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Control strategies, monitoring and management for the efficient behavior of Thermally Activated Building Systems (TABS)

Estrategias de control, monitorización y gestión para el comportamiento eficiente de las estructuras termoactivas

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Thermally Activated Building Systems (TABS) play an essential part in the thermal response of buildings, in terms of dynamic adaptation and energy storage, enabling the separation between thermal energy generation and use. TABS can operate with low temperature, allowing the efficient utilization of renewable energy. Their thermal capacity needs to be managed by a control system, shifting TABS operation to time periods when energy production is most efficient and cost-effective. In this paper, a review of the operation strategies adopted for TABS is provided, in their specific integration in an existing office building in Madrid (Spain). The present control strategies are part of an integrated process, including the design phase, commissioning of TABS, monitoring, and optimization during operation. The effort to take advantage of the energy potential of the original structure, in combination with constant follow-up and management, puts the building on track to achieve a LEED Platinum rating. In line with the standards pursued by the LEED Rating System, a systematic audit procedure is conducted, aiming at the optimization of TABS energy performance, with the identification of energy waste and execution of corrective operations for the improvement of thermal comfort for the occupants.

Thermally Activated Building Systems (TABS), Thermal inertia, Renewable Energy Sources (RES), Building Management Systems (BMS), LEED Rating System, Energy Efficiency, Thermal Comfort.

Los sistemas termoactivos juegan un papel importante en la respuesta térmica de los edificios, en términos de adaptación dinámica y almacenamiento de energía, generando un desfase entre la generación de energía térmica y su utilización. Las estructuras termoactivas pueden funcionar con bajas temperaturas, permitiendo el uso eficiente de energía renovable. Su capacidad térmica necesita ser gestionada por un sistema de control, que traslada la operación de las estructuras termoactivas a períodos en los que la producción de energía resulta más eficiente y rentable. En este artículo se proporciona un estudio de las estrategias operativas adoptadas para estructuras termoactivas, en su integración concreta en un edificio de oficinas existente en Madrid (España). Dichas estrategias de control forman parte de un proceso integrado que incluye la fase de diseño, la puesta en marcha, la monitorización, y la optimización del rendimiento de las estructuras termoactivas durante su explotación. El esfuerzo de aprovechar el potencial energético de la estructura original, en combinación con su constante seguimiento y gestión, hace que el edificio esté en el camino de lograr la certificación LEED Platino. En línea con los objetivos perseguidos por el sistema de certificación LEED, se aplica un procedimiento de auditoria especifico destinado a la optimización del comportamiento energético de los sistemas termoactivos, a través de la identificación de gastos de energía innecesarios y la ejecución de acciones correctivas para la mejora del confort térmico de los ocupantes.

Estructuras termoactivas, Inercia térmica, Fuentes de energía renovable, Sistemas de Gestión de Edificios, LEED Rating System, Eficiencia Energética, Confort Térmico.

ABBREVIATIONS:

TABS: THERMALLY ACTIVATED BUILDING SYSTEMS

CCA: CONCRETE CORE ACTIVATION

RES: RENEWABLE ENERGY SOURCES

IEQ: INTERNAL ENVIRONMENTAL QUALITY

EED: ENERGY EFFICIENCY DIRECTIVE

LEED: LEADERSHIP IN ENERGY AND ENVIRONMENTAL DESIGN

BMS: BUILDING MANAGEMENT SYSTEM

EMS: ENERGY MANAGEMENT SYSTEM

PID: PROPORTIONAL INTEGRAL DERIVATIVE

HVAC: HEATING, VENTILATION AND AIR CONDITIONING

GHP: GEOTHERMAL HEAT PUMPS

AHU: AIR HANDLING UNIT

1. INTRODUCTION

High-energy performance buildings represent case studies of particular complexity because of the integration of dynamic adaptation features and devices. In turn, technical installations are integrated with systems of energy production obtained from renewable sources. The use of passive heating and cooling resources, instead of active devices, is possible only if the buildings are carefully designed to make the building envelope, occupant needs and technical installation part of an integrated energy management system (Figure 1). The interaction with inertial energy storage devices, form and building construction, enables the implementation of efficiency strategies and partly respond to the possibilities offered by new materials, techniques and technologies [1].

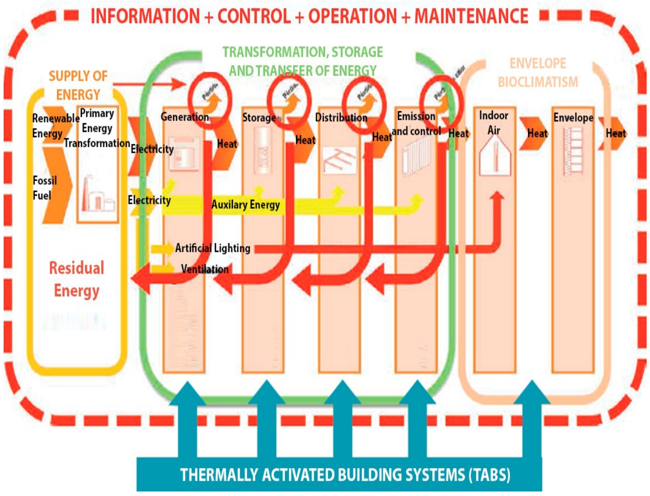


Figure 1: Thermally Activated Building Systems: Information, Control, Operation, Maintenance. Source: Eneres S.L.

Thermal mass has a major role: it can reduce indoor air temperature and load peaks. The temperature distribution within different materials varies with time, thermal properties and boundary conditions [2]. Thermally Activated Building Systems (TABS) are generally known as temperature control systems which actively incorporate the building mass into the climatization of buildings by slab-integrated circuits [3]. The key to taking the maximum advantage of TABS is to get control of their behavior, which depends on a wide number of operative parameters and boundary factors.

TABS operate at low temperatures, enabling efficient utilization of Renewable Energy Sources (RES). When low-grade energy production systems from RES, such as geothermal exchange systems, come into play with low demand architecture, this integration contributes to increasing the integral and projected efficiency over time. The energy obtained from the recovery of heat from RES can be stored in the ground and transferred seasonally to the occupants of a building, through the structure, preferably by its horizontal elements, which are in direct contact with users.

TABS operation can be summed up in three phases [1]:

- *Recharge phase* - Inertial elements are energy-charged by hot or cold water which circulates through the heat exchangers integrated in the building structure. When the water flows through the tube system, it is able to cool or heat slabs, depending on its temperature. This process can be actively controlled by varying the water temperature, flow rate and exchange time.

- *Energy storage* - Thermo-active slabs operate with a time lag between thermal energy generation and energy demand. Excessive daytime heat from solar exposure or internal gains from users and equipment are immediately converted into resources that are stored in slabs, improving the temperature of the building mass. This also increases the operating temperature of the room, although it is moderated by inertial mass.

- *Discharge phase* - Climatization by using TABS is carried out via two effects that occur in parallel: 60% of the heat stored in the concrete mass is transferred by radiation to the room and 40% by convection [1]. Due to the considerable inertia of the system, the discharge occurs in a passive and partially active way in the radiant interaction between the slabs and the users.

Heating and cooling strategies with TABS require recharge management. Building Management Systems (BMS) collect data on their operation, as TABS are involved in an exchange process in which the operational optimization is the key to achieving energy efficiency.

The control of TABS performance throughout the day, basically consists of activating their self-regulation and adaptation. Depending on the use of the building, inertial response of materials and boundary stimulation, different control strategies can be considered for the management of these systems [1]:

- *Day-Night operation* - In this case, thermo-active slabs are pre-charged during the night to heat (or cool), dissipating (or absorbing) heat throughout the day. TABS permit the building structure to store energy, enabling the separation between energy availability and use. In this way, thermal energy can be generated when costs are lower and/or efficiency is higher and then stored within the structure, which dissipates it when there is an energy demand for thermal comfort. As C.A. Balaras claims [2], the phenomena that take place during day and night periods, differ significantly, depending on whether the mass material is being charged (temperature increase) or discharged (temperature decrease), respectively. This strategy is more applicable to offices and other buildings which are unoccupied during the night, so that the structure can be cooled with nighttime ventilation, in summer [4]. This management can be improved if weather forecasts and an estimate of the internal load status are implemented in the system and used as control strategies [5,6].

- *Continuous operation* - Recharge of thermo-active slabs can be also continuous throughout the day and is regulated by water temperature changes in circuits, which transfer energy to the different zones of a building.

- *Control* - Slabs are recharged, cooled or deactivated depending on the outside temperature conditions, room temperature or difference between the impulse and return water temperatures. Supply temperature, flow rate, and hydronic pump operating time are used as control parameters to make adjustments to the room temperature.

A comprehensive review of general information on TABS, TABS design, simulation and control strategies can be found in [7]. These control concepts are part of an integrated process, including the design phase, commissioning, and TABS optimization during operation. TABS can be adopted optionally to improve energy efficiency and thermal comfort, depending on the given requirements.

In principle, the mass flow and the supply-water temperature can be controlled by pumps and control valves for the loading and unloading of TABS. The supply-water temperature is typically controlled via a mixing valve over a return-water admixture. Its control may be a function of the outside temperature, usually via the average outside temperatures over a time range of several hours to days. Depending on the system technology and the hydraulic variant used, a binary signal (for example, on/off for a heat pump or control valves) may be available as a manipulated variable instead of controlling the supply-water temperature [3]. This type of control for TABS was presented in [9,10] and was investigated for different TABS configurations by using simulations and experiments [11,12,13,14]. Actually, return-water temperature sensors are usually located in the heating and cooling circuits of a building, because, in contrast to the supply-water temperature, the return-water temperature contains information about the amount of energy transferred from the water to the slab and thus indirectly from the slab to the room. Furthermore, the difference between the supply and the return-water temperature can be used for controlling TABS. If this parameter, associated with TABS power, drops below a limit value, the TABS zone can be switched off in order to save pumping energy. The room temperature control can also be used as a supplementary strategy for supply-water temperature control. If the room temperature goes *below* the setpoint room temperature for heating (or goes *above* the setpoint room temperature for cooling), the zone pump or valve receives the switching command “ON” with the maximum supply-water temperature [3].

