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

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RESUME. Ce document propose une nouvelle méthode de gestion optimale de contrôle du système de chauffage. D'une part, ce système assure le confort thermique des occupants, d'autre part, il garantit la réduction de la consommation en énergie et par conséquent l'abaissement de la facture énergétique. Cette méthode est basée sur l'utilisation d'un générateur de nombres aléatoires pour le système de chauffage et d'un modèle thermique simplifié de bâtiment. La priorité pour cette génération concerne le confort thermique. Ensuite, l'analyse des séquences de production permet la détermination du contrôle optimal, au regard de la consommation en énergie ou du prix de celle-ci. Puis, cette séquence constituera le plan de chauffage pour le jour suivant. L'avantage de l'utilisation de cette méthode est son aptitude à employer la capacité thermique du bâtiment (inertie) d'une manière optimale en stockant la chaleur dans la structure du bâtiment et en l'utilisant ultérieurement, lorsque l'énergie sera plus coûteuse. Par ailleurs, coupler la consommation aux variations de prix de l'énergie permet de donner des moments privilégiés de chauffage quand l'énergie est moins chère. Cela signifie qu'un délestage d'énergie est automatiquement réalisé, contrairement aux PID existants et aux autres moyens de contrôle traditionnels qui utilisent l'énergie sans se soucier des heures de pointe ou des prix. Il est également important de préciser que cette méthode permet de trouver une solution optimale en testant un grand nombre d'itérations, signifiant qu'une optimisation est effectuée en commençant par des données médiocres.

MOTS-CLÉFS. confort thermique,gestion optimale,control de chauffage, délestage d'énergie

ABSTRACT. This paper proposes a new method for an optimal management of the control of the heating system. This system fulfills the occupants' thermal comfort from one side and guarantees the minimization of the energy consumption and the energy bills from the other side. This method is based on the use of both a random number generator for the heating system states and a simplified building thermal model. The priority for this generation concerns the thermal comfort. After that, analysis of the sequences outputs allows the determination of the optimal with regard to the energy consumption or price. Then this sequence will be the heating plan for the next day. The advantage of using this method is its ability to employ the building's thermal capacity (inertia) in the best way by stocking the heat in the building structure and using it later when the energy is more expensive. Moreover, coupling the consumption with the energy changing price helps giving heating preferred timings when the energy is cheaper which means that an energy shedding is automatically done contrary to the existing PID and other traditional controls that use the energy regardless the peak hours or prices. It is also important to mention that this method gives the possibility to find an optimal solution by testing a large number of iterations meaning that an optimization is done starting from very poor data.

KEYWORDS. Energy consumption control, random selection, energy optimization, comfort level, energy shedding

1 Introduction

Energy is considered nowadays one of the most challenging issues. The diminution of the fossil fuels resources together with the green house gas effects caused by burning them, make it crucial to reconsider the energy consumption as well as the emissions. In cold climates, heating is responsible for approximately 50% of total final energy consumption exploited in heating systems (Rezaie et Rosen (2012)). In France, buildings account for the highest energy consuming assets with 44% of the total energy consumption and 19% of the green house gas emissions according to ADEME and INSEE (Rouquette (2012), Carassus (2006)). Many strategies have been placed in order to reduce the energy consumption. Insulation requirements and pricing plans have been set to better control the energy losses and the consumption peaks. However, a considerable part of the energy consumed in the building sector is wasted either because of the bad insulation or because of the bad control of the heating systems (low efficiency, 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 (Richter et al. (2008), Fuchs et al. (2013)).

Existing controls use most likely one of the following systems(Mendes et al. (2003), Yahiaoui et al. (2006))

- On/Off system : traditional systems
- Proportional Controls : designed to eliminate the cycling associated with on-off control.
- PID control : combines proportional control with two additional adjustments, which helps the unit automatically compensate for changes in the system. (Naughton et al. (2011))
- Intelligent predictive controllers(Paris et al. (2010))

