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A simplified building thermal model for the optimization of energy consumption: Use of a random number generator

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ABSTRACT

This paper proposes a new method for an optimal control of the heating system at the building scale. This control is a new approach of energy planning that aims to decrease the heating consumption/expenses over a defined prediction horizon while respecting the occupants' thermal comfort. It employs a simplified building thermal model to simulate the building thermal behavior taking into consideration the weather predictions. This approach is based on the application of Monte Carlo method, i.e., a random generator for the heating system scenarios. The aim is to determine the optimal heating plan for the prediction horizon that fulfills the constraints regarding the thermal comfort of occupants and the minimization of the energy consumption/expenses together with achieving a load shedding.

1. State of art

1.1. Introduction

Energy is considered nowadays as one of the most challenging issues. In cold climates, heating is responsible for approximately 50% of the total final energy consumption [1]. According to ADEME and INSEE [2,3], buildings account for the highest energy consuming assets with 44% of the total energy consumption and 19% of the green house gas emissions in France. Strategies have been set in order to reduce the energy consumption. These strategies contain regulations to ameliorate the building thermal performance. Starting from January 2013, the thermal regulation reference (*RT*2012) is put in action in France. This reference includes many obligatory and complementary requirements that guarantee the conventional interior temperature and the reduction of energy consumption. It concerns building cold bridges (thermal bridges), building airtightness (air permeability) and building thermal characteristics [2,4]. Moreover, insulation requirements and pricing plans have been developed to reduce the energy losses and the consumption peaks. According to [5,6], a considerable part of the energy consumed in the building sector is due to either bad insulation or bad control of the heating systems (unoptimized consumption).

A study of the National Renewable Energy Laboratory (NREL) identifies the "lack of innovative controls and monitoring systems" as one of the principal challenges in achieving high energy efficiency in buildings [7,8]. The control of energy in buildings uses mainly one of the following systems [9,10]:

- On/Off system: traditional systems.
- Proportional controls: this system aims at eliminating the cycling associated with on-off control. It includes an effector device (heater) and a controller. The heating power is controlled on a proportional relationship according to the temperature of the controlled medium [11].
- PID control: this method is popular in heating control. It combines proportional control with two additional adjustments (error integral and derivative), which helps the unit automatically compensate for changes in the system. PID controllers are robust and allow accurate tuning, but they cannot reflect the outside temperature effects [10,12–14,10]. Fig. 1 shows a block diagram of a PID controller. Wemhoff [15] concludes that a good calibration of proportional coefficients can reduce the system energy

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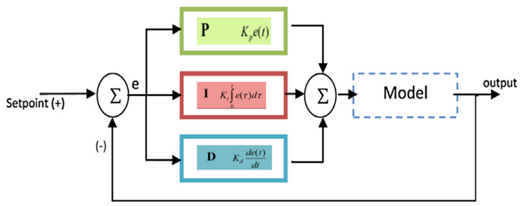

Fig. 1. PID controller block diagram.

consumption by up to 29% and can improve meeting temperature set points by up to 45%.

- Model predictive controllers (MPC) [10,16]: this method is considered as a powerful framework for the optimization of the buildings heat consumption as a constrained minimization problem considering both comfort requirements and limited capacity of the heating system. MPC is considered as an ideal framework to tackle this problem [17,18]. This approach depends on generating a heating plan for an upcoming prediction horizon which is a receding horizon where only the first step of the predicted plan is applied to the system while all other inputs are used only to make good decisions at the current time step. This requires an important computation power and a reliable weather prediction. However, nowadays with the powerful computation powers and the possibility to do the computation in external places such as clouds, MPC becomes more doable [19,20]. Castilla et al. [21] concludes that the non-linear MPC approach is able to maintain thermal comfort inside a comfort zone even in the presence of disturbances, and to minimize the energy consumption derived from the use of the HVAC system around a 53%, in comparison with other approaches.

1.2. Main idea of the paper

This paper presents a control approach that has a constrained optimization problem as in MPC. The optimization concerns the minimization of energy consumption by exploiting the occupation profile, the dynamic pricing and the building inertia (thermal mass).