BMS are designed to enable the control of a wide number of parameters and dynamic behavior strategies, affecting thermo-active structures operation, in combination with RES. Control systems make the building adapt itself to several conditions throughout the year and are oriented to the maximum comfort, energy efficiency and optimization of efficient production from RES.

In 2008 the *International Organization for Standardization* (ISO) developed the ISO 50001 – *Energy management system - Requirement with guidance for use*, as the future international normative about energy management. Since its publication in 2011, companies have been encouraged to conduct an energy audit regularly and comply with the requirements of the Energy Efficiency Directive 2012/27/EU, by implementing an Energy Management System (EMS). Its purpose is to encourage organizations to adopt a proper approach in achieving continual improvement of energy performance and proper use of energy resources, with the aim of energy efficiency and control of energy use and consumption. The structure of this approach is fundamentally based on the *Deming cycle* (continuous improvement), also known as the *Plan-Do-Check-Act* approach (planning, program implementation, check, action) [8]. This procedure includes planning and acting in accordance with mutual needs and targets. The audit role is strictly connected with the “check” phase. The “action” phase includes maintenance of buildings, which is a fundamental component of comprehensive, sustainable and energy efficient building operations.

Various sustainable building rating systems are established to express the degree of compliance with sustainability criteria, among the most meaningful aspects: rational use of resources, reducing energy consumption, use of RES, use of local materials, etc. Developed by the non-profit U.S. Green Building Council (USGBC), LEED includes a set of rating systems for the design, construction, operation, and maintenance of green buildings [15] aiming at assessing the strategies which optimize the relationship between buildings and their surrounding environment, while helping building owners and operators be environmentally responsible and use resources efficiently. The *LEED Green Building Rating System for Existing Buildings: Operations & Maintenance* is a set of performance standards for certifying the operations and maintenance of existing buildings of all sizes, both public and private [16]. The intent is to promote high-performance, healthful and durable in existing buildings. It breaks the certification process into seven sections organized in prerequisites and credits. LEED certification process is based on the allocation of points in each category, by using specific practices, certain materials, construction methods, control strategies to measure overall performance in terms of occupant thermal comfort and energy efficiency. *Energy and Atmosphere (EA)* is a section which promotes the improvement of energy performances of buildings, the use of energy from RES or alternative sources, the control of energy performance of buildings. Energy metrics credits focus on measurement of building energy performance. The section called *Indoor Air Quality (IEQ)* deals with environmental concerns in relation to indoor air quality, affecting health, comfort, and energy consumption, the effectiveness of air changes and the control of air contamination. These credits also include methods of heating and cooling management, implementation of building commissioning and use of BMS for the optimization of building energy systems [16].

In [17], Lim et al. show guidelines for TABS optimization on the basis of a university building. The parameters are mostly optimized on the basis of experience during operation. Other methods to adjust and optimize the control of TABS operative parameters have been developed and can be found in [18]. It has been proven that an initial operation phase for TABS, over a period of one to two years, is usually necessary. During this period the parameterization of the operating strategy should be adjusted by experts during the operation of the building. In other cases, the setpoint parameters may need to be readjusted, simultaneously to the change of internal loads, for example, the occupation of rooms [3]. In this sense, A. Mirakhorli and B. Dong are investigating the implementation of occupancy models that may be helpful to predict thermal loads and thus improve thermal comfort [5,6].

In the next paragraphs, a methodology of energy audit and thermal comfort monitoring for an existent office building is defined, with a particular focus on TABS. In line with the standards pursued by the LEED Rating System, the methodology proposed aims at the monitoring, tracking, and optimization of TABS energy performance, with the identification of energy waste and improvement of thermal comfort.

2. THE ROLE OF TABS IN A HIGH-ENERGY OFFICE BUILDING IN MADRID, SPAIN

In this paper, a control approach for TABS is presented and analyzed within its practical application in an existing office building located in Madrid, at Calle Apolonio Morales, 29 (Figure 2). It represents a case of energy renovation of a building, promoted and executed by *Fernández Molina Obras y Servicios*, and designed in its energy concept by *Eneres*, companies which are active in Madrid in the field of construction and sustainable energy systems. The goal was to provide the building with all it needed to be efficient, through an integrated design approach which was the added-value that enabled the building to undergo the LEED certification process. The effort of maximizing structural and morphological characteristics, combining them with passive devices and renewable energy sources puts the office building located at calle Apolonio Morales, 29 on track to achieve an optimal LEED Platinum rating, which is the maximum rating.

2.1. Integration: Passive and Active Systems

The HVAC system combines both active and passive utilization of solar and geothermal energy and uses inertial and instant devices simultaneously to transmit energy to the indoor environment, under the control of an integrated system of sensors and the "smart" management of a control system.

A correct orientation of the building allows the capturing of energy from solar radiation, following major sustainability criteria. The building location, orientation and inertial capability of the ground were taken advantage of. The building includes several passive technologies for the control of solar radiation and radiation losses, such as low-emissivity glass with high thermal and acoustic insulation and extruded aluminum mobile slats, which act as an anti-radiation barrier.

Appropriate integration of inertial elements in combination with Geothermal Heat Pumps (GHP) and Air Handling Units (AHU), under a BMS, provide a high degree of adaptation of the building operation, energy saving and dynamic interactivity with users, while improving the quality of the indoor thermal environment and reducing operating costs. Concrete Core Activation (CCA) of the original horizontal structure aimed at exploiting thermal inertial properties of materials and their storage capability, in combination with low -grade thermal energy sources. Concrete structures such as piles, foundation slabs, etc. are used to absorb geothermal energy from the ground and the groundwater. In Madrid, a soil temperature of approximately 15°C is considered, which

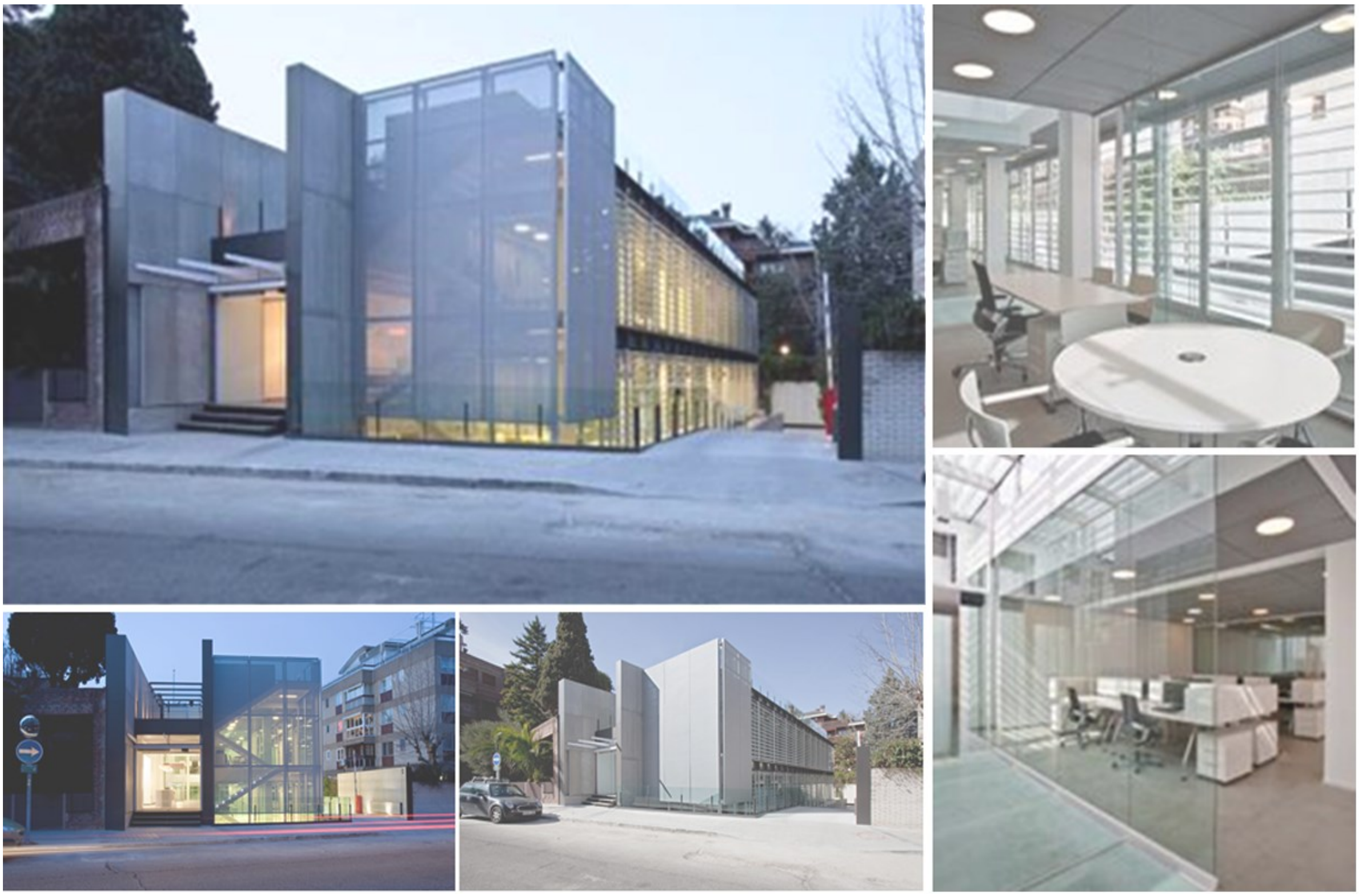


Figure 2: Apolonio Morales 29, Mardid. Source: Amparo Garrido, Eneres S.L.

is constant at a certain depth throughout the year. The energy is absorbed and transported to the building services center by means of fluid-filled pipe systems incorporated inside the foundation elements. This system allows contrasting the average building demand both in cooling and heating.

Figure 3 shows the primary thermal production system for heating and cooling. It is based on two Geothermal Heat Pumps (GHP), allowing heat exchange with the ground (geothermal system), taking advantage of the stability of its temperatures throughout the year. The heat pumps extract heat from the subsoil and transmit it from the construction elements of the foundation to the primary circuit.

The original horizontal structure, including a compression layer of 5 cm, was activated with water circulation circuits and an additional concrete mass of 7 cm to obtain an activated mass of around 280 kg/m^2 (Figure 4).

