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Design of a predictive control system for the smart regulation of renewable climatization systems

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ABSTRACT.

The objective of this Project is to design a predictive controller for Heating Ventilation and Air Conditioning in residential buildings is designed. A realistic residential home has been designed, establishing the dynamics of the temperature according to a theoretical model that has been elaborated, being the basis for the actuation of the temperature-regulation controller. Several simulations have been carried out, defining the objective function and the constraints associated, together with the controller parameters that allow an optimal performance, taking into account different criteria such as thermal comfort and reduction of power consumption for different scenarios. In addition, electricity self-generation has been also contemplated, integrating it into the controller actuation for leveraging the increase in economic savings.

KEY WORDS

Model Predictive Control, Climatization, Renewable energy, Smart regulation, Aerothermal climatization.

1 INTRODUCTION

The European Green Deal sets out a new strategy to reconcile economic growth with emission reductions, prosperity and social justice. In 2021, the EU approved the European Climate Law, which includes climate neutrality by 2050 as a binding target and a reduction of at least 55% of greenhouse gas emissions compared to 1990 as an intermediate target for 2030, and Spain has also approved the Climate Change and Energy Transition Law, which is also aligned with the global ambition of not exceeding a temperature increase of 1.5ºC.

As a reference, each person in Spain emits an average of 7 tons of greenhouse gases per year, 2 of which correspond to heating alone. Therefore, we must try to avoid using systems such as coal that is the most polluting of all heating technologies, responsible for the emission of 4 tons of greenhouse gases per family. Fortunately, they are almost no longer used in Spain. While natural gas heating, the most widespread in the Peninsula, is emitting about 1.8 tons of CO2, almost 2. In addition, conventional systems, like electric radiators, account for 2.1 tons and a bill of more than a thousand euros per year if used as the only method of heating. Therefore, the impact of heating must be reduced using cleaner technologies. Technologies such as Biomass (0.3 Tm.), Geothermal (0.5 Tm.), and Aerothermal (0.7 Tm.) help to reduce not only emissions but also the cost of heating a home. Moreover, the latter two technologies will become even cleaner as more and more renewables become available in the electricity sector.

This paper proposes the design of a model predictive controller to reduce energy consumption in homes. This control strategy is one of the modern control techniques that it is currently experiencing the greatest development for temperature regulation in buildings, since it allows to achieve the necessary thermal comfort for people, while minimizing the required energy consumption, unlike PID control, the most common control nowadays. In this way, it is possible to increase the energy efficiency of a building through the implementation of new technological regulation systems, which are framed within the guidelines provided by the European Union in its strategic plan.

2 LITERATURE REVIEW

There are several control strategies to achieve temperature regulation in buildings, including those for residential use. All these strategies aim to achieve and maintain thermal comfort inside the building [5].

Control strategies can be classified according to various criteria. If people have to actively intervene in the regulation, it is called manual control, while if they do not intervene, it is called automatic control. At the time of the first temperature controllers, manual control was performed, but nowadays it is automatic control, since it frees man from performing a repetitive task.

Depending on the type of controller and algorithm used, there are different control methodologies. All of them are grouped into 5 categories. The first category is classical control, which includes on/off control and PID control. The second category is strong control, based on system control theories, such as predictive model control. The third category is soft control, based on experience and data, such as fuzzy logic control or neural network control. The fourth category is hybrid control, which combines hard and soft control techniques. And the fifth category is other control techniques [6].

This control was introduced in the 1980s for the regulation of processes in the chemical industry, not being until the 2010s when its use has experienced significant growth in the field of thermal regulation for buildings, due to the high computational requirements needed [5].

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Previous papers, propose the implementation of linear MPC for building climate control [10]. Yang and Wan developed a machine-learning–based MPC with an instantaneous linearization scheme linear MPC to control the indoor climate of a hospital [11]. Although the approach has an advantage on computation time, the cooling energy consumption of MPC without linearization is still lower than that of linear MPC. In Ref. [12], temperature and humidity are considered but not renewable energy systems. In addition, besides HVAC, the modern technology of hybrid energy systems to heat up or cool down building indoor temperature has gained more popularity but has not been included in most MPC studies [13].

3 METHODOLOGY

3.1 Thermal model

The first step in designing a predictive controller for air conditioning is to define a theoretical model of the temperature evolution in an enclosure.