This paper aims to find a method to optimize the energy consumption by exploiting the building inertia (Thermal mass) in the best way and at the same time put constraints regarding the timing of consumption depending on the pricing plans as a reference which normally reflects the peak hours. Applying this, needs a model that reflects the building thermal behavior. We chose a simplified model to be to better integrate it in the control system (Berthou et al. (2012)) and to be able to do fast calculations which allows doing a large number of simulations, this mono-zone model is adjustable according to the available data used as entries. In literature studies, the problem of available data appears frequently when building a thermal model. That is also the reason why the model is preferred to be simplified according to the disposable data. At the same time, the entries chosen in this study are exterior temperature and the amount of energy (Including the solar gains and the heat flux from the heating system). The exterior temperature will be integrated in the model through a weather station forecast and the mission is to define the optimal amount of energy. This study proposes to control the central heating system depending on one indicator which is the interior temperature through defining an accepted level of thermal comfort. The coupling of energy consumption and price gives heating priority timings when the energy is cheaper, the stocked heat in the building structure (inertia) will then be re-pumped when the energy is expensive and the heating is off (Fuchs et al. (2013), Pirouti (2013)). This depends of course on the building insulation and thermal properties. This strategy will help avoiding consumption peaks or over consumption in the cases where there is a maximum consumption limit.

This new method depends on the concept of randomly generating many sequences of the heating system states, and then choose the best iteration according to the least consumption, the least price or both. The advantage of this method is that it can be actually applied to any heating system because the only information needed about the heating system is the utmost amount of kWh that can be provided whether it is the electricity or a boiler based system. This will also guarantee not to exceed the maximum allowed (in an electricity contract for example) no matter what happens. So the control system will find a solution to achieve the desired set temperature without exceeding the maximum allowed which means that a shedding of the energy is automatically being done. Another advantage to be mentioned is the fact that applying this method will guarantee having a relatively energy saver scenario (according to probability laws) of the heating system without the need to apply any mathematical based optimization processes.

2 OBJECTIVES

Thermal studies are dedicated to make sure that the building ambiance meets the thermal comfort. The latest is defined by several indicators such as the interior temperature, the relative humidity, the air velocity .. etc. Hence, the interior temperature is considered nowadays as the key element in heating studies and HVAC systems to express the thermal comfort. To achieve thermal comfort, a set temperature must be met. This set temperature varies between day and night or according to the building usage (Klein et al. (2011)).

Therefore, in this study, instead of defining a set temperature, we assumed an interval of temperatures that assures the thermal comfort. This interval will be designed according to three items :

- The building usage
- The thermal comfort of occupants (in the occupation periods :The 90% acceptability range)
- The internal heat gains to be considered

After defining this comfort level, the objective is to minimize the energy cost and consumption which is the integration of the power supplied over time.

Table 1 shows the considered hourly price of the electricity in France (Euro/kWh). In this study, the heating source in considered to be Electricity which is the case in special complexes as Eco-cities or small complexes with two or three buildings. While for the future work we will move on to consider a gas-based heating system as well.

	Normal hours	**Peak hours**	**High peak hours**
Hour	1h - 8h	9h - 16h 22h - 24h	17h - 21h
Price euro/kWh	0.0864	0.1275	0.255

Table 1: Hours classification according to the price of kWh

3 Control Method Assumptions and Heating Plan Generation

The proposed method is expressed in the flow chart shown in figure 1 Where n is the number of thermal zones, M is the number of heating system phases

- K is the number of the time steps Δt that correspond to the total simulation period and k is the time step

