT platform**, called Simon, on the **Humanitas healthcare "Il Fiordaliso"**, located in Rozzano (MI). Through Simon functionalities, consumptions, which are divided into two main categories (air handling unit and polyvalent pump) and internal variable trends (temperature, humidity and CO_2 level) have been monitored. Then, by analysing constraints of the building and data obtained, more efficient algorithms of functioning have been implemented.

Furthermore, the study can be **divided into four main parts**:

1. The first one, which contains **the initial three chapters**, describes not only the **European strategies** to reduce energy usage in buildings, especially in heating and cooling, with a more detailed review on the Italian policies but also, illustrates **Simon functionalities** by describing how it works, which devices are needed and how a new algorithm can be executed;
2. The second part, which includes **the fourth and fifth chapters**, starts with the **plant description** to understand where and which sensors have been installed. Then, a detailed **report of the thermomechanical plant** (air handling unit, polyvalent pump, production of domestic hot waters and active chilled beams) is provided. Next, after having illustrated **regulatory Standards**, not only energy consumptions of the air handling unit and polyvalent pump before the intervention are provided, but also trends of temperature, humidity and carbon dioxide level;
3. The third one, which holds **the sixth, seventh and eighth chapters**, begins with the description of the **new air handling unit algorithm**, based on CO_2 level. So, an experimental assessment of the performance of the CO_2 based ventilation control is represented. Then, after having compared the modification of both absorptions and internal variables caused by the new logic, an overview of **savings obtained in energetic** (primary energy saved, CO_2 not delivered in the environment) and **economic terms** is given. Moreover, also the **description of the polyvalent pump's new functioning**

is provided but, due to its constraints, it strictly depends on the season. Consequently, being outcomes detectable only during the heating season and being the logic implemented in May, an exact estimation of benefits achieved could not be witnessed;

4. The fourth part, which contains **the last chapters**, explains how restrictions imposed by **AICARR** (Associazione Italiana Condizionamento dell'Aria, Riscaldamento e Refrigerazione), caused by the **COVID-19 pandemic** the World is facing, influence the ventilation of the building. Finally, after having **compared the three operative modes** of the air handling unit, **conclusions and future perspectives** are indicated.

Nomenclature

AHU	Air Handling Unit
AI	Artificial Intelligence
AICARR	Associazione Italiana Condizionamento dell'Aria, Riscaldamento e Refrigerazione
ARERA	Autorità di Regolazione per Energia Reti e Ambienti
BMS	Building Management System
CP	Circulating Pump
CPS	Cyber Physical System
DCV	Demand Controlled Ventilation
DHW	Domestic Hot Water
EM	Energy Management
EMS	Energy Management System
EnPI	Energy Performance Indicator
GHG	GreenHouse Gas
GSE	Gestore Servizi Energetici
HVAC	Heating, Ventilation and Air Conditioning
I4MS	Innovation For Manufacturing SME
ICT	Information and Communications Technology
IoT	Internet of Things
KPI	Key Performance Indicator
M2M	Machine to Machine
NZEB	Nearly Zero-Energy Building
PI	Proportional Integral
PLC	Programmable Logic Controller
PNIEC	Piano Nazionale Integrato per l'Energia ed il Clima
PP	Polyvalent Pump
PSS	Product Service Systems
RFID	Radio Frequency Identification
RH	Relative Humidity
RTS	Real Time Systems

SAE	Smart Anything Everywhere
SCADA	Supervisory Control And Data Acquisition
SME	Small-Medium Enterprise
SP	Set Point
THL	Temperature Humidity Lux
VAT	Value Added Tax
VPN	Virtual Private Network
VPP	Virtual Power Pool
WSN	Wireless Sensor Network

Contents

1 Introduction

By the progress of the Industrial Age, the **acquisition of energy** has become a frequently daunting obstacle as society moves from one resource to others, such as from coal to oil to electricity. With time passing, each government has regulated the energy industry, building an intricate miscellany of rules and directions concerning the collection and consumption of several different sources. Moreover, these interventions generated a bureaucratic infrastructure of infinite complexity; consequently, other rules and guidelines were developed directly to the customer side [1].

Nowadays, **Product-Service Systems (PSSs) and digital technologies,** named **Industry 4.0 (I4.0)** [2], designate estimable business chances to intensify companies' competitiveness. While, PSSs present diverse varieties of extra aids to be mixed with the physical product through a suitable design process, digital technologies can represent a decisive factor in the exploitation of data [3]. The **main obstacles** against the transition from traditional to new business orientations, which include a combination of products and services, are identified in the user agreement and radical transformations in business culture [4]. Furthermore, the **absence of adequately professional expertise and specialist knowledge**, are relevant gaps in the digital technology application domain.

To correctly promote the commodities rise, the methods improvement and the business models adaptation to the digital age, **numerous drives** have been originated both at Europe and World level, such as the **ICT Innovation for Manufacturing SMEs (I4MS) initiative and the Smart Anything Everywhere (SAE)** [5]. In those circumstances, the choice of digital technologies promotes the service innovation of manufacturers, strengths the company competitiveness and move the owning and operational responsibility of the solution on the provider [6]. Moreover, industry and government institutions have been under the enormous financial and environmental influence in the last few times. **The primary driving factors** in almost all recent operational, fiscal and capital cost investments are the possibility to be economically ambitious in the global market and to meet growing environmental criteria to lessen air and water pollution. As a result, energy management has been a **vital tool** to support institutions in achieving decisive goals for their short-term durability and long-term benefit [7].

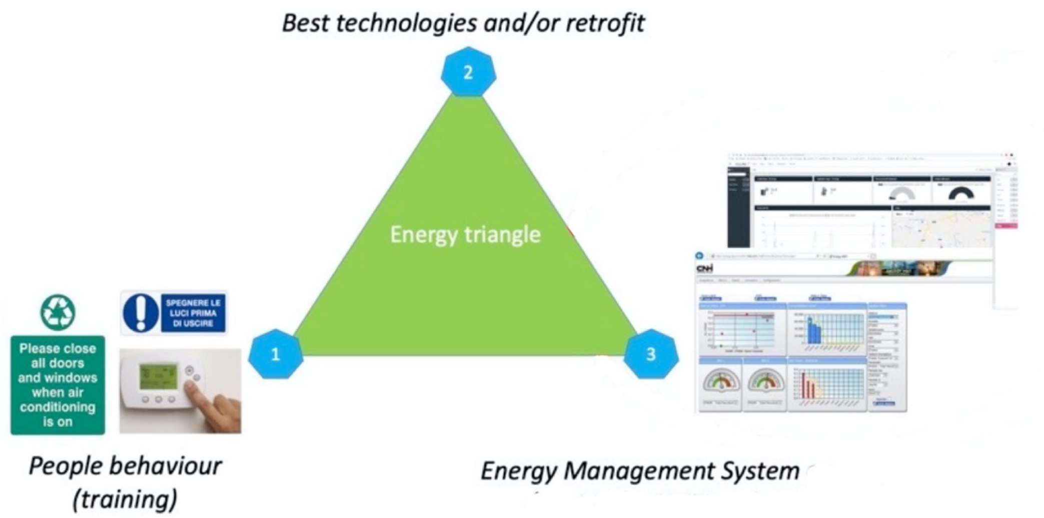


Figure 1 - Energy triangle for the reduction of energy consumption

Furthermore, as Figure 1 witnesses, energy management and consequently, the reduction of energy consumption, can be divided into **three key points**:

- **People behaviour**: each person has to be aware of the right behaviours to assume in every different situation;
- **Best technologies and retrofit**: thanks to their continuous development, useful and performing software has to be adopted;
- **Energy management systems**: they are the core of the policy. They allow continuous monitoring of operations and implementation of logics to manage the building/industry properly.

Overall, energy management is more and more present in ordinary life and is a tool destined to increase in importance over time.

2 European energy strategies

The energy union strategy, issued on February 25, 2015 [8], proposes to construct an energy connection that provides to European customers, such as households and businesses, stable, sustainable, competitive and affordable energy. From that moment, the **European Commission** has launched different models, which control the implementation of the following essential priorities:

- **Security, solidarity and trust**: varying EU reservoirs of energy and guaranteeing energy protection through solidarity and interaction between nations;
- **A completely unified internal energy market**: allowing the free stream of power through Europe by satisfactory infrastructure and without professional or administrative boundaries;
- **Energy efficiency:** upgraded energy performance will decrease the necessity of imports and discharges;
- **Climate response, decarbonising the economy:** Europe looks to strengthen its leadership in the renewable energy sector;
- **Research, innovation and competitiveness:** promoting discoveries in low-carbon and clean energy technologies by investing in research and innovation.

Moreover, in December 2018, the European Commission has updated through the "**Clean Energy for all Europeans Package**" the targets for 2030 (Figure 2), in continuity with the ones of 2020. This plan aims to implement **32%** of the energy produced by renewable sources in the EU's energy mix, to increase energy efficiency to **32.5%**, in comparison to a "business as usual" scenario and to reduce greenhouse emissions of **40%**, relative to 1990's level [9].

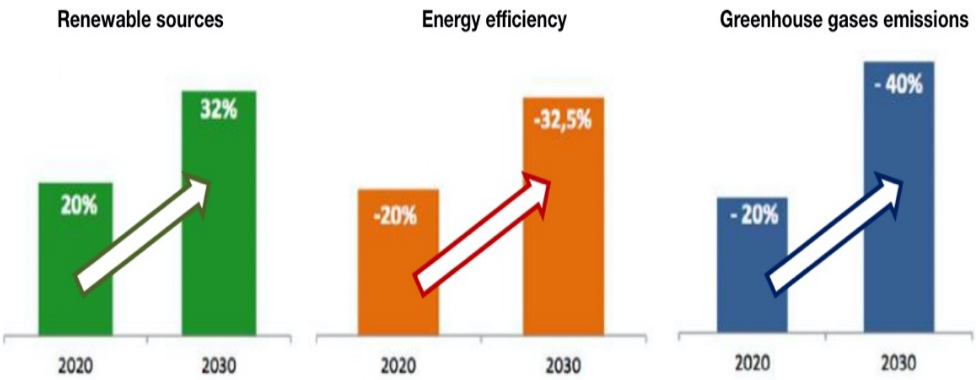


Figure 2 - European Targets for 2030 [10]

2.1 Energy performance in buildings

The **building sector** is essential to obtain the EU's energy and environmental objects because they account, as described in Figure 3, for almost **40% of energy using** and **36% of CO_2 emissions** in Europe; consequently, they are the largest energy consumer [9]. On the other hand, thanks to the energy performance rule, the consumption of buildings today is only half in comparison to ones of the 1980s [11].

Furthermore, the **Energy Performance of Buildings Directive** (2018/844/EU) includes strategies and supportive actions that may help reaching the objectives set. Examples are:

- smart technologies are supported, such as in the installation of building computerisation and control systems and tools that monitor temperature;
- European nations have to set robust long-term improvement strategies, pointing at decarbonising the national building stocks by 2050. For example, they have to introduce cost-optimal minimum energy performance terms for new buildings, for existing structures and the retrofit of heating and cooling systems;
- when a building is sold, not only the energy performance licenses has to be provided, but also datasheets for heating and air conditioning systems.

Overall, being around **35% of European buildings over 50 years old** and almost **75% of the energy building stock inefficient** (Figure 3), a renewal of existing structures may point to significant **energy savings like 5-6%** [11].

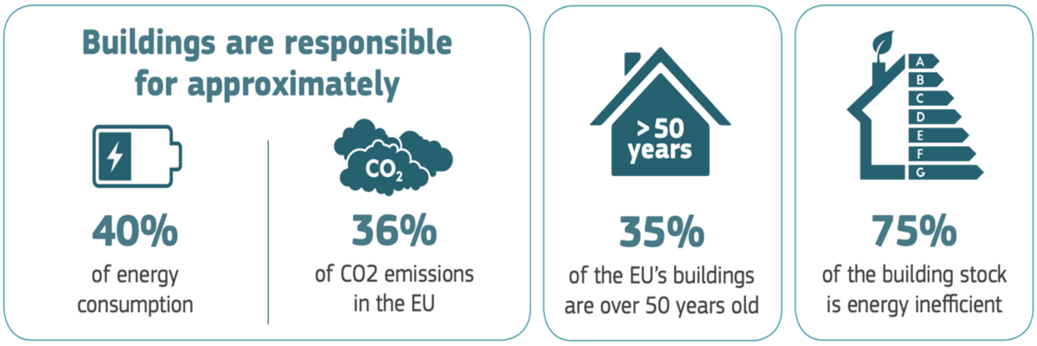


Figure 3 – Key numbers of European buildings [12]

2.2 Heating and cooling

Half of the European energy consumption comes from heating and cooling in buildings and industry. While in households, **heating and production of hot water** account for **79%** of total final energy use, cooling is less predominant. However, this trend is evolving rapidly due to climate change and global temperature rise. In industry, the pattern is very comparable, but, around **26.7% is used for lighting and electrical process,** such as engine motors [13].
As a result, in order to fulfil the EU's climate and energy goals, reducing the energy consumption, linked mainly to these processes, appear to be the key, also because a large amount of energy is still produced from fossil fuels.
These goals can be achieved either by smart solutions to regulate energy consumption, such as through **smart thermostats** or by adopting advanced architecture and design procedures and materials when building or restoring constructions. Nevertheless, a more expensive solution is substituting heating and cooling devices with high-level systems.

Finally, efficient and advanced programs can be applied in every industry by combining heat and power units and, consequently, the energy system and local energy generation will receive benefits.

2.3 Italy

Italy, as a member of the EU council, has developed its strategies, approved by the commission, in a report called **PNIEC** (Piano Nazionale Integrato per l'Energia ed il Clima).

The Italian country is entirely conscious of the possible advantages inherent to the widespread availability of renewables and energy efficiency, linked to the decrease in pollution and climate-changing emissions, developments in energy protection and aims to pursue this route with conviction. This expansion will be managed by a continuous focus on efficiency and promoted by cost reductions for some renewable technologies. As a result, Italy agrees with the European path, and in some circumstances, it tries to push up the boundaries, increasing the limit imposed by the EU.

Firstly, in order to reach objectives set in the renewable sector, the Italian government issued a decree, called **D.M. 4 Luglio 2019** [14], in which it incentives onshore wind turbines, solar photovoltaic systems, hydroelectric and gas-fired plants residual from purification processes. Consequently, with the help of this declaration, it expects that the **energy produced by renewable sources moves from 18,6%** (2020) **to 30%,** which is the target for 2030 [15].

Then, moving to energy efficiency, the **civil sector** is recognised as the main area to improve. Italy has **12.42 million residential buildings**, with nearly 32 million homes. Over **60% of this property is over 45 years old**, or in other words, they were built before Law 373/19763, the first energy-saving rule; so, the energy consumed varies from **160** $\boldsymbol{\frac{kWh}{m^2}}$ **to over 220** $\boldsymbol{\frac{kWh}{m^2}}$ **per year**. Furthermore, by 2030, to achieve the goal of almost complete decarbonisation by 2050, transforming existing buildings into NZEBs can be realistic.

On the other hand, constructions designed for non-residential purposes, such as schools, offices, shopping centres, hotels and, most important **health-sector facilities**, are about 435.000 and they also account for a large portion [15].

Figure 4, published in the PNIEC [15], illustrates the average consumption determined with reference to the distribution of buildings by climatic zone and period of construction and on the basis of the utilization data resulting from statistical surveys on a representative set of buildings.

Intended use	Electricity consumption (kWh/m^2/year)	Heating/cooling consumption (kWh/m^2/year)	Total consumption (kWh/m2/year)
Single-family households	21	124	145
Multi-family households	21	123	144
Schools	17	89	106
Offices	111	45	156
Hotels	110	150	260
Commercial			448
Public administration	55	143	198
Hospitals	253	385	638

Figure 4 - Annual energy consumed in the civil sector [15]

Overall, as expected, the annual power requested is very high in comparison with actual standards and to reach the European target of 32.5% reduction of energy consumed, Italy has to focus primarily on this sector through the use of new management systems, such as IoT platforms.

Finally, all **European and Italian targets for 2030** are summed up in Table 1.

	2030 Targets	
	Europe	Italy
Renewable energy		
energy from renewable sources in gross final consumption	32%	30%
energy from renewable sources in gross final consumption for cooling and heating	+1.3% per year	+1.3% per year
Energy efficiency		
reduction of primary energy consumption compared to 2007	-32.5%	-43%
Greenhouse gases emissions		
total reduction of greenhouse gases compared to 1990 levels	-40%	No national limit set

Table 1 - European and Italian targets for 2030 [10]

3 IoT Technology

The **Internet of Things or IoT technology**, according to the Internet Business Solutions Group, IBSG (2011) [16], is the moment in history when more "things or objects" will be related to the Internet than people. It is the networking of uniquely identifiable integrated computing devices within the existing Internet infrastructure. At present, the Internet of Things consists of a diverse set of disparate and purpose built channels. For example, vehicles have various networks to control engine operation, security features and so on; commercial and residential buildings also have multiple control systems for heating, ventilation and air conditioning (HVAC). With its evolution, these networks, and many others, will be connected with additional security, analysis and management capabilities. Consequently, IoT will **become even more powerful** in what it can help people reach [16].

It is also present in smart homes, retail, education, government services, smart services networks, agriculture, communication and business among others. Furthermore, IoT is the **result of a mixture of several technologies** belonging to software domains that interconnect objects or things through the Internet; therefore, objects acquire detection, monitoring and remote-control capabilities.

Some of the most common Internet of Things technologies include **cloud computing**, wireless sensor networks (WSN), radio frequency identification (RFID), networks and communication, machine-to-machine (M2M) interaction, real-time systems (RTS) and mobility support. The IoT can collect, distribute and analyse data to convert into knowledge and information. As a result, it is essential to investigate further research and develop energy efficiency optimization mechanisms through different IoT domains of application [17].

3.1 Description of Simon's functionality as a service delivery tool

By the adoption of an **Energy Management System (EMS)** based on IoT/AI technology, **Evogy S.r.l.** furnishes answers and assistance pointed at the management and optimization of energy consumption for consumers of the Industry

4.0 market, smart buildings and the multi-site retail market. Obviously, customers are not the same: from large businesses, who consider EM a core process, up to SMEs, that can not exploit the abilities and the force used in the large enterprises.
This issue pushed Evogy S.r.l. to **develop Simon**, that through the IoT platform called **SimonLab**, optimizes automatically and intelligently, the consumption **management of energy-efficient systems** by controlling energy costs in real-time as environmental and operating conditions change, both in the industrial and building market sectors.
It is also a digital way to replace the local supervision made mainly by the maintenance operator, making the management of plants more:

- **dynamic**, because it happens in real-time through remote controls;
- **efficient**, because it is linked to environmental and operational changes of systems;
- **intelligent**, because it is commanded by algorithms that autonomously regulate the "optimal" setup;
- **economically advantageous**, because it can respond to price signals coming from the markets.

Overall, Simon allows **real-time monitoring of environmental comfort** (CO_2, RH, temperature, lux), **energy consumption** (electrical energy, gas, fluids, etc.) and **set-point systems** (chillers, AHUs, heat pumps, boilers, etc.).
Within Simon model, three main technologies (IoT, Cyber-Physical Systems and AI) have been considered and embedded (see Figure 5):

- **Simon on the field** (IoT systems installed on existing devices): a control board collects information coming from a supporting data metering and transmission infrastructure (i.e. co-generator, sensors and field meters, photovoltaic (PV) systems, Building Management System). It is needed to provide to building plants sensors and hardware, signals to initiate the primary process to optimize the global EM efficiency;
- **SimonLab** (directly linked to the CPS of the equipment/buildings controlled): by including the simulation of the building, it takes into account customer constraints, such as people comfort in the environment;

- **AI**: algorithms that communicate with SimonLab to catch and replicate the operators' capability to optimize the EM.

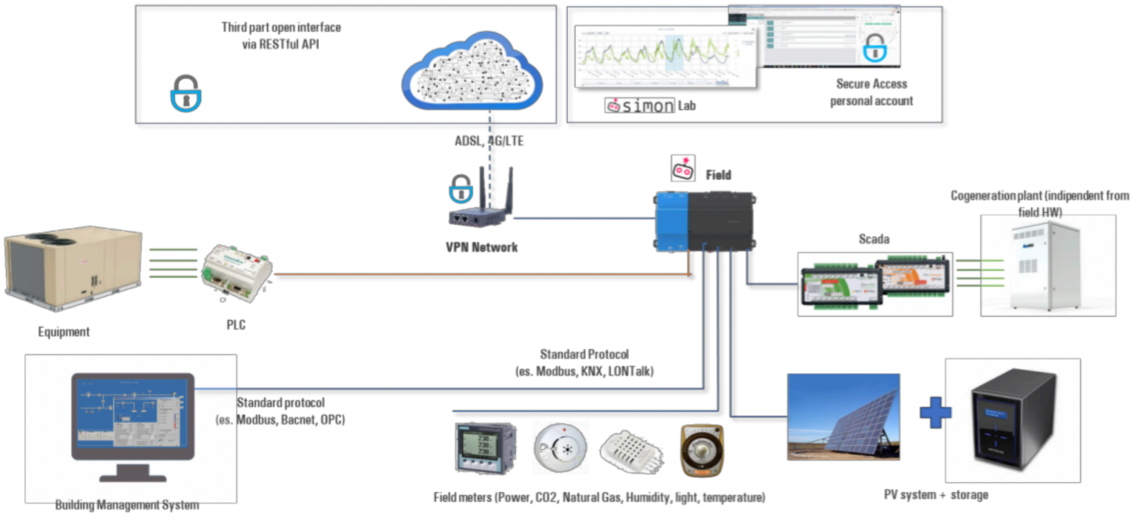


Figure 5 - SIMON model, the functional scheme [18]

Moreover, Simon is organized into **hierarchical levels** to manage systems in the multi-site configuration:

- **"Project" layer**: the most aggregate level of information. The human-machine interface is organized into hierarchical levels to manage systems in a multi-site configuration;
- **"Plant" layer**: individual site or plant level;
- **"Device" layer**: it is possible to log into a virtual representation of every single component of the system;
- **“Data-point" layer**: single elementary information level (e.g. multi-meter consumption value, set-point, alarm);
- **"Security" layer**: it is responsible for data security.

Furthermore, each layer is identified by specific characteristics and mutually provide to each of them:

- the **plants' geolocation** with digitized building planimetry;
- a **customized dashboard** with graphic widgets that can display both Key Performance Indicators (**KPIs**) and Energy Performance Indicators (**EnPIs**);
- **reports** based on the user's template;

- set **alarms and thresholds**, with automatic sending of emails.;
- **commands in ON/OFF** or set-point format, persistent or with duration according to CPS signals;
- **commands in single and aggregate form** (areas or floors), with and without time schedules and management of exceptional events;
- **advanced data analysis and model creation** (future goal) to optimize the plant management, by belonging to a baseline matched and stored on the platform;
- **Demand Response** (future goal) mode for balance grid congestion and electricity network services. It consists in creating real VPPs (Virtual Power Pools) of plants that, individually, could not participate in the electrical services market, but which, aggregated in clusters, can be used to intercept economic advantages both in terms of power and energy.

Last but not least, Simon's functionalities are divided into two parts: Simon Buildings and Simon Industrial.

3.1.1 Building platform

It is mainly employed in the **tertiary sector**. It works through a series of sensors, which measure the environmental comfort (lux, temperature, RH, CO_2, etc.) by **real-time monitoring** and they also allow **dynamic remote control** of assets and facilities, reaching potential **energy savings of between 20% and 40%.**

Thanks to this system, it is possible to have constant control of room comfort, an efficient air quality control by optimizing the hourly air exchange, dynamic load optimization and monthly reports on satisfaction and consumption trends. Moving to its interface, it has **web-based systems** accessible through App from smartphone or tablet or PC and a ticketing system for requests from/to the site and an alert system for ordinary and extraordinary maintenance interventions.

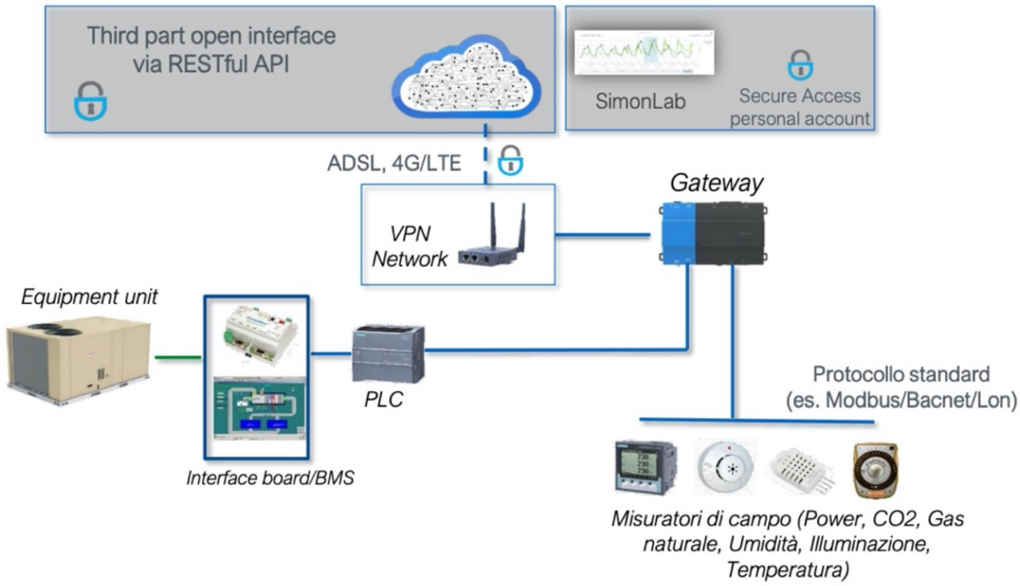


Figure 6 - Functional diagram of Simon Buildings [18]

Figure 6 shows all components required and how they interact. The **gateway**, which is Niagara or a router, is the core of data collection from the field. It interfaces to a **PLC,** such as a field automation system, which communicates with a **BMS**. It is associated with equipment units like chillers, heat pumps or all control systems linked to the cooling and heating of the building. Furthermore, while signals go from the gateway to the equipment units during the control phase, the opposite occurs when data are read; consequently, **signals are always bidirectional**.

Moreover, the measurement of variables, such as CO_2, temperature, power meter, happens through **sensors** placed in various parts of the building. However, in this case, signals go only to the gateway because they are typically in read mode. Then, if a write signal is needed, like an ON/OFF of devices, an **actuator** is fixed.

Finally, being Simon in Cloud, there is a **router (the VPN)**, which allows sending data to SimonLab.

3.1.2 Industrial platform

It is mainly employed in the **industrial sector**. It is a solution for companies, who need to make their products smart and predictive. Through Simon, the management

of the plant goes beyond the classic manual and local setting created by the operator, relying on the dynamic and remote control of the set-points and plant layouts.
Moreover, it is possible to have constant control of plant parameters, dynamic load optimization and monthly reports on consumption trends and production parameters of the plant.

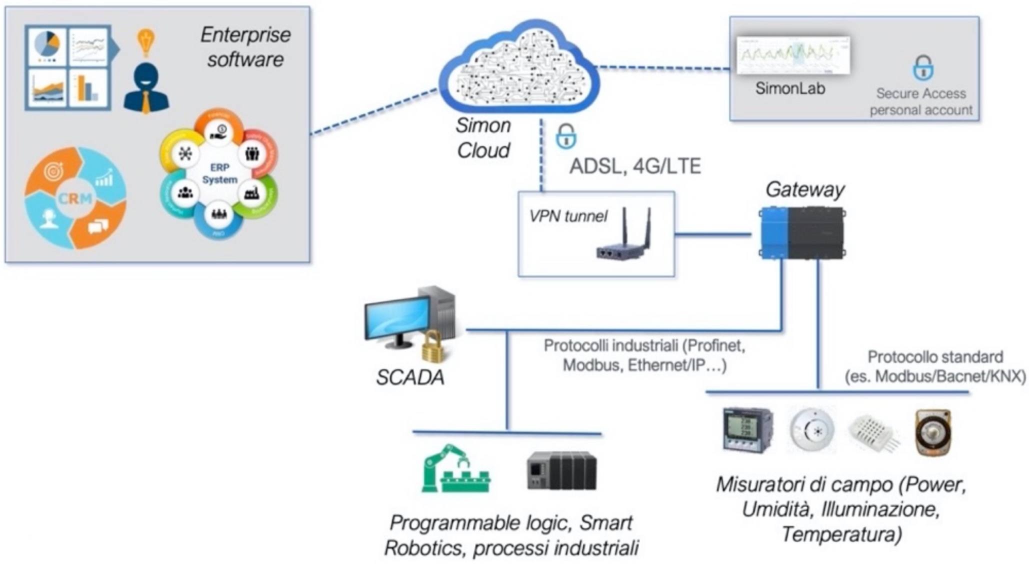


Figure 7 - Functional diagram of Simon Industrial [18]

Figure 7 illustrates how Simon Industrial works. It is very close to Simon Buildings with the only difference that the **control** is not only on heating and cooling, but also **on all machines**. The interface, instead of being directed to equipment, is to **SCADA**, which is a control system architecture including computers, networked data communications and graphical user interfaces for high-level process supervisory management, always linked to PLC automation. Simon interfaces to such operations through **industry-standard protocols**, such as Profinet, Modus and Ethernet.
Furthermore, the **dual nature of Simon** can be easily seen here; in fact, the gateway is able to interface with either existing components or with additional sensors. The VPN communicates through ADSL or 4G with Simon-Cloud (backhand), which can also interface with the enterprise software because very often in industrial systems, all information is linked to the existing management method. Therefore,

data can be elaborated either directly from the field or virtually from systems that already process them.

3.2 Niagara: gateway and logic developer

Niagara has a **double function**: it is not only the platform in which the **control of the system** can be implemented but also, the **gateway** because it is able to store, analyse and send data to the IoT platform, which is Simon in this specific case. As Figure 8 shows, while it has all signals coming from sensors as input, the output is the elaboration of data to the platform. However, if it also works as a management system, signals have to be **bidirectional**.

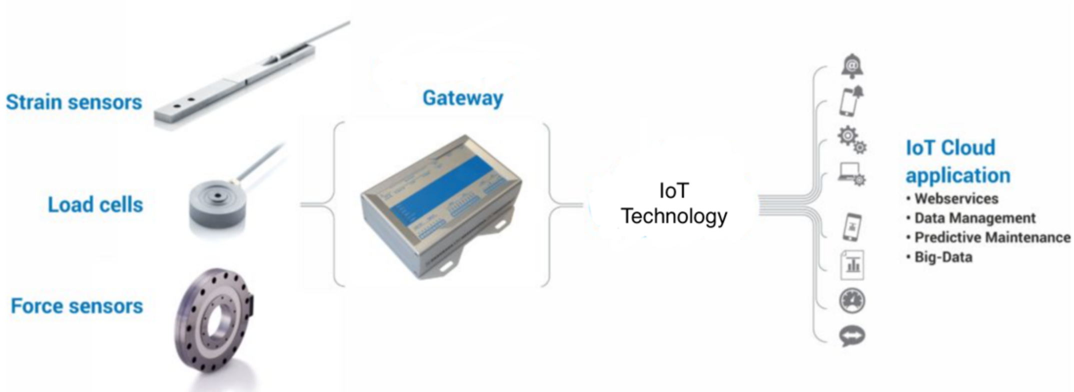


Figure 8 - Example of gateway [19]

Furthermore, to develop the logic to control the plant, **Niagara Framework** is used; it is a software that allows to manage and control diverse systems and devices, regardless of manufacturer. It can be used either locally or over the Internet with a standard web browser. It is the most suitable for **scalability needs**, thanks to the multiplicity of "off-the-shelf" drivers for both the building and industrial automation world. Moreover, Niagara has also been chosen for **its excellent data normalization features** on the platform, which make the task easier for data scientists.

Its structure is a set of software built on the **JavaBean model**, powered to solve real-world problems associated with a real-time distributed control system. At the core of the planning, there is a flexible framework designed to integrate heterogeneous devices and protocols into a common distributed infrastructure using plug-and-play software components.

Niagara can be used from the beginning to implement very different building automation solutions. It fully supports BACnet and LonWorks [20].

4 Description of the case under analysis

The study of the specific case, **the Humanitas medical Care "Il Fiordaliso",** has been performed in cooperation with Evogy S.r.l. . As said before, it is a Digital Energy Service Provider or, in other words, a provider of "data-driven" for energy management, situated in Seriate (BG).

4.1 Humanitas Medical Care: "Il Fiordaliso"

Humanitas Medical Care is the network of Humanitas medical centres, one of the largest and most consolidated companies on the **Italian healthcare field,** in terms of quality of treatment paths, professionals and installed technologies. These centres cover the whole set of specialist clinics and offer dedicated and prevention-oriented pathways for women, men, children, elderly and athletes using teams of experts coming mainly from local hospitals and most modern diagnostic technologies. The Humanitas Medical Care network also includes several sampling points, scattered throughout the territory, easy to reach, which patients can access for analysis certified by the Humanitas Laboratory, both in agreement with the S.S.N. (Servizio Sanitario Nazionale) and privately, enjoying reduced waiting times.

In order to be ever closer to people, both the clinics and the pick-up points are located in strategic areas, which are well served by public transport or inside business areas, such as "Il Fiordaliso". It is situated in Rozzano, a small town near Milan, in a shopping centre (see Figure 9). Its **opening time** depends on the service provided; all general examinations can be booked from Monday to Friday from 8.00 a.m. to 7.00 p.m. but not blood tests, which can be taken from Monday to Saturday from 7.30 a.m. to 12.00 p.m. [21].

Figure 9 - Healthcare location [22]

As Figure 10 shows, the health centre is **divided into two floors**: while the reception and blood tests rooms are on the ground, the outpatient facilities for X-rays and other examinations are on the first.

Figure 10 – Map of "Il Fiordaliso" [23]

4.2 On-site sensors

In order to analyse the energy consumption of the buildings, while Evogy S.r.l. placed sensors to measure the internal temperature, humidity, lux and CO_2 level, external data are provided **by the connected weather station**. Furthermore, having the health centre many small rooms, **sensors are located only in common areas**, such as the waiting room and corridor. Nevertheless, measurements obtained are significant because the highest values, especially in terms of carbon dioxide, due to the presence of more people, are reached in these places.

Figure 11 - Ground floor sensors

As Figure 11 shows, near the centre of the meeting room, there are the probe for CO_2 and temperature measurement (**C3**) and the CO_2 repeater (**R**), useful to amplify the signal. The THL probe (Temperature, Humidity, Lux; **T4**) is located at the corner on the upper-right hand side of the chamber. Then, having two temperature values, Simon gives as output also the arithmetic mean.
Finally, outside the building, there is the external THL probe (**E**).

