A PROTOTYPE FOR ON-LINE MONITORING AND CONTROL OF ENERGY PERFORMANCE FOR RENEWABLE ENERGY BUILDINGS

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Abstract: In this article, ways for improving the energetic performance of buildings are investigated. A state of the art leads to the introduction of a performance indicator expressed in kWh/m^2/yr. To improve the value of this indicator, a processor-based prototype of a real-time data-acquisition and monitoring system is developed in collaboration with two industrial companies. The set of measurements and corresponding sensors that are necessary to compute the value of the indicator while being consistent with the natural segmentation of energy consumption, is listed, thanks to the representation of the building using a systemic approach. Control algorithms are tested in simulation to improve renewable energy consumption while reducing fossil energy dependence, which are deemed to be applicable in practice using the proposed electronics. Simulations concerning the control and optimization of the power applied to two warmers in a room show large potential for fossil energy consumption reduction.

1 INTRODUCTION

Nowadays, it is widely admitted that climate change is induced by the intense human activity, and that greenhouse effect gases (GEG) exhaustion is one of the main contributors to this phenomenon. Hence, the decision to stabilize or to reduce GEG emission was taken in the late nineties by most of the industrialized country.

In France, 25% of GEG emissions and 46% of global energy consumption (Ademe, 2007) are due to the buildings. Using legal documentation, e.g. “Réglementation Thermique 2005” (RT2005), or “Diagnostic de Performance Energétique” (DPE), (Sesolis, 2006), French government would like to restrict building energy consumption while limiting wastefulness. Labels are investigated to promote good practice and make the French public opinion sensitive to these issues. In Europe, the situation is similar, witness the development of Swiss and German labels: “Minergie” and “Passivhause”, respectively. Hence, performance of building materials, design or management, needs to be improved.

However, one of the main difficulties when trying to achieve this purpose lies in the fact that energy consumption may vary from a building to another. In addition, energy consumption is segmented in terms of objectives. In this context, the method of choice for improving building energetic behaviour without reducing comfort is obviously to reduce the dependency to fossil energy by, e.g., developing the use of renewable energies. To achieve this goal, it is needed to: (i) characterize global and segmented energy consumption in a building, (ii) compute a performance indicator that takes into account the environment of the building, as well as the way energy is consumed, (iii) acquire and process data measurements to monitor energy consumption, (iv) propose control and optimization strategies for promoting the use of renewable energies.

The goal of this work, performed in collaboration with Apex BP Solar, Pyrescom and CSTB (Centre Scientifique et Technique du Bâtiment), is to develop a prototype of a commercially viable tool that will be able to perform the four aforementioned tasks. To be cost-effective, the tool needs to be small and easy to handle, to remain relatively cheap, to avoid the implementation of many sensors, to be applicable to various buildings, regardless their localization, and to propose solutions depending on energy consumption segmentation.

In this context, the goal of this paper is not only to discuss independently the choice of the electronics or the choice of a specific control law but rather to present the approach as a whole. To estimate energetic performance, an indicator is necessary that is firstly defined. To compute this indicator, the set of needed measurements and corresponding sensors is listed. These sensors are also capable of providing information about the segmentation of energy consumption. To process the acquired data, appropriate electronics are needed. Hence, a processor-based electronic architecture is proposed. The advantages of the use of a processor instead of a standard microcontroller are discussed. Finally, control laws should be implemented to reduce fossil energy consumption. Hence, such laws (potentially applicable using the chosen processor) are investigated in simulation to enforce the use of renewable energies.

The corresponding simulated illustrative example deals with the energy consumption reduction in a room, which is assumed to be equipped with two controllable warmers, respectively using renewable (W_{RE}) and fossil (W_F) energies. To reduce fossil energy consumption, a mix of on-line and predictive control laws is proposed and compared to open loop simulations and to standard online control laws. The general underlying idea is to use W_F if predictions or measurements indicate that W_{RE} reaches saturation. In simulation, this approach leads to a large energy consumption reduction.

This article is organized as follows: Section 2 discusses the choice of a performance indicator. Section 3 presents the prototype of the data-acquisition system, while its applicability for on-line control and optimization of the energetic behaviour of buildings is investigated in simulation in Section 4. Finally, Section 5 concludes the paper.

2 PERFORMANCE INDICATOR

2.1 Choice of the Indicator

Almost twenty years ago, the energetic performance of building was not a strong preoccupation for governments, building material suppliers or real estate developers. Then, energy performance turned to a priority due to the impact of greenhouse effect gases together with the high level of energy costs. The first indicator proposed was a measurement of energy consumption (Duffaure-Gallais, 2006). However, it did not allow performing comparisons regarding localization or areas of the buildings. Recent researches provided specific documentation, which explains the method for computing a global indicator, i.e. annual energy consumption per square meter ($kWh/m^2/yr$), and fixes clear objectives in terms of energy consumption. This unit allows comparison between different buildings, with different constraints.