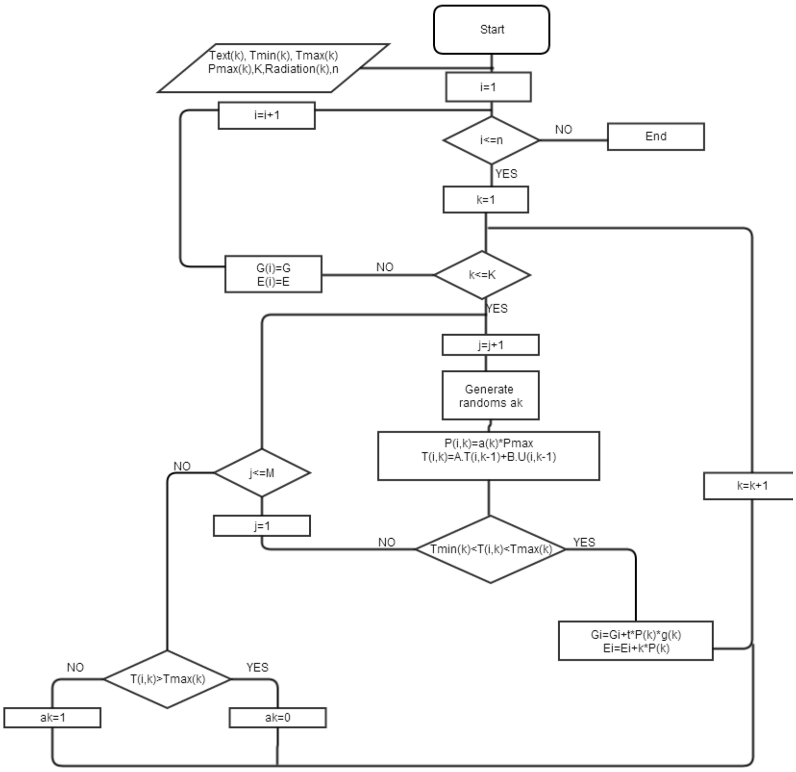

FIGURE 1. The control method flow chart

- $P_i(k)$ is the supply power for zone(i) over a period Δt
- $Q_i(k)$ is the consumption of zone(i) over a period Δt and $Q_i(k) = P_i(k) * \Delta t$;
- $c_i(k)$ is the cost of zone(i) consumption over a time step k
- $\alpha_i(k)$ is a random number where : $\alpha_i(k) \in [0; M-1] * \frac{1}{M}$
- M is the number heating system states

The optimization problem is Concerned by finding the best combination of a sequence $\alpha_i(k)$ over a study period $K * \Delta t$ that satisfies the following :
For building i case, the cost function is expressed as the following :

THE OPTIMIZATION PROBLEM :

$$minG_i = \sum_{k=1}^{K} c_i(k) * Q_i(k) \tag{1}$$

Note that in the special case where $c_i(k)$ is a constant witch value is one, the function will correspond to a minimization of energy consumption as well as the cost.

subject to :

$$\begin{cases} P_i(k) = \alpha_i(k) * P_{max}, \\ Q_i(k) = P_i(k) * \Delta t, \\ T_i(k) = A_i * T_i(k-1) + B_i * U_i(k-1), \\ \alpha_i(k) \in [0; M-1] * \frac{1}{M} \end{cases}$$

Maintaining the condition :

$$T_{i(min)}(k) \leq T_i(k) \leq T_{i(max)}(k) \tag{2}$$

For n buildings, we add the following conditions considering that the power source is limited :

$$\sum_{i=1}^{n} P_i(k) \leq P_{max} \Longleftrightarrow \sum_{i=1}^{n} \alpha_i(k) \leq 1 \tag{3}$$

The minimization will be done by choosing the best (cheapest) sequence of $\alpha_i(k)$ that fulfills the conditions of the problem.

3.1 Boundary conditions :

To make sure that the defined thermal comfort is respected and to exclude all unsatisfactory iterations and reduce the calculation time, additional conditions will be added. These conditions must be designed to overcome the comfort limit cross, for our example we chose the following knowing that it can be changed depending on M and the building dynamic :

$$\begin{cases} \text{if : } T_{i(min)}(k) \geq T_i(k) \text{ then } \alpha_i(k) = 1 \\ \text{if : } T_{i(max)}(k) \leq T_i(k) \text{ then } \alpha_i(k) = 0 \end{cases} \tag{4}$$

This condition will be applied respecting the priority pf buildings. A certain building is named prior when it's temperature is closer to the defined limits. Which means that the priority is dynamic depending on the most critical interior temperature.

4 Case Study

As mentioned before, the simplified thermal model was designed and learned using data taken from COMFIE as a valid thermal modeling software.

The historical weather data was taken as well from COMFIE, noting that for the application of the method, the predicted exterior temperature can be searched directly from any weather website or weather station. A recalculation must be anticipated in case there is a significant difference between the weather forecast and the real weather conditions to avoid any comfort failures. The analysis of the model and the application of the control method was done using MATLAB-SIMULINK which is a perfectly adapted environment for control systems.