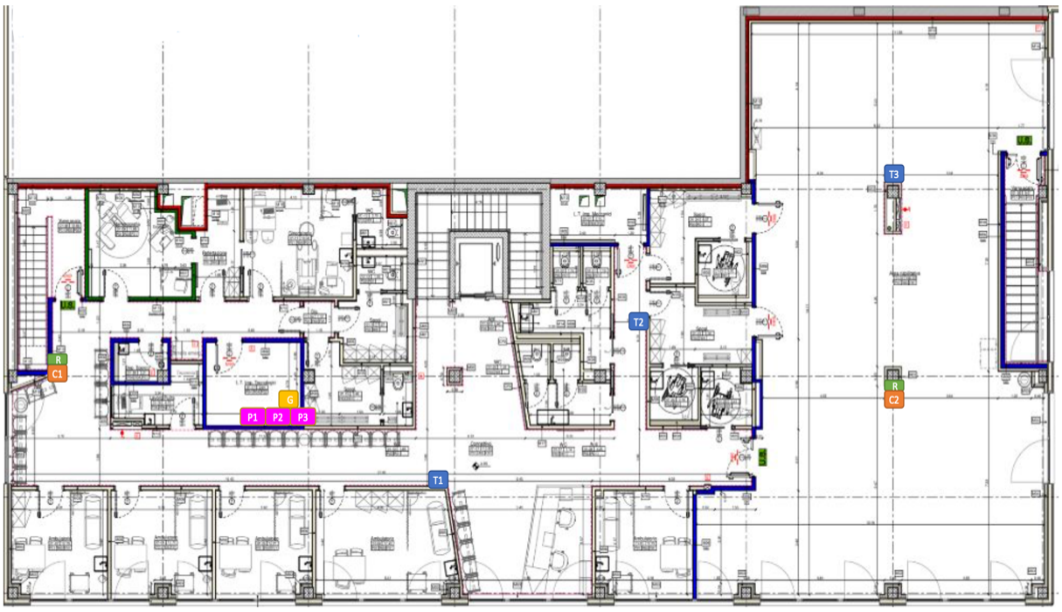


Figure 12 - First floor sensors

On the first floor, being the total surface nearly the double, there are not only more sensors, but also the gateway (**G**) and the display of the three power meters: general (**P1**), polyvalent pump (**P2**) and technical room (**P3**). Next, there are three THL probes (**T1, T2 and T3**) (Figure 12). Also, in this case, having different values of carbon dioxide and temperature, Simon displays the means of them.
Moreover, the plant shows also the presence of two probes for CO_2 and temperature measurements (**C1 and C2**) and two CO_2 repeaters (**R**) but, due to logistic problems, they have not been installed.
Overall, all sensors and their functions are summed up in Table 2.

Probe	Location	Functions
C1	Corridor 1° floor (not installed due to logistic problem)	CO2 and Temperature measurement
C2	Lobby 1° floor (not installed due to logistic problem)	
C3	Meeting room ground floor	
T1	Corridor 1° floor	Temperature, Humidity and Lux measurement
T2	Changing rooms 1° floor	
T3	Lobby 1° floor	
T4	Corner metting room, ground floor	
R	Lobby 1° floor (not installed due to logistic problem)	CO2 repeater
R	Corridor 1° floor (not installed due to logistic problem)	
R	Meeting room ground floor	
E	Outside	Temperature, Humidity and Lux measurement
P1	Technical room 1° floor	General Power meter
P2		Polyvalent Power Meter
P3		AHU power meter
G	Technical room 1° floor	Gateway

Table 2 - Sensors summary

4.3 Thermomechanical plant

Il Fiordaliso's thermomechanical plant is not hugely complicated but, at the same time, absolutely innovative. It is made of:

- A polyvalent pump;

- A boiler for the production of Domestic Hot Water;
- An Air Handling Units for both floors;
- Active chilled beams;
- Heaters located only in toilettes and changing rooms.

4.3.1 Polyvalent pump

The heating and cooling plant consists of a **polyvalent pump**, produced by **CLIMAVENETA** [24], with four pipes capable of **producing both hot and cold thermal fluids at the same time**.

It is able to operate up to an external temperature of -10 °C. As Figure 13 witness, the refrigerant is R410A, while water is mixed with glycol.

CIRCUIT :	Max allowable Pressure HP side (PS)	Max allowable Pressure LP side (PS)	Fluid type :	Fluid group (2014/68/EU)	Fluid state
Refrigerant	4,5 Mpa	2,8 Mpa	R410A	Group 2	Gas/liquid
Water	1,0 Mpa		Water (+glycol)	Group 2	liquid

Figure 13 – Thermal fluids of the polyvalent pump [25]

There are **three primary driving shapes,** which do not depend on external temperature conditions:

- production of chilled water only (the unit works as a simple chiller);
- production of hot water only (the unit works as an air-water heat pump);
- combined production of hot and chilled water.

In the last case, which is the one of the plant under analysis, the pump functions just like a water-water unit, controlling condensation and evaporation on two separate exchangers. The condensation heat is collected in a condenser to warm the water after. The coolant evaporates in the evaporator and cools the liquid in order to satisfy the request of cold water [24].

Moreover, the incoming cold water is directly derived from the city water supply network without any treatment, while before both distribution to the outlets and production of domestic hot water, it is distilled through a mechanical filter.

Additional data are provided in Figure 14.

ALLEGATO 1 **CARATTERISTICHE DELL'UNITA'**

a)	sigla unità		NECS/Q/SL 0704	
c)	peso	W	2450	Kg
d)	potenza frigorifera	Pf	159,70	kW
e)	potenza termica	Pt	178,00	kW
f)	potenza recupero	Pr	226,30	kW
g)(1)	dati elettrici :			
	potenza assorbita a pieno carico dall'unità	FLIT	91,4	kW
	corrente assorbita a pieno carico dall'unità	FLAT	160,94	A
h)	tipo fluido frigorigeno		R410A	

(1) somma dei massimi assorbimenti dei singoli componenti.
nelle condizioni usuali di esercizio, gli assorbimenti sono inferiori e dipendono dalle condizioni istantanee di lavoro.
n.b.:
le correnti a rotore bloccato (l.r.a.) e le correnti di spunto (s.a.) riportate nei cataloghi od altra documentazione climaveneta non tengono conto dei transitori.

Figure 14 - Additional data on the polyvalent pump [25]

Furthermore, the polyvalent pump produces hot water at **45±2 °C,** and cold water at **7±2 °C** in project condition. There are also two tanks useful to store the fluids produced.

Finally, circuits with all components are represented in Figure 15.

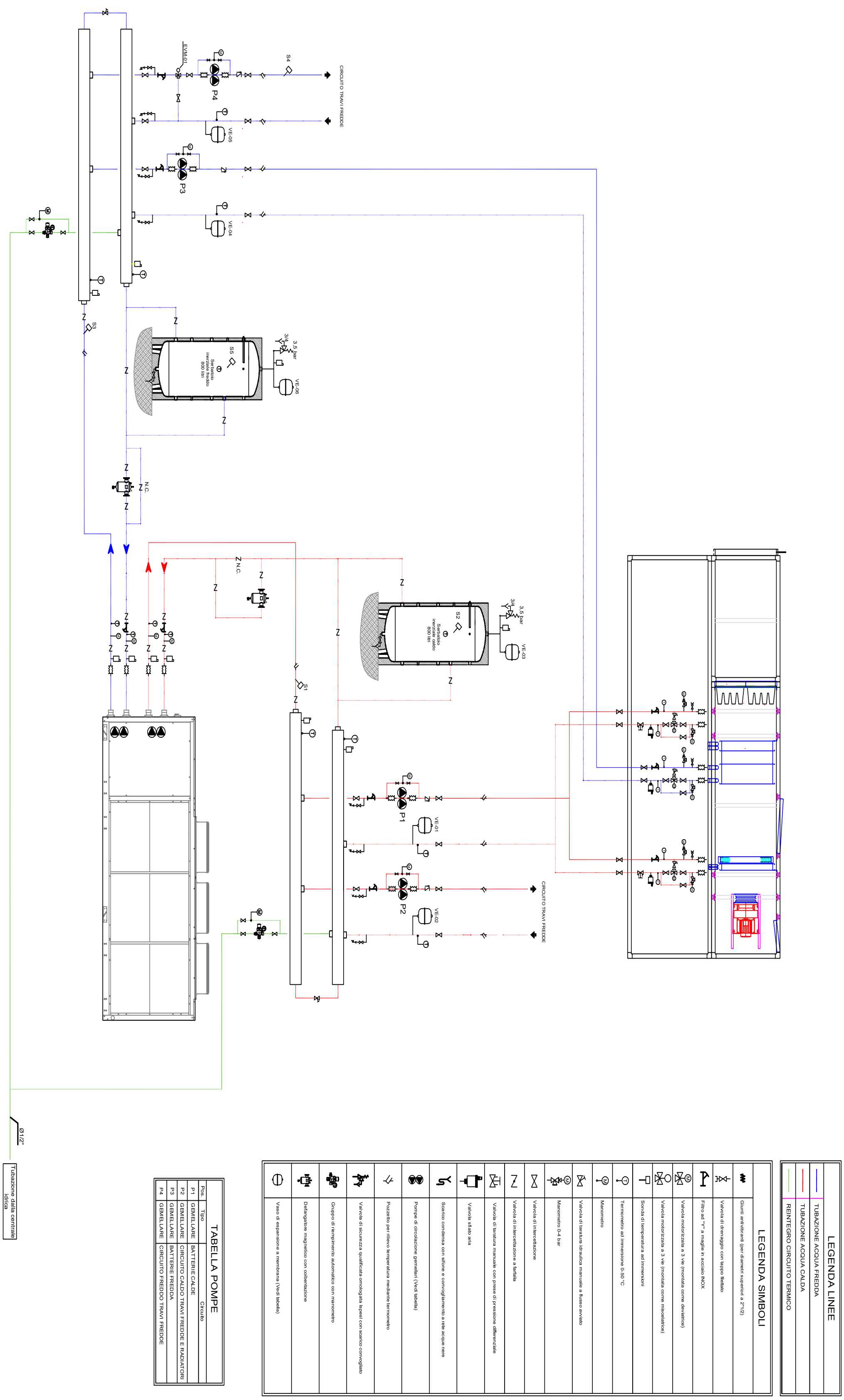


Figure 15 – Circuits of the polyvalent pump with all components [23]

4.3.2 Domestic Hot Water

The production of DHW is realized through a boiler Nuos Evo Split 300 (see Figure 16), built by Ariston, which contains a heat pump and a boiler of 300 litres [26]. Its maximum electrical absorption is 2.5 kW and, in order to avoid the production of **Legionella Pneumophila,** it provides hot water at 55 °C.

Figure 16 - Nuos Evo Split 300 [27]

4.3.3 Air Handling Unit

The AHU is a machine utilised to regulate and circulate air as a portion of an HVAC system. It is a large metal box containing numerous items, in which the most important ones are represented and listed in Figure 17 and Table 3, respectively.

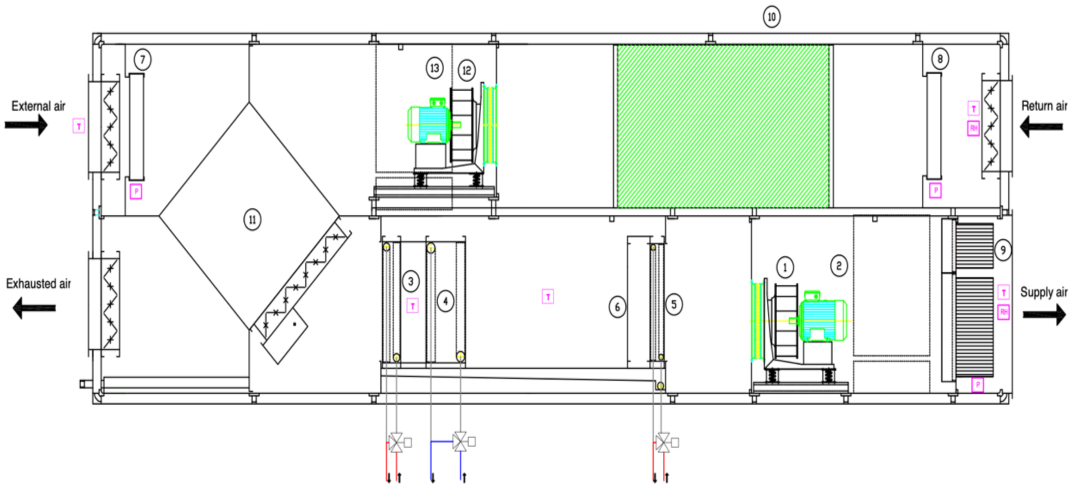


Figure 17 – Scheme of the AHU [23]

LEGEND	
1	Supply fan
2	Supply motor + inverter
3	Pre-heating coil
4	Cooling coil
5	Post-heating coil
6	Humidifier
7	Pleated filter
8	Pleated filter
9	Bag filter
10	Sound attenuators
11	Heat recovery
12	Return fan
13	Return motor + inverter
T	Thermostat
P	Pressure switch
RH	Humidity meter

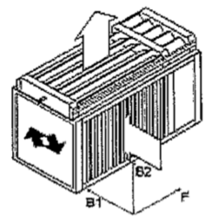
Table 3 - Components legend of the AHU [23]

SAMP built and projected it appositely for the "Il Fiordaliso". It is called "UTA 6.0" and the maximum allowed air rate is **6.100** $\frac{m^3}{h}$ [28]**.**

Starting with the **mixing chamber**, it is a stationary or, in other words, a static plate heat recuperator, which has no moving parts; so, it guarantees high reliability and operational safety. The use of such equipment also allows significant savings on operating costs, thus providing the recovery of energy, which otherwise would be lost in the form of heat. The two airflows, the fresh and the exhaust are separated into two chambers at the entrance of the recuperator. Furthermore, in order to prevent possible contamination between the two air rates, these passages are sealed. The exchange takes place through the plates, and the efficiency reaches values between **40% and 75%** [28]. Additional data about this component are provided in Figure 18.

Prestazioni		Inverno	Estate
Recupero	kW	37,7	12,6
Rendimento Umido	%	75,0	68,4
Rapporto di Temp. (EN 308 std) Umido	%	73,8	68,4
Rendimento Secco	%	69,0	68,4
Rapporto di Temp. (EN 308 std) Secco	%	67,8	68,4
Classe di recupero (EN 13053)		H2	
Efficenza energetica (EN 13053)	%	66,0	
Rinnovo			
Portata Std (1.2 kg/m³)	m³/h	6100	6100
Portata aria in peso	kg/h	7320	7320
Temperatura entrata	°C	-5,0	35,0
Umidità relativa entrata	%	80,0	50,0
Temperatura uscita	°C	13,4	28,8
Umidità relativa uscita	%	20,6	71,1
Perdita di carico	Pa	169	190
Velocità frontale	m/s	2,10	2,10
Velocità nel ByPass	m/s	13,67	13,67
Espulsione			
Portata Std (1.2 kg/m³)	m³/h	6000	6100
Portata aria in peso	kg/h	7200	7320
Temperatura entrata	°C	20,0	26,0
Umidità relativa entrata	%	50,0	50,0
Temperatura uscita	°C	5,6	32,2
Umidità relativa uscita	%	99,5	34,9
Perdita di carico	Pa	170	187
Velocità frontale	m/s	2,07	2,10
Umidità trasferita	l/h	12,0	

Dimensioni e pesi	
Altezza (B1)	mm: 905
Lunghezza (F)	mm: 1225
Profondità (B2)	mm: 1020
Diagonale	mm: 1310
Lunghezza Alettata	mm: 985
Peso	kg: 143



Pressione Atmosferica mbar 1013

Modo di calcolo
- Singolo
Calcolo di un recuperatore singolo.

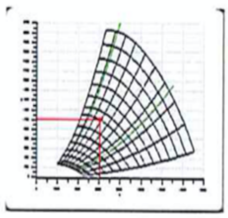
Figure 18 - Data mixing chamber [25]

Moving to **coils**, they are finned tube heat exchanger, in which tubes are made of copper and fins of aluminum [28].

Then, **fans** are centrifugal, and as Figure 19 and Figure 20 show, they are not precisely the same: while the inlet is able to supply at most 6100 $\frac{m^3}{h}$, the outlet can supply 6000 $\frac{m^3}{h}$.

Input data					
Volume	6100 m³/h	Temperature	20.0 °C	Density	1.20 kg/m³
Static Pressure	1200 Pa	Altitude	0 m	Free Inlet - Free Outlet	

Selected Fan	Catalogue data		
	n Max 1/min	Pw Max kW	J kg m²
NPA400 S.4	3700		0.42



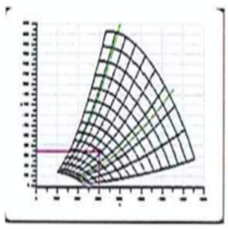
Fan Information											
c m/s	p tot * Pa	p sta Pa	p dyn ** Pa	tip speed m/s	RPM 1/min	eta Tot * %	eta Sta %	P fan kW	Min Mot. kW	P mot kW	Shaft diameter mm
	1278	1200	78	50.6	2415	76.24	71.60	2.84			0

(*)Theoric value calculated taking into account the dynamic pressure at the impeller outlet
(**)Theoric value, calculated at the impeller outlet

Figure 19 - Data inlet fan [25]

Input data					
Volume	6000 m³/h	Temperature	20.0 °C	Density	1.20 kg/m³
Static Pressure	700 Pa	Altitude	0 m	Free Inlet - Free Outlet	

Selected Fan	Catalogue data		
	n Max 1/min	Pw Max kW	J kg m²
NPA400 S.4	3700		0.42



Fan Information											
c m/s	p tot * Pa	p sta Pa	p dyn ** Pa	tip speed m/s	RPM 1/min	eta Tot * %	eta Sta %	P fan kW	Min Mot. kW	P mot kW	Shaft diameter mm
	775	700	75	42.0	2006	76.16	68.77	1.70			0

(*)Theoric value calculated taking into account the dynamic pressure at the impeller outlet
(**)Theoric value, calculated at the impeller outlet

Figure 20 - Data outlet fan [25]

Each fan is equipped with a three-phase power supply and an inverter. **Motors**, which are made by Siemens, are alimented with 400 V and 50 Hz [25]. Furthermore, while the nominal power of the inlet one is 4 kW (see Figure 21), the nominal power of the outlet is 2.2 kW (see Figure 22) [25]. This difference comes from the static pressure, which is much higher in the first case (1200 Pa) with respect to the second one (700 Pa) [25]. However, their efficiencies are still very high also at low potential.

SIEMENS

Foglio dati per motori trifase con rotore a gabbia

Data sheet for three-phase Squirrel-Cage-Motors

Dati per l´ordinazione: **1LE1023-1BA22-2AA4**
Ordering data:

Motor type: **1AV3112A**
N. d´ordine del cliente / *Client order no.*:
N. d´ordine Siemens / *Order no.*:
N. di offerta / *Offer no.*:
Annotazione / *Remarks*:
N. di item / *Item no.*:
N. di commessa / *Consignment no.*:
Progetto / *Project*:

U	Δ / Y	f	P	P	I	n	M	NOM. EFF at ... load [%]			Power factor at ... load			I_A/I_N	M_A/M_N	M_K/M_N	IE-CL
[V]		[Hz]	[kW]	[hp]	[A]	[1/min]	[Nm]	4/4	3/4	2/4	4/4	3/4	2/4	I_I/I_N	T_I/T_N	T_B/T_N	
230	Δ	50	4,00	- / -	12,90	2950	13,0	88,1	88,7	88,2	0,89	0,86	0,78	8,7	2,5	4,0	IE3
400	Y	50	4,00	- / -	7,40	2950	13,0	88,1	88,7	88,2	0,89	0,86	0,78	8,7	2,5	4,0	IE3
460	Y	60	4,55	- / -	7,20	3550	12,0	88,5	88,7	87,6	0,90	0,87	0,81	9,0	2,6	4,1	IE3
460	Y	60	3,70	5,00	6,00	3560	10,0	88,5	88,0	86,2	0,88	0,84	0,76	10,8	3,2	5,1	MG1

IM B3 / IM 1001		FS 112 M	34 kg	IP55	IEC/EN 60034	IEC, EN, UL, CSA, NEMA MG1-12-12	kVA Code: P	

Figure 21 - Data inlet motor [25]

SIEMENS

Foglio dati per motori trifase con rotore a gabbia

Data sheet for three-phase Squirrel-Cage-Motors

Dati per l´ordinazione: **1LE1003-1AB42-2AB4**
Ordering data:

Motor type: **1AV3104B**
N. d´ordine del cliente / *Client order no.*:
N. d´ordine Siemens / *Order no.*:
N. di offerta / *Offer no.*:
Annotazione / *Remarks*:
N. di item / *Item no.*:
N. di commessa / *Consignment no.*:
Progetto / *Project*:

U	Δ / Y	f	P	P	I	n	M	NOM. EFF at ... load [%]			Power factor at ... load			I_A/I_N	M_A/M_N	M_K/M_N	IE-CL
[V]		[Hz]	[kW]	[hp]	[A]	[1/min]	[Nm]	4/4	3/4	2/4	4/4	3/4	2/4	I_I/I_N	T_I/T_N	T_B/T_N	
230	Δ	50	2,20	- / -	7,70	1465	14,3	86,7	87,3	86,4	0,83	0,77	0,66	7,6	2,1	3,6	IE3
400	Y	50	2,20	- / -	4,40	1465	14,3	86,7	87,3	86,4	0,83	0,77	0,66	7,6	2,1	3,6	IE3
460	Y	60	2,54	- / -	4,35	1760	13,8	87,5	87,9	87,1	0,84	0,79	0,68	7,7	2,2	3,7	IE2
460	Y	60	2,20	- / -	3,90	1770	11,9	87,5	87,4	85,8	0,81	0,75	0,63	8,7	2,5	4,3	IE2

IM B3 / IM 1001		FS 100 L	30 kg	IP55	IEC/EN 60034	IEC, DIN, ISO, VDE, EN		

Figure 22 - Data outlet motor [25]

Finally, while the control of the inlet temperature is at fixed-point: **22 ± 2°C in winter and 16 ± 1°C in summer**, the relative humidity regulation of the supply air is in feedback according to the room recovery value, in which set states are: **40 ± 5% in winter and 55 ± 5% in summer** [26].
Overall, a summary of main data is illustrated in Table 4.

Supply fan	**Supply motor**
Type: NPA 400 S.4	Number of poles: 2
Nominal flow rate: 6100 m^3/h	Nominal power: 4 kW
Total pressure: 1278 Pa	Supply: three phase AC - 400 V/50 Hz
	Nominal speed: 2950 rpm
Return fan	**Return motor**
Type: NPA 400 S.4	Number of poles: 4
Nominal flow rate: 6000 m^3/h	Nominal power: 2.2 kW
Total pressure: 775 Pa	Supply: three phase AC - 400 V/50 Hz
	Nominal speed: 1465 rpm
Heat recovery system	
Type: cross flow plate heat exhanger	
Nominal efficiency: 66 %	
Heating coil	**Post-heating coil**
Capacity: 56.3 kW (heating)	Capacity: 14.6 kW (heating)
In/out water temperature: 45/40 °C	In/out water temperature: 45/40 °C
Cooling coil	
Capacity: 91.8 kW (cooling)	
In/out water temperature: 7/12 °C	

Table 4 - Summary AHU

4.3.4 Active chilled beams

The engineering project's choice involved the construction of a hydronic plant with **active chilled beams**, built by **TROX**. They guarantee optimal environmental comfort for the occupants of the various rooms and also allow, through a single ceiling element, to integrate both ventilation and winter and summer air

conditioning. Furthermore, it is of the **4-pipe type** to secure both heating and cooling. Their pipes are suitable for the transport of the fluid with temperatures of **16 °C in cooling and 45 °C in heating** [26]**.** However, despite their nature, they work as a 2-pipe type because the air-conditioning depends only on the season.
Moreover, they allow to integrate into a single terminal both the climate control, through the radiant effect and the ventilation; in fact, the primary air supplied not only guarantees the appropriate levels of mechanical ventilation but also, actively contributes to the air conditioning of the rooms.
Finally, the terminals' layout in each floor, as Figure 23 and Figure 24 illustrate, is made in such a way to assure the maximum possible comfort inside the occupied area and in any case with **air velocities always lower than 0.2** $\frac{m}{s}$ [26].

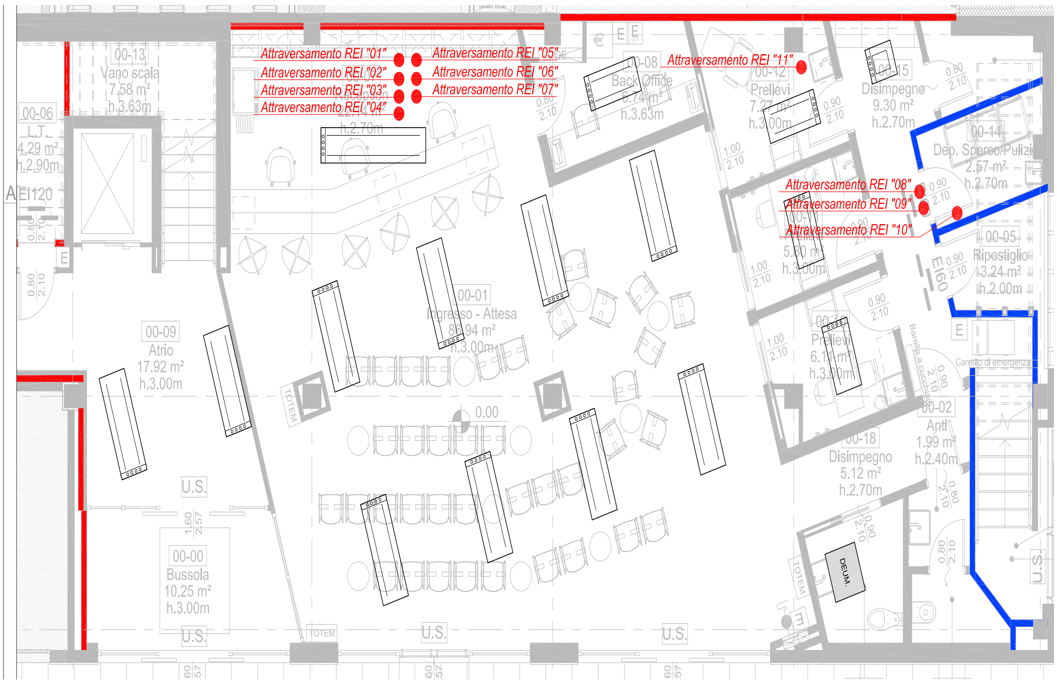


Figure 23 – Active chilled beams ground floor [23]

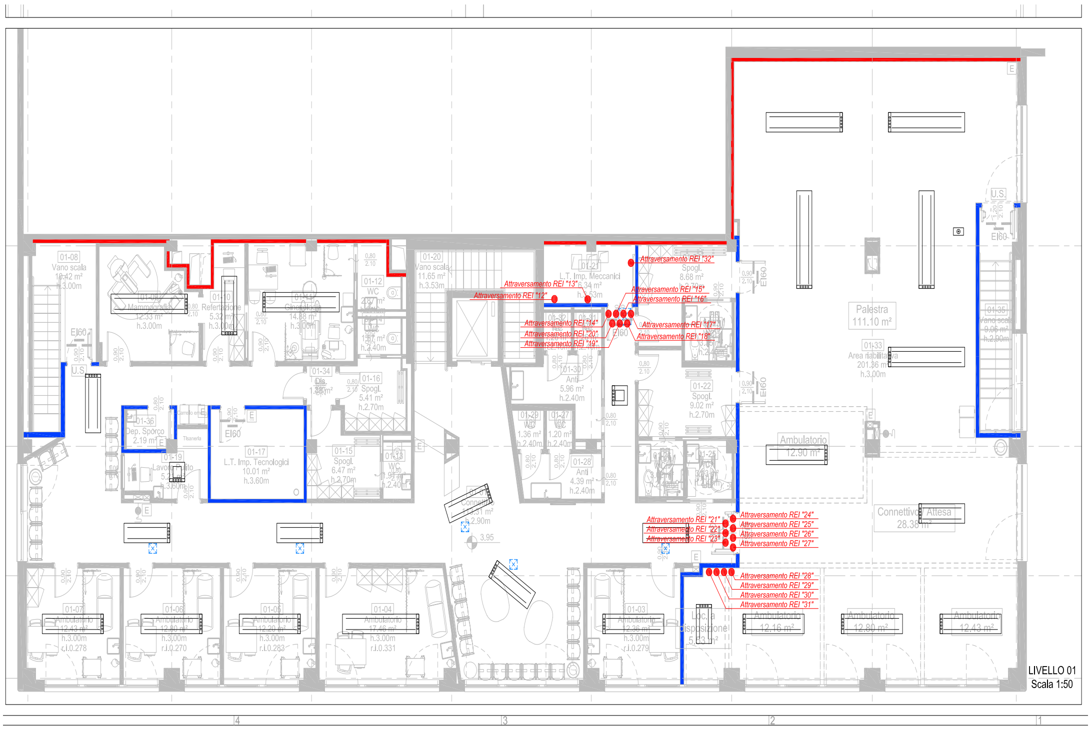


Figure 24 – Active chilled beams first floor [23]

5 Energy consumption analysis before the action

After having described the plant, the components that have been investigated further, in order to check if some more efficient functioning may be implemented, are the **AHU and the polyvalent pump**. The study is carried out in winter, during the heating season and, the choice of the baseline week is made by analysing the energy consumption at first, and then, the external temperature trend, **both in December and in the first half of January**. Nevertheless, to understand the circumstances in which the two main components work, a **complete summary of one distinct day** is also provided.
Moreover, due to the company's policy, the air handling unit has been studied firstly. Obviously, not only the energy variation is taken into account, but also the pattern of all other relevant variables, such as temperature, humidity and CO_2 level.

5.1 Regulatory references

Before introducing the project under analysis, it is fundamental knowing which are the limits in terms of temperature, CO_2 and humidity to respect in order to achieve internal comfort conditions.

5.1.1 Temperature

The standard that norms the internal temperature is the **European Standard UNI EN 12831:2002** [29] and it includes by dated or undated reference, provisions from other statements. **Appendix D** of this standard gives knowledge on the suitable data required for implementing the heat load calculation. Where no national addition to this standard is available as a reference, the essential information can be obtained from the default values cited in appendix D.

The internal temperature, also utilised for estimation of the design heat loss, is the **internal design temperature** and the standard allows to assume that the operative temperature and the internal air temperature are equal.

Table D.2 - Internal design temperature

Type of building/space	$\theta_{int,i}$ °C
Single office	20
Landscaped office	20
Conference room	20
Auditorium	20
Cafeteria/Restaurant	20
Classroom	20
Nursery	20
Department store	16
Residential	20
Bathroom	24
Church	15
Museum/Gallery	16

Figure 25 - Internal temperature from European Standard UNI EN 12831:2002 [29]

By comparing Figure 25 with the spaces of "Il Fiordaliso", it can be deduced that:

- the waiting room and lobby can be approximated to a conference room, in which the temperature to maintain is **20 °C**;
- ground and first floor offices correspond to a nursery (**20 °C**);
- changing rooms may be matched with the bathroom's temperature (**24 °C**);
- the corridor is not standardized but, its temperature should always be close to **20 °C**.

5.1.2 Ventilation and CO_2 level

Ventilation and CO_2 measurement are strictly linked together but, while the first is normed by the **Italian Standard UNI 10339/95** [30], the second is not standardised yet.

Firstly, the Italian norm provides the amount of new external air per person that has to be changed and, as Figure 26 illustrates, it is around 0.011 $\frac{m^3}{s*person}$.

Categorie di edifici	Portata di aria esterna o di estrazione	
	Q_{op} (10^{-3} m^3/s per persona)	Q_{os} (10^{-3} m^3/s m^2)
OSPEDALI, CLINICHE, CASE DI CURA E ASSIMILABILI **		
• degenze (2-3 letti)	11	-
• corsie	11	-
• camere sterili	11	-
• camere per infettivi		-
• sale mediche/soggiorni	8,5	-
• terapie fisiche	11	-

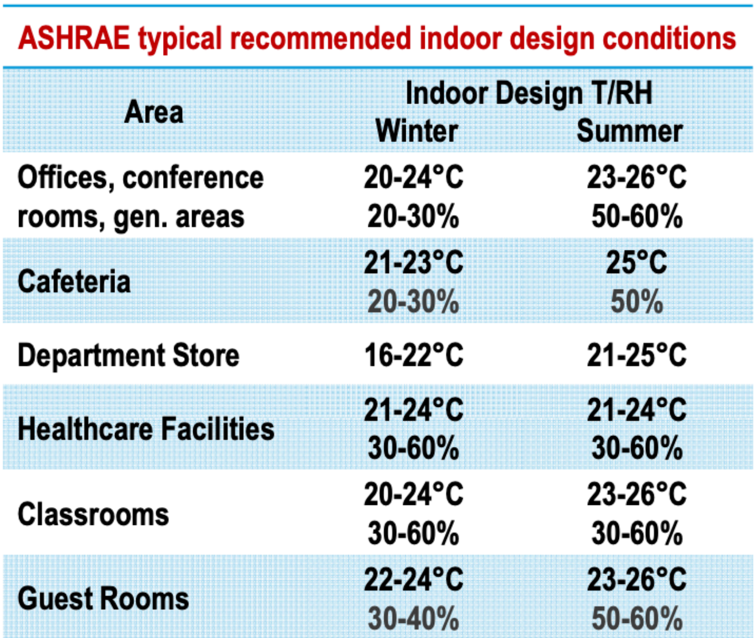
Figure 26 - External airflow rate from Standard UNI 10339/95 [30]

However, the minimum flow rate, always recommended by the norm is 2 $\frac{V}{h}$, and it meets the **UNI 10339/95** requirement of 11.1 $\frac{L}{s}$ (40 $\frac{m^3}{h}$) per person. Furthermore, the recommended flow rate for a good substitution of polluting particles is 4 $\frac{V}{h}$ for classic wards, 15 $\frac{V}{h}$ for protected wards and 6 $\frac{V}{h}$ for infectious ones. Toilet facilities must have expulsion ventilation of 8 $\frac{V}{h}$ [31].

Secondly, **the ASHRAE Standard 62.1-2016 "Ventilation for Acceptable Indoor Air Quality"** [32] provides the value of internal CO_2 level that can pose a health risk: 5000 ppm. In most buildings, concentrations seldom rise to that level. CO_2 at the concentrations commonly found in edifices is not a direct health risk, but it can be used as an indicator of occupant odours and occupant acceptance of these smell. Moreover, ASHRAE has recommended not only to preserve a steady-state CO_2 **concentration in a space no higher than 700 ppm above outdoor air level**, which is in a range from 300 to 500 ppm, but also to maintain it below 800 ppm in offices. Furthermore, a study on a Chinese hospital demonstrates that a limiting amount of 1000 ppm is widely accepted [33]. Consequently, values between **700 and 1000 ppm** may guarantee the internal comfort.

5.1.3 Humidity

Finally, also the RH is not standardized yet but, always the **ASHRAE** [34] provides the suggested values. As Figure 27 witnesses, referring to healthcare facilities, humidity should be between **30-60%.**



ASHRAE typical recommended indoor design conditions		
Area	Indoor Design T/RH Winter	Indoor Design T/RH Summer
Offices, conference rooms, gen. areas	20-24°C 20-30%	23-26°C 50-60%
Cafeteria	21-23°C 20-30%	25°C 50%
Department Store	16-22°C	21-25°C
Healthcare Facilities	21-24°C 30-60%	21-24°C 30-60%
Classrooms	20-24°C 30-60%	23-26°C 30-60%
Guest Rooms	22-24°C 30-40%	23-26°C 50-60%

Figure 27 - Humidity levels from ASHRAE [34]

Last but not least, **ASHRAE Standard 62.1-2016** [32] suggests that relative humidity in occupied spaces has to be to less than 65% to lessen the probability of diseases that can lead to microbial growth.