According to the First Law of Thermodynamics applied to a control volume, the law of conservation of energy governs the evolution of temperature in that volume. This differential equation is stated generically as follows:

$$\dot{E}_{est} = \dot{E}_{in} - \dot{E}_{out} + \dot{E}_g$$

Where $\dot{E}_{est}$ is the rate of change of energy stored in the volume, expressed in W; $\dot{E}_{in}$ is the rate of energy entering the volume, expressed in W; $\dot{E}_{out}$ is the rate of energy leaving the volume, expressed in W; and $\dot{E}_g$ is the rate of energy generated in the volume, expressed in W.

If we particularize that generic control volume to an enclosure, we obtain the equation that determines its thermal behavior. In this case, a number of considerations can be made, which allow us to break down the previous terms.

The $\dot{E}_{est}$ term is taken as the thermal energy variation per unit time experienced by the air inside the enclosure. The air temperature throughout the enclosure is to be considered homogeneous and uniform. Thus, it is obtained that:

$$\dot{E}_{est} = m_{air} \cdot c_p \cdot \frac{dT}{dt}$$

Where m_{air} is the mass of air in the enclosure, expressed in kg; c_p is the specific heat of the air, expressed in J/(kg·K); and $\frac{dT}{dt}$ is the time variation of air temperature.

The $\dot{E}_{in}$ and $\dot{E}_{out}$ terms cover the thermal powers associated with the solar radiation received $\dot{Q}_{rad}$; the heat transmitted by the enclosure enclosures $\dot{Q}_{cerr}$; and the ventilation thermal load necessary to maintain healthiness levels that meet the legally established requirements, $\dot{Q}_{vent}$. Thus, the breakdown of terms is obtained as follows:

$$\dot{E}_{in} - \dot{E}_{out} = \dot{Q}_{rad} + \dot{Q}_{cerr} + \dot{Q}_{vent}$$

The heat by solar radiation $\dot{Q}_{rad}$, expressed in W, is:

$$\dot{Q}_{rad} = G_i \cdot S \cdot F \cdot Or \cdot f$$

Where G_i is the global irradiance, expressed in W/m^2; S is the area of the window on which it is incident, expressed in m^2; F is the modified solar factor; Or is the solar radiation coefficient according to the orientation of the window; and f is the attenuation correction factor for elements such as curtains or awnings.

The heat transmitted through an enclosure j, denoted $\dot{Q}_{cerr\,j}$, expressed in W, is calculated as:

$$\dot{Q}_{cerr\,j} = U_j \cdot A_j \cdot (T_{ext} - T_{int})$$

Where U_j is the overall heat transmission coefficient, expressed in W/(K m^2); A_j is the area of the enclosures through which heat is transmitted, expressed in m^2; T_{int} is the temperature of the enclosure, expressed in K; and T_{ext} is the temperature of the external environment with which the enclosure area contacts, expressed in K. It is important to note that this external environment includes both the external environment and other possible enclosures.

Considering that an enclosure has several enclosures, the general expression is:

$$\dot{Q}_{cerr} = \sum_j U_j \cdot A_j \cdot (T_{ext} - T_{int})$$

Where the subscript j denotes the number of enclosures present in the enclosure in question.

The ventilation thermal load $\dot{Q}_{vent}$, is expressed in W and takes the following form:

$$\dot{Q}_{vent} = \dot{m}_{vent} \cdot c_p \cdot (T_{amb\,ext} - T_{int})$$

Where $\dot{m}_{vent}$ is the mass flow rate of ventilation air required for the enclosure, expressed in kg/s; c_p is the specific heat of the ventilation air, expressed in $J/(kg\ K)$; T_{int} is the temperature of the enclosure, expressed in K; and $T_{amb\,ext}$ is the outdoor ambient temperature, expressed in K. The flow rate $\dot{m}_{vent}$ can also be calculated as the product of the outdoor air density ρ_{ext}, expressed in kg/m^3 by the ventilation flow rate $\dot{V}_{vent}$ introduced into the enclosure, expressed in m3/s. Therefore, this component is:

$$\dot{Q}_{vent} = \rho_{ext} \cdot \dot{V}_{vent} \cdot c_p \cdot (T_{amb\,ext} - T_{int})$$