As a case study, an office building model was built in COMFIE and used. It is a two story brick building with an approximate ground area of $200m^2$. The walls consist of 4 layers and double glazed windows of $40m^2$ area. Table 2 shows the walls composition and characteristics, while the heat exchange with the ground is ignored supposing that the floor is well insulated. The building is considered as mono-zone so the temperature is homogenous in all parts of building.

Wall layer	Density $[kg/m^2]$	Thickness $[m]$	Specific heat capacity $[J/kg.K]$	Thermal Conductivity $[W/mK]$
Plaster board	950	0.012	840	0.16
Insulation	25	0.2	1000	0.035
Air	1.4	0.05	1005	0.022
Brick wall	1700	0.15	800	0.84

TABLE 2: Wall specification

Furthermore, as mentioned before, the energy price is directly integrated so the price of the consumed energy will be calculated in the same loop for each iteration. Figure 2 shows how the building model was integrated in the control loop. The simulation time step is 5 min while on the other hand the control is done with a different time step of 30 minutes to avoid the continuous change of the heating system state(unless in urgent cases when the temperature crosses the comfort limits).

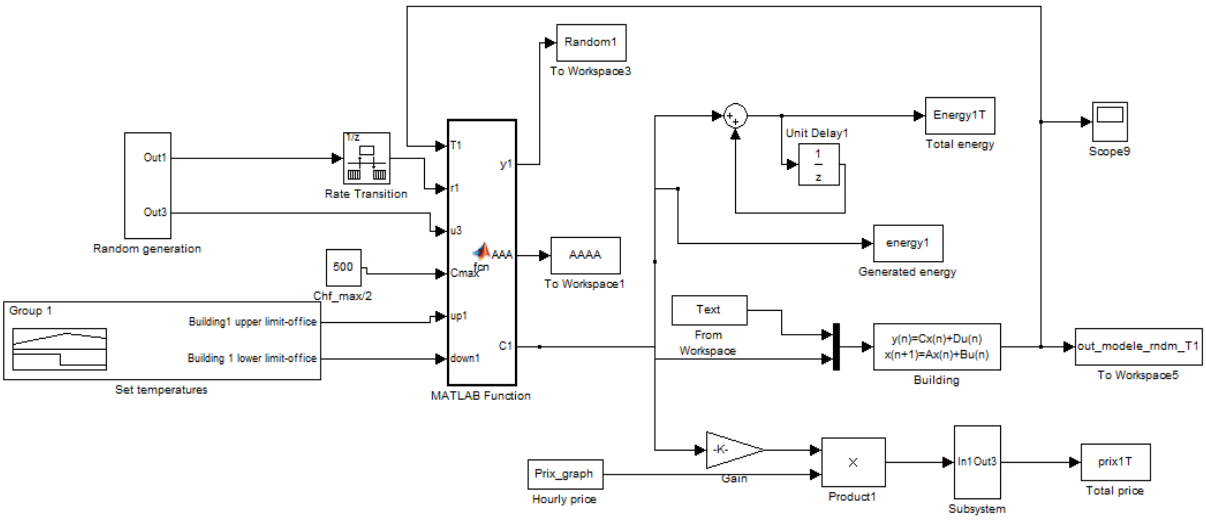

FIGURE 2. The coupling of the building model with the proposed control system

5 A COMPARISON OF THE PROPOSED METHOD WITH A TRADITIONAL PID SYSTEM

To see how efficient is the proposed method, it is necessary to compare it to another traditional method. The one we chose for this comparison is one of the most used methods to control the heating systems nowadays which is a PID controller. The choice was built regarding that the PID is in the middle between the primitive On-Off control and the intelligent predictive methods.

For the PID controller, we need a defined profile of set temperatures which can not be expressed by intervals. So for a justified comparison, we will use a reference set temperature taking into consideration that a PID is always sure to stick to it (when well designed). To do the comparison, we will consider the minimum level of the interval designed for the building considering it as a set temperature (which means we have a minimum level of comfort). Another important note is that a PID controller needs a system with the ability to work with different percentages which needs valves and maintenance costs. In this case, the PID is sure to consume the minimum energy possible but it is not necessarily the minimum price. Moreover, it doesn't take into consideration the peak hours. And here appears the advantage of the proposed system that can provide a better solution either in terms of price or consumption timings [1].