5.2 The choice of the target period

A baseline period is a fixed time of reference, useful for comparison purposes. In energy studies, it strongly depends on the goal of the analysis: it may vary from one day to one week to one solar year. However, in this case, the best trade-off is **seven days** because, being a health centre in which the energy consumptions are almost stable during different weeks, it is interesting checking their variation between working (from Monday to Saturday) and off (Sundays) days.

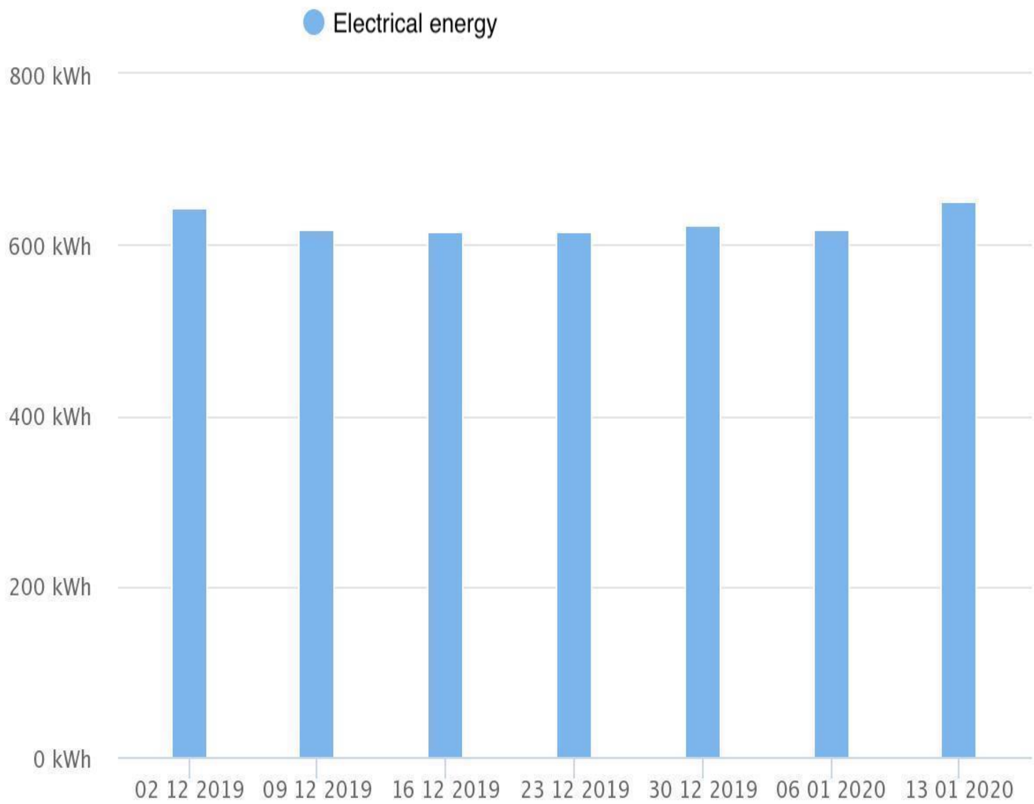


Figure 28 - Electrical energy consumption of the AHU before the action

Figure 28 illustrates the electrical energy consumption of the AHU. Data are provided in kWh, and each bar represents the energy usage. It is almost stable at a value of 620 kWh. Overall, being the power consumed strongly dependent on the state of the inverters, it does not have a significant link with the external conditions.

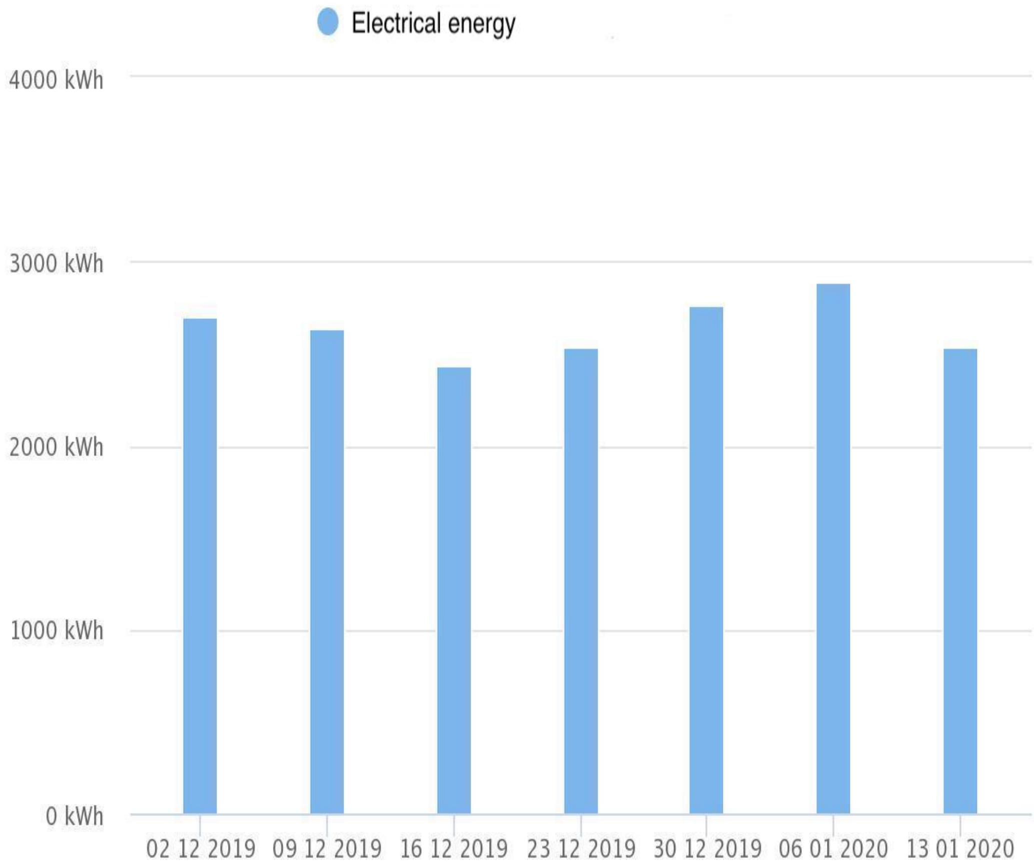


Figure 29 - Electrical energy consumption of the polyvalent pump before the action

On the other hand, having the heat pump a strong dependence on the external temperature, its consumptions fluctuate more during different weeks. Nevertheless, as Figure 29 witnesses, its values vary between 2430 kWh and nearly 2900 kWh, reached in the second week of January. Overall, its energy consumed is much more significant because the production of both hot and cold fluids requires more power than the one needed by the AHU.

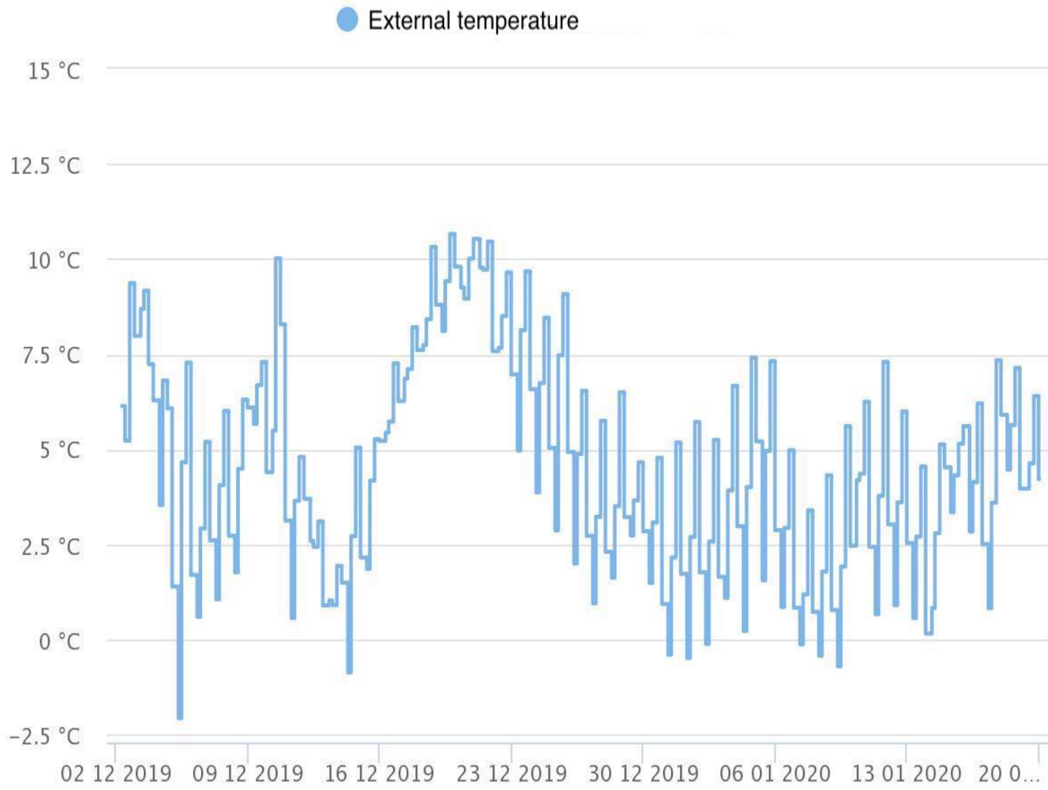


Figure 30 - External temperature before the action

Finally, being located in Milan outskirts, the external temperature in winter is considerably low. As Figure 30 shows, while it varies between -2 °C and 11 °C in December, the peak is only 7.5 °C in January.

Consequently, due to both previous energy consumptions and temperature trend, **the baseline week chosen goes from January 06, 2020 to January 12, 2020**. The reason is that it is not only the one with the lowest hot temperature, but also with the highest energy usage.

5.3 Weekly review

In the week chosen, a more detailed study of all variables that Simon can measure is implemented to understand where and how a more efficient logic might be adopted. Firstly, there is the analysis of energy and power absorbed and then, the examination of the environmental internal variables (temperature, humidity and CO_2 level), always referring to values set by standards.

5.3.1 Electrical energy, active power and airflow rate of the AHU

The paragraph's primary goal is to analyse the consumption variation between different days.

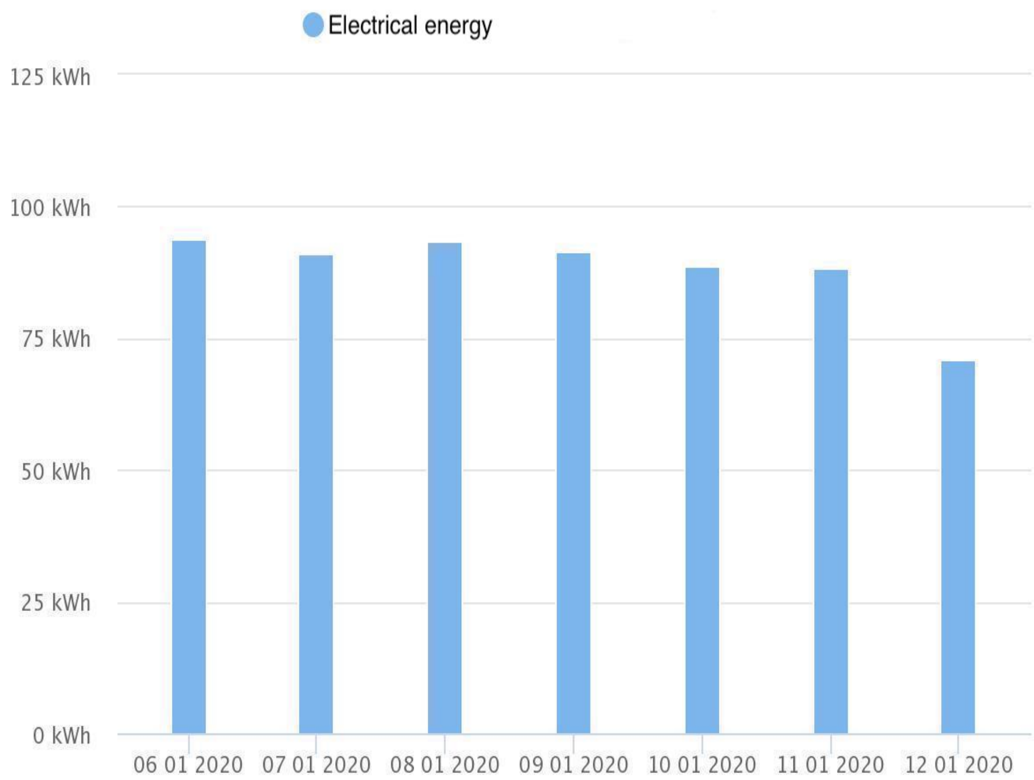


Figure 31 – Weekly electrical energy consumption of the AHU before the action

Figure 31 illustrates the weekly electrical energy consumption of the AHU. Overall, it is immediately apparent that while the utilization from Monday to Saturday is almost stable, it decreases on Sunday. Consequently, the consumption in working time is around 90 kWh. However, being the healthcare open only half day on Saturday, the energy usage is still comparable with the previous value; in fact, there is a drop of only 2 kWh. Finally, by consuming around 70 kWh, the Sunday decline is more marked but, not too steep.

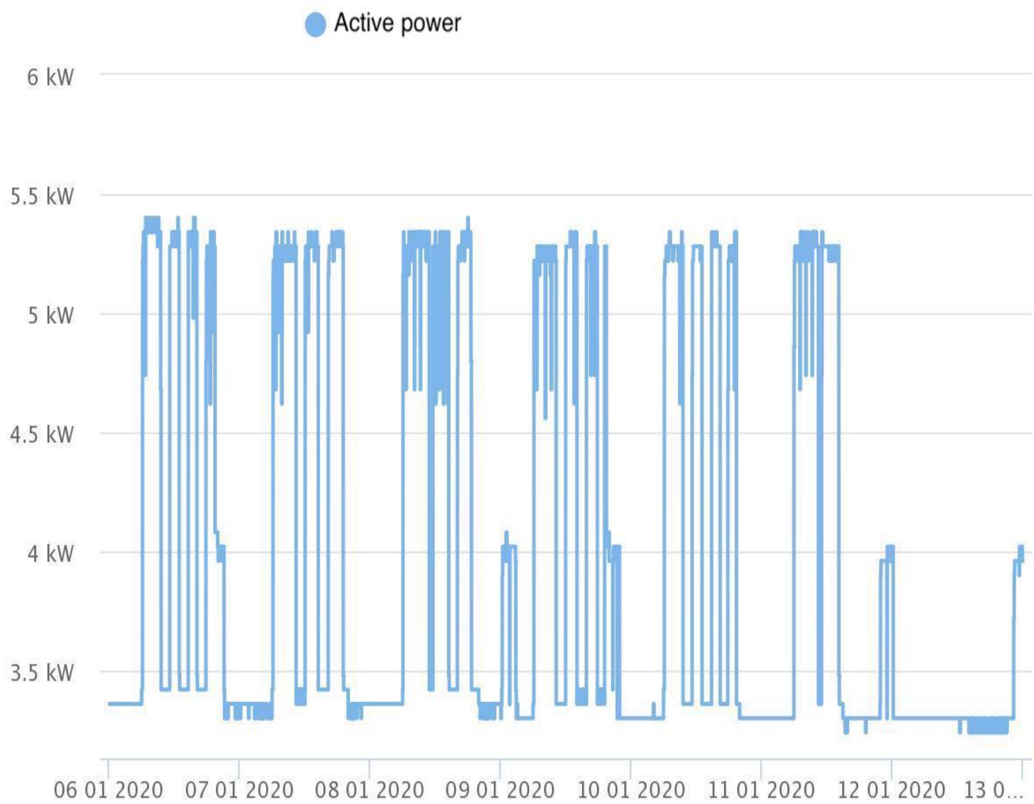


Figure 32 - Weekly active power absorbed by the AHU before the action

Complementary to the previous one, Figure 32 shows the power always absorbed by the air handling unit and, as it should be, it follows the energy pattern. Its usage fluctuates continuously during working days between 5.3 kW and 3.3 kW. However, while peaks are only reached during daytime hours, troughs are present not only at nights but also during mornings, afternoons and Sundays.

Overall, from the comparison of the two figures, it is clear how the consumption of the last day of the weak may be only due to minimum absorptions. Thanks to these patterns, for a more detailed analysis, it is possible to pick a random twenty-four hours working period because days appear identical from the energy point of view.

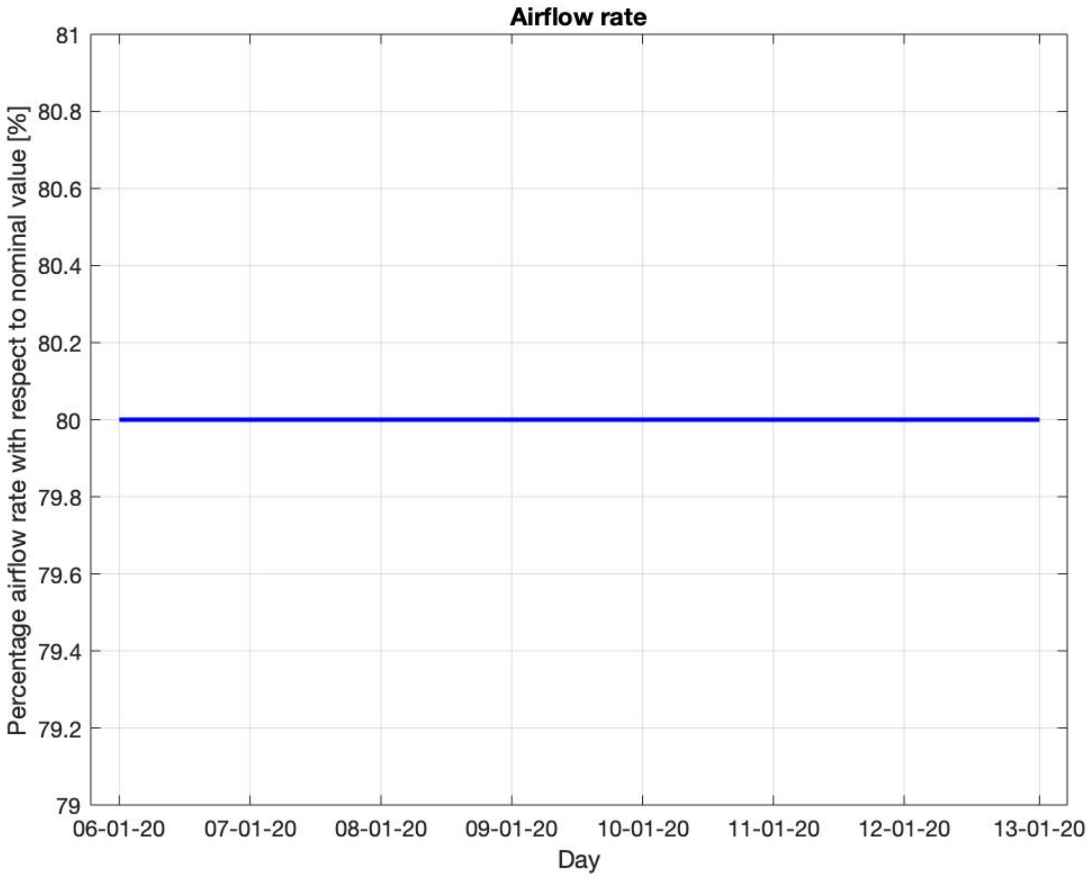


Figure 33 - Weekly airflow rate before the action

Finally, Figure 33 illustrates the percentage of supplied and extracted airflow rate in comparison with nominal values. The AHU works always at fixed point, suppling and extracting respectively 4880 $\frac{m^3}{h}$ and 4800 $\frac{m^3}{h}$.

5.3.2 Electrical energy and active power of the polyvalent pump

Without any priority order, the second component studied is the polyvalent pump.

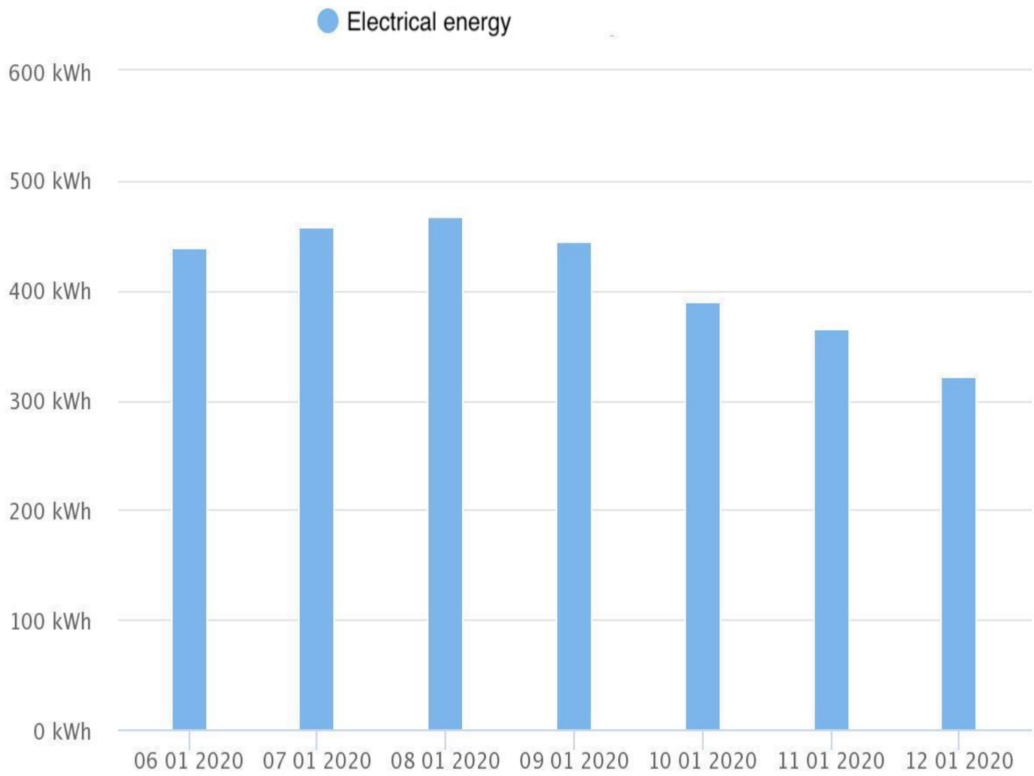


Figure 34 - Weekly electrical energy consumption of the polyvalent pump before the action

As said before, the energy consumption of the polyvalent pump, represented in Figure 34, is much larger than the one of the AHU. Overall, its shape strictly depends on external temperature; in fact, when it is very cold, the absorption reaches a peak of more than 450 kWh. However, while it is around 320 kWh on Sunday, it is rarely less than 400 kWh during working days.

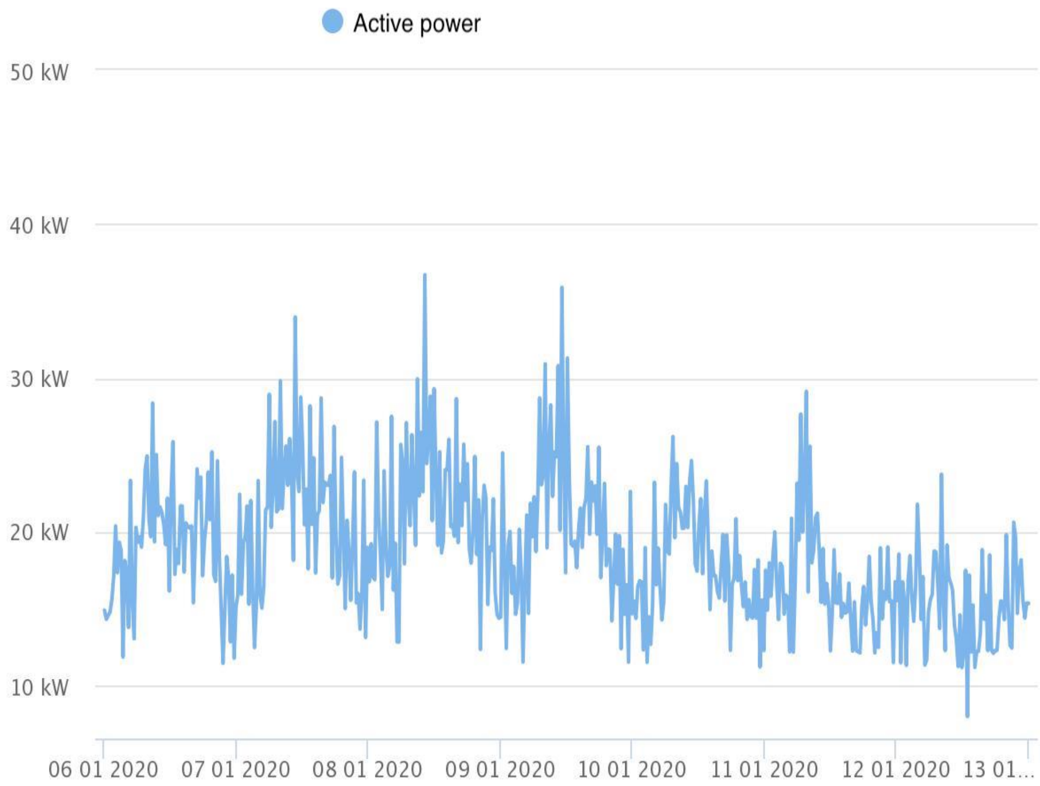


Figure 35 - Weekly active power absorbed by the polyvalent pump before the action

On the other hand, Figure 35 witnesses the power absorbed by the same item. Its shape oscillates continuously between 12 kW and 35 kW, which is a value always reached in the morning. Moreover, when the health centre is close, while the maximum amount is around 25 kW, its pattern does not change. Furthermore, it does not provide only hot water to the active chilled beams, but also to the AHU's coils. So, it can be deduced that the **polyvalent pump is always switched on** due to its double functions and that the building is also heated on Sunday.

5.3.3 Temperature, humidity and CO_2 level

The description of these three key performance indicators is divided not only by floors, but also by each probe.

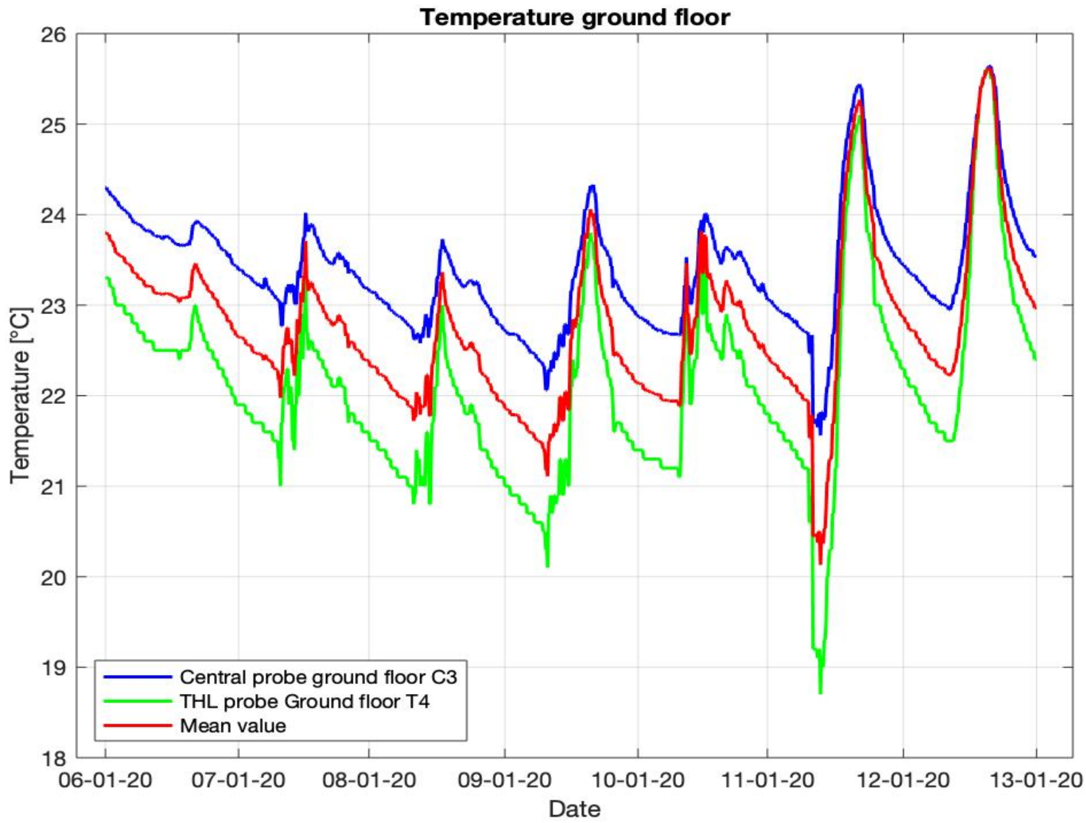


Figure 36 - Temperature ground floor before the action

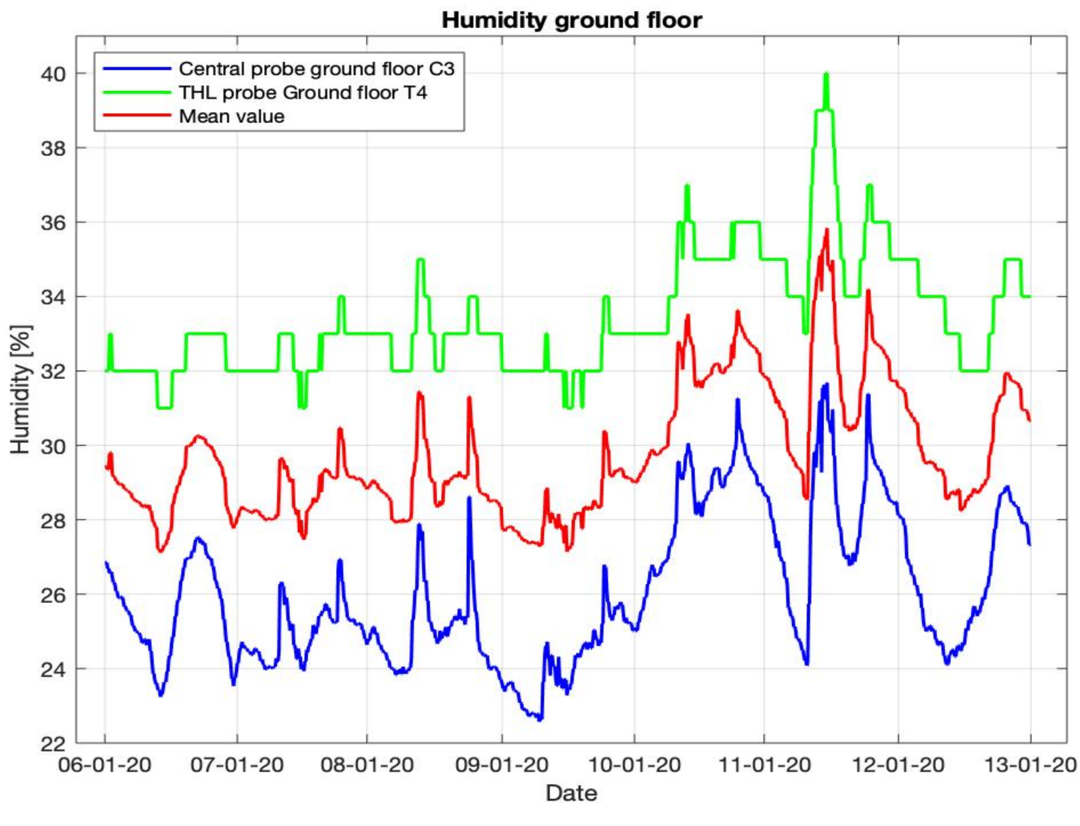


Figure 37 - Humidity ground floor before the action

Figure 36 and Figure 37 (see Figure 11 for a better understanding of each probe) describe the weekly variation of temperature and humidity on the ground floor. Overall, while the mean value of the first variable oscillates between 20 °C and 24 °C, the average of the second fluctuates between 27% and 36%. These two trends confirm that not only the polyvalent pump, but also the AHU is switched on during days off. Moreover, the sudden temperature increase of the last two days may be due to a reduction of the opening time, which causes a drastic decline in heat exchanges.

Then, humidity appears a few percentages lower than values suggested by ASHRAE; it may be caused, again, to elevate heat exchanger with the external atmosphere, especially through entrance doors. However, being its mean value not lesser than 27% and temperature high enough, internal comfort is guaranteed.