In France, successive governments have been showing a strong will to reduce human impact on climate (Maïzi, 2007), witness the attribution of "HPE" and "THPE" (Journal Officiel, 2006) labels whenever the energetic performance is 10% or 20% less than standard energy consumption. The underlying idea is very similar to the American "Energy Star" (Boyd, 2007) that is used in industry. Recently, the "HPE ENR" label was created to promote renewable energies. For old constructions, the DPE (Energetic Performance Diagnosis) label is expressed in $kWh/m^2/yr$ as well. Software, such as "3CL Excel©" (CSTB), which are based on building materials parameters (thermal conductivity insulation, glazing losses …), on the building design or equipment, can be used to compute the DPE index to classify buildings according to their levels of energy consumption.

However, the chosen indicator only provides a cumulated indication about energy consumption that aggregates different consumptions, e.g. for heating or cooling. In practice, European labels do not always use the same variables to compute this indicator and do not fix the same goals to reach: "Minergie" label suggests 42 $kWh/m^2/yr$ only for heating, while "PassivHause" label considers 30 $kWh/m^2/yr$ as normal energy consumption for heating and ventilation...

2.2 Environmental Factors and Energy Segmentation

In order to establish a fair diagnosis of the energetic behaviour of a building and to control energy consumption, buildings can be represented as dynamic systems, interacting with their environment, which consume energy with regard to different objectives (fig. 1).

It is proposed to focus on the following environmental factors:

1. Indoor and outdoor temperatures that can be acquired with smart transducers…

2. Wind and solar radiation that can help explaining many consumption levels or provide information about renewable energy availability.
3. Indoor relative humidity, which represents a specific comfort parameter and, thus, affects the user's behaviour.
4. If meteorological predictions are available, which is recommended, pressure can also be measured.

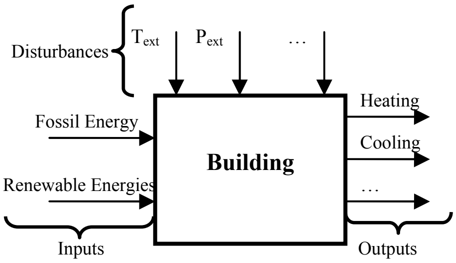

Figure 1: Building System and Interactions.

Buildings use different energies with a large emphasis on electricity. In the case of several kinds of sources (fuel, gas, electricity are used), computation rules exist to estimate the individual contributions to the indicator. The following list summarizes the main sources (inputs) of energy consumed in buildings, together with the objectives (outputs):

1. Electricity (includes heating …).
2. Specific electricity: (electricity that cannot be substituted by any other type of energy).
3. Cooling and ventilation energy.
4. Heating energy (apart from electricity): fuel oil, gas or wood.

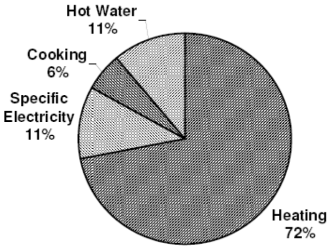

Figure 2: Segmentation of Energy End-Uses in Household (Ademe).

Figure 2 provides the typical energy consumption segmentation. Obviously, the main output is heating, hence the need for focusing on heating control and optimization for reducing energy consumption.

3 INSTRUMENTATION AND DATA ACQUISITION

3.1 Monitoring System Prototype

The acquisition of the aforementioned variables requires the choice of appropriate electronics. However: (i) implementation should be easy and (ii) total cost should remain rather low. In collaboration with our industrial partners, such architecture was developed and implemented at three different locations (Apex BP Solar and Pyrescom headquarters and at the University of Perpignan).

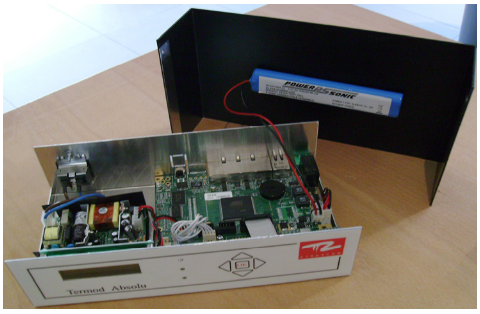

Figure 3: Monitoring System Prototype.

The prototype, which can be seen on Figure 3, is divided into two separate parts: (i) a core-bloc (composed of a low power processor, corresponding memory, and integrated hosts controllers), and (ii) a set of adaptable bloc sensors, which means that it is possible to record and process different data.