In support of the primary production system using GHP, an Air Handling Unit (AHU) is installed on the roof of the building and is equipped with heat recovery and free cooling section. Auxiliary systems have the role to rapidly contrast, demand peaks generated while meeting the thermal comfort requirements in particular conditions of internal gains and external temperature fluctuations.

Besides this, the installation of solar cell panels, located on the

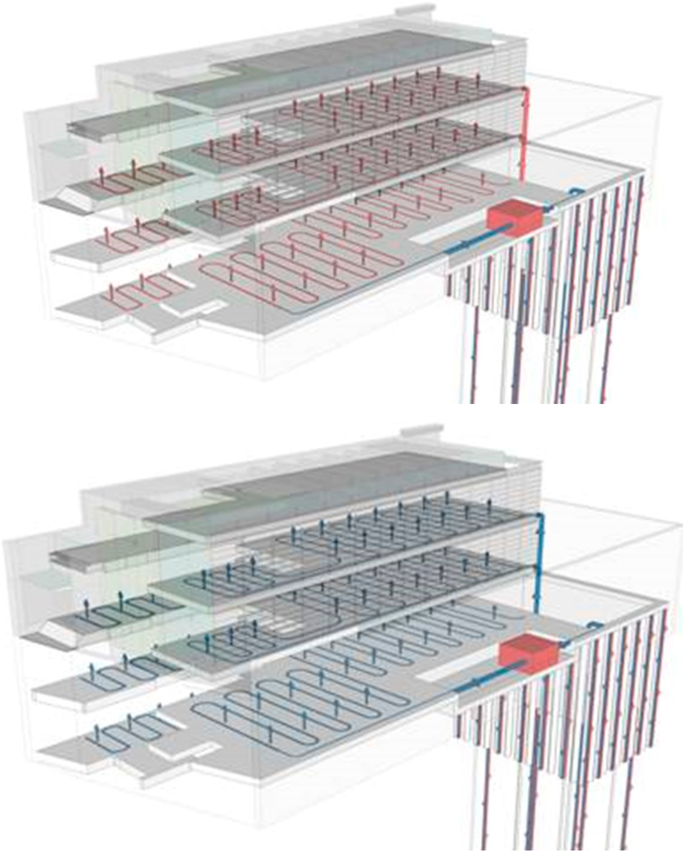


Figure 3: Thermally Activated Building System. Heating and Cooling System. Apolonio Morales 29, Madrid. Source: IEI Instituto Europeo de Innovación.

roof, enables taking advantage of solar radiation in winter, since it allows the preheating of the air coming into the AHU.

Figure 4: Concrete Core Activation. Apolonio Morales 29, Madrid. Source: IEI Instituto Europeo de Innovación.

2.2. Information: operative parameters and monitoring

The parameters characterizing TABS design and operation in the building located at calle Apolonio Morales 29 are as shown in Table 1 below:

Winter | Heating mode	
Surface floor temperature	29°C
Room temperature	21°C
Fluid-temperature range	5°C
Maximum supply temperature	49ºC
Normalized power for heating	75 W/m²
Summer | Cooling mode	
Surface floor temperature	20°C
Room temperature	25°C
Fluid-temperature range	2°C
Minimum supply temperature	18ºC
Normalized power for cooling	42 W/m²

Table 1: TABS operative parameters. Apolonio Morales 29, Madrid (Spain).

An integrated system of sensors and devices managed by a control computer system, also called "Building Manage System" (BMS), administers these parameters. It controls the interaction between passive systems and active devices, including TABS.

The control system analyzes real-time parameters: internal and external temperature, concrete-slab temperature, indoor and outdoor relative humidity, wind speed, exterior lighting, etc. External parameters affect the thermal behavior of the building, as well as the control of the operative strategies. They are monitored by a set of sensors, listed in Table 2.

Figure 5 shows the outside temperature and humidity sensor installed on the roof. Room and floor temperatures are measured by two sensors per floor (Figures 6-7), that are connected to the control system.

Sensors	*Units*	*Parameters*	*MU*	*Position*
Combined Outside Air Humidity Temperature Sensor	1	Outdoor Air Temperature	ºC	Roof
		Outside Relative Humidity	%	Roof
Pressure Transmitter	1	Atmosphere Pressure	Pa	Roof
Solar Sensor	3	Solar Radiation	W/m²	Roof
				East Façade (Ground Floor)
				East Façade (First Floor)
Rain Detector	1	Rain	0/1	Roof
Wind speed sensor	1	Wind Speed	m/s	Roof
Luxmeter	2	Lighting	lux	East Façade (Ground Floor)
				East Façade (First Floor)

Table 2: External sensors. Apolonio Morales 29, Madrid (Spain), Control System.

Figure 5: Honeywell - H7508A1042 - Outside Air Humidity Sensor. Apolonio Morales 29, Madrid, Control System. Source: Self-elaboration.

Figure 6: Honeywell - H7012B - Humidity and Temperature Room Sensors. Apolonio Morales 29, Madrid, Control System. Source: Self-elaboration.

Figure 7: Honeywell - T7413A1041 - Immersion Temperature Sensor. Apolonio Morales 29, Madrid, Control System. Source: Self-elaboration.

Additionally, the control system is able to provide information about the opening state of the shut-off valves, shown in Figure 8, that adjust the flow rate of the supply and return water in radiant circuits, depending on the setpoint programmed on each floor.

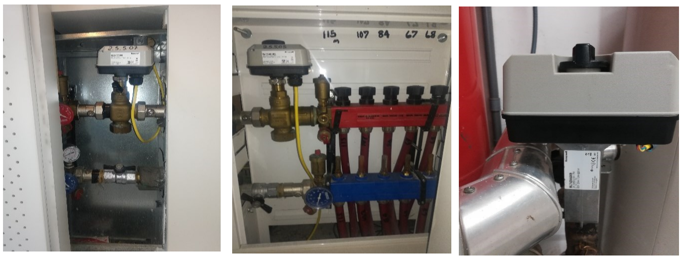


Figure 8: Honeywell - ML7420A - Electric Linear Valve Actuator. Apolonio Morales 29, Madrid, Control System. Source: Self-elaboration.

The number of units, operative parameters and position of the internal sensors and devices which control the TABS operation are listed in Table 3. In addition, a number of immersion temperature sensors (Figures 9-10) measures supply- and return-water temperatures in pipes and ducts. All the sensors and devices installed in the machine room, affecting the TABS operation, are listed in Table 4. Finally, three energy meters are installed at the energy consumer system level (final use) to discriminate between HVAC, lighting and general consumption. The parameters monitored can be found in Table 5.

Sensors/ Devices	*Units*	*Parameters*	*MU*	*Position*
Humidity and Temperature Room Sensors	6	Room Temperature	°C	Semi-basement Floor (2 units)
				Ground Floor (2 units)
		Internal Relative Humidity	%	First Floor (2 units)
Immersion Temperature Sensor	6	Concrete Slab Temperature	°C	Semi-basement Floor (2 units)
				Ground Floor (2 units)
				First Floor (2 units)
Electric Linear Valve Actuator	4	Opening of shut-off valves	%	Semi-basement Floor (2 units)
				Ground Floor (1 unit)
				First Floor (1 unit)

Table 3: Internal sensors and devices. Apolonio Morales 29, Madrid (Spain), Control System.

Sensors/Devices	*Units*	*Parameters*	*MU*	*Position*
Pipe Temperature Sensors	10	Supply and return water temperature in collectors, heat pumps and radiant floor circuit	°C	Machinery Room
Electric Linear Valve Actuator	2	Opening of 3-way valves	%	Machinery Room
Geothermal Heat Pump	2	Operational status	0/1	Machinery Room
Hydronic Double Pump	5 (x2)	Operational status	0/1	Machinery Room

Table 4: Machine Room sensors and devices. Apolonio Morales 29, Madrid (Spain), Control System.

Sensors/ Devices	Units	Parameters	MU	Position
Three-phase power analyzer	1	HVAC Active, Apparent, Inductive, Conductive, Reactive Electrical Energy	kWh	Utility Room
		HVAC Active, Apparent, Inductive, Conductive, Reactive Electrical Power	kW	
	1	Lighting Active, Apparent, Inductive, Conductive, Reactive Electrical Energy	kWh	Utility Room
		Lighting Active, Apparent, Inductive, Conductive, Reactive Electrical Power	kW	
	1	General Active, Apparent, Inductive, Conductive, Reactive Electrical Energy	kWh	Utility Room
		General Active, Apparent, Inductive, Conductive, Reactive Electrical Power	kW	

Table 5: Energy consumption devices, Apolonio Morales 29, Madrid (Spain), Control System.

Figure 9: MAMAC SYSTEMS - TE-703-B-17-B-2 - Pipe Temperature Sensors. Apolonio Morales 29, Madrid, Control System. Source: Self-elaboration.