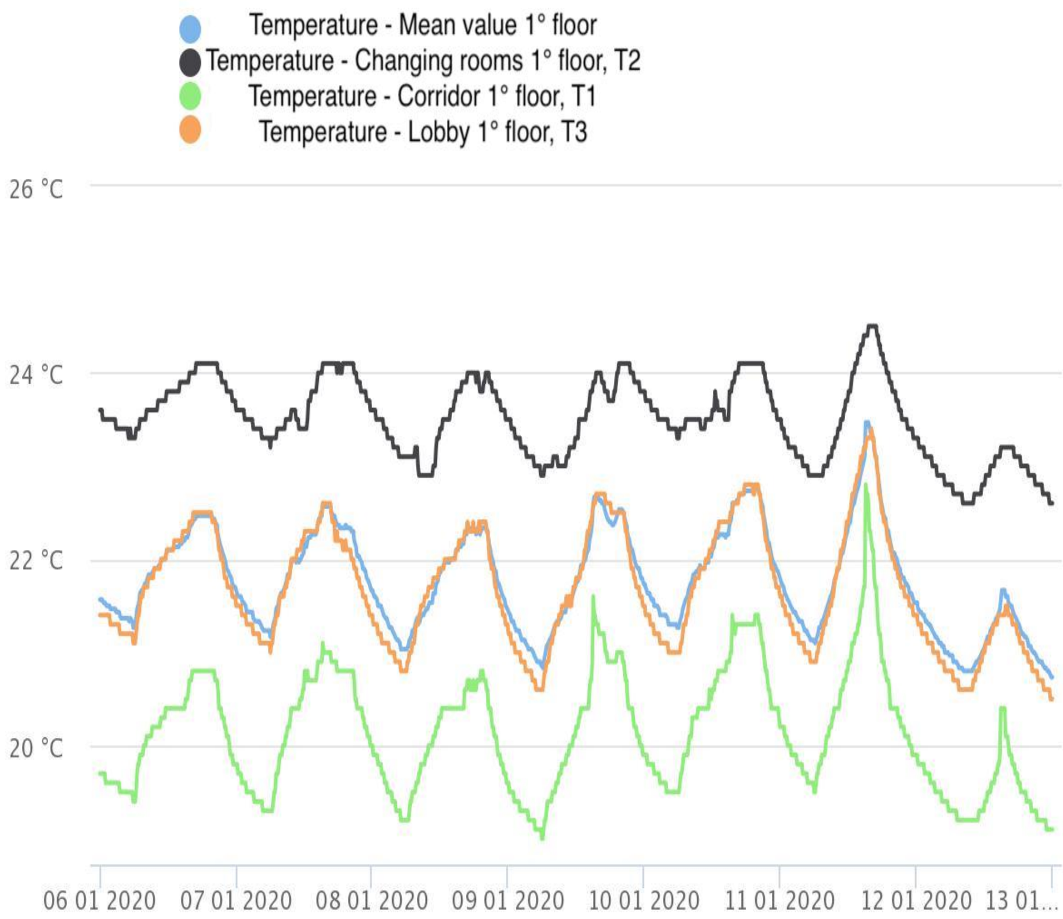


Figure 38 - Temperature 1° floor before the action

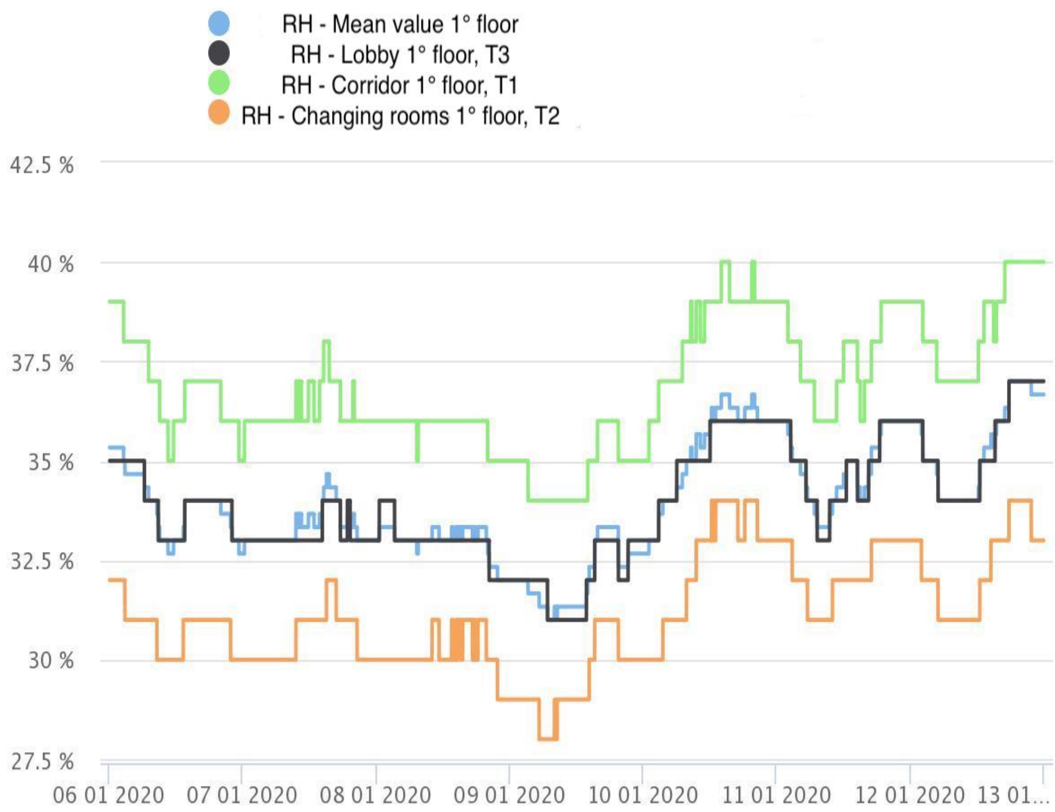


Figure 39 - Humidity 1° floor before the action

On the other hand (see Figure 12 for a better understanding of each probe), being the first floor constituted of several locals with different purposes**, three thermal zones**, as Figure 38 and Figure 39 show, can be observed:

- **corridor**, in which the temperature varies between 19 °C and 21.5 °C, with a spurious peak of 23°C;
- **lobby**, in which the temperature oscillates between 20.5 °C and 23 °C;
- **changing rooms**, in which the temperature is included between 23 °C and 24.5 °C.

Nevertheless, humidity is almost always larger than 30%, reaching peaks of 40% in the corridor in specific timeframes.

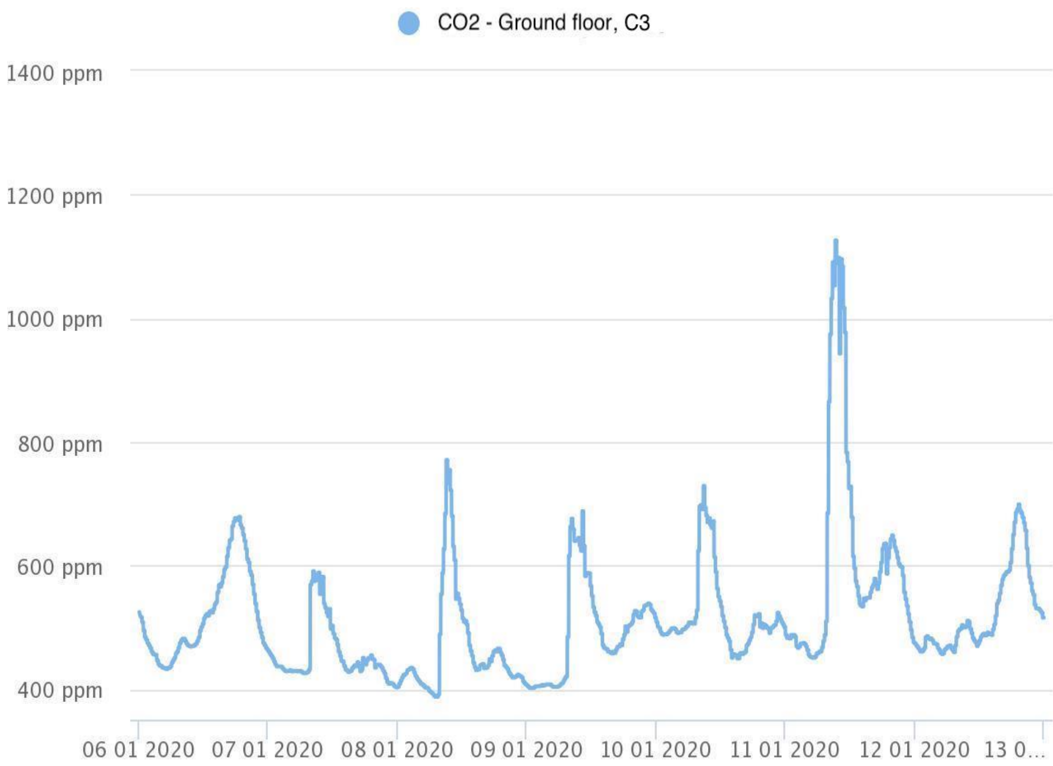


Figure 40 – CO_2 level ground floor before the action

Finally, Figure 40 (see Figure 11 for a better understanding of the probe) witnesses the variation of CO_2 on the ground floor. During the weak in analysis, the CO_2 probe is not useful for the control of the ventilation system; in fact, it has been installed to increase the efficiency of the plant later on. Overall, its values, as it was expected, are higher during working hours, with maximums of about 800 ppm.

However, a spurious peak of 1200 ppm can be observed on Saturday. As Figure 41 shows, it is reached in the morning between 9.00 and 11.00 and, being the health centre open during this time, it is **undoubtedly due to the massive presence of patients.**

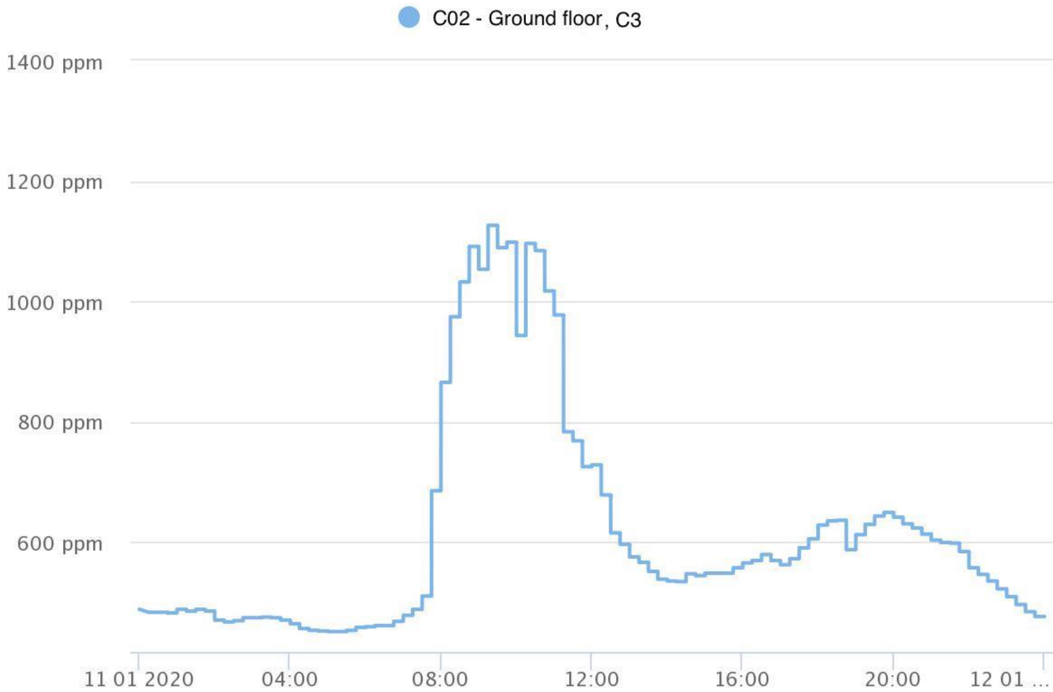


Figure 41 – CO_2 on Saturday 11-01-2020

5.4 Daily review

The daily review is useful to understand which **are precisely the consumption along 24 hours** and how the three **main internal variables behave**. They are crucial indicators for the implementation of a more efficient functioning.
To complete this study, the day chosen is Tuesday, 07 January because, by looking at the external temperature, it is the one with the coldest values. Nevertheless, another timeframe could have been chosen because, thanks to all previous data, patterns do not vary hugely for the goal of this paragraph.

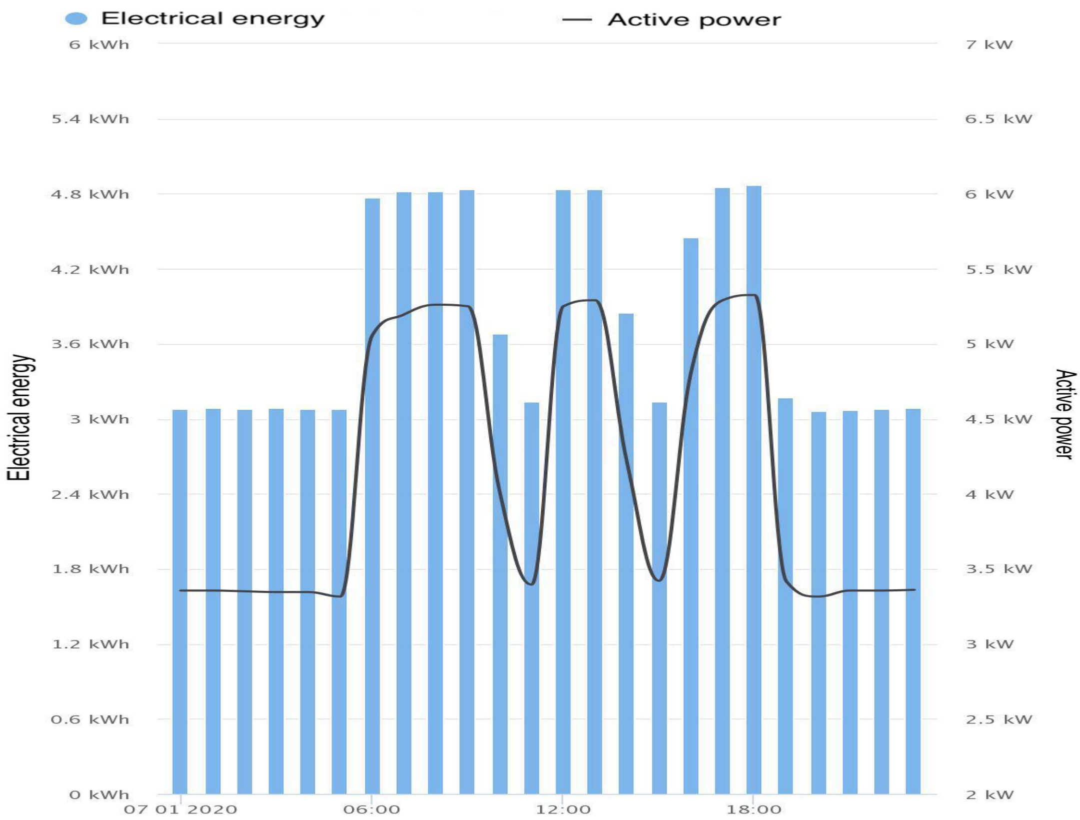


Figure 42 – AHU's daily electrical energy and active power consumption before the action

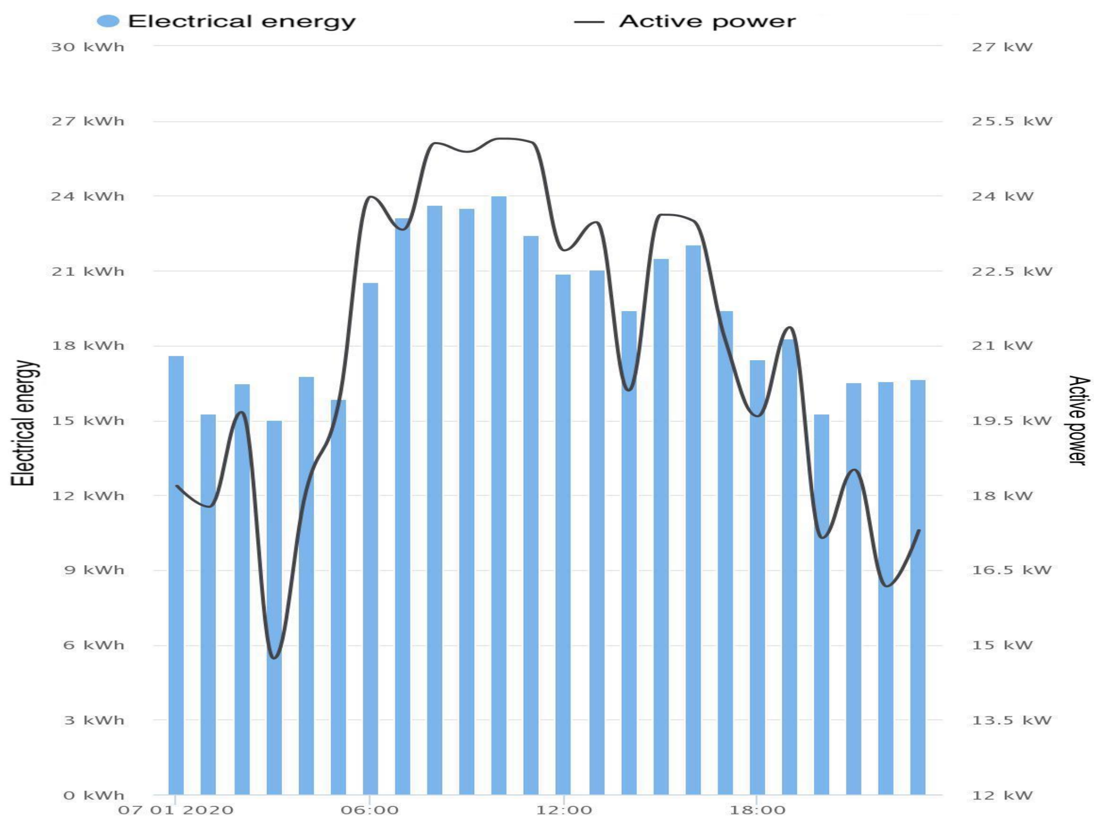


Figure 43 - Polyvalent pump's daily electrical energy and active power consumption before the action

Figure 42 and Figure 43 show the energy and power trends of the air handling unit and the polyvalent pump, respectively. Being the healthcare heated and cooled by active chilled beams, they are strictly connected.
The power absorbed by the AHU is minimum (3.3 kW) until 05.00, time at which it changes its behaviour to 5.3 kW in order to set the internal conditions before the arrival of both workers and clients. Before reducing its absorption again, it works continuously in this way for 4 hours. Moreover, it is possible to detect three peaks (5.3 kW) during the day: in the morning, around lunchtime and in the evening. Finally, it minimizes consumption again only around 19.00.
On the other hand, the pump starts working at its peak value of 25 kW always around 05.00 and, also in this case, it is possible to see the three peaks at different times of the day. However, spurious heights before 05.00 or in the late evening are due to its double functions.

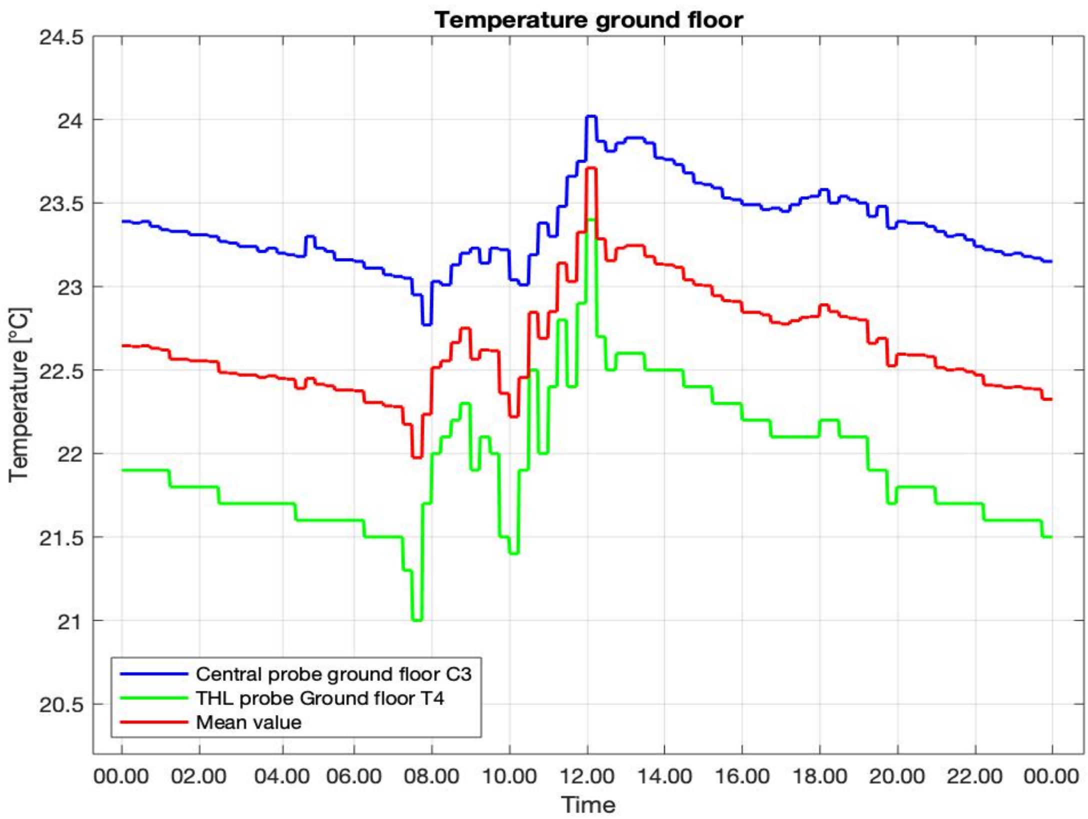


Figure 44 - Daily temperature ground floor before the action

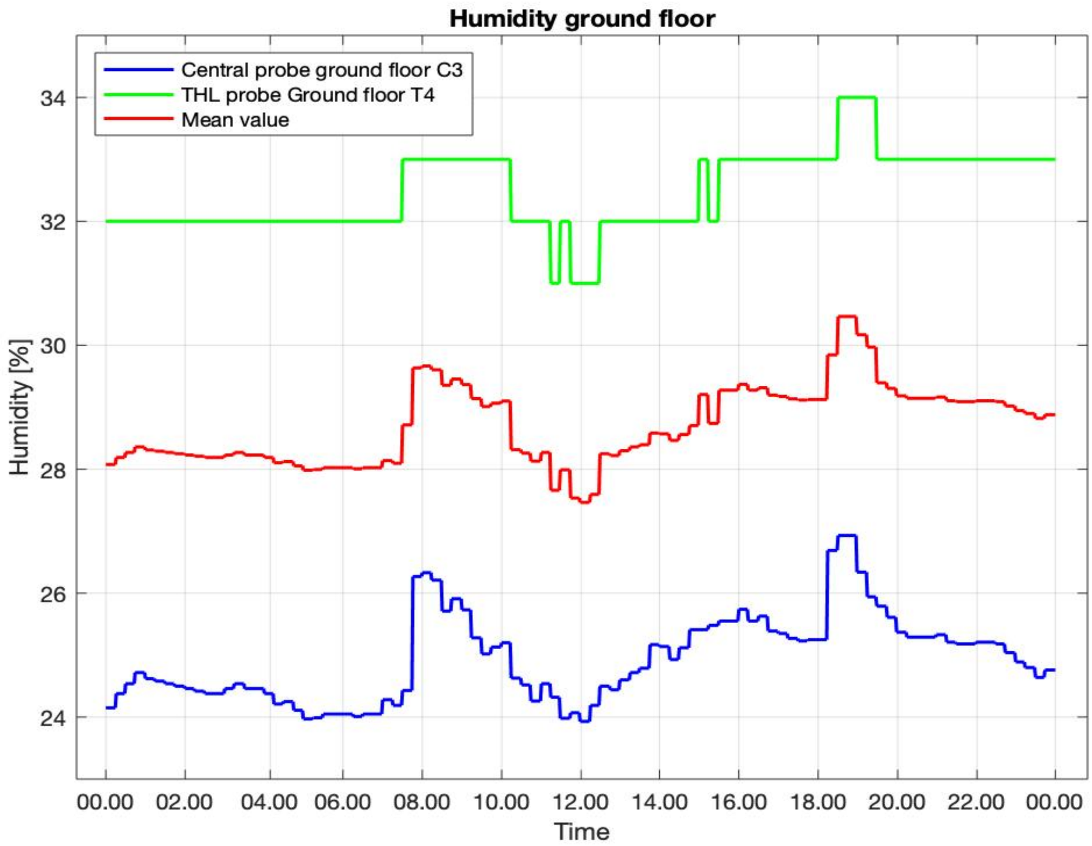


Figure 45 - Daily RH ground floor before the action

Figure 44 and Figure 45 (see Figure 11 for a better understanding of each probe) witness temperature and humidity daily trends on the ground floor. As expected, both start increasing around 07.00. However, while the average of the first oscillates between 22 °C and 23.5 °C, without going under the value set by standards, the mean of the second rarely reaches the minimum suggested value of 30%. Again, it may due to either excessive thermal exchanges or to temperature extremely high.

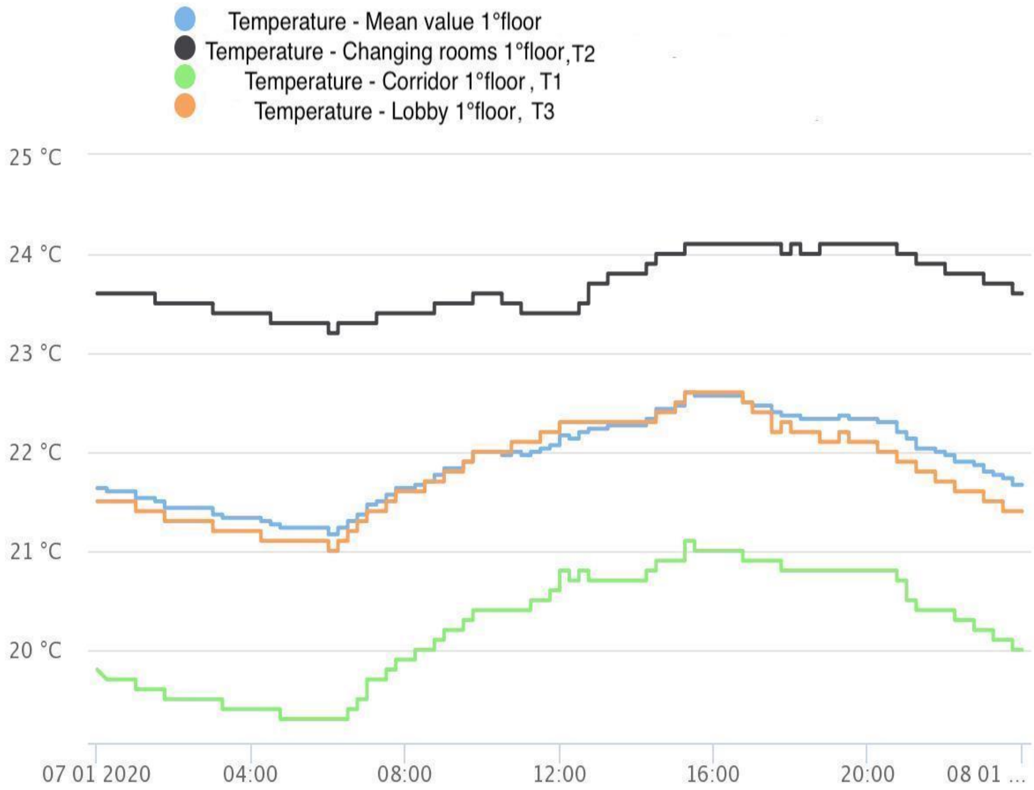


Figure 46 - Daily temperature 1° floor before the action

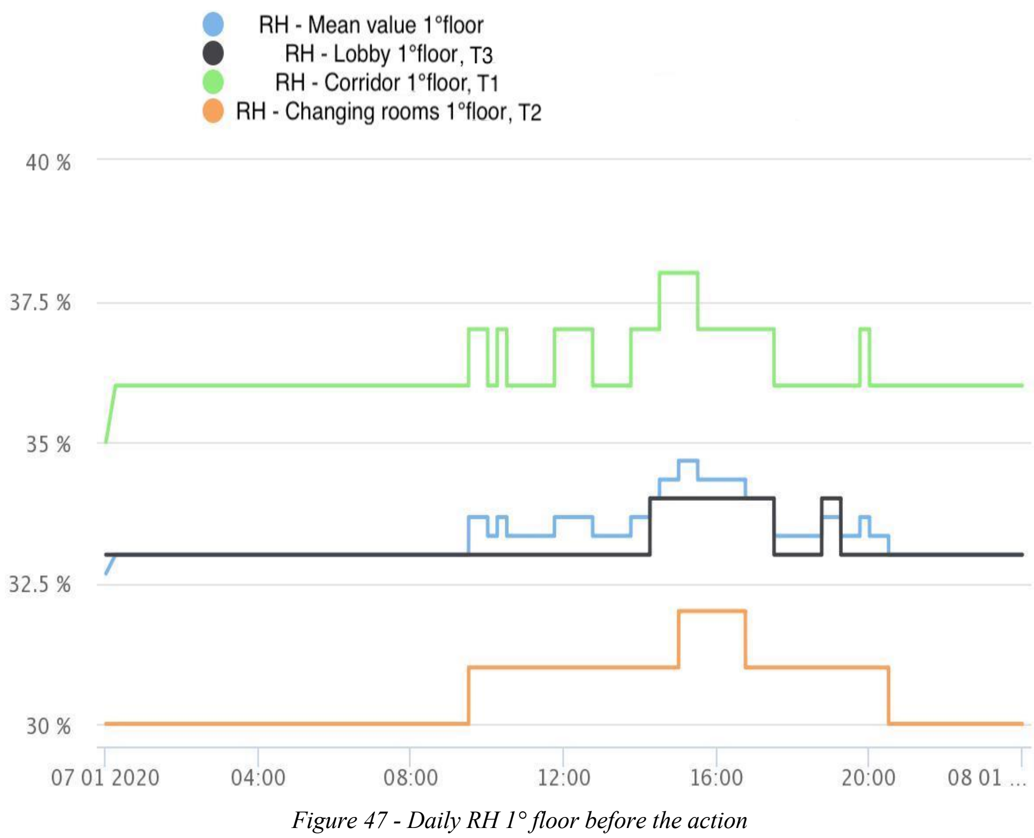


Figure 47 - Daily RH 1° floor before the action

Last but not least, (see Figure 12 for a better understanding of each probe) the first floor temperature and humidity trends are illustrated in Figure 46 and Figure 47. Overall, also in this case, it is possible to see the action of the heating system after 07.00. Furthermore, the three thermal zones respect always the minimum requirements for both variables. Even if humidity is still low, it never goes under 30%.

5.5 Absorption comparison between working and off days

The last analysis made before planning a new logic that minimizes consumption is the comparison between the power absorbed during work and off days. This kind of study gives as output not only information about the utilization of the AHU and the polyvalent pump on Sundays, but also which is **the gap between these two different days**.

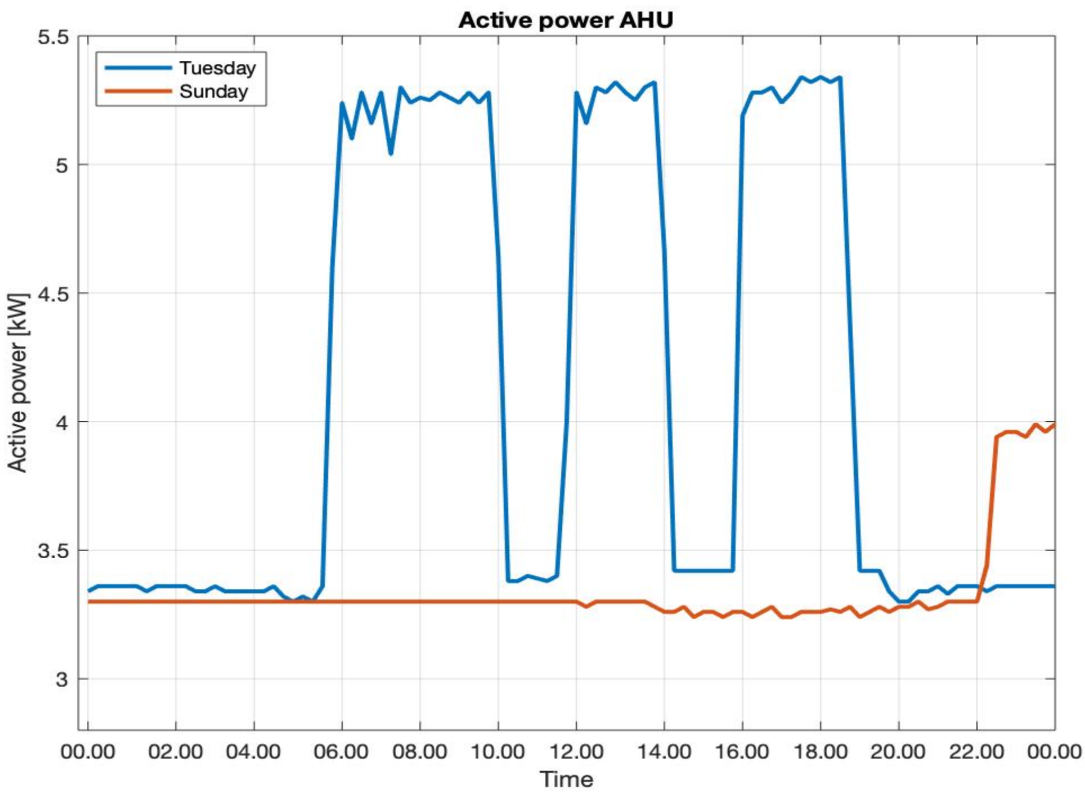


Figure 48 – AHU's active power absorbed on working and off days before the action

As always, the first system analysed and represented in Figure 48 is the air handling unit. Its absorption during a day off is almost stable at the minimum value of 3.3 kW. However, an unusual increase of around 0.5 kW begins around 22.00; it may be due either to a false reading or to a change of state of some components.
Overall, when their functionings are not the same, the gap between these two days is about 2.5 kW.

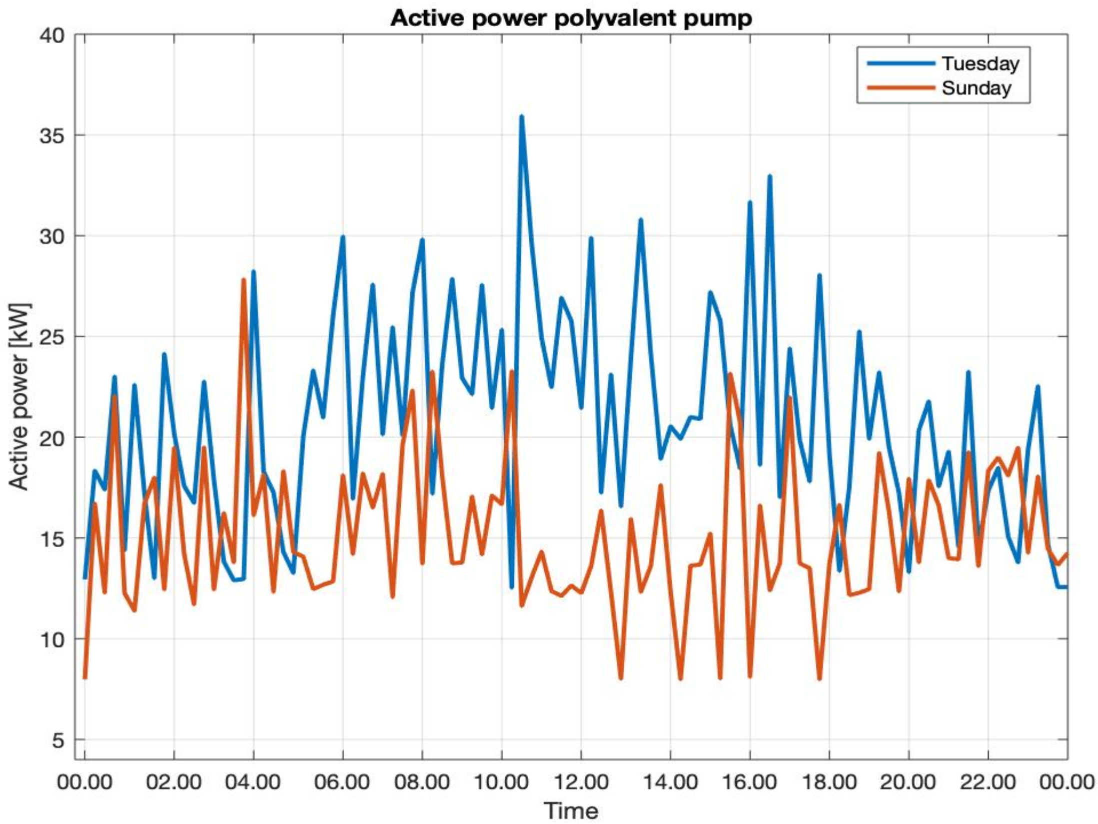


Figure 49 - Polyvalent pump's active power absorbed on working and off days before the action

On the other hand, pump's absorption, represented in Figure 49, has a different pattern. While it oscillates between 9 kW and 28 kW on Sunday, it is rarely less than 14 kW on a working day. Moreover, the two patterns are very close in the early morning and night but, the main differences are between 06.00 a.m and 08 p.m. . Consequently, next targets are looking for gaps' reasons and understanding the nature of minimum base loads in order to reduce them, if it is allowed.