This approach is based on the application of Monte Carlo method, i.e., randomly generating sequences of the heating system states, testing these sequences then choosing the best one for the heating according to the least consumption or the least price. The simplicity of the optimization process is the main difference between the proposed approach and MPC. Since the method is based on the use of three elements: the building inertia, the occupation profile and the dynamic pricing, it could lead to a higher heating consumption in the case of no-occupation. This allows shifting the energy consumption to the cheap pricing period. By doing this, we benefit of building slow heat dynamics to turn off the heating during the expensive pricing period maintaining the comfort needed in the occupation periods [22]. In other words, we benefit of the building thermal time constant which helps to maintain an acceptable level of comfort for a certain period. Meanwhile, heating can be reduced or even shut down [23,24]. The application of this method results in a heating plan which is optimal for the prediction horizon period (between all tested plans). Which constitutes the necessity of a large number of sequences to insure having an optimal plan.

Table 1
Hours classification according to the price of *kWh* in France 2014.

	Normal hours	Peak hours
Hour	22:00–06:00	06:00–22:00
Price (TTC) euro/kWh	0.1044	0.1510

2. Objectives

The thermal comfort is defined by several indicators such as the interior temperature, the relative humidity and the air velocity. Hence, the interior temperature is considered nowadays as the key element in building's heating. The thermal comfort temperature varies between day and night or according to the building usage [25,26]. A study of the American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) proposed an interval of accepted indoor temperature according to the exterior one [26,27]. It is delicate to define the comfort temperatures because it highly affects the energy consumption and it depends on different factors as:

- the building usage;
- the activities of occupants (in the occupation periods);
- the internal heat gains to be considered.

Some scientific works studied the determination of optimal environment in buildings considering energy consumption and human comfort in a building [28] or in a certain type of buildings as the study related to office buildings optimal working environment in [29,30] and the study about residential buildings in [31]. Fig. 2 shows an example of a chosen comfort interval for an office building. It is essential to note that the thermal comfort in an occupation period in not to be compromised. While on the other hand, in the no-occupation period, we can authorize a higher heating to benefit of the cheap price of the energy. Afterwards, according to the building thermal constant, the building will keep a certain level of comfort for a certain period. This period depends on the building inertia and is taken into consideration.

After defining this comfort level, the objective is to minimize the energy consumption and cost. The energy consumption is the integration of the power supplied over time. In France, normally the electricity subscription is priced depending on the supplied power $P(watt)$ and the consumed energy $Q(kWh)$, a day time is also priced into two types: peak hours and normal hours. Table 1 shows the considered dynamic pricing of the electricity in 2014 in France ($euro/kWh$). Thereby the timing of consumption must be well planned in order to not exceed the maximum power supplied on one hand and to minimize the consumption cost on the other hand.

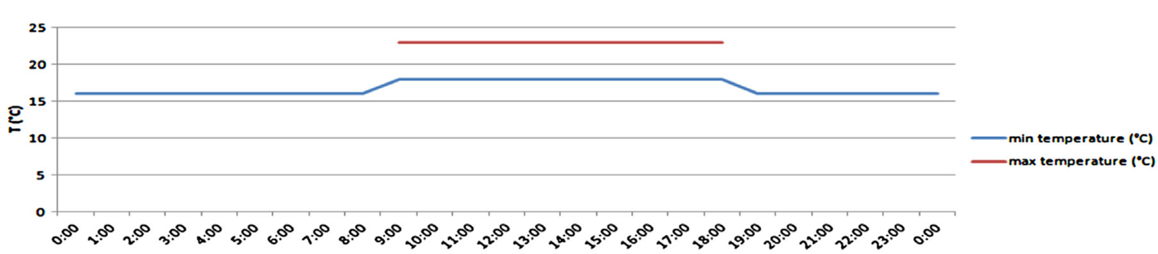

Fig. 2. An example for the a chosen temperature interval for an office building.