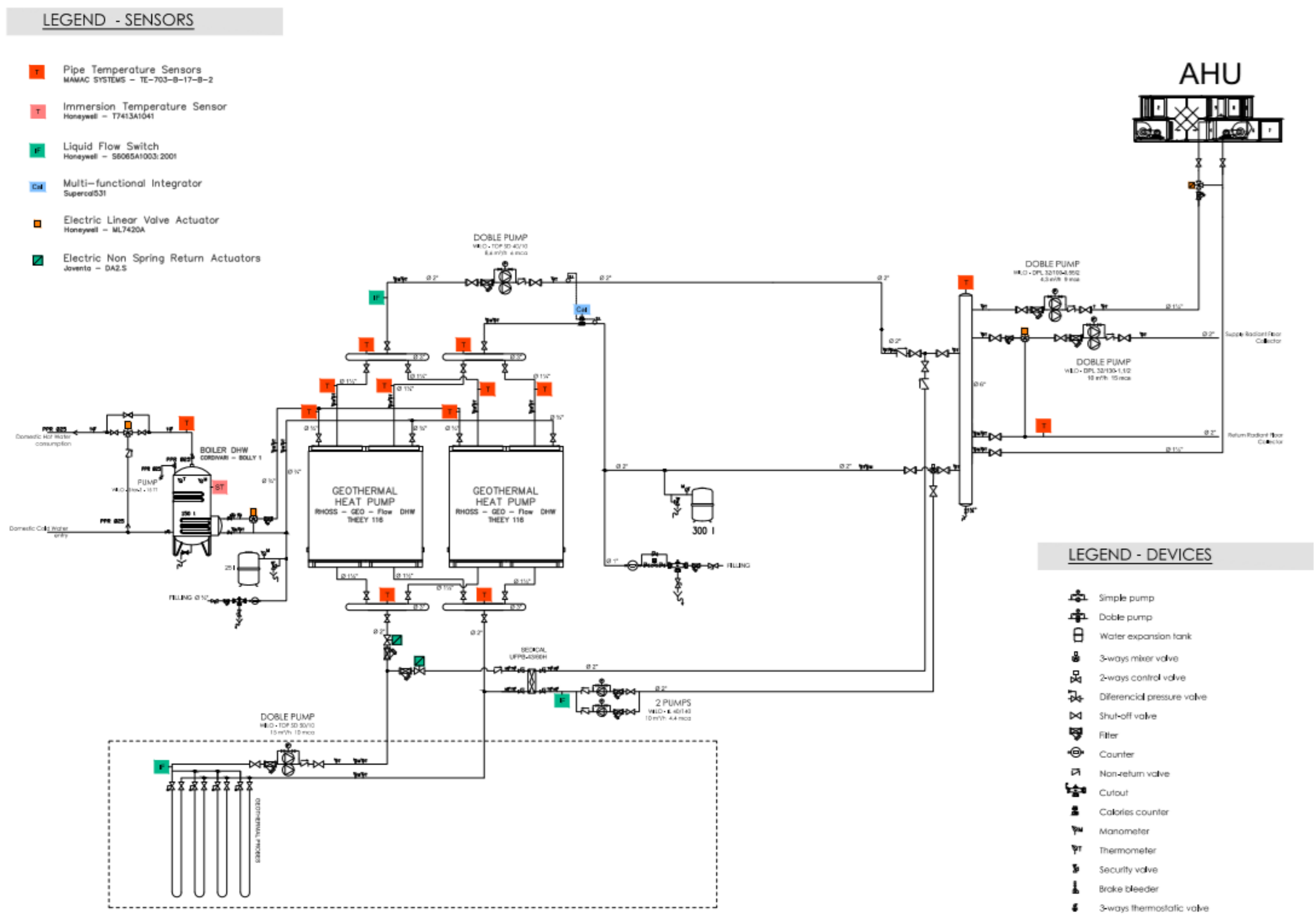


Figure 10: HVAC Scheme and Sensors. Apolonio Morales 29, Madrid. Source: Self-elaboration .

2.3. *Control: operation strategies*

The openness and versatility of the BMS have allowed the implementation of a multitude of devices and systems of different natures. The control system was designed to control a wide number of combined strategies and scenarios, enabling the building to adapt itself to several conditions throughout the year. The aim is optimal comfort, the efficient use of energy sources and optimization of energy consumption and production from renewable sources. The implementation of the BMS enables taking control of the large thermal capacity of TABS and shift their operation to the time periods when energy production is most efficient and/or cost-effective.

Floors serve as radiant elements during the day and accumulators during the night. This helps to avoid load peaks during the morning and reducing consumption costs (the "overnight operation" is used to take advantage of the reduced night rate for electricity). In summer, during the nighttime periods, GHP work for cooling slabs so that the building is pre-cooled for the next day. In winter, during the night, GHP run to keep heat in the floors and prevent activation peaks in the morning. This strategy takes advantage of the inertia of the building structure at night to maximize the benefits of the geothermal exchange system. In this way, thermal energy is produced when costs are lower (electric night rate). Then energy is stored within the structure, which dissipates it whenever there is an energy demand.

Each floor is characterized by different thermal demand, due to different thermal insulation conditions, orientation and sun exposure. Hence, the heating and cooling strategies are controlled by two setpoint values per floor: one for the day, the other for the night ("PC Dia" and "PC Noche" in Figure 11). Their application depends on the time schedule shown in Figure 12, which is programmed in the control system interface: the yellow bars correspond to the activation of the daytime setpoint, the green ones here show when the night setpoint ("PC Noche") is applied. The "PC Actual" in Figure 11 is calculated depending on the timetable mentioned above: during the night (from 12:00 a.m. to 07:00 a.m.), the setpoint temperature is calculated with a linear interpolation between two outside temperature values, as displayed in Figure 11 (the graph named "CALOR" is used in winter, the other, "FRIO", in summer). In the same figure it is possible to observe that in

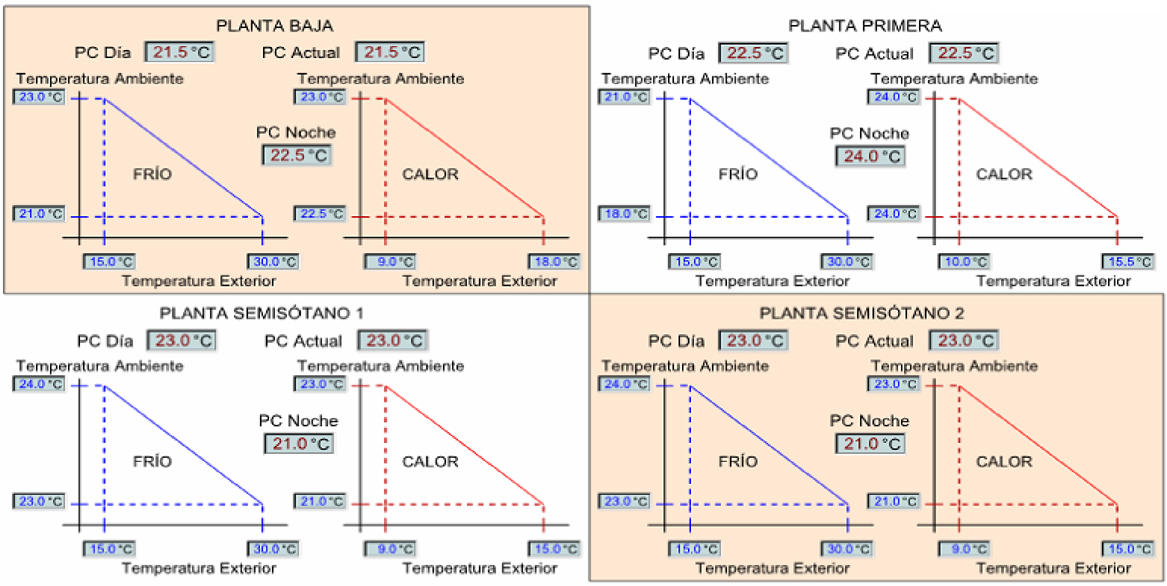


Figure 11: TABS Setpoint Manager: Room Temperature Control. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73).

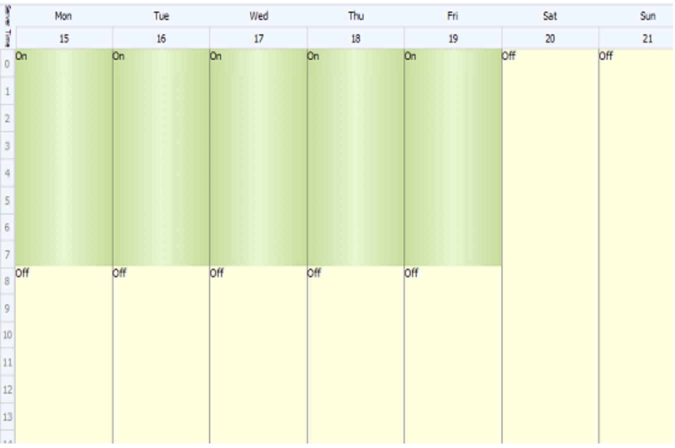
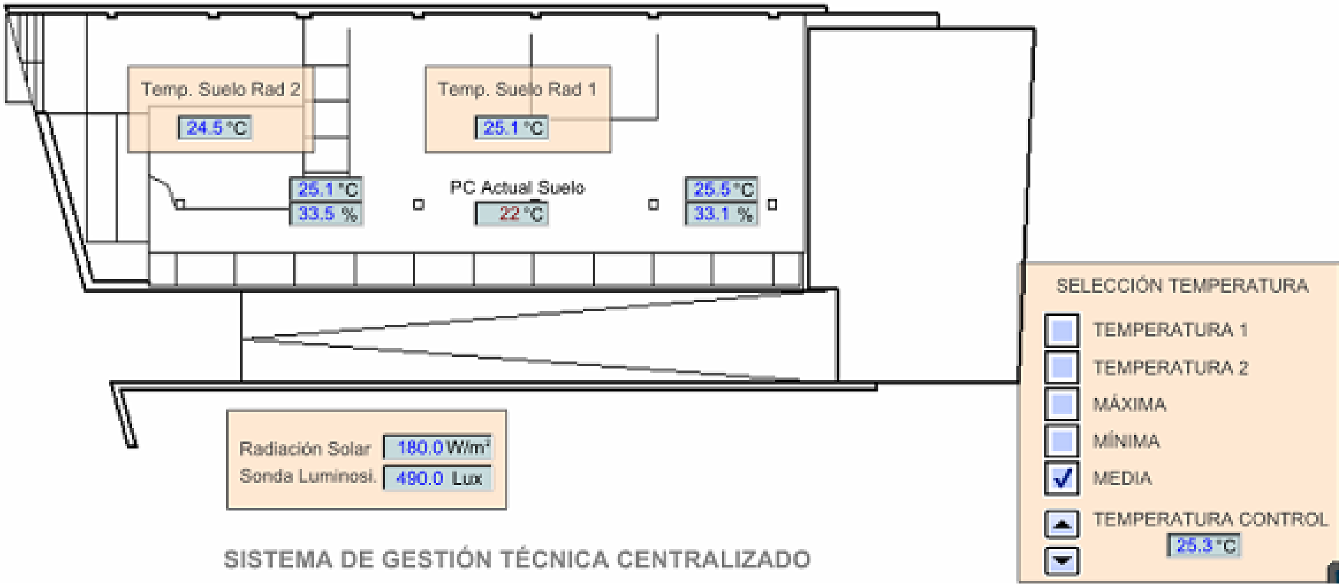


Figure 12: TABS Setpoint Manager | Hourly Schedule. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73).