6 New algorithms description

After having analysed in detail the absorption of the main components of the plant, it is clear how **more dynamic logics** of control can be implemented. Their developing depends on the following **constraints**:

- Stopping the polyvalent pump would also mean stopping the AHU otherwise, the air supplied inside the building would be either too cold (winter) or too hot (summer);
- In case of extremely low external temperatures (below 3 °C), the polyvalent pump must continue running, otherwise the fluid inside pipes would risk freezing and blocking the normal operation of the system;
- Domestic hot water has very strict temperature limitations: to avoid the presence of Legionella inside the tank, it must never fall below 45-55 °C;
- Since it is a healthcare, there are rooms (for example those in which there are medicines), which must always be within a set temperature range: 20-24 °C.

Consequently, **a complete stop of the system** is not allowed during nights and weekends. The only option is **improving the actual functioning** by modifying parameters and setpoints without changing environmental conditions and comfort. Furthermore, since **Siemens manages the entire plant through a Desigo supervision system**, which is a BMS and can not be deactivated, it will always have priority over the logic set by Evogy S.r.l. , which works on another level. Consequently, in the case of the AHU, in order to bypass Desigo algorithm, in addition to the PI controller, another check has been added that avoids abrupt and unwanted variations of the air rate.

6.1 Air Handling Unit

The control of the AHU is based on a **PI controller**, which operates **according to the amount of CO_2 in the environment**. It is a very efficient solution in places distinguished by a highly changeable occupancy. The success of CO_2-based Demand Controlled Ventilation (DCV) prevails in the direct verifying of indoor air quality level and the following evaluation of necessary air changes. Thus, this component moves **from a programmed operation to one dependent on the level of carbon dioxide in the building**.

Since it is a healthcare, which only works on appointments, a PI and not PID system has been chosen because a sudden and massive presence of patients is not expected. Consequently, it can be inferred that **the dynamic of the system is slow**. In fact, PI controllers are used when a low-speed error is required together with a good speed response to stress variations; therefore, they are mainly utilised in systems where load variations occur slowly.

Overall, a summary of the states before and after the action are represented in Figure 50.

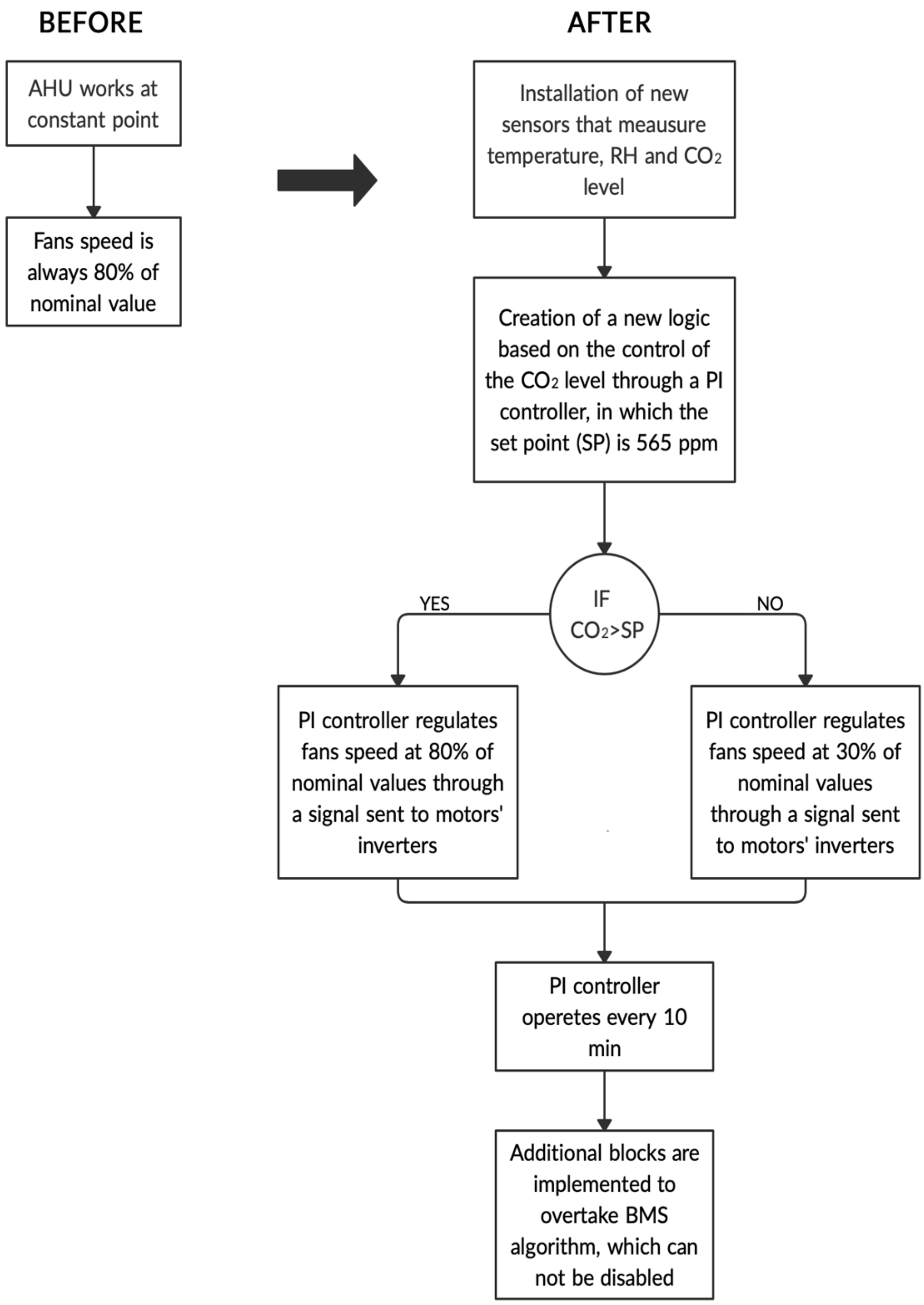


Figure 50 - Flowchart AHU functioning before and after the action

6.1.1 Brief recap on PI controllers

A **proportional-integral controller** is a control loop mechanism applying feedback that is generally used in mechanical systems and a diversity of other purposes demanding continuously modulated control.
Its functioning is summed up in Figure 51, in which:

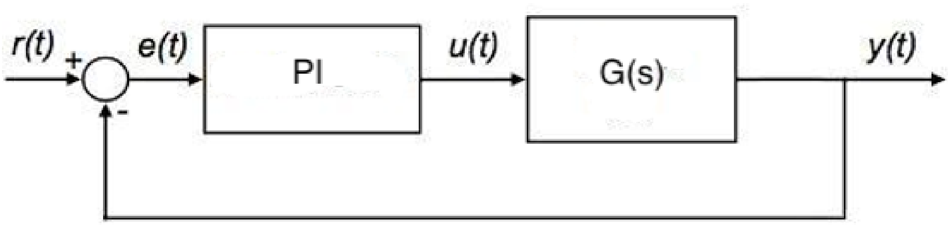


Figure 51 - PI functioning [35]

- r(t) is the input reference signal;
- y(t) is the feedback control system output signal;
- e(t) is the error due to the algebraic difference between the reference signal r(t) (input) and y(t) (output);
- u(t) is the control input;
- G(s) is the controlled system.

In the proportional action, the input e(t) and the output u(t) are algebraically linked by a **K_P coefficient, called proportional action coefficient**, or only proportional gain.

$$u(t) = K_p * e(t)$$

The meaning of this parameter lies in the fact that the higher is the error e(t) at the controller input, the greater is the control activity carried out by the controller itself. However, the answer of the system, if only a proportional controller is used, will never be equal to r(t) due to a difference, called **offset,** between the constant value required at full speed and the one obtained. Furthermore, if K_P is too high, unexpected oscillations could be present (see Figure 52).

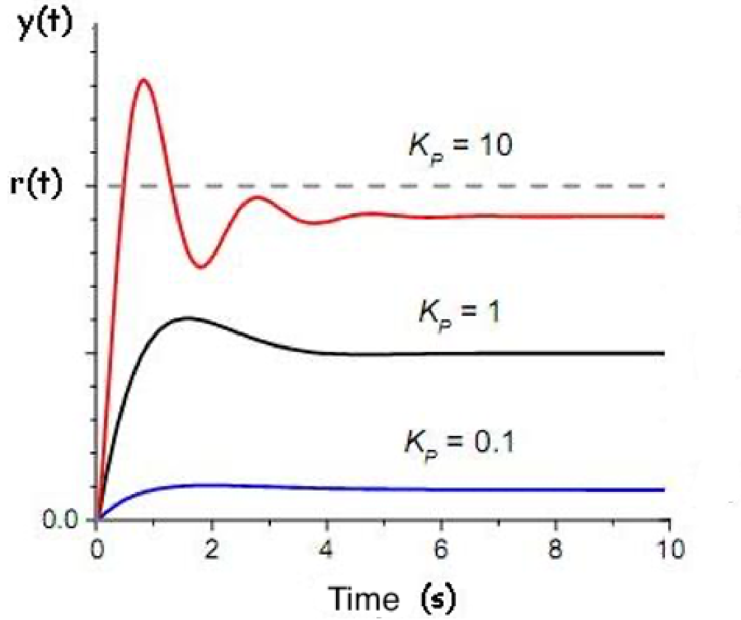


Figure 52 - Proportional controller [35]

Then, in the integral action, the contribution is proportional to the integral of the error e(t), and **the coefficient of the integral action K_I defines the integral time constant T_I** (also called reset time):

$$u(t) = K_I \int_0^t e(\tau)\, d\tau \qquad\qquad T_I = \frac{K_I}{K_P}$$

This controller is particularly crucial in applications because it ensures a zero error at full speed for step changes of the reference r(t). The error remains zero even in the presence of process gain variations, as long as the stability of the closed-loop system is preserved.

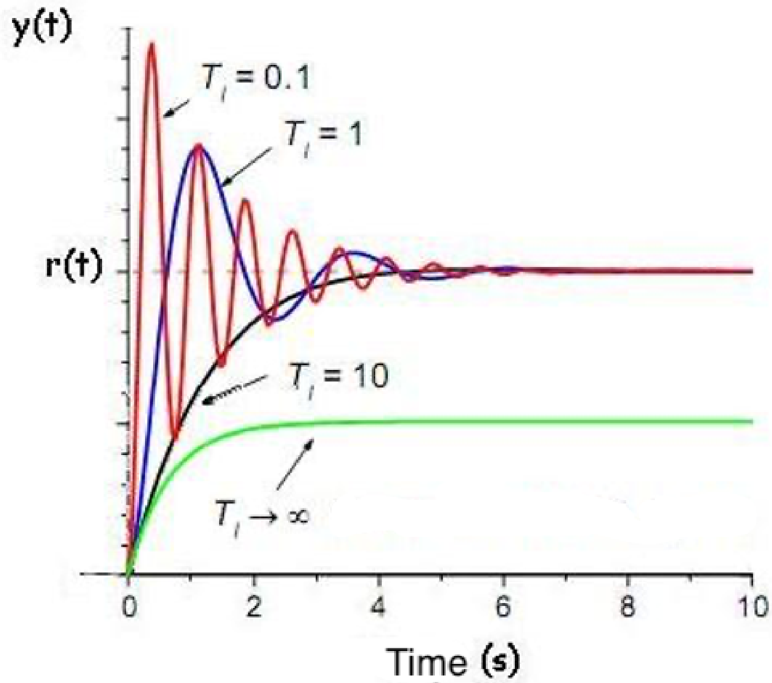


Figure 53 - Integral and proportional controller [35]

The effect of T_I is shown in Figure 53. Note that the offset is present when operating only with the proportional controller, while it disappears by activating the integral term. By reducing T_I, the system responds faster to the transient, but more oscillations are also witnessed.

6.1.2 Control description

The control implemented, illustrated in Figure 54, can be **divided into two parts**: the first, in which there is the PI controller and the second, useful to overtake the logic implemented on the AHU by Siemens Desigo. As stated before, it has a priority with respect to Evogy's code because they operate on two different levels of importance.

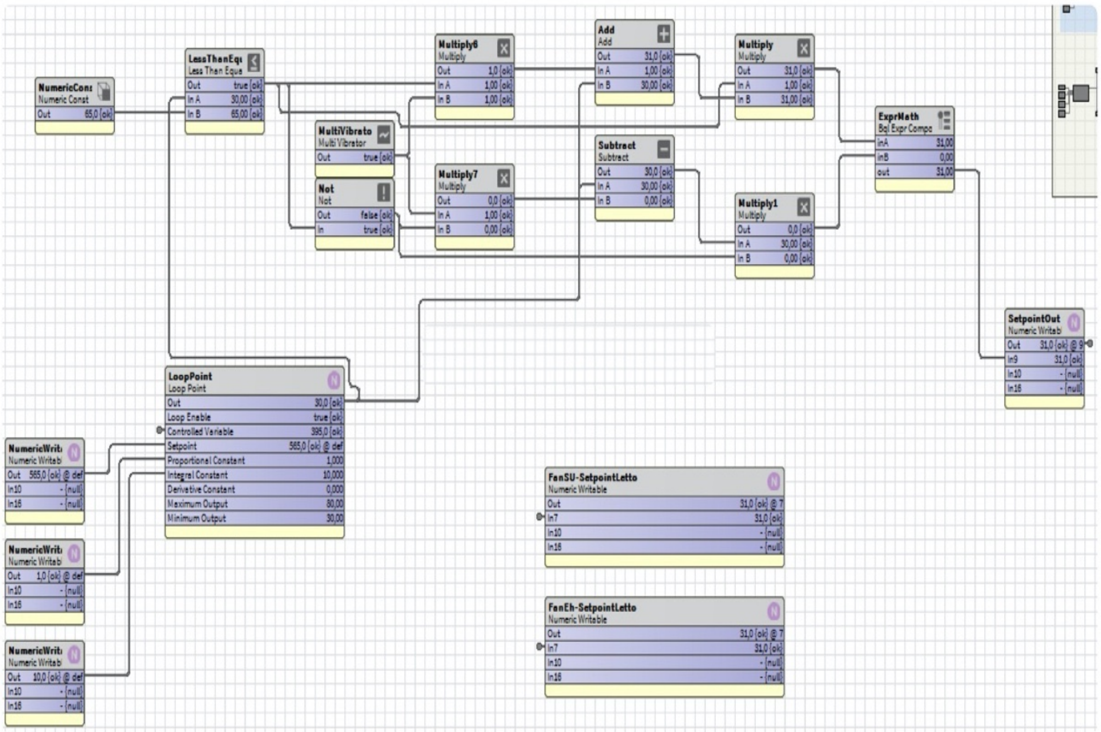


Figure 54 - AHU new logic

Starting with the description of the PI controller (see Figure 55), **inputs are**

- the **setpoint of CO_2**, equal to 565 ppm;
- the internal level of CO_2;
- the value of the two constants of the PI, which are **1** for the proportional (K_p) and **10** for the integral (K_I).

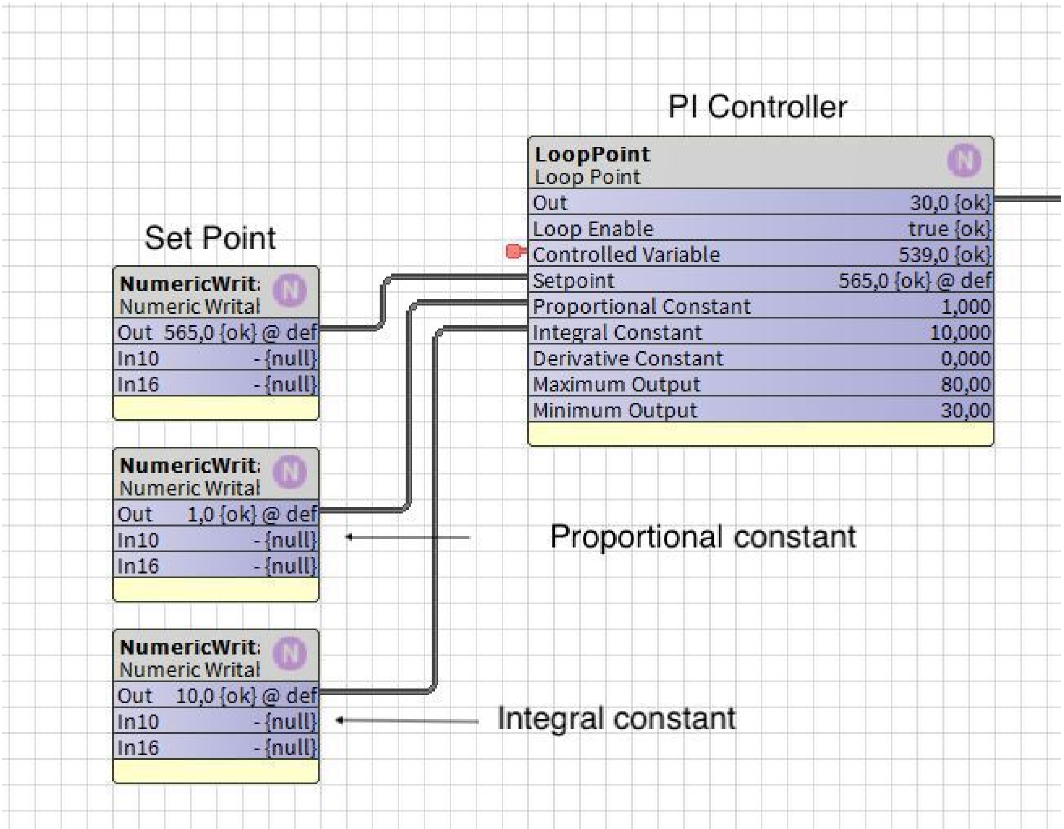


Figure 55 - Zoom on PI controller

Then, after a comparison of the two carbon dioxide levels, which happens **every ten minutes**, the controller provides as output the percentage at which fans has to run, in comparison with their maximum values, Furthermore, in order to ensure always fresh air inside the building, the **output can vary between 30% and 80%** (Table 5).

CO_2 Level	Fans Speed
Set point > internal value	30% of nominal speed
Set point < internal value	80% of nominal speed

Table 5 - Summary of the AHU new logic

However, an important step that has to be done before applying the new algorithm is the **tuning of the PI controller**. The most used is the "frequency response method” or “Ziegler-Nichols' II method” and it operates with the system in unitary feedback.

In order to apply this method, a sequence of steps is needed, which are illustrated in the following list:

- first of all, the integration action has to be eliminated, making the controller working in a purely proportional way. To do this, T_I has to be set equal to zero.
- Then, the value of the control variable K_P is gradually increased until it is observed that the output of the system (y(t)) oscillates permanently (stability limit). This value, called critical gain K_0, corresponds to the limit value of K_P, while T_0 is the period of oscillation measured when this limit is reached. Figure 56 shows an example of output that oscillates permanently.

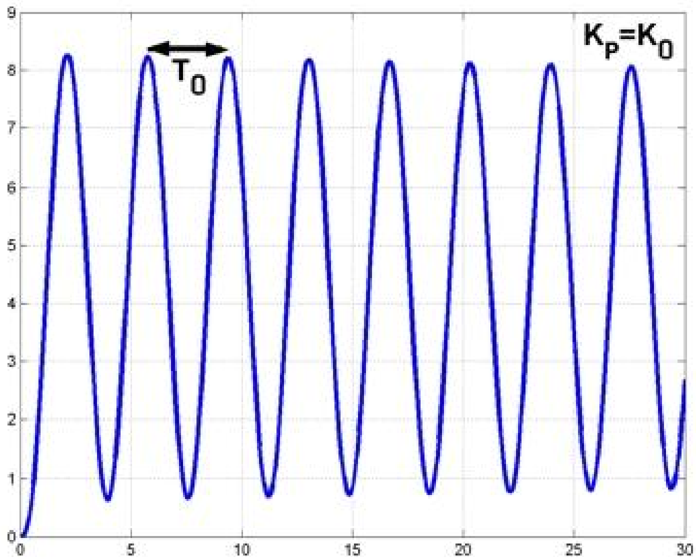


Figure 56 - PI tuning [35]

In the end, a conversion table (Figure 57) is used to set the control parameters correctly to have an excellent rejection of disturbances on the load.

	P	PI	PD	PID
K_P	$0.5K_0$	$0.45K_0$	$0.5K_0$	$0.6K_0$
T_I		$0.85T_0$		$0.5T_0$
T_D			$0.2T_0$	$0.12T_0$

Figure 57 - Converter parameters [35]

However, the tuning of the plant under analysis has not been done following precisely this method.

According to **Costergroup** [36], when starting the tuning of PI controllers with adjustable K_P and T_I, steps to follow are:

- Set T_I to a very high value and K_P to a quantity suitable for the system;
- Produce a small variation by modifying the value identified and observe the reaction of the system: if after a short stroke, it stops in a new position or at most, makes a couple of oscillations before positioning, K_P is set correctly. Consequently, after a few runs, **the value found is 1**;
- Decrease T_I gradually until the system is stable. In the end, its **final value is 10**.

Overall, despite the different approach, the system has been tuned perfectly.

Secondly, the other part of the logic is illustrated in Figure 58.

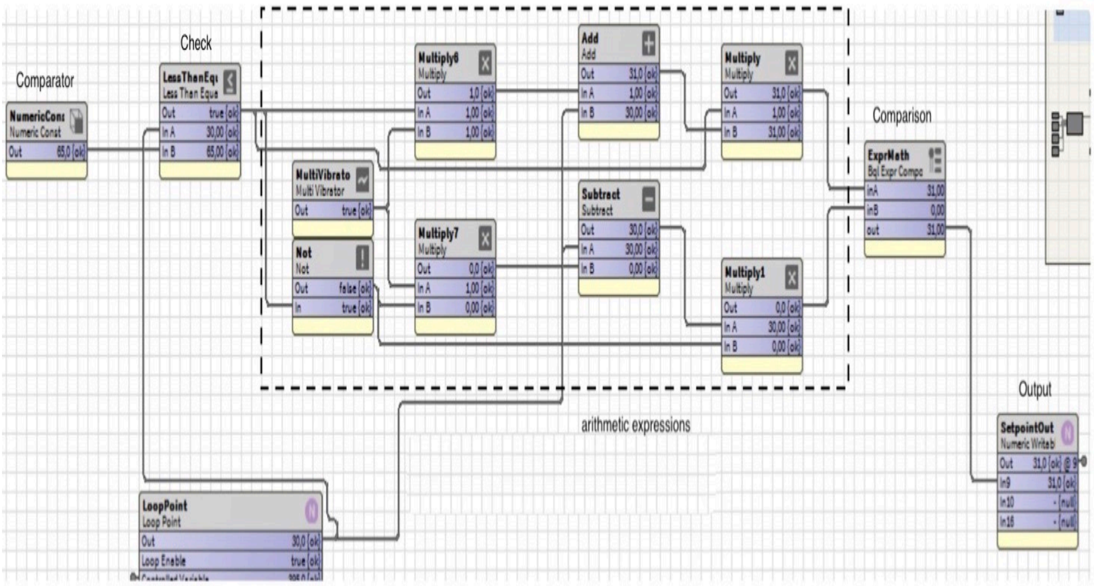


Figure 58 - Zoom on filter circuit

The reason why it is realised is to **maximise the computational time**; in fact, **it occurs every minute**, and it requires much less time than repeating the PI loop. Through various blocks, which are just merely arithmetic expressions, such as sum, multiplication and comparison, the code **either adds or subtracts one unit** if the output of the PI is **smaller or larger than 65%**, avoiding unexpected and useless variation of the velocity of the fans.

As a result, it is another reason for which a classic and more appropriate tuning could not be done.

6.2 Polyvalent pump

The new functioning of the polyvalent pump is represented in Figure 59.

In this case, **two further constraints** have to be taken into account:

- the production of a single heat carrier fluid has always been discouraged by operators because it generates maintenance problems inside the system due to the absence of both exchanges between refrigerant gas' internal circuits and lubrication in some sections;

- if Siemens does not allow the variation of the functioning, Evogy S.r.l., through its platform, is not authorised to interact directly with the machine and it can modify only the process of the state established. Consequently, Siemens intervention is required to provide the change of mode.

As a result, the only possible improvement is on **the temperature of the cold transfer fluid** since the hot fluid can never be lower than 45 °C due to heating and post-heating coils. Furthermore, being the minimum temperature (7 °C) required by the cold coil and necessary only in summer, it is not essential to produce water at this state even in winter. Therefore, it is reasonable to **raise the setpoint to 11°C** in the cold season in order to minimize the compressors' consumption dedicated to the production of such fluid.

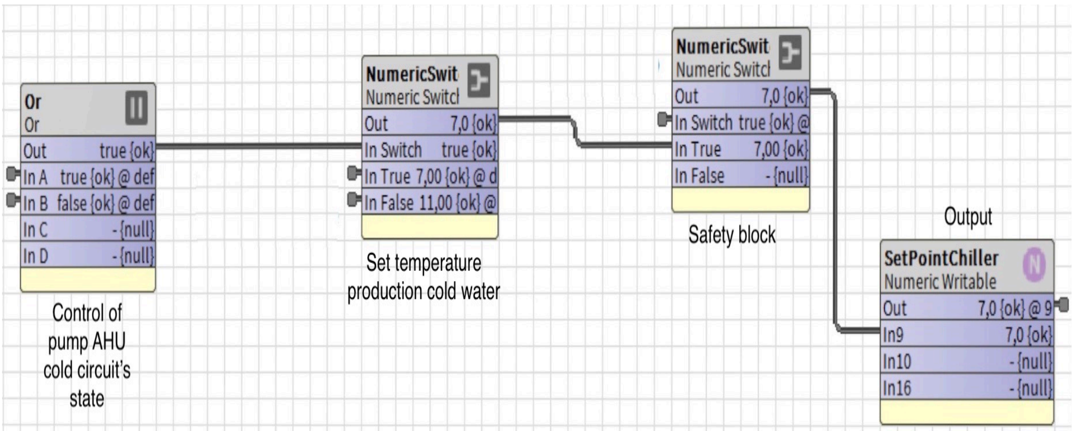


Figure 59 - Polyvalent pump new logic

In order to do so**, a control on circulating pumps (CPs)** (see Figure 15 for a better understanding), which states are managed by Siemens Desigo and provide cold water to the AHU's coil, is made. If one of them is in "ON" state, means that the setpoint of the polyvalent pump has to be 7°C, while, in the other case, the minimum temperature is set to 11°C. Furthermore, in order to **avoid a false signal,** a double check is implemented; in fact, if the first control does not provide a temperature value, it will be set equal to 7 °C through the second block.

Overall, the new functioning is summed up in Table 6.

AHU cold circuit circulating pump’s (CP) state	**Set point cold water polyvalent pump (PP) [°C]**
ON	7
OFF	11

Table 6 - Summary of the polyvalent pump new logic

However, being the benefit of this new schedule possible to see only during the heating season, the exact saving can not be estimated because it has been implemented at the end of May due to COVID-19 delay.
Finally, a summary of the actions on this component is provided in Figure 60.

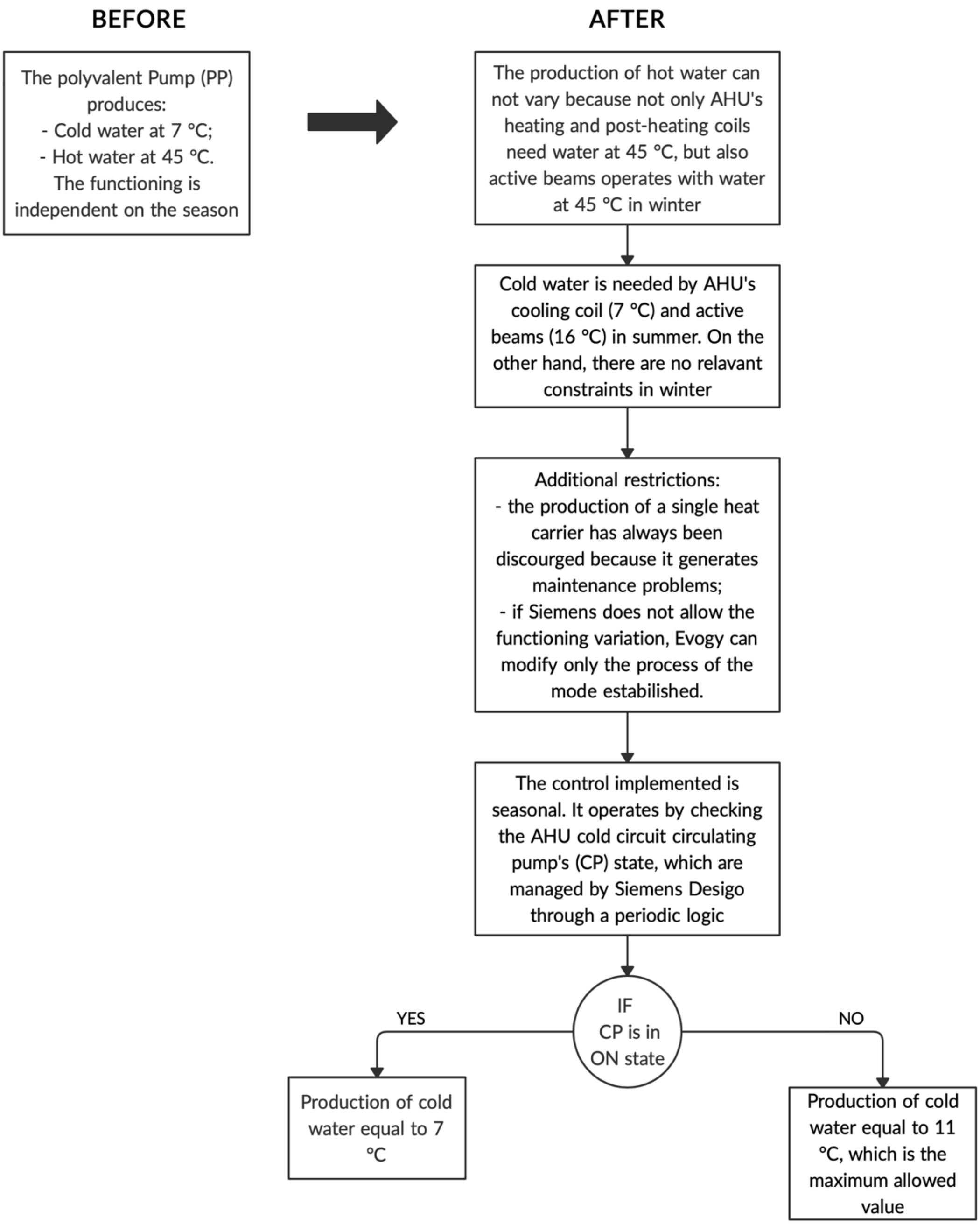


Figure 60 - Flowchart polyvalent pump before and after the action

7 Energy consumption analysis after the action

The second consumption analysis is made between March 16, 2020 and March 22, 2020. However, the external conditions (Figure 61) are not the same as the first investigation (Figure 30), but, being the absorption of the AHU almost the same in each month (Figure 62), the action of the new algorithm can be easily seen also in this period.

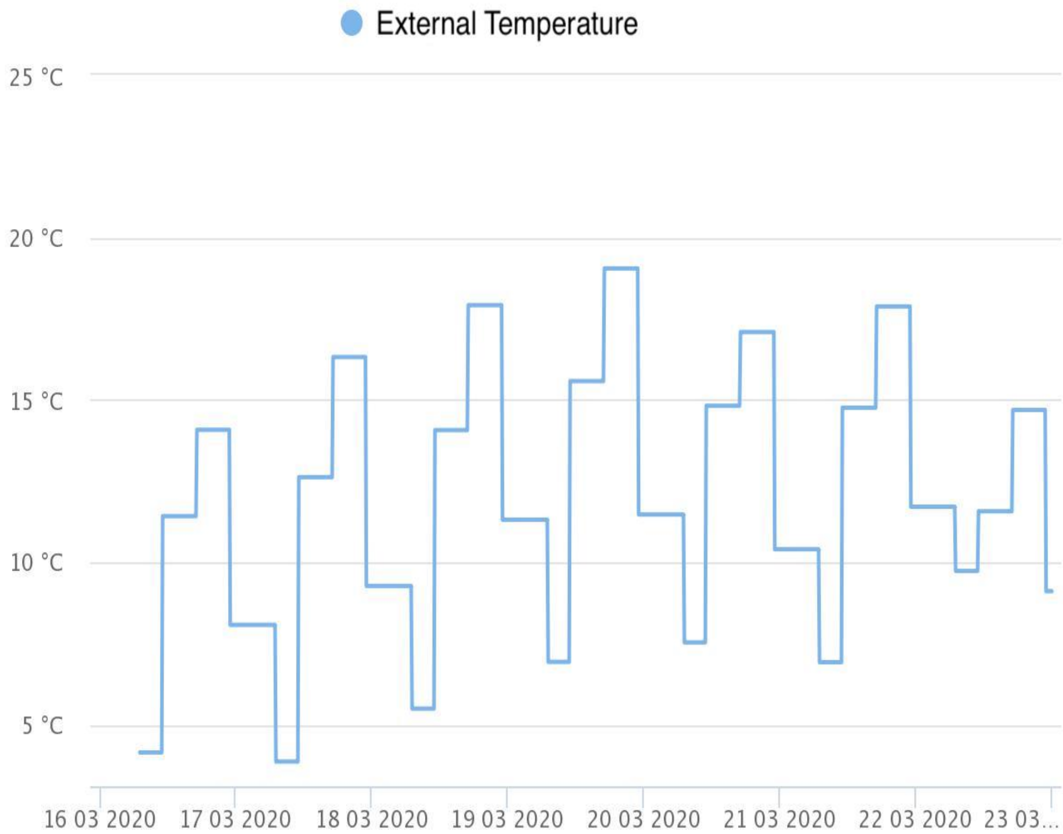


Figure 61 - External temperature second period

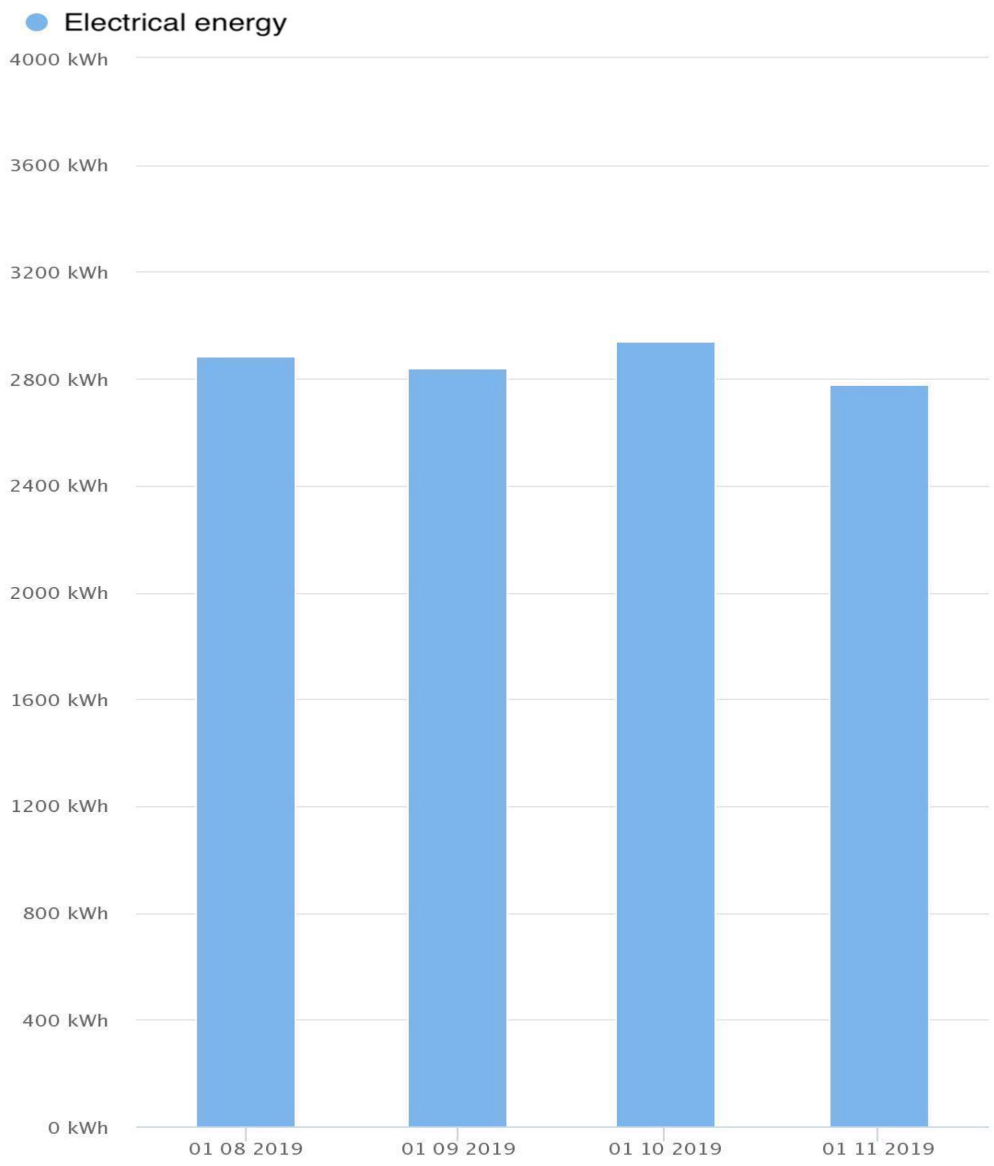


Figure 62 - Consumptions of the AHU in four different months

7.1 Weekly analysis

The goal of this chapter is showing the advantages obtained and demonstrating that the internal comfort is still maintained.