Both methods were applied with the same set of entries (exterior temperature and initial interior temperature) on the building represented by the simplified model, for the proposed method we ran the simulation 2000 times while for the PID one simulation is enough.

Figures 3, 4 shows the energy consumed using both methods together with the associated temperatures (For 2 cases : M=3, M=5). From the figure we can see two obvious advantages for the proposed method :

- An energy shedding is done by exploiting the building inertia heating (avoid heating in the peak time)
- Due to this shedding of energy, the price of energy is less than the one of PID (because the energy is more expensive in the peak time)

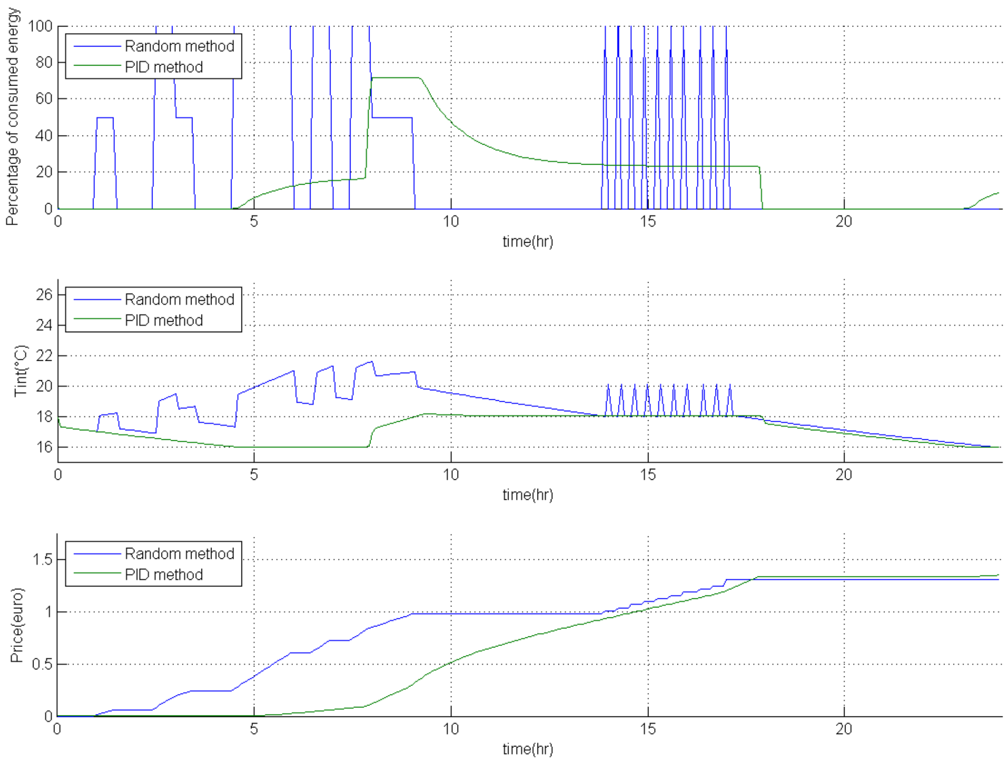

FIGURE 3. A comparison of the energy consumption between the traditional PID system and the proposed random system(M=3)(4.6% less expensive)

Table 3 shows some chosen iterations from a simulation done 2000 times. From the table, it is obvious that the least price is not necessarily associated with the least consumption. While on the other hand, two different iteration with exactly the same amount of consumption don't necessarily have the same price(terations 16,102).

6 Discussions

The proposed method is very effective if the simulation is repeated for a large number of iterations. So that there is a real need for a powerful machine to make sure of having a sufficient number of iterations. On the other hand, even the mathematical detailed optimization method, need the same powerful machines with the advantage for our method that we can build the model