(Figure 13) goes *above* the relevant setpoint temperature value ("PC Actual" in Figure 11), the corresponding shut-off valve (Figure 14) opens and one of the hydronic pumps associated with the primary loop runs; hence, one of the heat pumps receives the signal "ON";

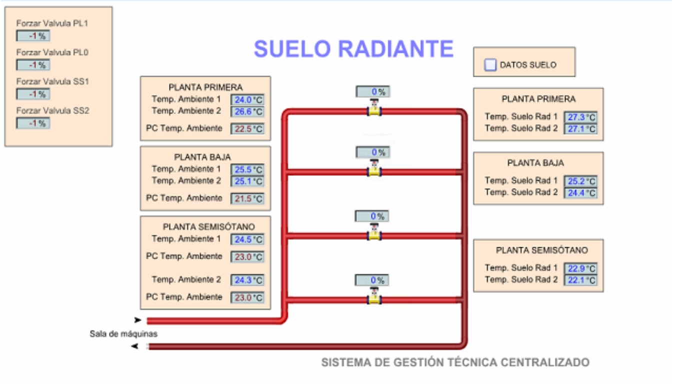
2. If the temperature measured in the return loop goes *above* the relevant setpoint return-fluid temperature ("PC Activo Frio", in Figure 16, which coincides with "PC Calculado" - 1 in Figure 15), the compressor in the heat pumps runs for cooling; such setpoint is associated with the fluid temperature in the return loop ("Temp. Retorno", marked with green arrows in Figure 16).

3. If the fluid temperature in the main collector takes a long



SELECCIÓN TEMPERATURA
☐ TEMPERATURA 1
☐ TEMPERATURA 2
☐ MÁXIMA
☐ MÍNIMA
☑ MEDIA
TEMPERATURA CONTROL 25.3 °C

Figure 13: Ground Floor, Control System interface. Source: Apolonio Morales 29, Madrid, Control System, *Building Operation WorkStation* (1.4.1.73).



Forzar Valvula PL1 -1 %
Forzar Valvula PL0 -1 %
Forzar Valvula SS1 -1 %
Forzar Valvula SS2 -1 %

PLANTA PRIMERA
Temp. Ambiente 1 24.0 °C
Temp. Ambiente 2 26.6 °C
PC Temp. Ambiente 22.5 °C

PLANTA BAJA
Temp. Ambiente 1 25.5 °C
Temp. Ambiente 2 25.1 °C
PC Temp. Ambiente 21.5 °C

PLANTA SEMISÓTANO
Temp. Ambiente 1 24.5 °C
PC Temp. Ambiente 23.0 °C
Temp. Ambiente 2 24.3 °C
PC Temp. Ambiente 23.0 °C

PLANTA PRIMERA
Temp. Suelo Rad 1 27.3 °C
Temp. Suelo Rad 2 27.1 °C

PLANTA BAJA
Temp. Suelo Rad 1 25.2 °C
Temp. Suelo Rad 2 24.4 °C

PLANTA SEMISÓTANO
Temp. Suelo Rad 1 22.9 °C
Temp. Suelo Rad 2 22.1 °C

Figure 14. Valves (Radiant Floor Collectors) Control System interface. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73).

time to attain its setpoint temperature value (“PC Calculado” in Figure 15), the second heat pump runs;

4. If both heat pumps are working, the second hydronic pump runs too, increasing the flow rate in the loop.

The “PC Calculado” setpoint value (in Figure 15) affects the water temperature in a particular node of the plant loop – under the main collector – as marked in the green square in Figure 16. In contrast to the supply-water temperature, the return-water temperature contains information about the energy transfer. For this reason, return-water temperature sensors are located in the heating and cooling circuit. The supply-water temperature is controlled via the mixing valve, shown in the same square. The role of this valve is to adjust the temperature in the radiant floor circuits, depending on the external temperatures. Indeed, the supply-water temperature in loops is obtained with a linear interpolation between the higher outdoor temperature and the lower one, according to the rule displayed in Figure 15.

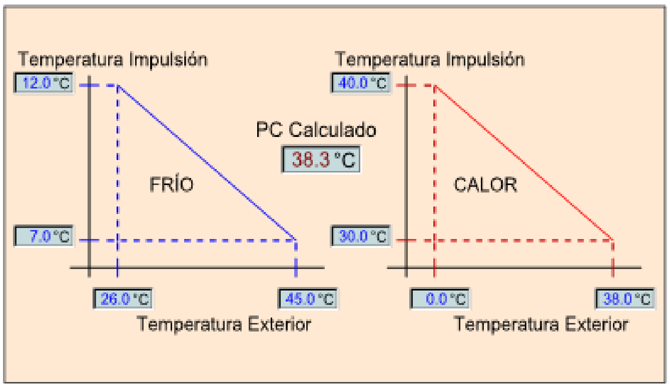


Figure 15: TABS Setpoint Manager: Supply-water Temperature Control. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73).

The heat pumps usually perform in an alternating way. When one of them is no longer capable of satisfying the demands, they run together. This type of operation is controlled based on a PID (Proportional-Integral-Derivative) controller, a control loop feedback mechanism, requiring continuously modulated control (it is calculated with a mathematical algorithm related to k-proportional, k-integral, k-derivative values, which are in turn adjustable).

The operational arrangements, as described above, will be more understandable in the analysis of the graphs set and generated by the BMS software, that are used in the monitoring phase (see paragraph 2.4 below).

2.4. Follow-up: report capabilities

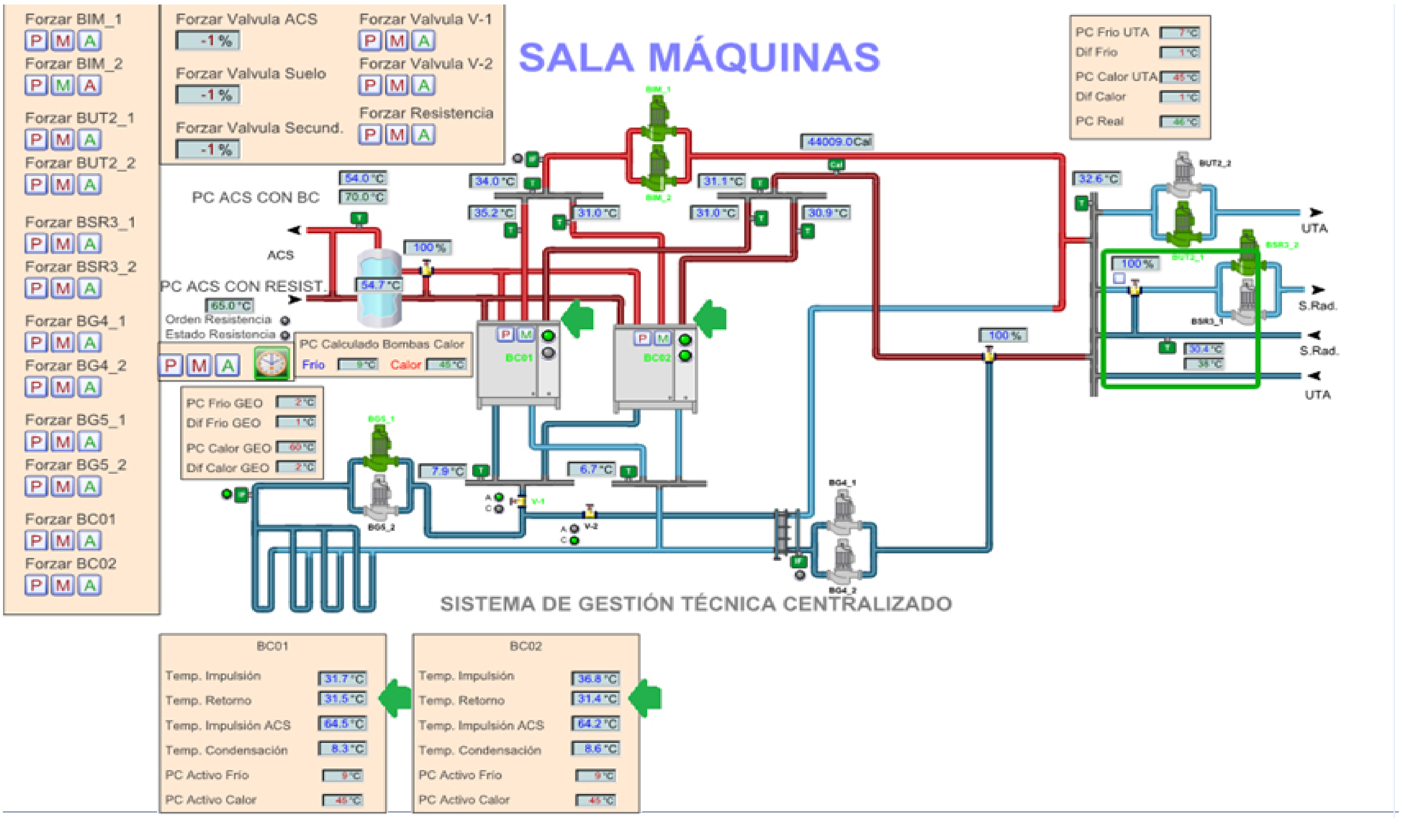
The BMS enables the monitoring of operative parameters and the management of setpoints via a control interface. In line with the targets pursued by the LEED Rating System, a proper audit and maintenance procedure is applied, aiming at monitoring, optimizing and improving the building’s energy performance. This paper provides a specific focus on those aspects which characterize TABS operation and management. Indeed, the approach follows a well-defined process included in a comprehensive project, which also considers key stakeholders and valuable experience feedback [16].

The reporting capabilities of the control system include all facets of the building HVAC system. Reporting includes current weather conditions (temperature, humidity, solar radiation, solar lighting, atmospheric pressure, wind speed), alarms, heating/cooling system operational status (heat pump and pump status, supply/return temperatures, energy consumption), supply/exhaust fan status, floor-by-floor plans with thermostat sensor readings, AHU operational status (fan speed, temperatures, static pressure, damper position), etc

Conductive maintenance generally includes sensory inspections, reading parameters in the control system, reading parameters on-site (with local instrumentation), effective measurements and simple tasks for first level maintenance [20]. In practice, these tasks have been translated into a systematic protocol that includes:

- motoring of energy consumption;
- monitoring and storage of trend logs and trend charts through the control system interface;
- recording of events and detection of anomalies;
- measuring of comfort parameters;
- checking of the existence of alarm signals registered by the system, through its communication interface;
- adjusting operations and proposals aimed at improving the energy performance of the building and guaranteeing users’ comfort;
- annotation of results, events, operation and adjustment in a daily register;
- building energy simulations.