7.1.1 Electrical energy and active power

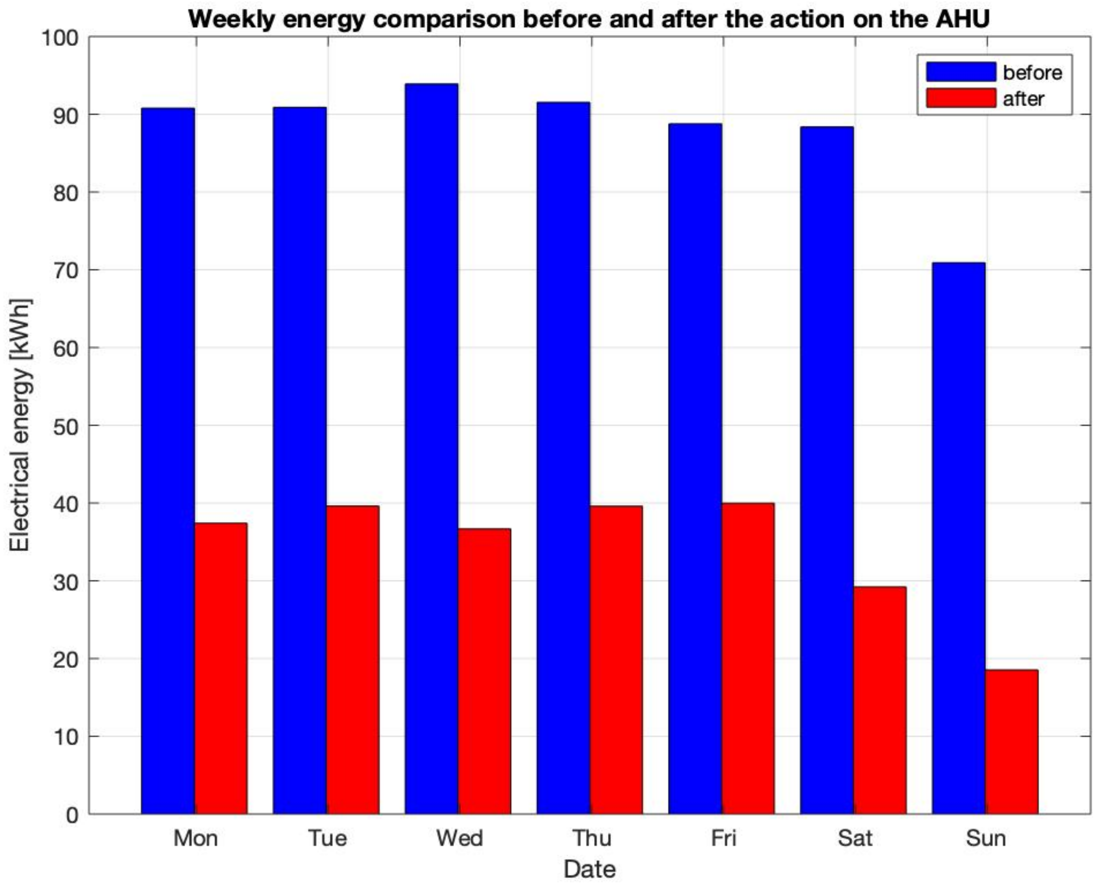


Figure 63 – Weekly electrical energy consumption AHU before and after the action

Figure 63 shows the electrical energy consumption of the air handling unit before and after the action. It is immediately apparent the **usefulness of the new logic**; in fact, the **daily usage is more than halved**, moving from around 100 kWh to less than 45 kWh.

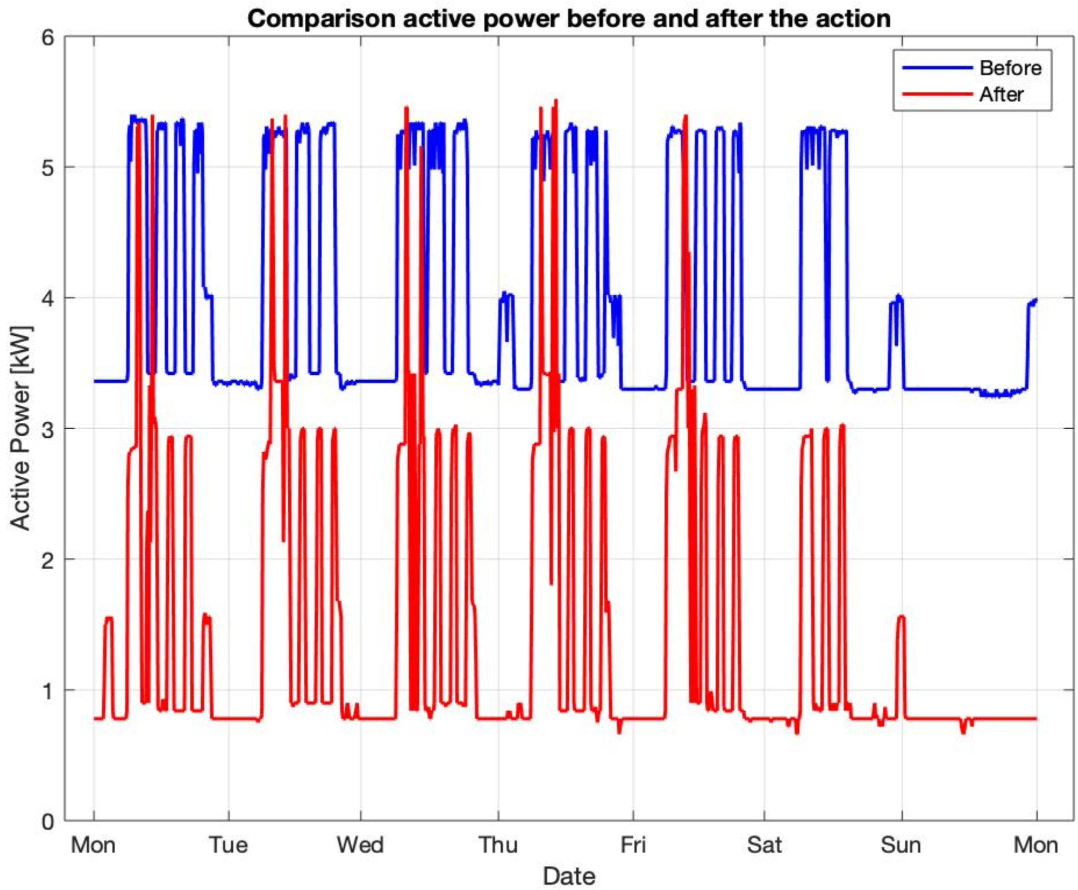


Figure 64 – Weekly active power absorbed by the AHU before and after the action

Figure 64 illustrates the power absorbed by the AHU, always in the two periods.

First of all, the minimum load is decreased from 3.3 kW to less than 1 kW, confirming how the previous value was due to an incorrect functioning of the system.

Nevertheless, three local peaks are still present in each day: through further analysis of the plant, it has been discovered that the variable "Active Power" and, consequently, "Electrical energy", **do not measure only the power absorbed by the two fans' motors, but also the ones of both the production of DHW and circulating pumps**. As a result, as Figure 65 shows, the maximum peak is due to all of them, while the two secondary components cause local heights.

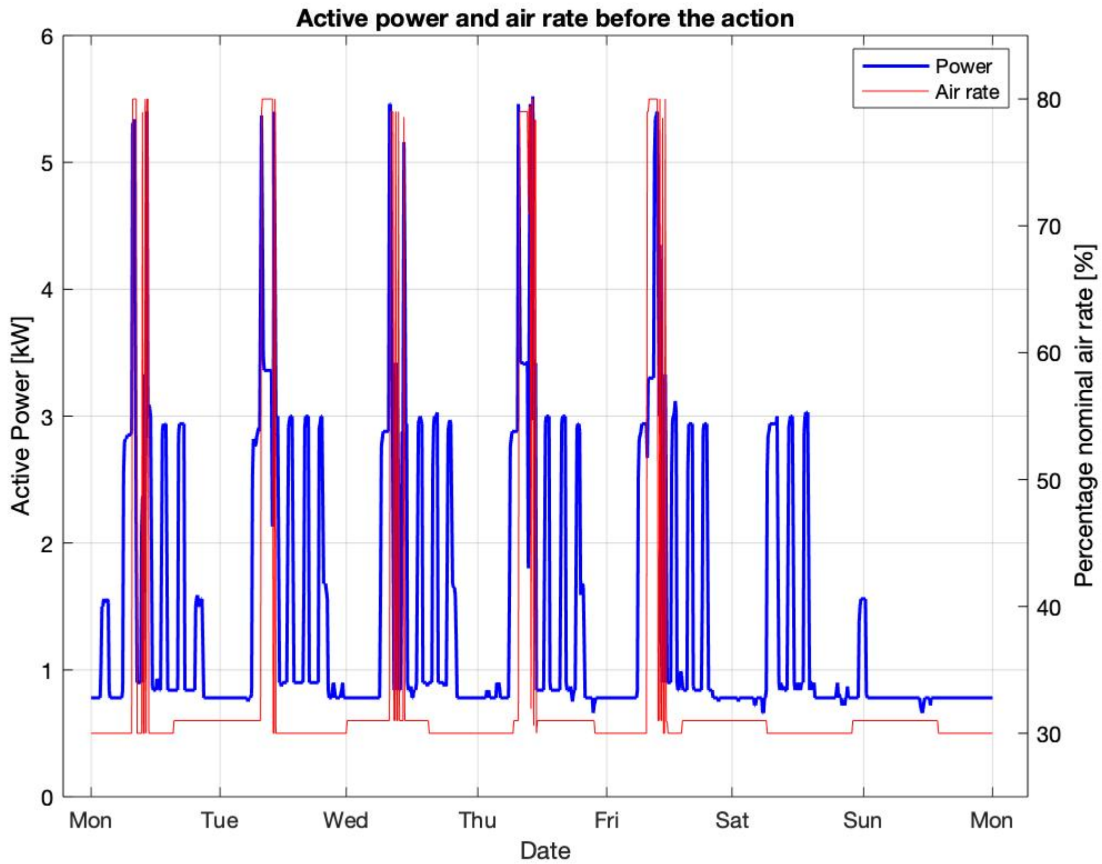


Figure 65 - Active power absorbed by the AHU and airflow rate after the action

7.1.2 CO_2 level and air rate

As regards DCV performance estimation, the monitoring produces essential knowledge, such as the **percentage opening quota of each air damper and the signals for the inverters**, which modify the speed of the fans by the controller integrated into Simon.

Each signal ranges in an interlude from 0% to 100%, which corresponds to a linear slope of the frequency, in which 50 Hz matches to 100% [37].

Consequently, final values are listed in Table 7.

Airflow rate $\dot{V}$ $\left[\frac{m^3}{h}\right]$	Fans speed [rpm]
$0.8*\dot{V}_{nom}$	$0.8*n_{nom}$
$0.3*\dot{V}_{nom}$	$0.3*n_{nom}$

Table 7 - Airflow rate and fans speed after the action

Furthermore, in order to see clearly the action of the algorithm, Figure 66 illustrates the percentage of nominal airflow rate in comparison to CO_2 concentration. As described in chapter 6.1, the airflow rate increases to 80% of the nominal value only when the set amount of carbon dioxide, equal to 565 ppm, is reached.
Obviously, being closed on Sunday, it works for all-day at its minimum speed.

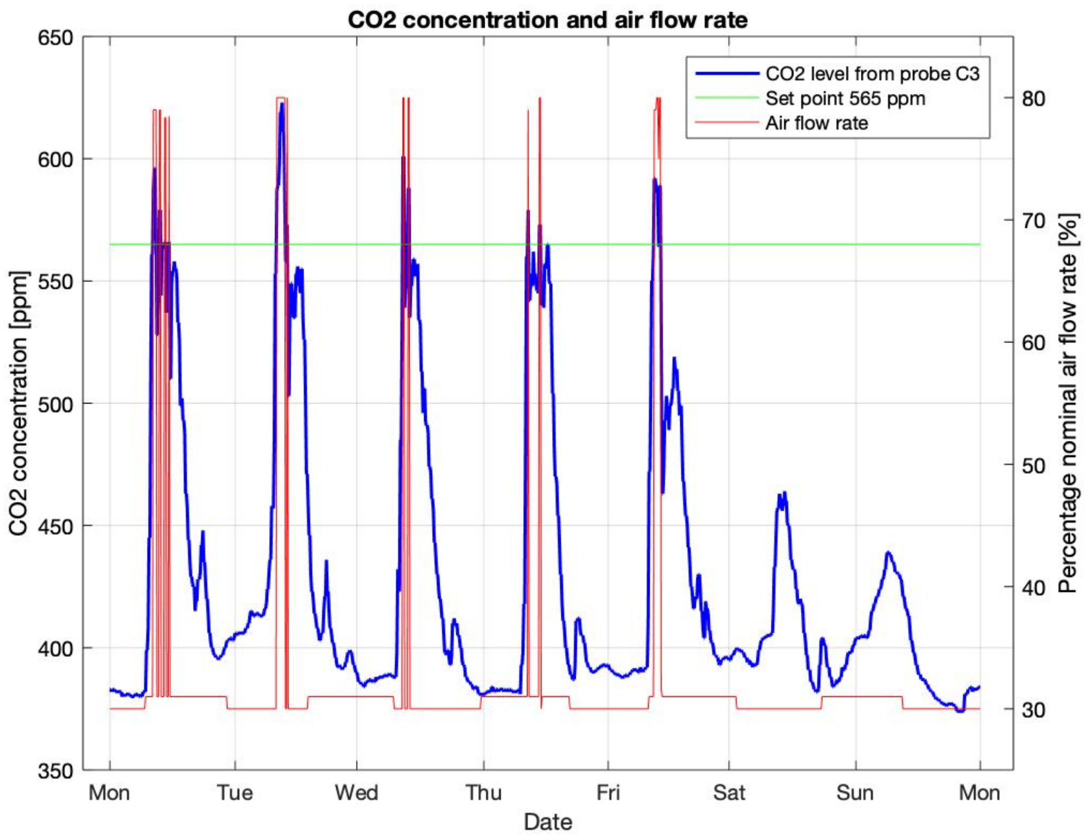


Figure 66 - Action of the new algorithm

Last but not least, Figure 67 witnesses the carbon dioxide level before and after the action. Another indirect benefit of the new functioning is the CO_2 concentration's drop of around 60 ppm in the building. Consequently, maximum values never go above 650 ppm, and not only experiencing headaches, agitation, drowsiness is unlikely, but also having no difficulty in completing simple or complex jobs and making decisions.

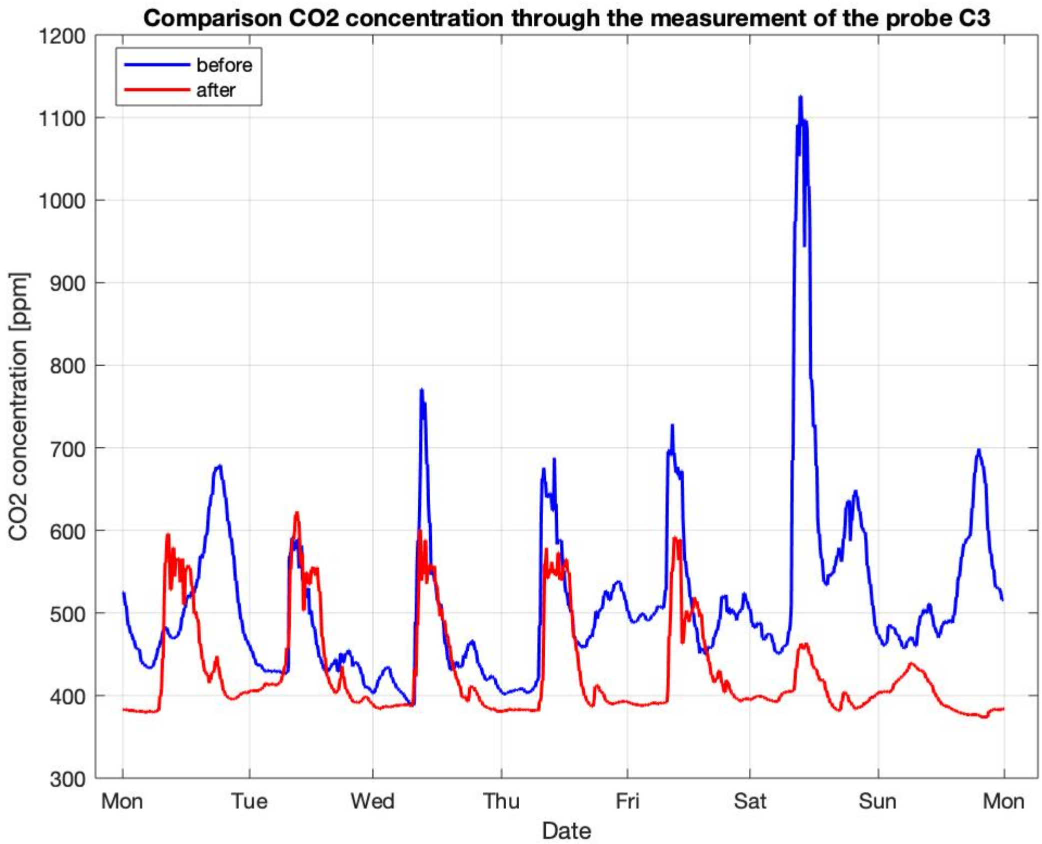


Figure 67 – CO_2 concentration in the two periods before and after the action

7.1.3 Temperature and humidity

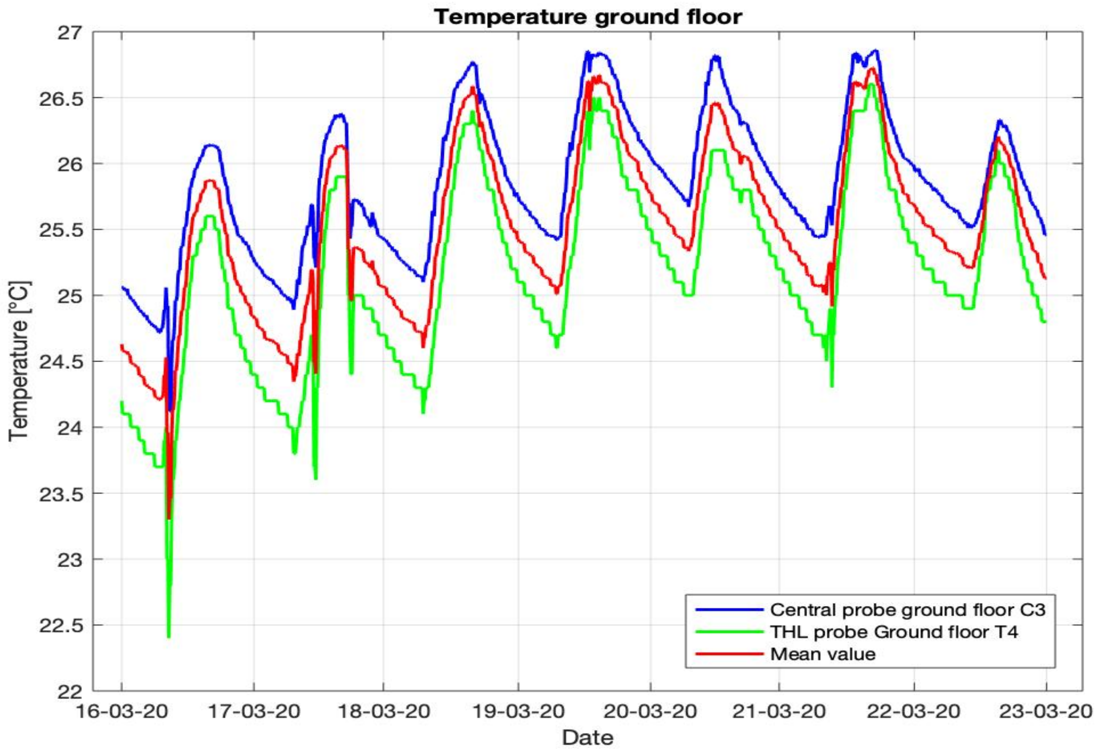


Figure 68 - Weekly temperature ground floor after the action

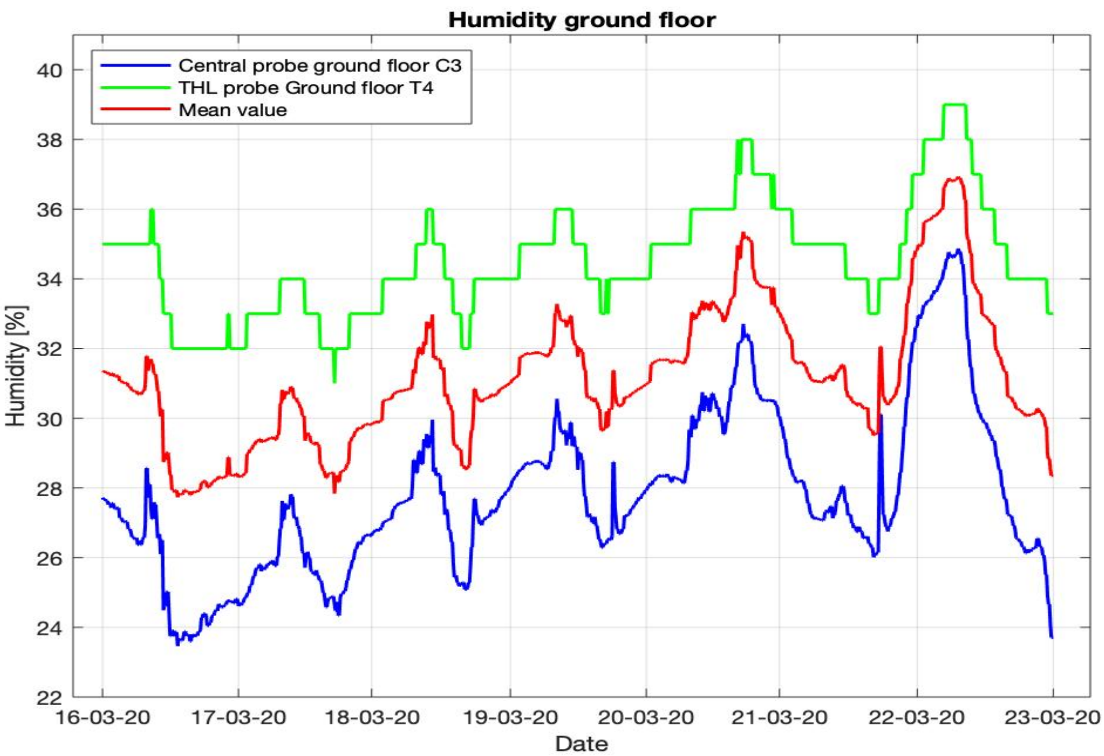


Figure 69 - Weekly RH ground floor after the action

Figure 68 and Figure 69 illustrate the variation of ground floor temperature and RH (see Figure 11 for a better understanding of each probe). First of all, by a comparison with Figure 36, the internal temperature is increased of around 2 °C, reaching peaks of 26.5 °C and never going under 22 °C.

On the other hand, humidity compared with Figure 37, follows the same pattern of the previous variable, increasing of a few percentages, too.

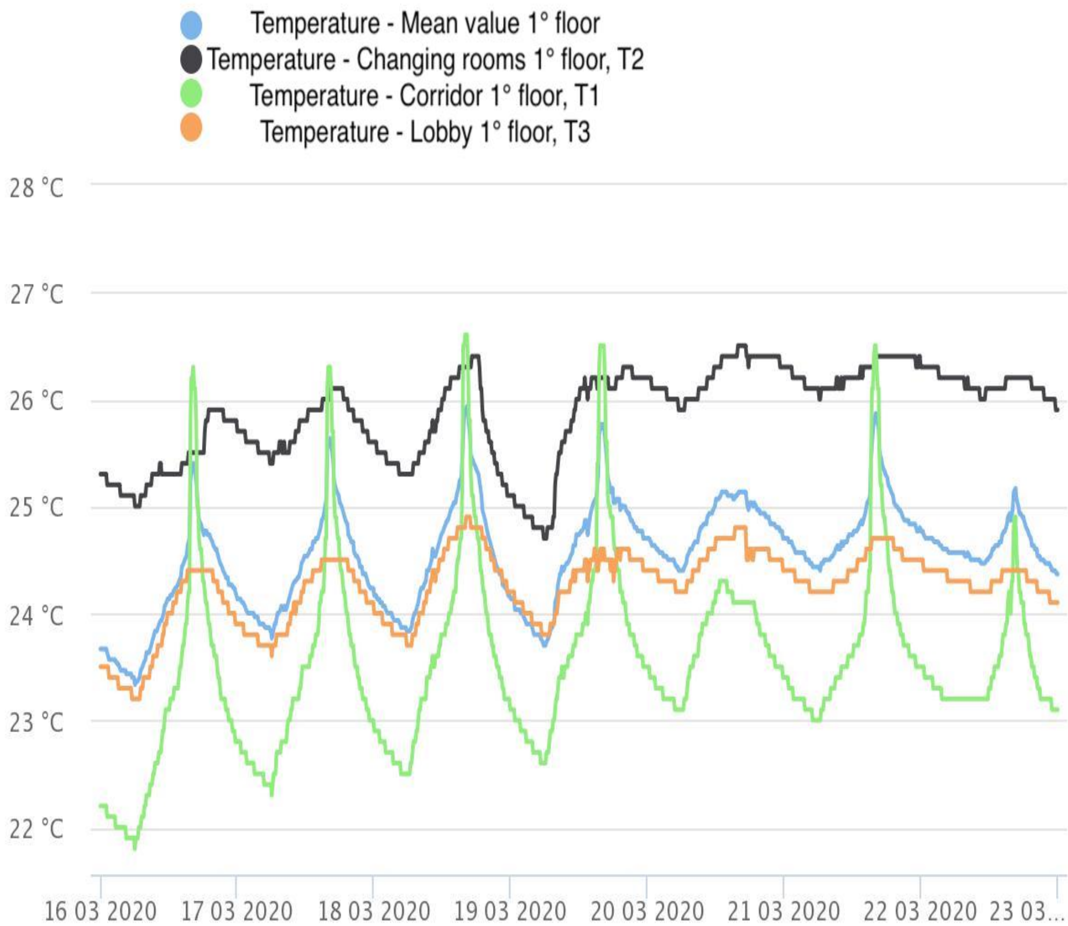


Figure 70 - Weekly temperature 1°floor after the action

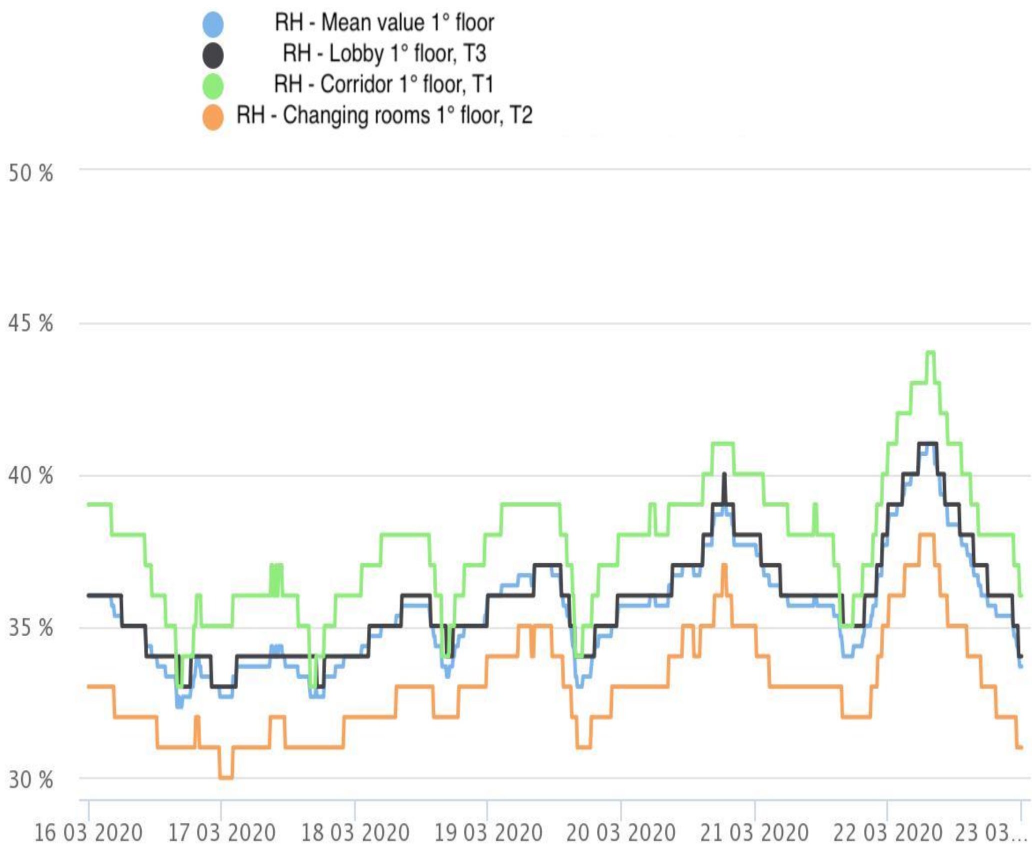


Figure 71 - Weekly RH 1°floor after the action

Figure 70 and Figure 71 witness the variation of the first floor's temperature and RH (see Figure 12 for a better understanding of each probe). As for the ground level, both variables rise by 2 °C and a few percentages, respectively (see Figure 38 and Figure 39 for comparison with the first period). Furthermore, while it is not too beneficial for the temperature even if its mean value is always around 24 °C, humidity reaches heights of more than 40%, according to ASHRAE suggestions [34].

7.2 Daily analysis

To carry out the study, the day chosen is Tuesday, 17 March. Again, as for the first period, another timeframe could have been chosen because, patterns do not vary hugely for the goal of the paragraph.

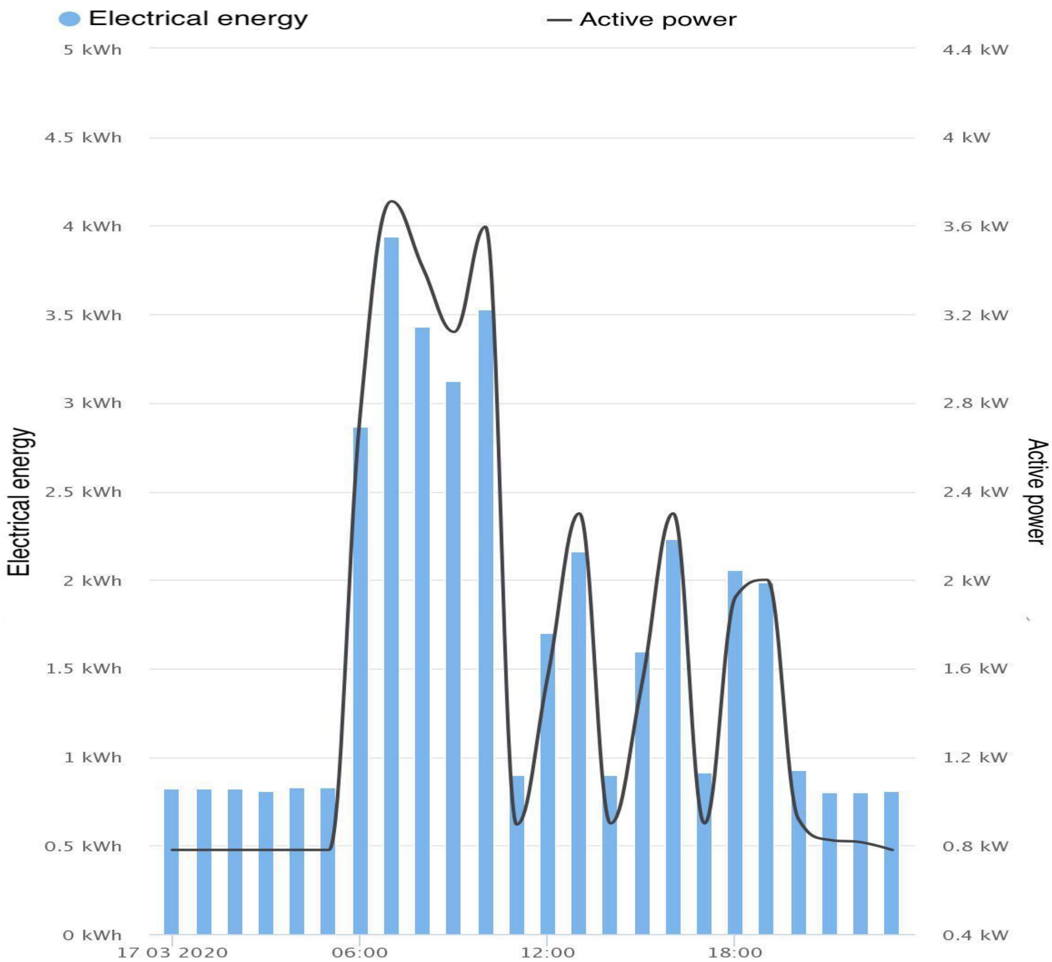


Figure 72 – Daily electrical energy and active power of the AHU after the action

Figure 72 shows the energy and power trends of the air handling unit. By comparison with Figure 42, it is clear how its functioning has not changed: it works at its minimum power (around 0.8 kW) until 05.00, time at which it changes its behaviour to about 3.6 kW. Again, three local peaks can be detected and, as stated before, they are due to the multiple measurement of the variables "Active Power" and "Electrical Energy".