Finally, the $\dot{E}_g$ term comprises the thermal loads due to lighting $\dot{Q}_{ilum}$, equipment $\dot{Q}_{equip}$; and occupancy $\dot{Q}_{ocup}$, which has a latent heat component in addition to a sensible heat component. The thermal load introduced by the air conditioning system present in the enclosure $\dot{Q}_{clim}$ have to be incorporated. Therefore:

$$\dot{E}_g = \dot{Q}_{ilum} + \dot{Q}_{equip} + \dot{Q}_{ocup} + \dot{Q}_{clim}$$

Getting all the developments of the terms that have been made, we obtain the following differential equation that determines the time evolution of the temperature:

$$\rho \cdot V \cdot c_p \cdot \frac{dT}{dt} = \dot{Q}_{rad} + \dot{Q}_{cerr} + \dot{Q}_{vent} + \dot{Q}_{ilum} + \dot{Q}_{equip} + \dot{Q}_{ocup} + \dot{Q}_{clim}$$

The regulation of the thermal power term associated with the air conditioning system is achieved with the predictive control that has to be designed.

3.2 Integration of climate control with self-consumption

The purpose of the PV self-consumption plant is to serve as a source of auxiliary power for the air conditioning system, so a new thermal power generated term, called $\dot{Q}_{aut}$, expressed in W, has to be considered in the previous equation. This term represents the part of thermal power generated by the air-conditioning system from the electrical energy conversion provided by the photovoltaic panels.

The power provided by the photovoltaic system is:

$$\dot{Q}_{aut} = HSP \cdot A_{panel} \cdot N_{paneles} \cdot \dot{W}_{pico} \cdot COP$$

Where $\dot{Q}_{aut}$ is the thermal power provided by the PV system, expressed in W; HSP is the peak sun hours received by the system; A_{panel} is the area of a PV panel, expressed in m^2; $N_{paneles}$ is the number of panels of the PV system; $\dot{W}_{pico}$ is the peak power provided by a panel, expressed in W; and COP is the coefficient of performance of the air-conditioning system.

The value of HSP can be expressed as the global irradiance $G_i$divided by 1000 W/m^2, then the final expression of the thermal power for air conditioning from the PV system is:

$$\dot{Q}_{aut} = \frac{G_i}{1000} \cdot A_{panel} \cdot N_{paneles} \cdot \dot{W}_{pico} \cdot COP$$

Therefore, the differential equation to be considered is:

$$\rho \cdot V \cdot c_p \cdot \frac{dT}{dt} = \dot{Q}_{rad} + \dot{Q}_{cerr} + \dot{Q}_{vent} + \dot{Q}_{ilum} + \dot{Q}_{equip} + \dot{Q}_{ocup} + \dot{Q}_{clim} + \dot{Q}_{aut}$$

Where thermal control is achieved through the appropriate choice of thermal power values associated with air conditioning and self-consumption.

4 DEVELOPED MODEL

A residential house has been considered as a model of enclosure, specifically a single-family home for 6 people. Its location has been established in the mountains of Madrid, since it is a location where it is interesting to achieve energy savings. The house has 2 floors above ground, a basement floor, and a sloping gable roof.

For the calculations in this paper, we have taken as design conditions operating temperatures of 24ºC and 22ºC in summer and winter respectively, in addition to a relative humidity of 50% in both seasons for all air-conditioned rooms of the house.

For the sizing of the photovoltaic installation, the available surface area for the placement of the solar panels on the roof has been considered; the absence of shadows that prevent the correct reception of radiation; the geographical location of the house; and the greater energy consumption needs in winter for the air conditioning of the house.

Thus, a photovoltaic installation consisting of 14 JA Solar 450 W panels has been considered, providing a total peak power of 6.3 kW.