The control system collects data and records it in a database. Through its interface, it allows the consultation of historical and real-time data. The energy manager can analyze it to draw conclusions and assess strategies already implanted, as well



Forzar Valvula ACS -1 %
Forzar Valvula Suelo -1 %
Forzar Valvula Secund. -1 %

PC ACS CON BC 54.0 °C 70.0 °C
PC ACS CON RESIST. 65.0 °C
Orden Resistencia
Estado Resistencia

PC Calculado Bombas Calor
Frio 9 °C Calor 45 °C

PC Frio GEO 2 °C
Dif Frio GEO 1 °C
PC Calor GEO 60 °C
Dif Calor GEO 2 °C

PC Frio UTA 7 °C
Dif Frio 1 °C
PC Calor UTA 45 °C
Dif Calor 1 °C
PC Real 46 °C

BC01
Temp. Impulsión 31.7 °C
Temp. Retorno 31.5 °C
Temp. Impulsión ACS 64.5 °C
Temp. Condensación 8.3 °C
PC Activo Frio 9 °C
PC Activo Calor 45 °C

BC02
Temp. Impulsión 36.8 °C
Temp. Retorno 31.4 °C
Temp. Impulsión ACS 64.2 °C
Temp. Condensación 8.6 °C
PC Activo Frio 9 °C
PC Activo Calor 45 °C

Figure 16: HVAC System Scheme, Control System interface. Source: Apolonio Morales 29, Madrid, Control System, *Building Operation WorkStation* (1.4.1.73).

as to improve building management or the system itself. The control interface is provided by *Building Operation WorkStation (1.4.1.73)* software. This software enables reading real-time parameters thanks to a certain number of custom displays. Additionally, it allows the creation of *Trend Log Lists* and *Trend charts*, that are required to be programmed, for reading historical data and assessing parameter time trends:

- *Trend Log Lists* have been programmed with a 10-minute reporting interval for each parameter.
- *Trend charts* have been programmed in order to combine and compare different parameters with the relevant setpoints.

The performance of each active and passive system of the building is described by the relevant chart, created by combining parameters characterized by mutual influence or connected by cause-and-effect relationships. They are updated in real time and are used for monitoring and checking the correct operational status of the systems and sensors, while analyzing the relationships between parameters.

The most relevant data collected by the BMS is transferred by its acquisition interface. Logs, as well as annual, monthly, weekly, daily and hourly charts, can be viewed and downloaded at any time. Data can be organized and managed in specific spreadsheets, removing irrelevant values, in order to filter data (“Data filtering”) [19]. The company is provided with an archiving system to archive monthly engineering logs on installed points. Charts are archived and analyzed weekly and monthly, comparing them with specific events or operations that are recorded in a dedicated register. The analysis of these charts enables action to be taken quickly, as well as faults to be identified and corrected, in response to thermo-higrometrical conditions, occupant comfort and consumption.

2.4.1 Energy consumption

Among the LEED credits, EA Credit 3.2. *Performance Measurement — System-Level Metering* (2 points) aims to provide a tool to acquire accurate energy-use information, to support energy management and to identify opportunities for additional energy-saving improvements.

Metering must be continuous and data logged to allow for an analysis of time trends. It can be used to establish energy use baselines, which allow the monitoring and tracking of energy efficiency from improvements and upgrades over time [16]. Electrical energy consumed and power evolution for HVAC systems are analyzed annually, monthly and weekly, in order to assess the efficiency of TABS operation strategy and identify abnormal peaks or energy waste.

The graph in Figure 17, generated by the software, shows the evolution of HVAC energy consumed weekly, throughout the year, which in turn enables awareness of peak consumption

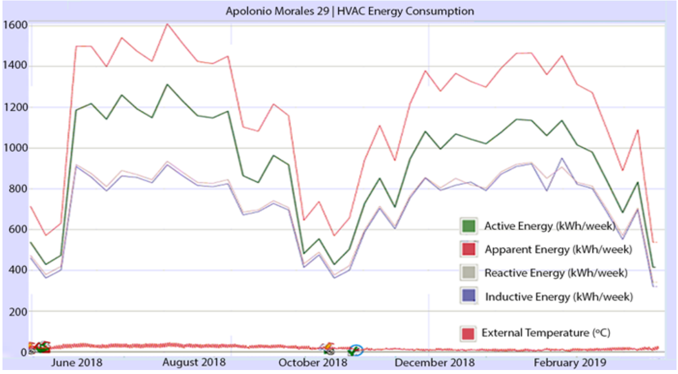


Figure 17: Energy consumption in HVAC. Period: June 2018 – March 2019. Source: Apolonio Morales 29, Madrid, Control System, *Building Operation WorkStation* (1.4.1.73). Self-elaboration.

periods, linking them to specific events or operations.

Figures 18-19 depict some graphs which shows the external temperature (understood as "energy driver"), while analyzing the mutual effects between the operational status of the heat pumps [on/off], HVAC energy consumption by hours [kWh/h] and fluid temperature variation [°C] in the geothermal loop (source side) and the primary heating and cooling loop (building side).

According to a cause-and-effect relationship, it is possible to observe that the effects of the operational state of GHP, are reflected on energy consumption and on the fluid temperature in the geothermal loop. This last temperature decreases as the energy consumption increases: when heat pumps run, they absorb heat from the ground, reducing the fluid temperature in the geothermal loop. On the other hand, when there is no demand and the building does not need to be heated, fluid in the borehole heat exchangers, that are in contact with the ground, gets warmer. The phenomenon described above is reversed in summer: supply-water temperature in the geothermal loop increases in proportion to energy consumption for cooling. It means that when heat pumps run for reducing fluid temperature in the primary loop, they discharge heat to the ground (Figure 19).

The basis used for the energy analysis includes energy meters (CVM MINI - Three Phase Power Analyzers). Moreover, energy bills are analyzed for the estimation of costs (€/kWh) for heating and cooling, over the year.

2.4.2. Thermal comfort

IEQ Credit 2.3. *Occupant Comfort — Thermal Comfort Monitoring* (1 point) aims to support the appropriate operations and maintenance of buildings and building systems so that they continue to meet target building performance goals over the long term and provide a comfortable thermal environment that supports the productivity and well-being of the building occupants [16]. The human body is considered a further load within a system whose primary objective is to maintain a homogeneous thermal environment inside the building envelope [21]. The requirements include the provision of a monitoring system to ensure ongoing building performance to the desired comfort criteria as determined by ASHRAE Standard 55-2004, *Thermal Comfort Conditions for Human Occupancy* [22]. Continuous monitoring of, at least, air temperature and humidity in occupied spaces, is required by the *LEED Reference Guide*, with a sampling interval that cannot exceed 15 minutes [16].

The graph in Figure 20, generated by the software, shows the time trend of the thermal comfort parameters (room temperature and relative humidity) on the first floor of the building. This graph confirms the statement that TABS are able to ensure uniform temperatures, thanks to their storage

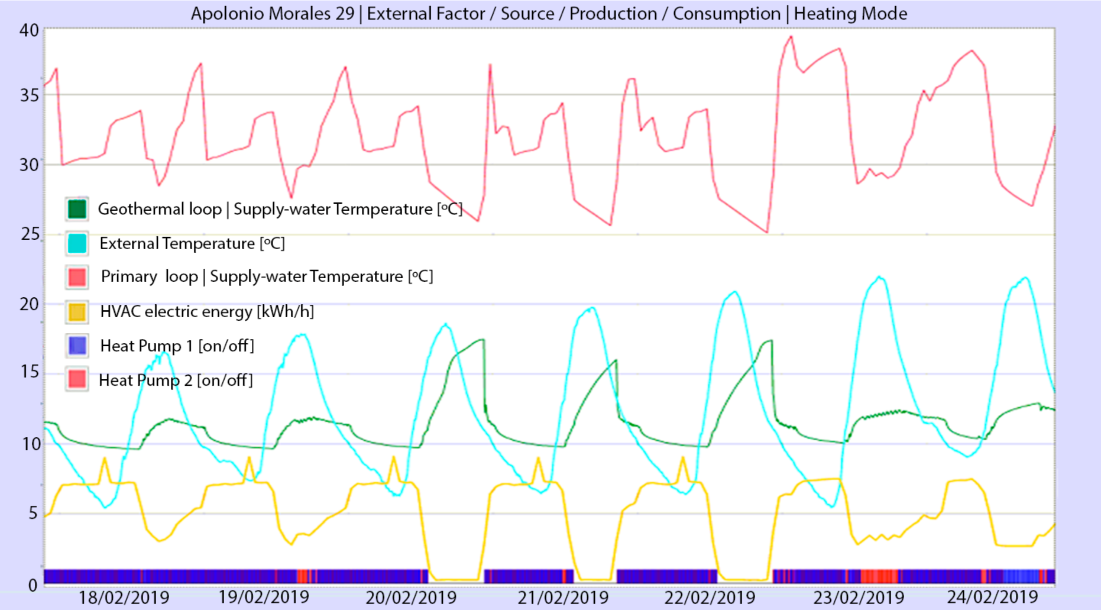


Figure 18: External Factor / Source / Production / Consumption | Heating Mode. Period: Monday, February 18, 2019 – Sunday, February 24, 2019. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73). Self-elaboration.