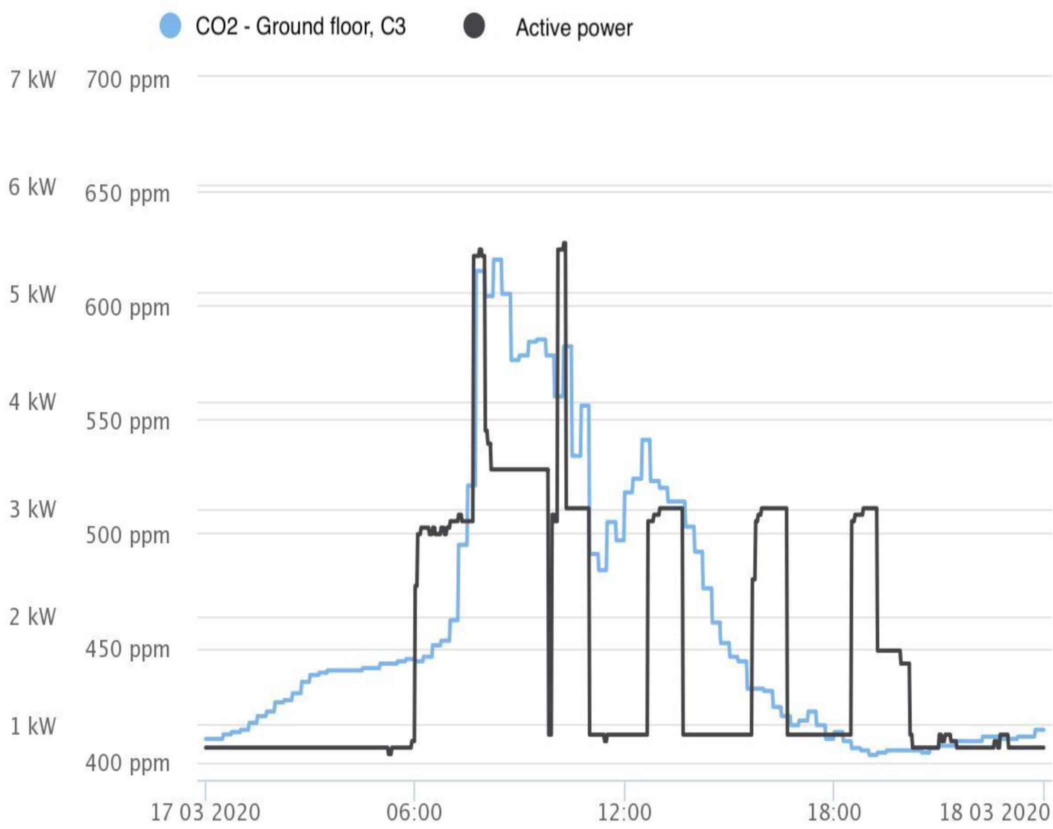


Figure 73 – Daily active power of the AHU and CO_2 level

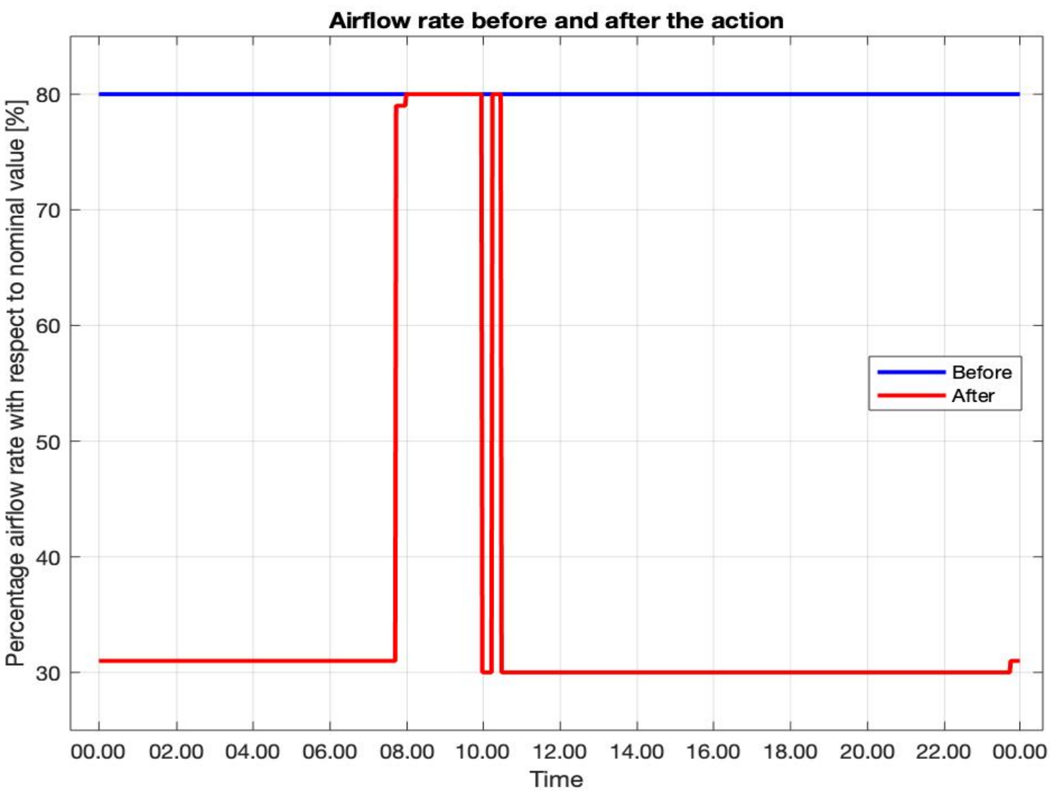


Figure 74 – Daily percentage of inlet and outlet airflow rate before and after the action

Figure 73 and Figure 74 witness the active power of the AHU and the CO_2 level and the percentage of inlet/outlet airflow rate, respectively. By comparing these two figures, it can be easily seen how the air rate increases to 80% of the nominal value only when the ppm of carbon dioxide has reached the setpoint (565 ppm).

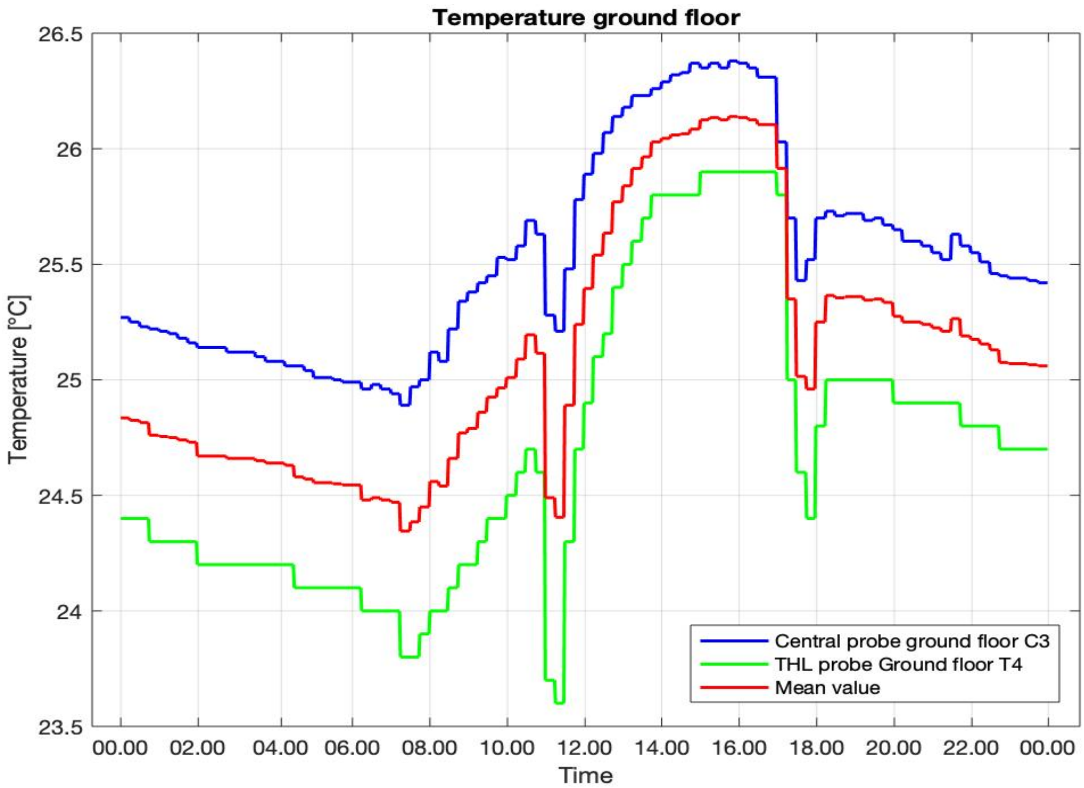


Figure 75 - Daily temperature ground floor after the action

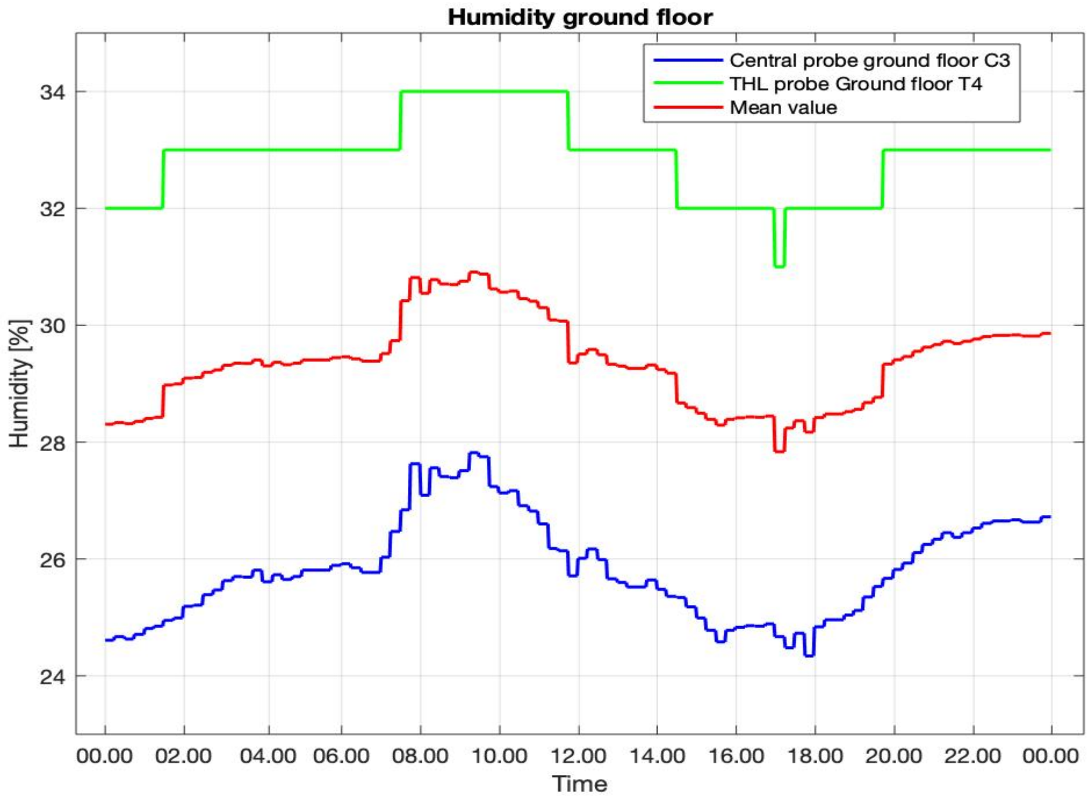


Figure 76 - Daily RH ground floor after the action

Figure 75 and Figure 76 (see Figure 11 for a better understanding of each probe) witness temperature and humidity daily trends on the ground floor.
As expected, their patterns have both modified in comparison with Figure 44 and Figure 45, but, their values are slightly higher than before.

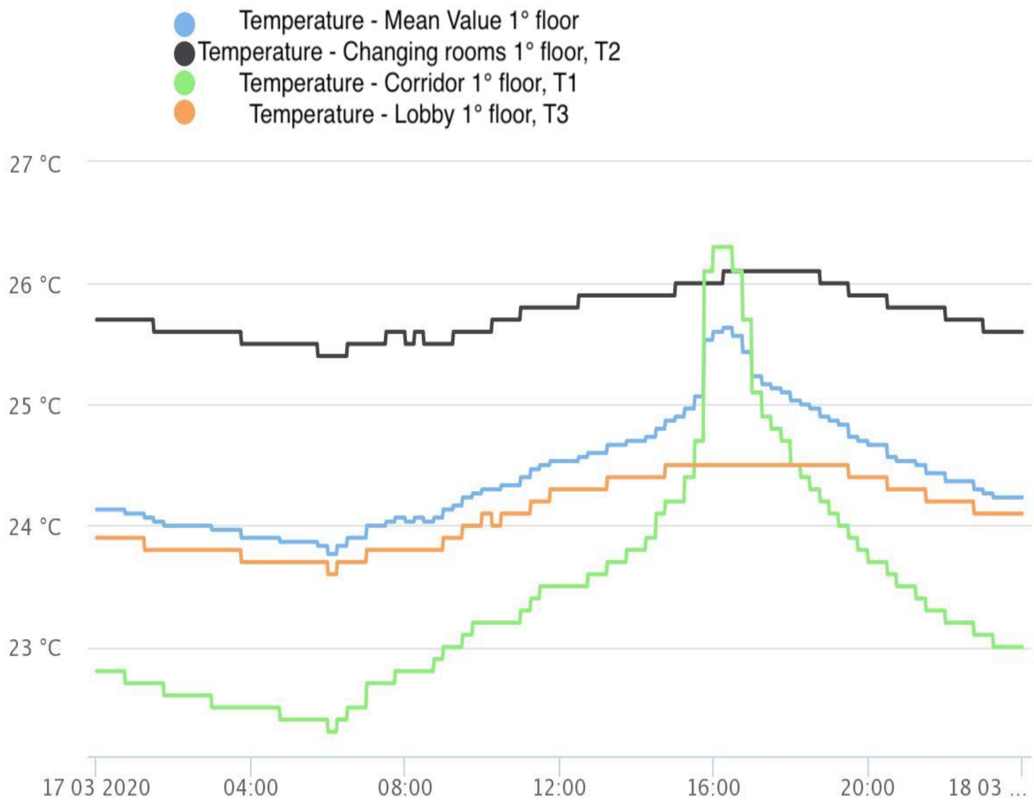


Figure 77 - Daily temperature 1°floor after the action

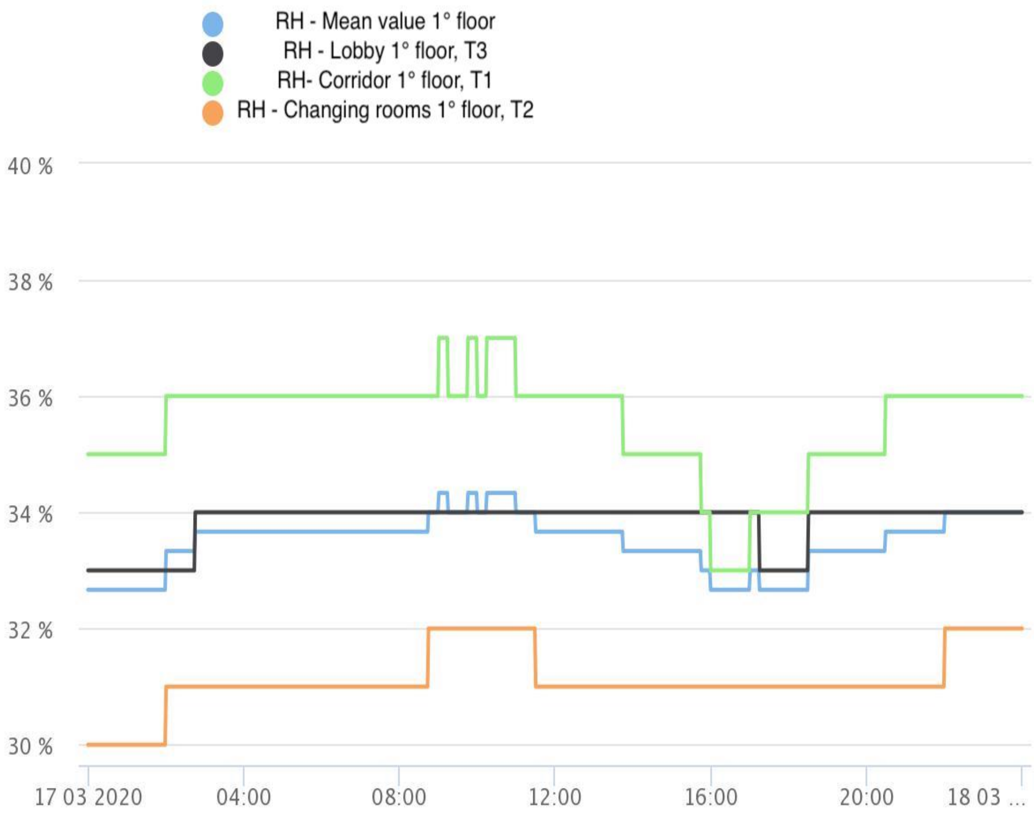


Figure 78 - Daily RH 1°floor after the action

Last but not least, (see Figure 12 for a better understanding of each probe) the first floor temperature and humidity trends are illustrated in Figure 77 and Figure 78. Again, by comparing them with Figure 46 and Figure 47, a lightly rise can be detected.

7.3 Absorption comparison between working and off days

The last correlation made is the one between the power absorbed during work and off days.

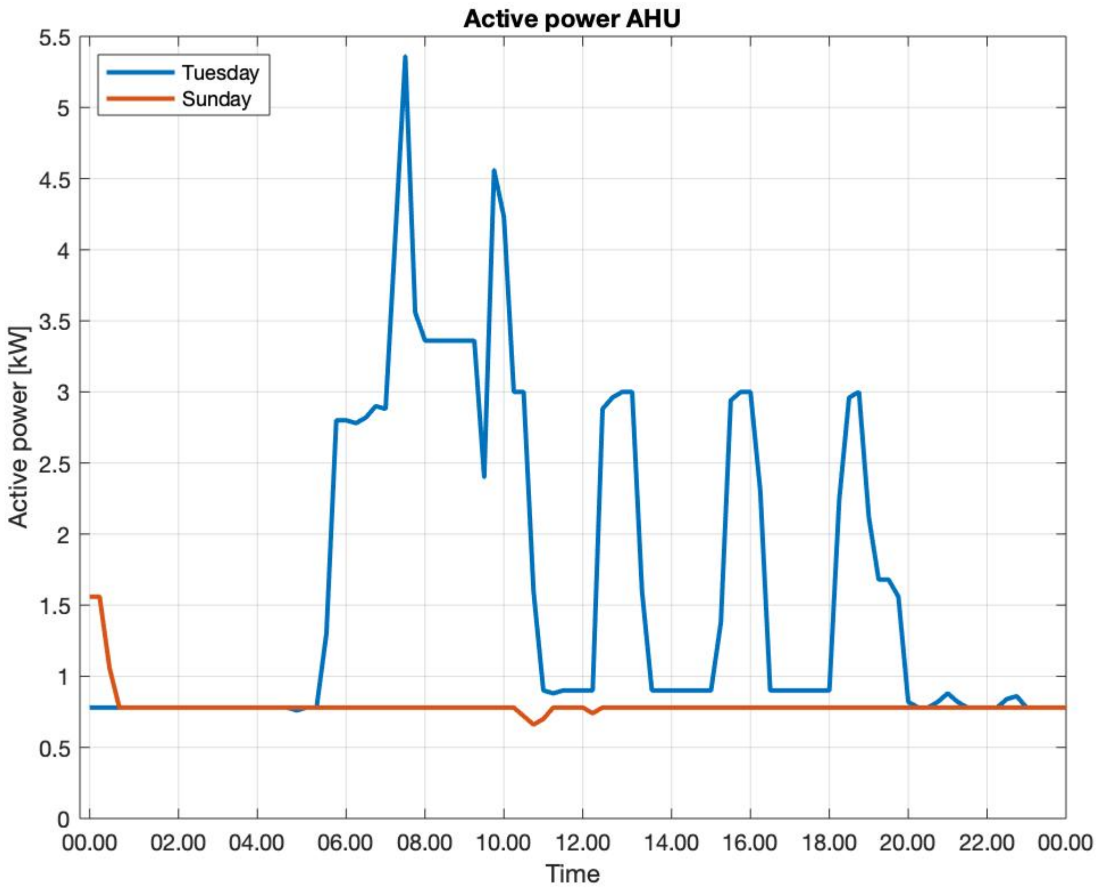


Figure 79 – AHU's active power absorbed on working and off days after the action

The new absorption, illustrated in Figure 79, is almost stable at its minimum value of nearly 0.8 kW during Sundays. Overall, gaps between these two days are very close to the ones of Figure 48, but the benefit is that all absorptions are shifted down.

7.4 Discussion of the results

The **goal** of the new algorithm is having a **more dynamic schedule** for the functioning of the AHU, with a successive **reduction of baseload absorptions**.

	Weekly values	
	Before	After
Energy [kWh]		
Maximum	93,3	39,6
Minimum	70,9	18,5
Power [kW]		
Maximum	5,3	5,3
Minimum	3,3	0,78

Table 8 - Results of the new logic on the AHU

As Table 8 witnesses, while the maximum **power** is always stable, the minimum is more than three times less. As stated above, the variable "Active Power" and, consequently also, "Electrical energy", do not measure only the power absorbed by the two motors, but also the ones of both the production of DHW and circulating pumps. So, also after the action, there are moments in which all of them work at maximum allowed capacity but, when the two additional measurements are nearly null, the only absorption is due to fans' motors and, for this reason, the minimum power is much lower.

Furthermore, this decline can also be observed in the **electrical energy** consumed. In fact, since the power absorbed is equal to its minimum for almost all time, the old trough, equal to 70.9 kWh is still much higher than the peak after the activation of the new algorithm (39.6 kWh).

	Weekly values	
	Before	After
CO2 [ppm]		
Maximum	780 (spurious 1100)	720
Minimum	400	380

Table 9 - Summary CO_2 concentration before and after the action

Moving to **CO_2 concentration** in the environment, as Table 9 lists, a slight modification can be perceived. However, being its level not too high to cause illness or difficulties in performing jobs, the **primary goal of the algorithm was not its reduction**. In fact, the decline of only 20-50 ppm is due in part to the new logic, but, the leading cause is undoubtedly the presence of fewer patients.

	Weekly values			
	Before		After	
	Temperature [°C]	**RH [%]**	**Temperature [°C]**	**RH [%]**
Ground floor				
Central probe C3	20,2-25,5	23-31	24,3-26,8	24-35
THL probe T4	18,8-25,5	31-40	22,5-26,5	31-39
Mean	19,5-25,5	27-35,5	23,4-26,6	27,5-37
1° floor				
Corridor T1	19,2-22,7	34-40	21,9-26,6	33-44
Changing rooms T2	22,4-24,5	28-34	25-26,5	30-38
Lobby T3	20,6-23,3	31-37	23,2-24,9	33-41
Mean	20,7-23,5	31-37	23,4-26	32-41

Table 10 - Summary of temperature and RH before and after the action on the AHU

Last but not least, Table 10 describes how **temperature and humidity** changed during the two timeframes. Overall, it is immediately apparent how an increase of more than 2 °C is witnessed on each floor. Consequently, while temperature appears being too high, and overtaking values set by the **European Standard UNI EN 12831:2002** [29], a sparse rise of a few percentages is observed in RH, reaching states almost always larger than 30%.

Two **reasons justify** this gain: being the external temperature in the second period higher than usual (Figure 61), there are no needs of heating the building in many circumstances. Furthermore, in some cases, it requires cooling but, as the **D.P.R.**

n.412 26 Agosto 1993 [38] said, the heating season in Rozzano lasts until 15 April; so, cooling is not allowed.
Surely, as Figure 80 witnesses, it is not a consequence of the new algorithm because the supply air temperature of the AHU always **behaves around 20 °C ± 2 °C** and, most of the time, it is lower than the one of the first period. Moreover, being the **set point of the active beams always the same**, this increment is undoubtedly due to an increase of the external temperature, or in other words, to free gains. In fact, being the main growth in the afternoon, it is caused by both **sunlight** and **thermal inertia,** which generates phase-shift due to heat absorption of opaque walls at warmer times and subsequent release.

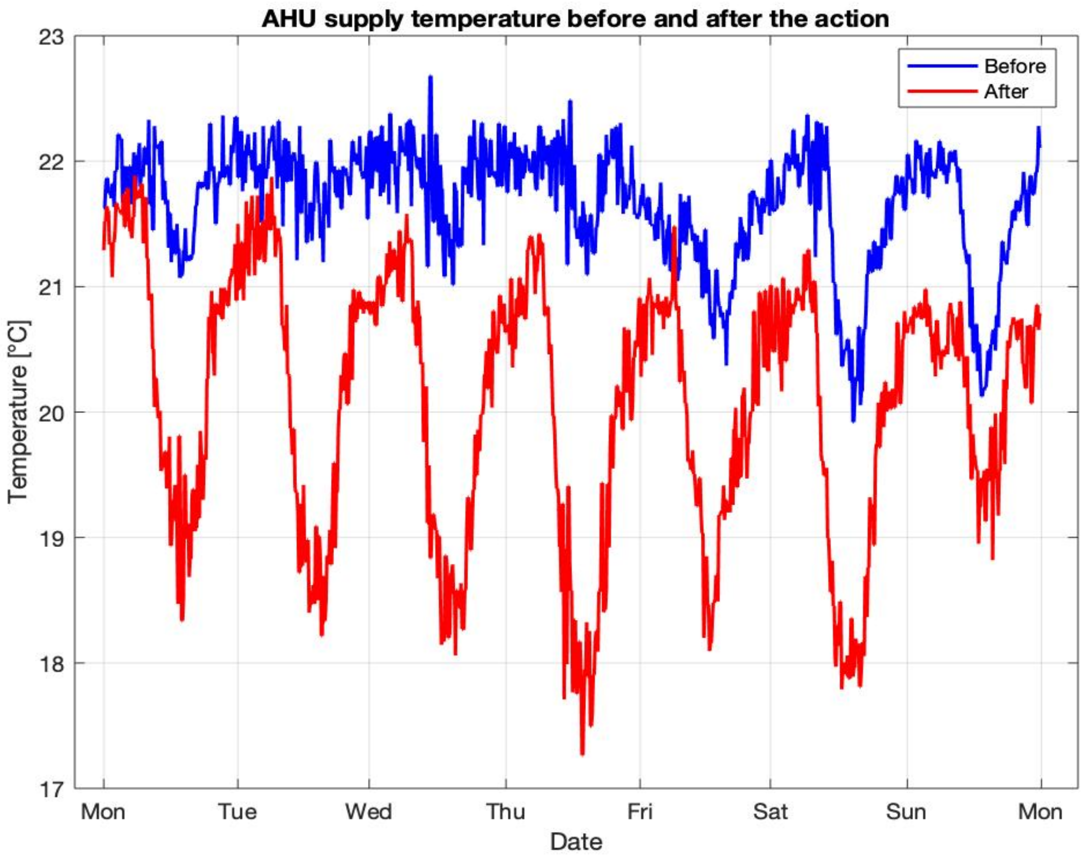


Figure 80 - AHU supply air temperature before and after the action

Further confirmation comes from Figure 81 and Figure 82, which illustrate the temperature trends once the system is turned in cooling mode. In this case, values set by **UNI/TS 11300-1** [39], which are equal to 26 °C, are respected correctly.

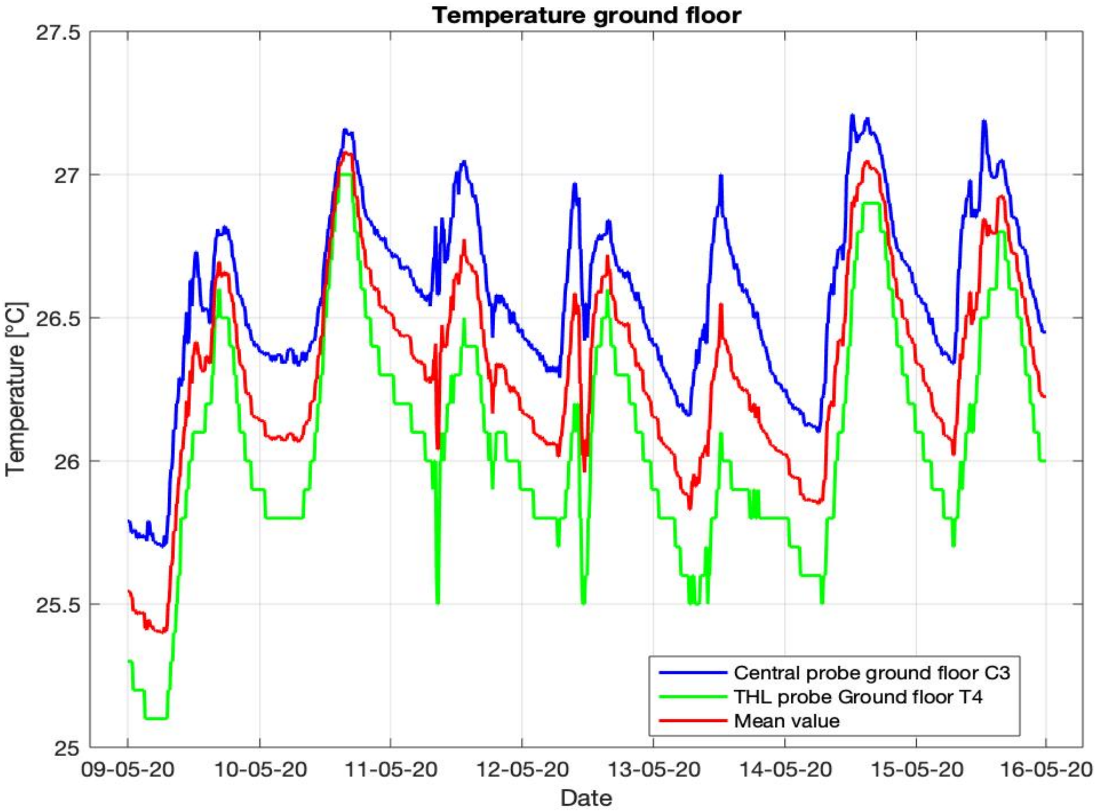


Figure 81 - Temperature ground floor in cooling mode after the action

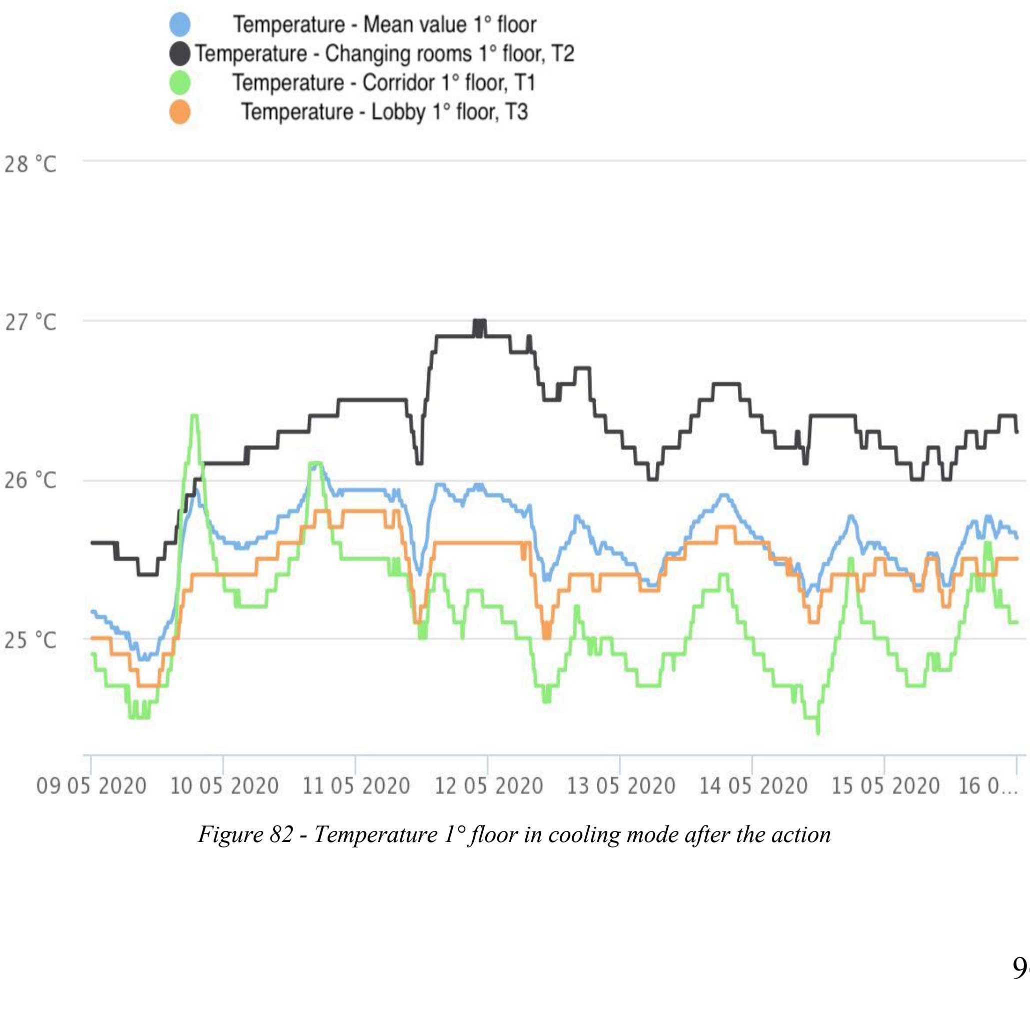


Figure 82 - Temperature 1° floor in cooling mode after the action

8 Savings obtained

One of the last steps is the analysis of the **energetic and economic benefits**. Obviously, this study is made on the two periods mentioned above: 06/01/2020-12/01/2020 and 16/03/2020-22/03/2020.