4.1 Model hypotheses

A number of additional assumptions have been made about the model developed. These assumptions are:

- The calculated values for the model parameters have no uncertainties, assuming perfect knowledge of the thermal model.
- Doors and windows are assumed to be closed. This implies that heat flow is established by conduction through them.
- The specific heat and density of both internal and external air are constant and independent of the air temperature value.
- The dwelling can be considered as a composition of zones that present their own temperatures, with existence of thermal homogeneity. [7]

4.2 Design of a predictive air conditioning control system

As already indicated, the thermal model that allows to control the temperature in an enclosure is given by the following equation:

$$\rho \cdot V \cdot c_p \cdot \frac{dT}{dt} = \dot{Q}_{rad} + \dot{Q}_{cerr} + \dot{Q}_{vent} + \dot{Q}_{ilum} + \dot{Q}_{equip} + \dot{Q}_{ocup} + \dot{Q}_{clim} + \dot{Q}_{aut}$$

When it is desired to control the temperature of several rooms simultaneously, a system of differential equations must be solved. Each equation is associated with the temperature dynamics of an enclosure, the unknowns to be determined are the thermal power for air conditioning and the one associated with self-consumption. Specifically, the single-family home considered as an example of application, consists of 23 rooms, but only 17 are air-conditioned. Therefore, a system of 23 differential equations will have to be solved, with unknowns in 17 equations, since for the 4 non-heated rooms $\dot{Q}_{clim}$ and $\dot{Q}_{aut}$ are null.

This system of equations will be solved using the Model Predictive Control (MPC) method, which will be implemented by programming in Matlab, incorporating the Yalmip software, whose purpose is to model optimization problems [8]; and the Ipopt software, whose utility is to solve optimization problems [9].

Specifically, a centralized MPC is going to be developed, characterized because there is a single controller that regulates the dynamic behavior of all the enclosures of the house in order to meet the desired thermal operating conditions.

In an MPC controller the parameter values of the sampling time, the prediction horizon and the control horizon have to be set. The values assigned to them have a very relevant influence on the results provided by the controller, so it is necessary to select them properly to achieve the best results. However, there are no analytical methods that allow determining the optimal combination of these 3 parameters, beyond a series of general considerations that allow starting the iteration of values, finally obtaining through the trial-and-error method, those values that allow the generation of adequate results.

In addition to these 3 parameters, it is also necessary to fix the positive values of the coefficients of the different terms that constitute the objective function that the controller tries to minimize. Similarly, these weights have a notable influence on the results provided by the controller, and must be carefully chosen by trial and error, there being no analytical methods for this purpose. It is emphasized that for these parameters as well as for those mentioned above, their values that provide optimum controller behavior vary with the modeling that has been carried out in each case as well as with the initial conditions that are considered.

In the different cases analyzed, the control horizon is equal to the prediction horizon, a fairly common practice. The choice of sampling time, prediction horizon and weights is made considering several criteria, such as the accuracy of the temperature results, the energy cost associated with power consumption or the computation time needed by the controller to solve the system of differential equations.

4.2.1 Temperature control of the house

The objective of this first case is that the temperature of all the air-conditioned rooms of the house should be the set operating temperature, 24°C in summer and 22°C in winter. To achieve this, an objective function must be defined, which the MPC controller will minimize over the entire simulated time period in which it operates, together with constraints that reflect the existing physical situation and limit the power values the controller must consider.

The objective function is expressed as the difference between the temperature existing at an instant in each enclosure and the operating temperature at which it should be. The minimization of this difference must be performed along the established prediction horizon. In order to weight the importance of this term of the objective function, a weight is incorporated in the objective function. Thus, initially, the objective function is:

$$F = \sum_{i=1}^{Np} \sum_{j=1}^{Nu} K_1 \cdot \left(T_{op} - T_{i,j}\right)$$

Where FO is the objective function; Np is the prediction horizon; Nu is the number of air-conditioned rooms in the dwelling; K_1 is the weight of the temperature difference term; T_{op} is the operative temperature; and $T_{i,j}$ is the room temperature at the time instant associated to step i of the prediction horizon.

A usual and recommended practice is to dimension the terms of the objective function, to avoid that the terms whose values belong to a higher order of magnitude, do not present more weight than the remaining ones. For this purpose, it will be divided by the operating temperature. Moreover, since the difference in this term can be negative or positive, it will be squared, so that the result always adds up in the objective function. At this point, the objective function has the following expression:

$$F = \sum_{i=1}^{Np} \sum_{j=1}^{Nu} K_1 \cdot \left(1 - \frac{T_{i,j}}{T_{op}}\right)^2$$

The restrictions to be considered by the controller to solve the minimization problem are the following:

1. The initial temperature of the rooms is the one existing at the moment of the beginning of the controller action.
2. The existing temperature in the rooms after the application of the air conditioning power during one step of the prediction horizon and the following one, of temporal duration the value of the sampling time, must comply with the dynamics established by the thermal model.
3. The power calculated by the controller to achieve the operating temperature must be in a range of values limited by the maximum cooling power and the maximum heating power.