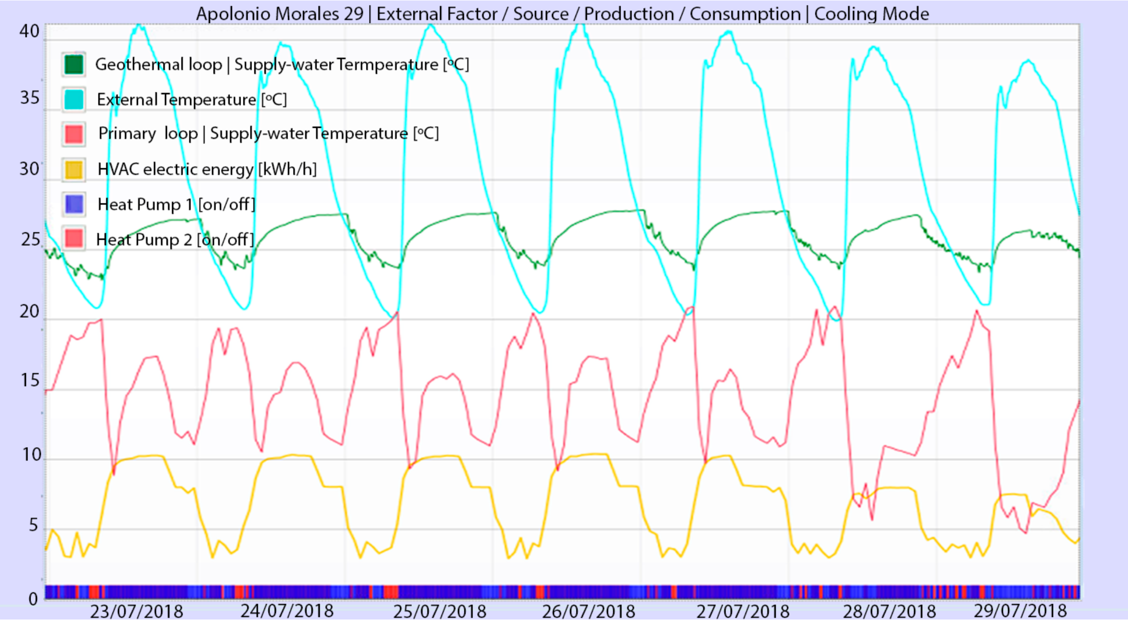


Figure 19: External Factor / Source / Production / Consumption | Cooling Mode. Period: Monday, July 23, 2018 – Sunday, July 29, 2018. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73). Self-elaboration.

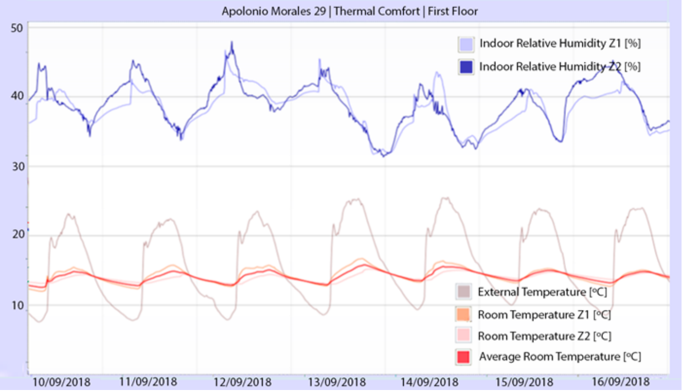


Figure 20: Thermal Comfort (First Floor). Period: Monday, September 10, 2018 – Sunday, September 16, 2018. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73). Self-elaboration.

capability. The monitoring of thermal comfort parameters enables checking that the acceptable comfort ranges are normally respected.

Additionally, *IEQ Credit 2.3* requires the provision of alarms for conditions that require system adjustments or repair. The control system enables the creation of an alarm system for any monitored parameter. With reference to the topic of thermal and hygrometric comfort, the set of alarms emit a warning when the parameters of temperature and humidity are outside the acceptable ranges shown in Table 6.

	Winter	*Summer*
Room Temperature	21°C – 23°C	23°C – 25°C
Internal Relative Humidity	30% – 55%	40% – 65%
Floor-surface temperature	23°C – 29°C	18°C – 23°C

Table 6: Thermo-hygrometrical comfort conditions, Apolonio Morales 29, Madrid (Spain), Control System.

In the case of observing the presence of any alarm, the equipment or the component emitting that alarm signal is checked, thus it is necessary to act in order to take the appropriate measures. The results of previous interventions are annotated in the daily register. Once the alarm situations have been solved, the energy manager or maintenance technician carries out the tasks of preventive maintenance, scheduled according to the protocols [23].

The graphs shown in Figures 21-22 represent the graphical transposition of the above-described overnight operation strategy. In Figure 21 the blue curve charts represent the variation of room temperature on the ground floor, throughout a winter week from November 26 to December 2, 2018.

In Figure 22 the blue curve charts represent the variation of room temperature on the same floor, throughout a summer week from July 23 to 29, 2018. The red curve represents the time trend of the setpoint room temperature ("PC Actual"), for the ground floor, in winter (Figure 21) and in summer (Figure 22). It is constant during the day and variable during the night, depending on the external temperature (according to the linear dependence depicted in Figure 11).

These graphs show that in winter mode, during the first hours of the day, TABS work with a higher setpoint to hold heat in floors and avoid ignition peaks during the morning. In summer, during the night, the setpoint is lower for pre-cooling floors. If the average room temperature value (blue curve) goes below (in winter) or above (in summer) the relevant setpoint room temperature (red curve), the shut-off valve opens (grey bars)

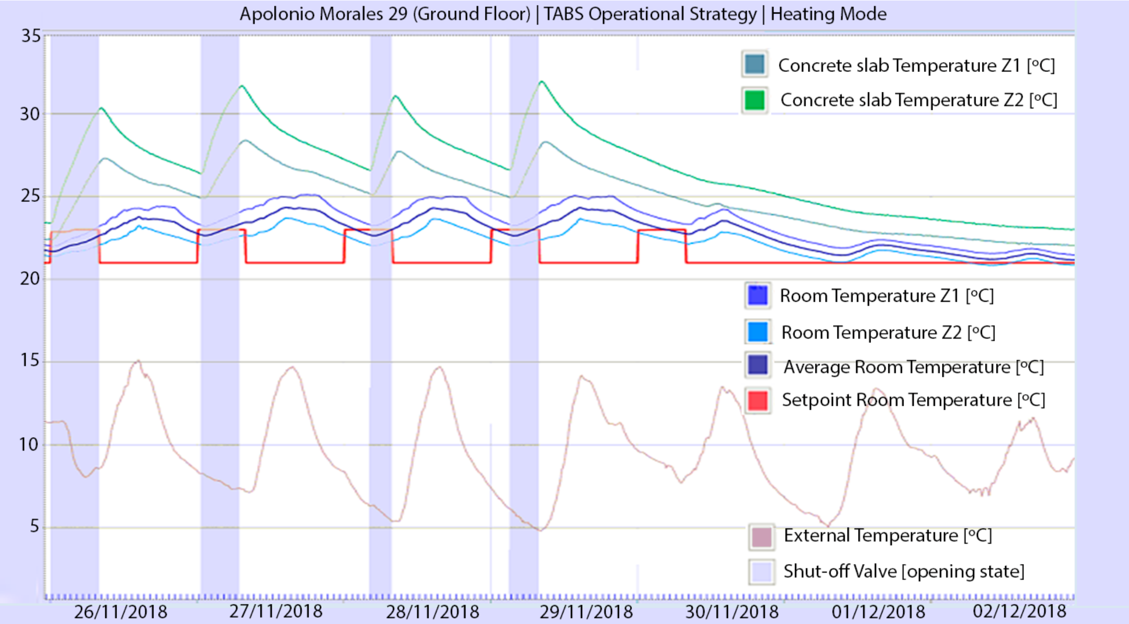


Figure 21: TABS Operational Strategy | Heating Mode (Ground Floor). Period: Monday, November 26, 2018 – Sunday, December 2, 2018. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73). Self-elaboration.

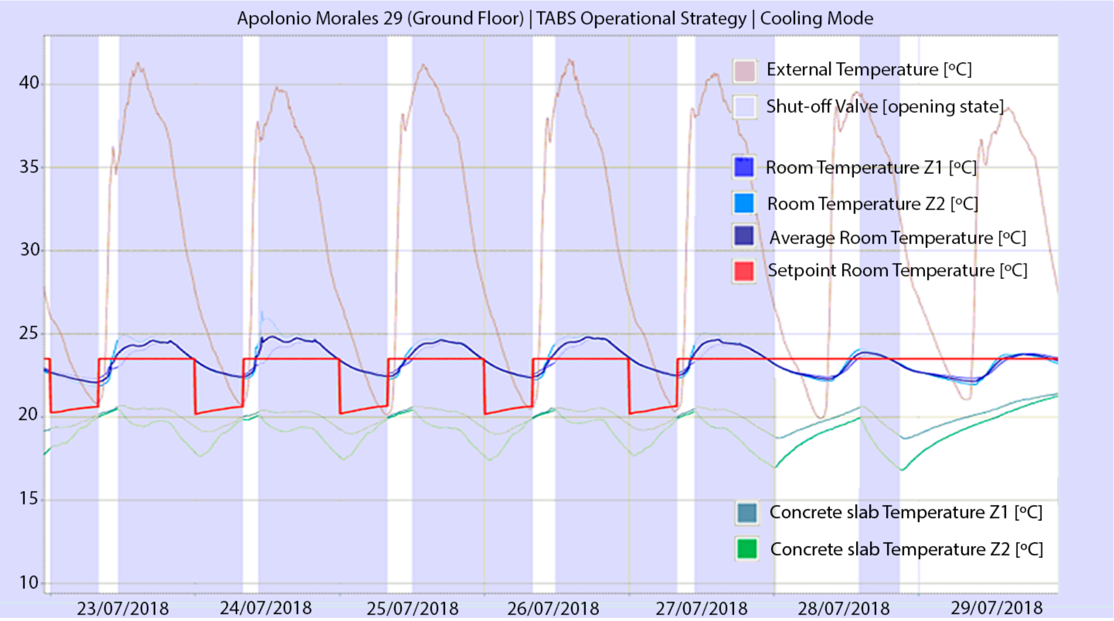


Figure 22: TABS Operational Strategy | Cooling Mode (Ground Floor). Period: Monday, July 23, 2018 – Sunday, July 29, 2018. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73). Self-elaboration.

to enable the circulation of water for (pre-)heating or (pre-) cooling floors. For the length of time during which the valve is open, floor temperature increases (or decreases) gradually and then the floors dissipate heat (in winter) or recharge (in summer) according to a time lag, characteristic of the inertial mass. The green curves show the temperature trend of the floor slabs, measured in two points per floor: it is possible to distinguish the recharge and discharge phases, which coincide with the opening and closing of the valves (grey bars).