8.1 Energetic saving

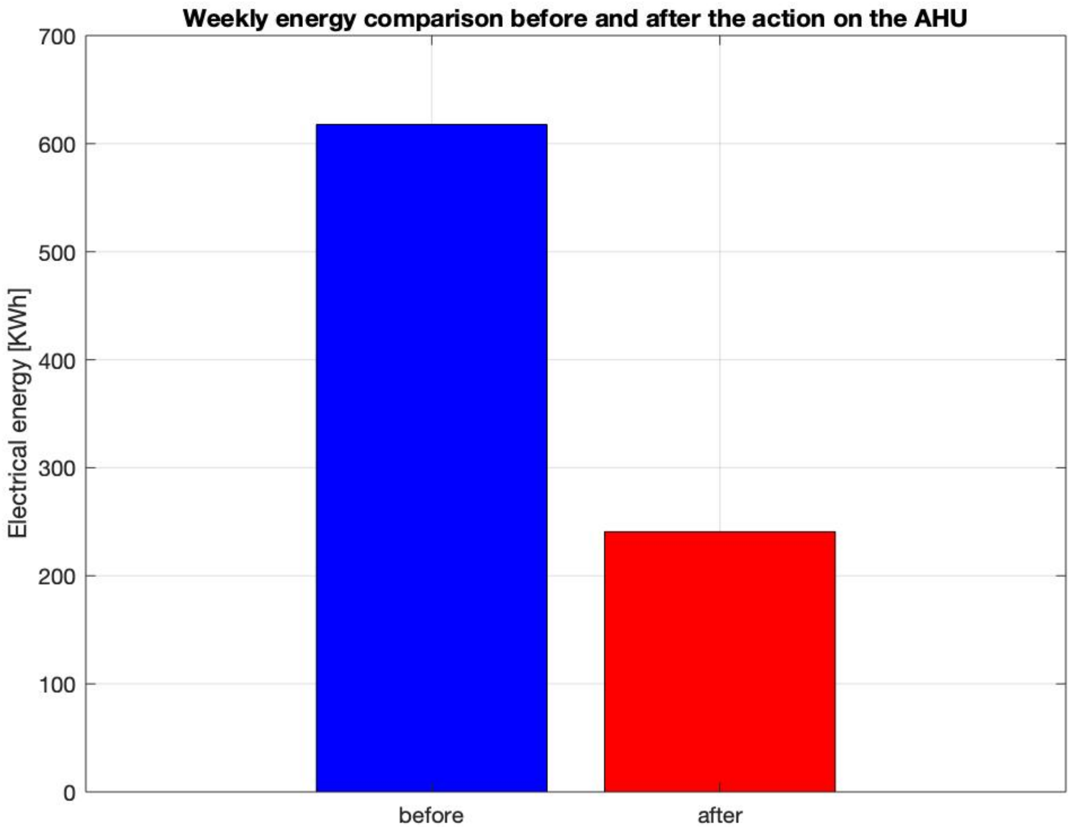


Figure 83 – Electrical energy comparison before and after the action AHU

Figure 83 illustrates the electrical energy consumed by the air handling unit in the two different periods. Before the intervention, the weekly usage was 614 kWh, while it decreased suddenly to 240 kWh after the action. Overall, a **saving of about 60%** is obtained.

Furthermore, in order to obtain the **primary energy** behind electricity, the conversion coefficient used is **2.42** $\frac{kWh_{prim}}{kWh_{el}}$, which corresponds to the official average primary conversion factor of electricity in Italy, as indicated in the **DM 26 Giugno 2015** [40]. Consequently, being the weekly energy saved around 370 kWh_{el}, the corresponding primary energy saved is about 900 kWh_{prim}.

However, to achieve a more significant number, the consumption of the AHU in the whole year is needed. By analysing its energy usage trend in 2019, the energy absorbed is always around 620 kWh per week, also during the summer break (see Figure 62). Consequently, **the assumption of a similar decrease for the entire cycle can be made** and, the primary energy saved, expressed in tep, in which the conversion coefficient, as indicated by ARERA in **EEN 3/08** [41] is $\mathbf{0.187 * 10^{-3}} \frac{tep}{kWh}$, is around 8.037.

Last but not least, the action taken has an impact also in terms of **CO_2 equivalent delivered in the atmosphere**. By considering the Italian conversion factor "Fattore emissivo LCA GHG consumi elettrici IT" indicated by the **GSE**, which is equal to **434** $\frac{g_{CO2_{equiv}}}{kWh}$ [42], the weekly CO_2 not delivered in the atmosphere is around 160 kg, while in a whole year, it is around 7.7 ton.

Overall, the resulting savings, illustrated in Table 11, are very significant.

	Savings		
	Week	Month	Year
Energy [kWh]	370	1480	17760
Primary energy [tep]	0.167	0.669	8.037
CO2 equivalent [Kg]	160	640	7700

Table 11 - Savings obtained on the AHU

8.2 Economic benefits

In order to evaluate the economic benefits, it is necessary to analyse the electricity bill, which provides the **purchase price of the electrical energy** of the healthcare.

8.2.1 Electricity bill

First of all, the company that supplies the building is **ENEL.**
"Il Fiordaliso" is connected to the **low-voltage grid (380 V)** and, as reported by the ARERA, **energy losses are equal to 10.4%** of the total energy consumed [43].
It has an **available power** or, in other words, a maximum withdrawable potential, above which the supply could be interrupted, equal to **150 kW**. The power shared is one of the non-negotiable items on the bill and it is paid differently among users. Domestic and non-domestic consumers up to 30 kW pay the monthly fee on all contractually committed power, even if not used. Since 2008, on the other hand, industrial consumers or users with a power larger than 30 kW (healthcare's case) pay the monthly fee only on the peak power absorbed in the month (as measured by the meter) [44].
On the other hand, the energy cost varies at different times of the day and on different days of the week; so, it is divided into **time bands**, and different prices are also applied to the final customer depending on the time of use. In the case under analysis, **the division refers to a different aggregation of hours**:

- **Peak hours**: from 8 a.m. to 8 p.m., from Monday to Friday;
- **Out peak hours**: from 8 p.m. to 8 a.m., from Monday to Friday and Saturday, Sunday and public holidays.

Overall, the items considered are listed in Table 12.

ITEM	Price peak hours [€/kWh]	Price out peak hours [€/kWh]
	from 08.00 a.m. to 08.00 p.m. Mon-Fri	from 08.00 p.m. to 08.00 a.m. Mon-Fri + Sat, Sun and public
Energy expenditure		
Energy and losses (10.4% of total usage)	0,05698	0,04782
Dispatching	0,010756	
Transitory safeguard refund	0,000574	
Transport and meter management		
Energy	0,0082	
"Meccanismi perequativi"	0,00072	
System expenditure		
Energy	0,043037	
Arim Energy	0,004075	
Excise tax		
Excise duty on electricity	0,0125	
Total	**0,136842**	**0,127682**

Table 12 - Purchase price of the electrical energy [45]

As can be seen, **only voices linked to energy** are taken into account, while the ones related to power and fixed consumptions are neglected. The reason is that, through the actions made, the reduction of the peak power may at most be to 3-4 kW and, consequently, in the period comparison, the cut will be equal to a few euro cents. The same happens for fixed costs, which do not modify savings between the two periods.

Furthermore, the presence of the voice **"Meccanismi Perequativi"** means that the supply of energy takes place through the "**Mercato Vincolato**".

8.2.2 Saving

The economic benefit is evaluated by multiplying the energy consumed by its cost, both on each timeframe. Furthermore, in order to consider **the VAT at 22%**, the final price is multiplied again by 1.22.

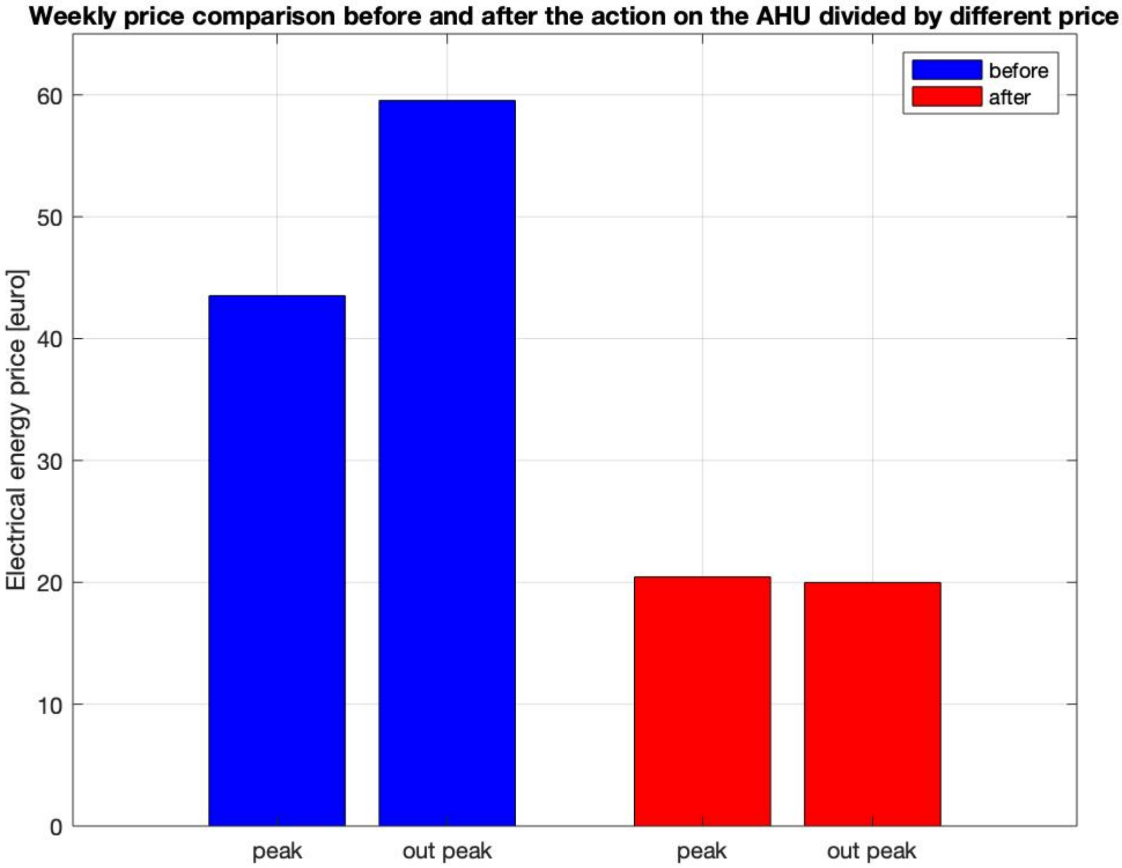


Figure 84 – Electrical energy cost of the AHU divided by time bands before and after the action

Figure 84 describes the comparison between the energy costs, divided by time bands, before and after the action on the AHU. As can be seen, the difference between peak and out-peak was around 20 $\frac{€}{week}$, due to high baseline absorptions (see Figure 32), while it has been reduced to nearly zero. Furthermore, the peak consumption is more than halved, moving from 43 $\frac{€}{week}$ to 20 $\frac{€}{week}$ but, the most significant decrease is achieved on the out-peak band, in which the cost is three times less than before (from 60 $\frac{€}{week}$ to 20 $\frac{€}{week}$).

As a result, the two bands, after the intervention, have a comparable price.

Figure 85 – Electrical energy cost AHU before and after the action

Moreover, Figure 85 illustrates the total economic benefits obtained on the AHU. It is immediately apparent how the weekly energy price has experienced a sudden fall, moving to about 100 $\frac{€}{week}$ to around 40 $\frac{€}{week}$.

Overall, all data are summed in Table 13.

Time	Peak hours	Out-peak hours	Cost losses [€/week]	VAT [€/week]	**Total [€/week]**
Cost Before [€/week]	34,19	46,97	3,31	18,58	**103,05**
Cost After [€/week]	16,05	15,77	1,31	7,29	**40,42**

Table 13 - Economic saving on the period under analysis

Finally, by always analysing its trend in 2019, the assumption of a similar decrease for the entire cycle can be made and, potential savings obtained are listed in Table 14.

	Savings		
	Week	Month	Year
Money saved [€]	62,63	250,52	3006,19

Table 14 - Economic benefit on the AHU

9 The Impact of COVID-19

The **COVID-19 pandemic** in Italy had its initial epidemic manifestations on January 31, 2020, when two tourists from China tested positive for SARS-CoV-2 virus in Rome. An outbreak of this infection was subsequently detected on February 21, starting from sixteen confirmed cases in Lombardy, in **Codogno**, in the province of Lodi [46]. At present, it has circulated **everywhere around the world**. Due to its high mortality and ease of transmission, the **AICARR** (Associazione Italiana Condizionamento dell'Aria, Riscaldamento e Refrigerazione) has published the **changings on the HVAC system in workplace**. It provides the following constraints [47]:

- **Increased airflow**: it is carried out by changing the number of fan rotations, and since two inverters control them, the power supply frequency has only been changed;
- **Forcing dampers in external air only:** for the sole purpose of increasing the external airflow rate, the recirculation damper must be closed, and the inlet one must be opened at the same time, but as there is no recirculation in the AHU, this point has not caused any variation;
- **Deactivation or by-pass of the heat recuperator:** being a cross-flow recuperator, the risk of contamination is unlikely; so, also in this case, it has not produced any change;
- **Maintaining the set-point of the relative humidity above 40%:** useful because low RH values tend to make the mucous membranes dry, facilitating the entry of the virus. In this case, humidity is already above the minimum value;
- **Continuous operation of the external air supply:** this intervention consists of letting the AHU works continuously to guarantee the presence of fresh air, even during non-occupancy hours of the building.

These five points are in contradictions with the CO_2 algorithm but, to ensure safety inside the healthcare, they have to be implemented, always trying to limit the amount of energy spent.

9.1 The choice of the airflow rate

According to AICARR [48], a person should always be regarded as a source of dust and, through breathing, speech, sneezing and coughing, he emits droplets, which may contain the virus. The first thing to establish is the **number of elementary viral loads** present in the environment because the risk of contracting the virus rises if this number increases, too. In this context, important is **the elemental viral charge**: it is defined as the nucleus of an airborne droplet capable of causing infection of people susceptible to the virus with a 63% probability [48]. Persons susceptible to the virus are defined as those who are neither vaccinated nor immune for other reasons.

The total number of elementary viral loads over time is given by equation 1:

$$N_t = \frac{qI}{n} + \left(N_0 - \frac{qI}{n}\right) * e^{-nt} \tag{1}$$

in which:

- $\mathbf{N_t}$ is the number of elementary viral loads at time t;
- $\mathbf{N_0}$ is the number of elementary viral loads at time t=0;
- **q** is the number of elementary viral loads produced per hour by an infected person;
- **I** is the number of infected people;
- **n** is the ventilation rate.

So, it can be seen that the higher is the fresh air flow rate, the lower is the number of elementary viral charges present in the environment, as illustrated in Figure 86.

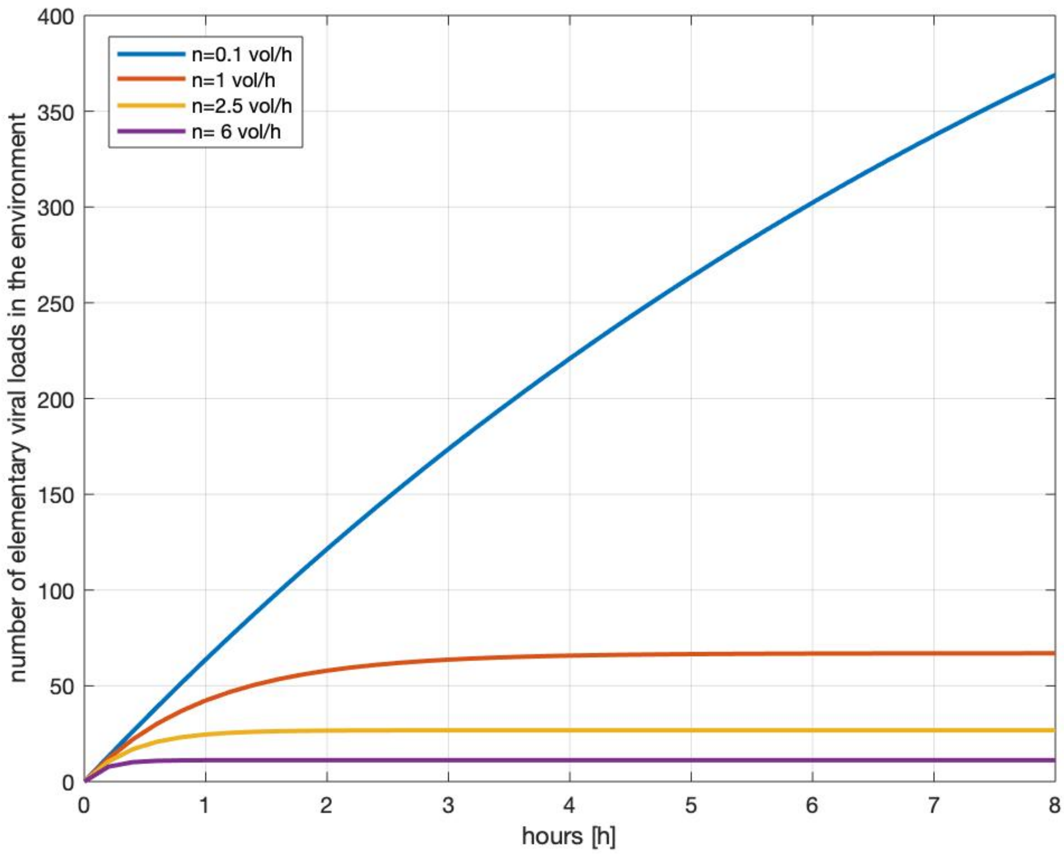


Figure 86 - Number of viral charges at different airflow rates

With a ventilation rate of 0.1 $\frac{vol}{h}$, typical of infiltration or rare window openings, the number of elementary viral loads grows continuously. By increasing the external airflow rate until 1 $\frac{vol}{h}$, the number of elementary viral charges remains constant, as the renewal of the air gradually dilutes the introduction of the virus into the environment until it is stabilised. By increasing the external airflow rate again until 6 $\frac{vol}{h}$, the final number of elementary viral charges remains constant but, lower than before.

However, being both the total volume equal to 2180 m^3 and the maximum supply flowrate equal to 6100 $\frac{m^3}{h}$, it is possible to change **at most around 3 $\frac{vol}{h}$**. Furthermore, it should not cause any unexpected illnesses because the healthcare will not work at its maximum capacity.

Consequently, in order to ensure components' integrity, it has been chosen to set the supply fan at 80% of the nominal power from 06.00 a.m. to 07 p.m. from

Monday to Friday and from 06.00 a.m. to 1.00 p.m. on Saturday. In comparison, it operates at 30% of its peak power for the remaining time. In this way, it is ensured 2.5 $\frac{vol}{h}$ during the occupied hours and 1 $\frac{vol}{h}$ in the other period.
All data are listed in Table 15.

Day	**Time**	**Fan speed [rpm]**	**Air changes $\left[\frac{vol}{h}\right]$**
Monday-Friday	06.00 a.m – 07.00 p.m.	80% n_{nom}	2,3
Saturday	06.00 a.m – 01.00 p.m.	80% n_{nom}	2,3
Other	-	30% n_{nom}	1

Table 15 - Summary ventilation due to COVID-19 constraints

9.2 Consumptions

In order to estimate the pandemic's impact in energetic and economic terms, the consumptions of the AHU in **three different configurations** are taken into account:

- Scheduled (first period);
- Control based on CO_2 level (second period);
- COVID-19 constraints.

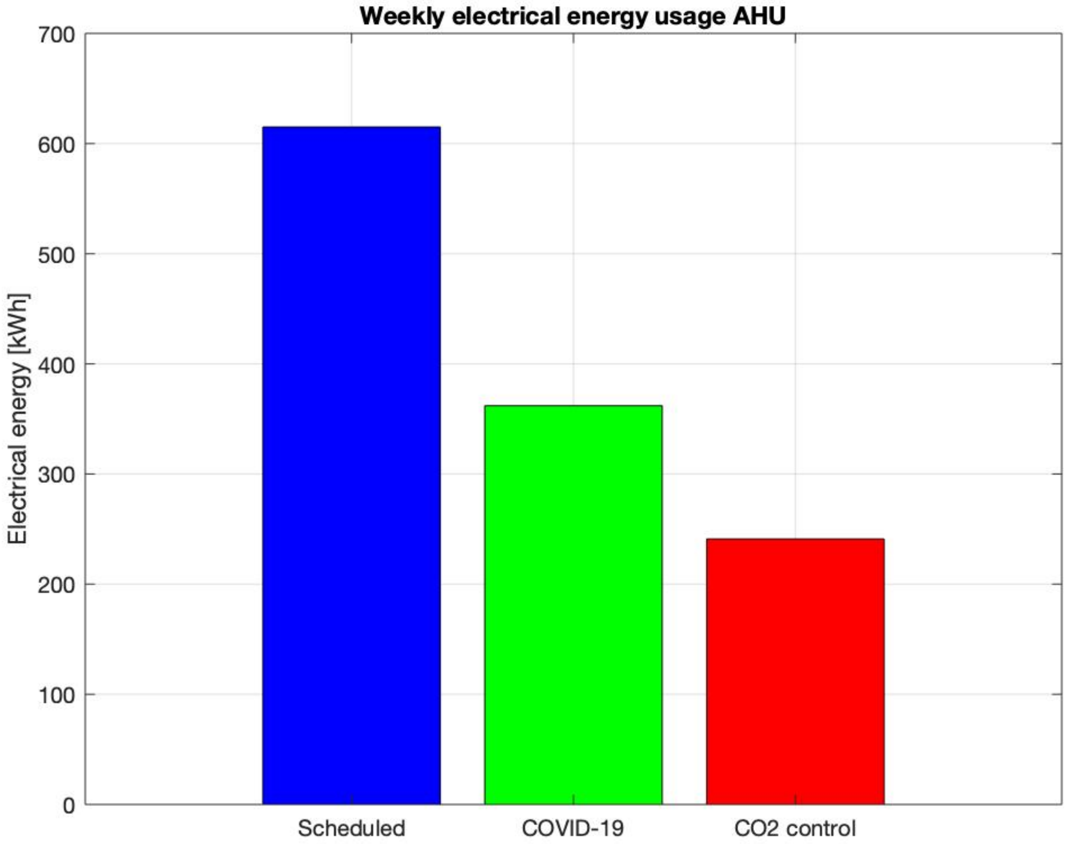


Figure 87 – Comparison of electrical energy consumption AHU between COVID-19 constraints and the other two configurations

Figure 87 illustrates the electrical energy consumption of the AHU in all three configurations. As expected, COVID-19 constraints increase the amount of electrical energy needed with respect to the CO_2 control, moving from around 240 kWh to nearly 360 kWh. However, by comparison with the oldest functioning, a saving of about 250 kWh can still be obtained.

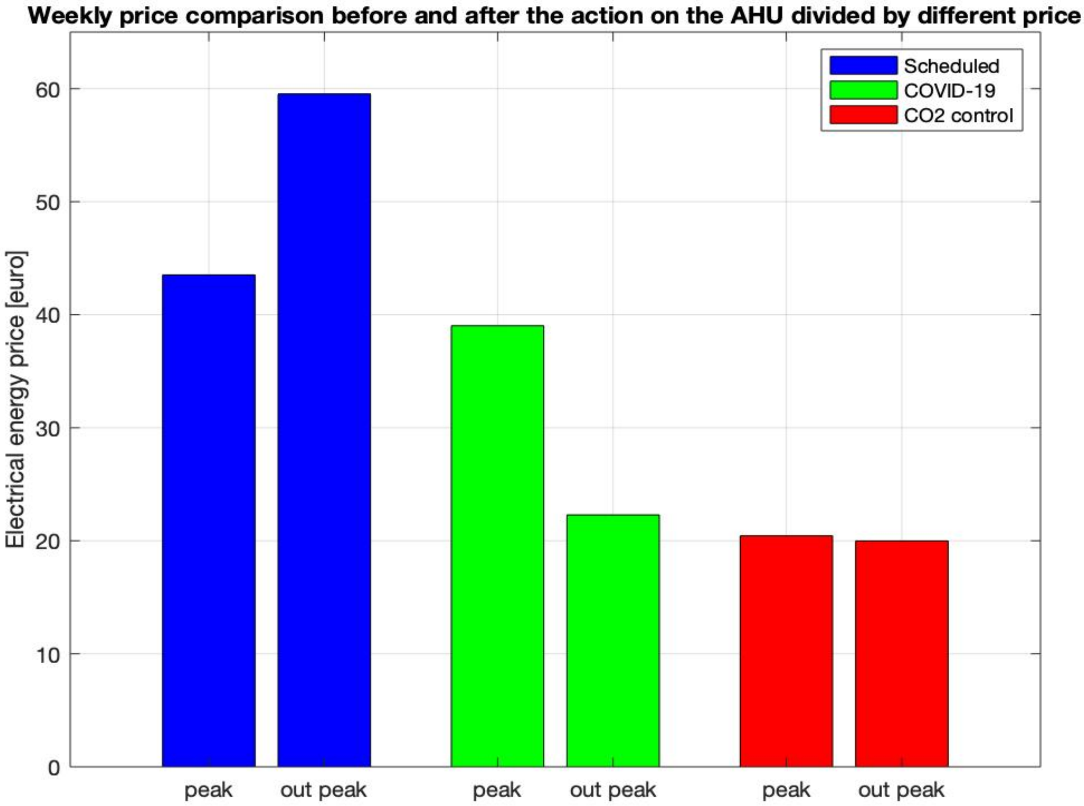


Figure 88 – Comparison electrical energy cost AHU divided by time bands between COVID-19 constraints and the other two configurations

Looking at energy costs, Figure 88 represents the relation between prices, sorted by time bands, in all three functioning. While in the scheduled mode, the out-peak hours' energy price was much higher than the complementary group, in the other two configurations, trends are the opposite. It underlines, once again, the initial mismanagement. However, being the shape of COVID-19 and scheduled modes' peak hours very close, costs are similar.

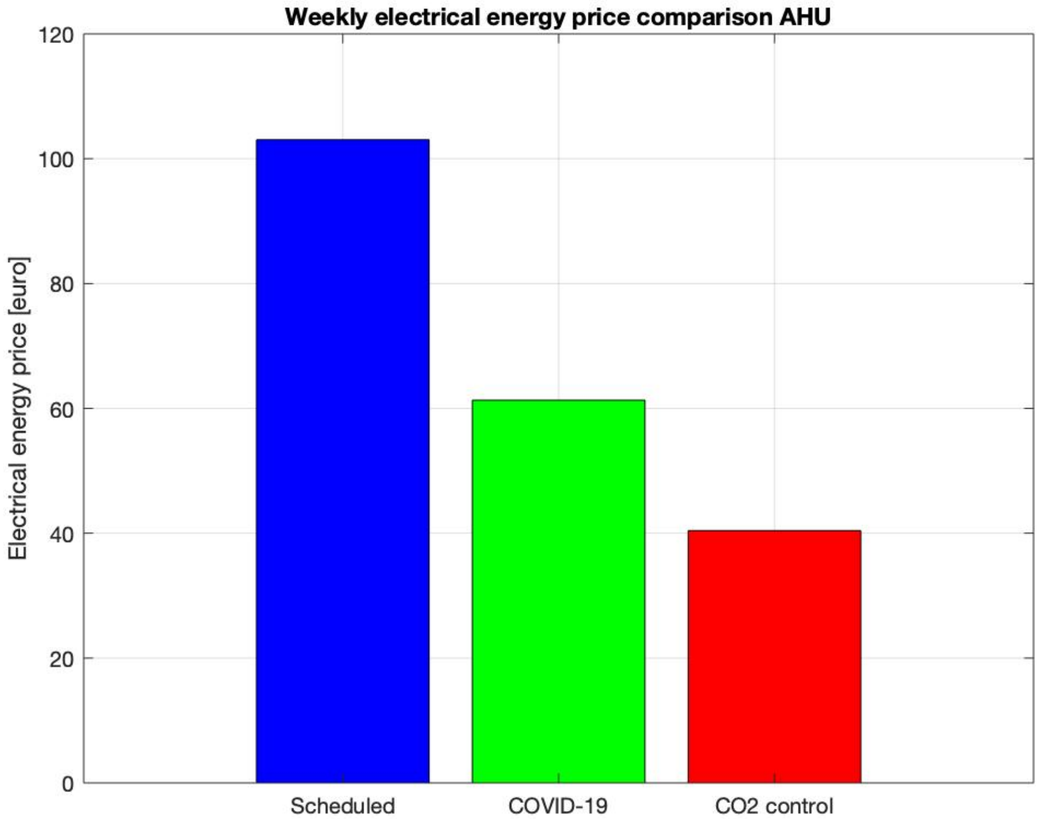


Figure 89 - Comparison of electrical energy price AHU between COVID-19 constraints and the other two configurations

Then, Figure 89 witnesses the weekly price of electrical energy, always in all functioning. Obviously, patterns are the same of the previous bar charts, in which the most efficient logic is always the one based on the CO_2 control ($40.4 \frac{€}{week}$) but, by comparison with the scheduled algorithm, COVID-19 mode produces a saving of more than $40 \frac{€}{week}$.

Overall, while the pandemic has caused an increase in consumption, a reasonable profit can still be obtained compared with the oldest state.

Finally, all data are summed up in Table 16.

Configuration	Electrical energy $\left[\frac{kWh}{week}\right]$	Cost $\left[\frac{€}{week}\right]$
Scheduled	615	103.1
COVID-19	362	61.3
CO_2 control	241	40.4

Table 16 - Summary of AHU weekly values in all different modes

10 Conclusions and future perspectives

"Il Fiordaliso", being a new construction, is a healthcare truly innovative from the aspect of energy management and all components are projected perfectly without over- or under-sizing. Consequently, looking for possible improvements has been challenging but, as shown above, the **results obtained are impressive**.

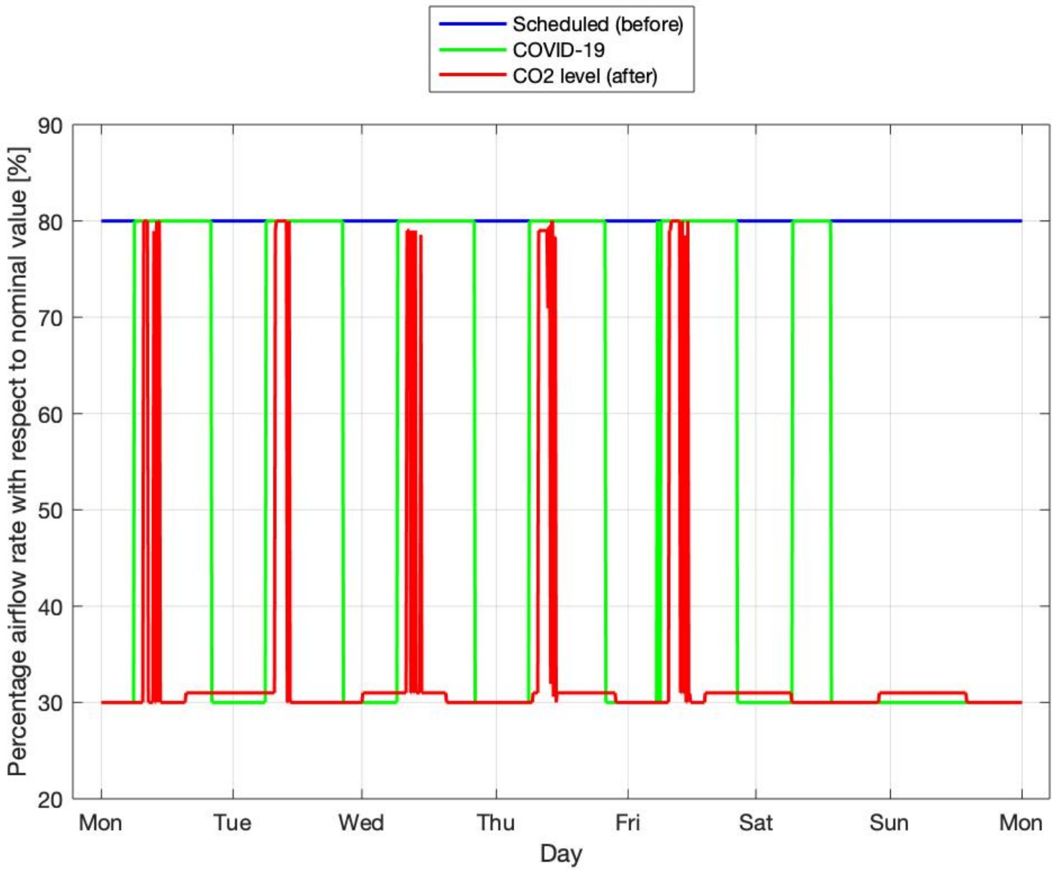


Figure 90 - Airflow rate in all three configurations

As illustrated in Figure 90, the old functioning (blue line) of the **AHU** has been overtaken by one which operates through the monitoring of the CO_2 level (red line). In that way, more efficient usage of the energy has been reached, obtaining enormous savings in terms of money, energy and CO_2 equivalent not discharged in the environment, which are **questioning to obtain trough other types of algorithms**. Consequently, the use of both IoT platform and CO_2 sensors are confirmed as a logical approach at this time; in fact, DCV technology has shown its easy utility even in historical raisings and its important supplement to HVAC system efficiency optimization [37]. However, due to COVID-19 restrictions, this logic has been modified again (green line) but, most important, savings are still obtained in comparison with the oldest configuration, demonstrating the initial mismanagement.

All results obtained on this component are summed in Table 17.

	Yearly values			
	Electrical energy [kWh]	Primary energy [tep]	CO2 discharged [ton]	Energy cost [€]
Scheduled (Before the action)	29520	13,36	12,81	4948
COVID-19 constraints	17376	7,86	7,54	2942
CO2 algorithm (After the action)	11568	5,23	5,02	1939

Table 17 – Summary data obtained on the AHU in all configurations

Also significant, through this study, **spurious peaks in the afternoon on the AHU's active power trend** (see Figure 64) have been justified, confirming how they are not due to an abrupt change of functioning but, to other parameters (recirculating pumps, production of domestic hot water) measured by "Active Power".

Furthermore, temperature and humidity have not changed their trends; in fact, as shown in paragraph 7.4, **they continue to respect Standards values**.

On the other hand, benefits of the new functioning of the **polyvalent pump**, being seasonal, have not been estimated but, being the algorithm much lesser impacting than the one on the AHU, savings will be much less significant (**no more than 10%**) and not comparable.

However, the pandemic the World is facing has led to a drastic modification in ventilation and climatization rules but, once it is defeated, trying to implement either **a predictive method for ventilation scheduling** or a **building behaviour modelling** through the use of self-learning algorithms that, based on the weather forecast, propose the setting logic of the systems and environmental comfort, may be the key to maximize savings.

Furthermore, as said by ARERA, the **"Mercato Tutelato" ends on January 1, 2021** for SMEs [49] and being the healthcare on it, the contract has to be changed, **moving to "Mercato Libero".** Last but not least, also the offer could be modified, moving from "Peak Out-Peak hours" to the one divided into three bands "F1 F2 F3", in order to increase the gap between working and off hours.

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