The optimization problem is stated as:

$$\min \sum_{i=1}^{Np} \sum_{j=1}^{Nu} K_1 \cdot \left(1 - \frac{T_{i,j}}{T_{op}}\right)^2$$

Subjected to the following restrictions:

$$T_{i+1,j} = T_{i,j} + \Delta t \cdot f(T_{i,j}, Q_{i,j})$$
$$Q_{ref\ i,j} \leq Q_{i,j} \leq Q_{cal\ i,j}$$

With this formulation it may happen that there is no solution to the optimization problem, being impossible to control the temperature of the rooms. To solve this problem, a deviation margin is allowed in the temperature of the rooms with respect to the operative temperature, the controller being in charge of minimizing this deviation as much as possible. This means that the final formulation of the optimization problem is as follows:

$$\min \sum_{i=1}^{Np} \sum_{j=1}^{Nu} K_1 \cdot \left(1 - \frac{T_{i,j}}{T_{op}}\right)^2 + K_2 \cdot \left(\frac{\Delta T_{i,j}}{T_{op}}\right)$$

Subjected to the following restrictions:

$$T_{i+1,j} = T_{i,j} + \Delta t \cdot f(T_{i,j}, Q_{i,j})$$
$$T_{k+1,j} - \Delta T_{i,j} \leq T_{op}$$
$$\Delta T_{i,j} \geq 0$$
$$Q_{ref} \leq Q_{i,j} \leq Q_{cal}$$

Where FO is the objective function; Np is the prediction horizon; Nu is the number of air-conditioned rooms in the dwelling; K_1 is the weight of the temperature difference term; T_{op} is the operating temperature; and $T_{i,j}$ the temperature of enclosure j at the time instant associated with step i of the prediction horizon; K_2 is the weight of the temperature deviation term; Δt is the sampling time; $\Delta T_{i,j}$ is the temperature deviation of enclosure j at the time instant associated with step i of the prediction horizon; Q_{ref} is the maximum possible cooling power; Q_{cal} is the maximum possible heating power; and $Q_{i,j}$ is the power determined by the controller to adequately air condition room j at the time instant associated with step i of the prediction horizon.

4.2.2 Temperature control of the house by minimizing the consumption of power from the grid and maximizing the consumption of power from photovoltaic sources

The objective of this second case is to reduce the power from the electrical grid consumed for air conditioning, allowing longer transients to achieve the target operating temperature, but in any case, reaching the reference temperature in the rooms of the house. Part of this reduction can be achieved using power from the home's photovoltaic installation, the use of which is maximized by the controller.

For this purpose, two new terms are added to the objective function to include the influence of using power from the electrical grid and power from the photovoltaic system. Thus, the objective function is:

$$\mathrm{F} = \sum_{i=1}^{Np} \sum_{j=1}^{Nu} K_1 \cdot \left(1 - \frac{T_{i,j}}{T_{op}}\right)^2 + K_2 \cdot \left(\frac{\Delta T_{i,j}}{T_{op}}\right)$$
$$+ K_3 \cdot \left(\frac{\left|Q_{red\ i,j}\right|}{Q_{ref}}\right) + K_4 \left(1 - \frac{\left|Q_{aut\ i,j}\right|}{Q_{ref}}\right)^2$$

Where K_3 is the weight of the power utilization term of the electric grid; $Q_{red\ i,j}$ is the power from the electric grid consumed in room j at the instant of time associated to step i of the prediction horizon; Q_{ref} is the reference thermal power used in the air conditioning of the house during 1 day, regardless of the origin of the power consumed in the air conditioning system; K_4 is the weight of the power utilization term of photovoltaic origin; and $Q_{aut\ i,j}$is the power from the photovoltaic system consumed in room j at the time instant associated to step i of the prediction horizon.

For the controller to favor the consumption of power from the PV system, it is necessary to impose that the weights K_3 and K_4 are related to each other. The K_4 weight must be significantly smaller than the K_3 weight so that its influence on the objective function is smaller and the controller allows to increase the absolute values of $Q_{aut\ i,j}$ compared to $Q_{red\ i,j}$.