Those charts represent the main tool to check the smooth operation of TABS and its effectiveness, translating into energy consumption and thermal comfort terms. Corrective measures for TABS also integrate key stakeholders, users and valuable experience feedback. It enables the execution of the following adjustment operations, in response to any problems identified in thermal conditions by monitoring graphics or thanks to occupant feedback:

- manual switching between heating and cooling;
- forced opening or closing of valves;
- modulation of setpoint values, that affect:
  - room temperature;
  - supply-water temperature (in radiant floor circuits or primary loop);
- changes to the time scheduled for TABS operation (day and night setpoints).

2.5. Corrective action

This paragraph provides a practical demonstration of how all the strategies, sensors, parameters, tools and graphs described in this paper are used to track TABS behavior and assess their effects on thermal comfort and energy consumption.

Figure 23 represents a case of setpoint adjustments that were executed during the winter period, precisely on January 15, 2019. A lower external temperature during the weekend provoked cold thermal discomfort in users, which was solved by adjusting the relevant "day setpoint" from 22°C to 24°C.

In this case, the graph shows how the heating operation went from an "overnight heating strategy" to a "24-hour heating strategy". The control valve was open 100% of the time to ensure thermal comfort during the colder period.
The effects of the corrective measures on energy consumption are evident in Figure 24. The increment of the "day setpoint" to improve thermal comfort converts to an increase in energy consumption. After the adjustment, the electrical energy consumed by the heat pumps [kWh/h] generally remains constant over the time, with a few peaks that coincide with the

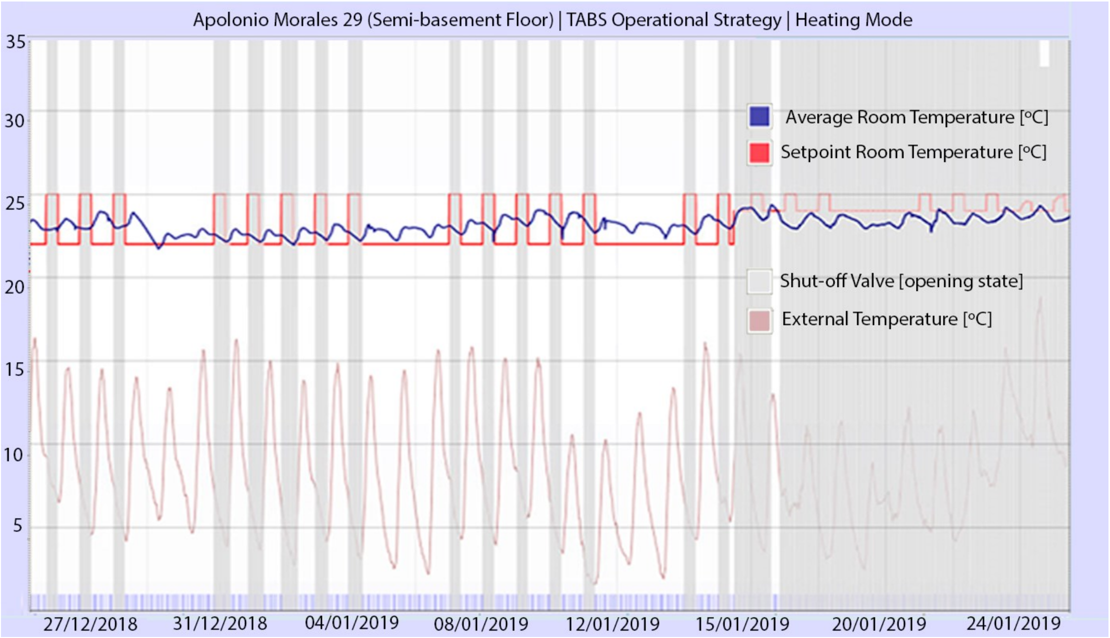


Figure 23: TABS Operational Strategy | Heating Mode (Semi-basement Floor). Period: December 27, 2018 – January 25, 2019. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73). Self-elaboration.

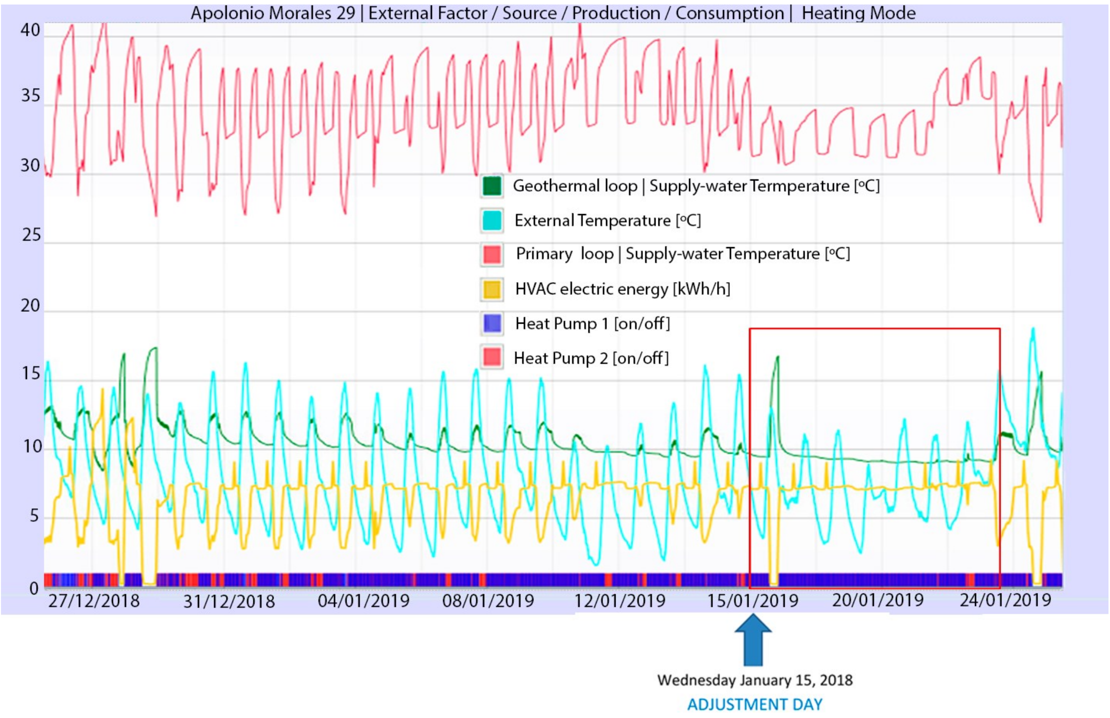


Figure 24: External Factor / Source / Production / Consumption | Heating Mode. Period: December 27, 2018 – January 25, 2019. Source: Apolonio Morales 29, Madrid, Control System, Building Operation WorkStation (1.4.1.73). Self-elaboration.

first hours of the morning, when demand is greater. An isolated case took place on January 16, between 3:00 p.m. and 7:00 p.m. It is evident that, during these hours, there was no thermal energy demand in the building, hence all zone valves were closed, and energy consumption was almost zero. Another solution might have been to increase the setpoint supply-fluid temperature. Thus, water temperature in circuits would have increased reducing the operating time of the heat pumps.

3. CONCLUSIONS

This paper has revealed a number of parameters that need to be considered for describing, monitoring and tracking the thermal mass effect on the heating and cooling load and overall behavior of buildings. The monitoring of the electrical energy consumed per hour by the heat pumps is the key to take awareness of the moments of the day when consumption is most concentrated, in relation to the evolution of the other parameters and setpoints. In this sense, the trend of the energy consumed throughout the day is an index of the effectiveness of the overnight strategy for TABS.

In general, the operational strategies adopted for TABS take advantage of their thermal mass inertial properties in order to reduce peak heating and cooling loads, while sustaining a steadier overall thermal environment. The room temperature control described in this paper as a supplementary strategy for supply-water temperature control is a good strategy for buildings with zones characterized by different thermal demand and conditions. However, the need for manual switching between the heating and cooling modes, as well as the need for the manual tuning of parameters, sometimes reveals it is essential to reduce conflicts and cope with internal gains and boundary condition effects on TABS behavior.

Energy use of the building and thermal comfort of the occupants are terms that generally come into conflict [24]. TABS need to be designed, to the extent of their thermal inertia properties and operation control, from an integrated perspective, in which energy waste and thermal discomfort are the most common objectives to minimize. A well-structured follow-up approach can assist in reaching these aims.

As Gwerder et al. [12] claim in their research, room temperature feedback control can improve comfort if heating and cooling curves are placed incorrectly or if the intermittent zone pump operation is inaccurate due to modeling errors. Moreover, energy efficiency can be increased when room temperatures are controlled making full use of the room temperature comfort range. This also leads to less frequent switching between heating and cooling demand of the zone. Additionally, commissioning and the adjusting effort can be reduced since the feedback control corrects settings that are wrong. However, the intermittent operation can lead to more switching between heating and cooling demand than necessary [25]. This can also contribute to reducing the achievable comfort level. During off-times, no heat is exchanged to the water circuit. This has to be compensated by higher (heating) or lower (cooling) supply water temperatures during on-times, respectively, which reduces the self-regulating effect.

Systematic control of TABS operation, which takes account of their inertial response, occupant feedback, internal gains and boundary conditions, has positive effects on the indoor air environment during the summer and winter periods. The control, monitoring, auditing and managing of building systems are key to comprehensive, sustainable and energy efficient building operations. Therefore, it has been demonstrated that properly conducted optimizing operations after the commissioning of TABS are essential to minimize thermal discomfort and energy waste and to adapt the control parameters to the effective situation in buildings [26]. LEED Platinum rating is very comprehensive in applying IEQ-related measures and therefore should be viewed as providing greater productivity and health benefits. The application of a “Plan-Do-Check-Act” approach, in line with the protocol pursued by the LEED rating system, is necessary to achieve high standards in terms of building energy performance. In the same way, following a systematic procedure for TABS that deliver prompt adjustments or repairs in response to problems identified, is positive for enhancing thermal comfort and achieving continual improvement of TABS energy performance.

The approach adopted enables acquiring greater awareness of the operative parameters that are used to account for TABS, while catching cause-and-effect relationships which links one to the other. The monitoring of building performance is possible thanks to the availability of historical and real-time data, provided by a control system, which produces information and allows the adoption of strategies, with the aim to reduce the trade-off between energy savings and thermal comfort of the occupants.

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