1. That depends on the heating system capacity as well as the building inertia

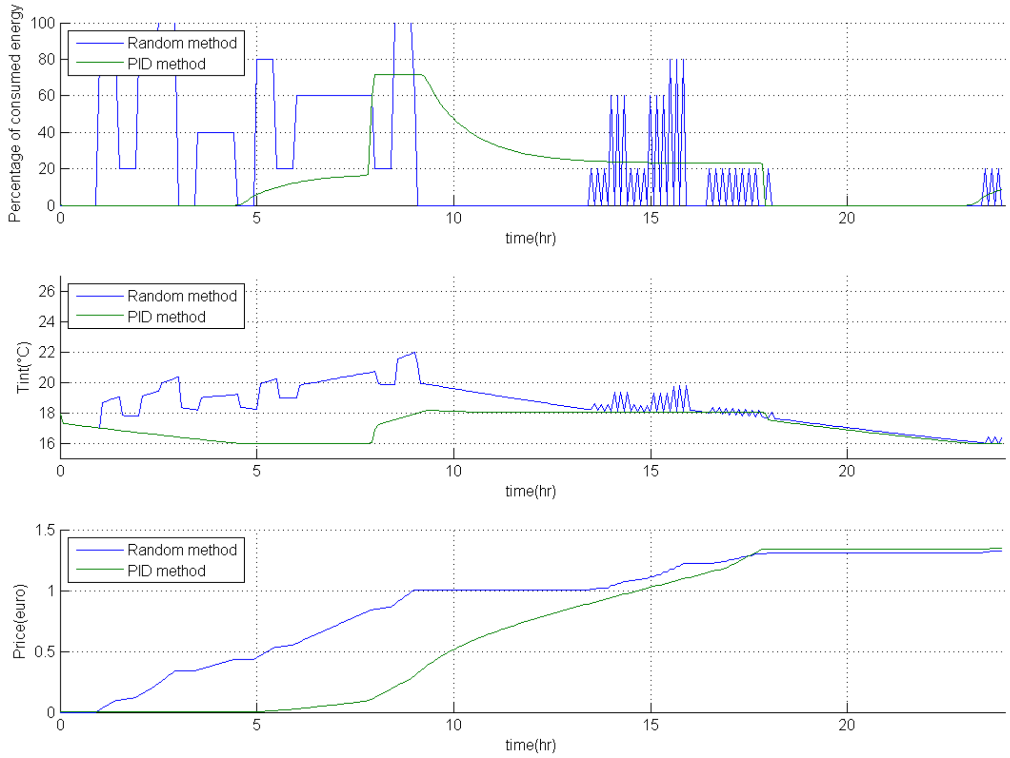

FIGURE 4. A comparison of the energy consumption between the traditional PID system and the proposed random system(M=5)(1.75% less expensive)

Iteration	Total consumed energy (% of PID)	Price (% of PID)
3	158,71	107,38
16	198,9	144,96
102	198,9	137,8
1371	154,4	125,17
1578	131.2	91.78
PID	100	100

TABLE 3: Some iterations from 2000 iteration made, consumption - price comparison

starting from the available data while for mathematical optimizations, details about the building and data are needed. Another advantage of this method is that some iterations will actually have the same consumption but different prices or the other way around which means that in fact we can get a better solution.

As the simulation will be done taking into consideration the limited available power, no over consumption can happen. That is simply because the system will automatically adapt to get the desired temperature in each time step considering the maximum power available. A traditional control system uses the energy when it is needed disregarding the price (the example of PID) while in this approach, a load shedding is automatically done.

The most important advantage of this method is its potential to do the energy consumption plan for more n buildings (urban scale) unlike many other control methods.

7 Conclusion and future work

In this paper, a new approach to optimize energy consumption is presented. This approach has some advantages in terms of simplicity and efficiency as explained before. Moreover, the thermal comfort of users is guaranteed due to the thermal intervals at the same time where a load shedding is automatically done. However, further developments can be done to improve the method and guarantee the optimization. One of these developments is to add the condition to use less energy when it is more expensive. This will minimize the cost of the energy.

A procedure to apply the best iteration as a heating plan for the next day will be foreseen together with a real time monitoring and correction one. Finally, this method will be generalized to be applied on more than one zone or building. In this case, more conditions should be set in terms of maximum available power and comfort scenarios. Doing that will facilitate employing this approach on a traditional district heating system (boiler system) which has different levels of energy distribution to be added as conditions as well as other limitations and constraints regarding the distribution network. The same approach with more constraints can be applied regarding that the available maximum capacity for each system is the one of the higher level system.

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