In addition, the constraints imposed must be modified. On the one hand, it is now necessary to ensure that the sum of the thermal power, either from the grid or from the photovoltaic system, does not exceed the power limits that can be provided by the air-conditioning system. On the other hand, two new restrictions must be added, since neither the thermal power $Q_{aut\ i,j}$ of room $,j$, nor the sum of the powers of all the rooms can ever be greater in absolute value than the thermal power generated by the photovoltaic installation from the incident solar radiation at the time instant associated to step i of the prediction horizon.

That is, the complete formulation of the optimization problem is:

$$\min \sum_{i=1}^{Np} \sum_{j=1}^{Nu} K_1 \cdot \left(1 - \frac{T_{i,j}}{T_{op}}\right)^2 + K_2 \cdot \left(\frac{\Delta T_{i,j}}{T_{op}}\right)$$
$$+ K_3 \cdot \left(\frac{\left|Q_{red\ i,j}\right|}{Q_{ref}}\right) + K_4 \left(1 - \frac{\left|Q_{aut\ i,j}\right|}{Q_{ref}}\right)^2$$

Subjected to the following restrictions:

$$T_{i+1,j} = T_{i,j} + \Delta t \cdot f(T_{i,j}, Q_{i,j}, Q_{aut\ i,j})$$
$$T_{k+1,j} - \Delta T_{i,j} \leq T_{op}$$
$$\Delta T_{i,j} \geq 0$$
$$Q_{ref\ i,j} \leq Q_{i,j} + Q_{aut\ i,j} \leq Q_{cal\ i,j}$$
$$0 \leq \left|Q_{aut\ i,j}\right| \leq \frac{G_i}{1000} \cdot N_{paneles} \cdot \dot{W}_{pico} \cdot COP$$
$$\sum_{j=1}^{Nu} \left|Q_{aut\ i,j}\right| \leq \frac{G_i}{1000} \cdot N_{paneles} \cdot \dot{W}_{pico} \cdot COP$$

Where COP is the Coefficient of Performance of the air conditioning system, estimated at a value of 3.

4.2.3 Temperature control of the house minimizing the consumption and economic cost of the power coming from the electrical grid and maximizing the consumption of photovoltaic power

The objective of this third case is to achieve a reduction both in the consumption of power from the electrical grid and in the economic cost associated with its use, which depends on the time of day when the power is consumed. In this way, the aim is to minimize the total economic cost of the air conditioning of the house, while maximizing the use of the power from the solar photovoltaic installation, which has no costs for its use.

For this purpose, a fifth term has been added to the objective function. This term represents the economic cost derived from the use of the power coming from the electrical grid to feed the air conditioning system. The objective function has the following expression:

$$F = \sum_{i=1}^{Np} \sum_{j=1}^{Nu} K_1 \left(1 - \frac{T_{i,j}}{T_{op}}\right)^2 + K_2 \left(\frac{\Delta T_{i,j}}{T_{op}}\right)$$
$$+K_3 \left(\frac{|Q_{red\ i,j}|}{Q_{ref}}\right) + K_4 \left(1 - \frac{|Q_{aut\ i,j}|}{Q_{ref}}\right)^2 + K_5 \left(\frac{|Q_{red\ i,j}| \cdot C_{i,j} \cdot \Delta t}{COP \cdot C_{ref}}\right)$$

Where K_3 is the weight of the economic cost term of the power consumed from the electrical grid; $C_{i,j}$ is the cost of the electrical power from the electrical grid consumed in the air conditioning of room j at the time instant associated with step i of the prediction horizon, expressed in $€/J$; and C_{ref} is the reference cost of air conditioning the house for 1 day.

The constraints are not affected, so the final formulation of the optimization problem is:

$$min \sum_{i=1}^{Np} \sum_{j=1}^{Nu} K_1 \left(1 - \frac{T_{i,j}}{T_{op}}\right)^2 + K_2 \left(\frac{\Delta T_{i,j}}{T_{op}}\right)$$
$$+K_3 \left(\frac{|Q_{red\ i,j}|}{Q_{ref}}\right) + K_4 \left(1 - \frac{|Q_{aut\ i,j}|}{Q_{ref}}\right)^2 + K_5 \left(\frac{|Q_{red\ i,j}| \cdot C_{i,j} \cdot \Delta t}{COP \cdot C_{ref}}\right)$$

Subjected to the following restrictions:

$$T_{i+1,j} = T_{i,j} + \Delta t \cdot f(T_{i,j}, Q_{i,j}, Q_{aut\ i,j})$$
$$T_{k+1,j} - \Delta T_{i,j} \leq T_{op}$$
$$\Delta T_{i,j} \geq 0$$
$$Q_{ref\ i,j} \leq Q_{i,j} + Q_{aut\ i,j} \leq Q_{cal\ i,j}$$
$$0 \leq |Q_{aut\ i,j}| \leq \frac{G_i}{1000} \cdot N_{paneles} \cdot \dot{W}_{pico} \cdot COP$$
$$\sum_{j=1}^{Nu} |Q_{aut\ i,j}| \leq \frac{G_i}{1000} \cdot N_{paneles} \cdot \dot{W}_{pico} \cdot COP$$

5 RESULTADOS Y DISCUSIÓN

En esta sección se presentan y se discuten los resultados obtenidos a partir de las simulaciones realizadas para el comportamiento térmico de los diferentes casos indicados en la vivienda unifamiliar.

5.1 Winter

In this situation, the use of power from both the grid and the photovoltaic installation for self-consumption is considered. The operating temperatures are maintained at 18ºC from 11 p.m. to 6 a.m. and 22ºC for the rest of the hours.

The best combination of parameters to obtain the best balance between thermal comfort, power savings and maximization of photovoltaic consumption is given by the following values: $K_1 = K_2 = 1$, $K_3 = 0{,}001$, $K_4 = K_3/1000 = 10^{-6}$, $K_5 = 5 \cdot 10^{-4}$, $N_p = 2$ and $\Delta t = 1\ h$.

Figure 1, Figure 2 and Figure 3 show the results of the temperatures obtained.

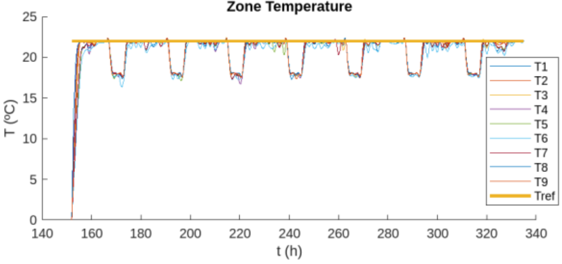

Figure 1. First floor rooms temperatures during winter

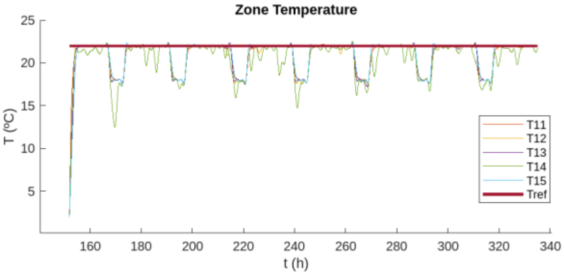

Figure 2. Ground floor rooms temperatures during winter

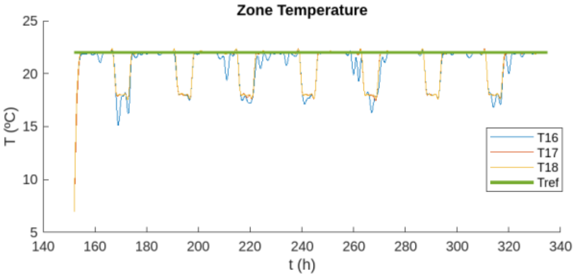

Figure 3. Basement room temperatures during winter

The thermal power generated by the air-conditioning system is shown in Figure 4.

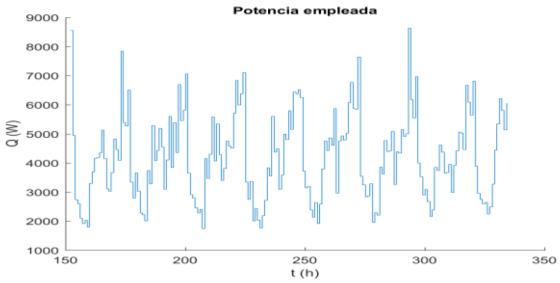

Figure 4. Heating thermal power for the house.

Thus, the annual electricity consumption for heating was 7980 kWh, of which 5460 kWh came from the grid and 2520 kWh from the photovoltaic system.

5.2 Summer

In this situation, the use of power from both the grid and the photovoltaic system for self-consumption of the house is considered. Similarly, for the summer conditions described above, the best combination of parameters to obtain a balance between thermal comfort and electricity savings thanks to the maximization of the photovoltaic consumption is given by the following values: $K_1 = K_2 = 1$, $K_3 = 0{,}01$, $K_4 = K_3/1000 = 10^{-5}$, $K_5 = 0{,}01$, $N_p = 2$ y $\Delta t = 0{,}5\ h$.

Figure 5, Figure 6 and Figure 7 show the results of the temperatures obtained.

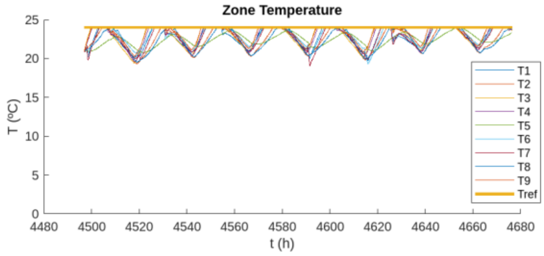

Figure 5. First floor rooms temperatures during summer

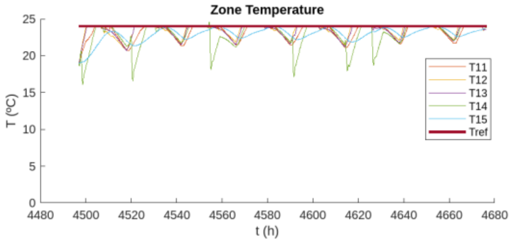

Figure 6. Ground floor rooms temperatures during summer

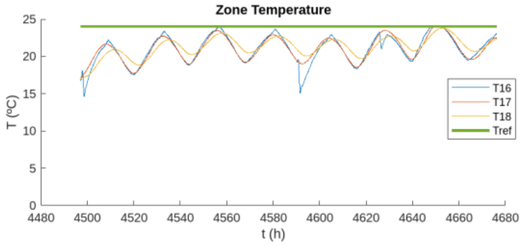

Figure 3. Basement room temperatures during summer

The thermal power generated by the air-conditioning system is shown in Figure 8.

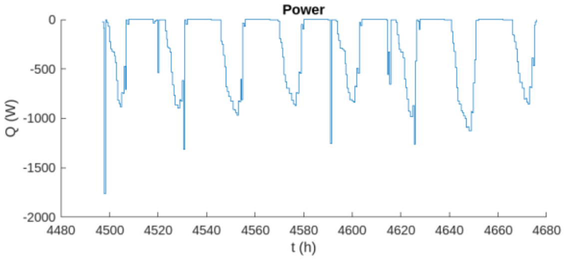

Figure 8. Cooling thermal power for the house.

Thus, the annual electricity consumption for cooling was 3140 kWh, of which 980 kWh came from the grid and 2160 kWh from the photovoltaic system.

6 CONCLUSIONS

After analyzing the different results obtained, we can conclude that the thermal model adequately reflects the thermal evolution of a single-family home and the thermal properties of the materials used in the construction of a single-family house have been considered accordingly to the actual legislation.

Also, the operating parameters of the controller have been determined by predictive model that allow an optimal performance of the controller. For each of the simulated situations, a set of parameter values has been found that always ensures the thermal comfort of the house, in addition to complying with the other optional functionalities of the controller.

The consumption and the associated economic cost of the energy coming from the electrical network have been minimized. Moreover, a reduction in consumption and cost has been achieved in both winter and summer seasons with respect to the base case of single temperature control. In winter, the reduction in consumption and cost was 9.02% and 15.50%, respectively. In summer, a reduction in consumption and cost of 69.23% and 71.38%, respectively, was achieved.

The consumption of electricity from the photovoltaic installation for self-consumption of the single-family home has been maximized. In both winter and summer, the value of electrical energy used by the air conditioning system from the photovoltaic installation has been increased. In winter this increase was 1.89%, while in summer the increase was 11.11%.

The controller has a correct behavior when there are intense disturbances in the thermal loads. It has been demonstrated that with the parameter values obtained in common situations, the controller is able to act adequately in exceptional situations such as heat waves or cold waves, maintaining at all times the thermal comfort in the single-family house.

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