3.2 Data Acquisition System

As mentioned, with the chosen architecture, it is possible to use both information concerning energy consumption segmentation and operating conditions measurements. The smart transducers transmit data to the monitoring system discussed in the next subsection, through preferably a Controlled Area Network (CAN) bus. To avoid drilling, or pulling cable, wireless or Power Line Communication (PLC) systems are also studied.

Constraints discussed previously have been taken into account and the quantity and localization of implemented transducers depend on the interactions within the building and on the impact of disturbances.

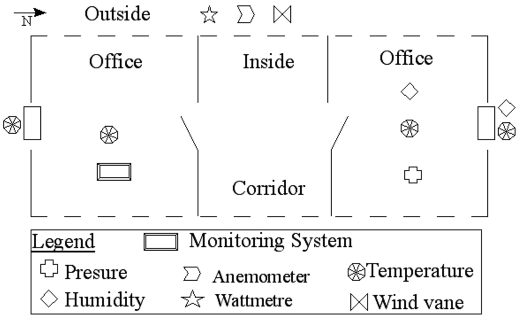

Figure 4: Smart Transducers and Monitoring System Localization (University Offices).

Figure 4 shows the example of the University's offices, where one of the three experimental setups is under implementation. Researches (Hensen, 1991) on heating control systems or on energetic efficiency (Mendoça, 2003, 2007) showed that north front temperature and inside temperature measurements are definitely musts for heating control purposes.

In addition, a compromise was found between the number of transducers, avoiding information redundancy and total cost. To generalize this approach to a broader range of customers, indirect measurements were preferred whenever possible. Note that, for confidentiality reasons, more details concerning the sensors cannot be given. However, all these sensors can interact with the processor described in the following subsection.

3.3 Core Architecture

It is proposed to use an ARM9© processor instead of a microcontroller, which is typically used in the metrology literature (Gungor, 1997, Leong, 1998), since:

1. ARM9© has a low level of energy consumption.
2. Hosts controllers are already integrated for: (i) connectivity, (ii) control purposes, (iii) human interface (CSI, Keypad…), (iv) memory expansion (MMC, PCMCIA…), and (v) providing e.g. Bluetooth communication.
3. Computation power is higher (4-8 bits versus 32-64 bits, 40 MHz versus 100-400 MHz).
4. Its high level of memory allows the handling of a higher number of different kinds of signals (Segars, 1998, Xingwu, 2006).
5. Control laws can be implemented, e.g. energy consumption prediction (Kalogirou, 2000), fuzzy logic (Lygouras, 2006) or fault diagnosis (Kalogirou, 2007).

4 ILLUSTRATIVE EXAMPLE

In this section, modelling and control of university offices temperature was investigated in simulation. The control methods were chosen to be potentially applicable with the prototype discussed above.

4.1 Model Description

The modelled room (Figure 4) corresponds to a University office, where one of the prototypes is installed, and is 10m long, with a north/south orientation. To represent the thermal behaviour of this room a dynamic model is developed as shown in Equation (1):

$$\begin{aligned}\frac{\partial T}{\partial t} &= \sum_{i=\{x,y,z\}}\left\{a_i(x,y,z)\frac{\partial^2 T}{\partial i^2}+\frac{h_i(x,y,z)}{\rho_i(x,y,z)Cp_i}\frac{\partial T}{\partial i}\right\}\\ &+ \sum_i \frac{a_{pi}(x,y,z)}{\lambda_{pi}(x,y,z)}P_i(x,y,z)\end{aligned} \tag{1}$$

Where: $(\lambda/\rho C_p)$ is the diffusivity coefficient (m^2/s), λ is the conduction coefficient (W/m.K), ρ is the density (kg/m^3), C_p the calorific capacity (J/kg.K), h stands for the convection coefficient ($W/m^2.K$) and P_i is power density of the i^{th} heat source (W/m^3). In order to fine down equation (1), the room is supposed to be constituted by a homogenous and isotropic material, and y- and z-axes are assumed to have infinite lengths. Thus, equation (1) becomes:

$$\frac{\partial T}{\partial t}=a_x\frac{\partial^2 T}{\partial x^2}+\frac{h}{\rho Cp}\frac{\partial T}{\partial x}+\sum_i\frac{a_{xi}}{\rho_i Cp_i}P_i \tag{2}$$

The Crank-Nicholson discrimination method was preferred due to the increased simulation stability and the reduced truncation error (Nougier, 1993). One-dimension heat propagation was considered to promote the preferential direction. External conditions influence the front temperature of the walls by convection, as can be seen in Equation (3):

$$\frac{\partial T}{\partial x}=\frac{h\Delta T}{\rho Cp} \tag{3}$$

Model parameters used were (Sacadura, 1993): air diffusivity coefficient: $2.22.10^{-5}$ m^2/s, concrete diffusivity coefficient: $4.2.10^{-5}$ m^2/s, air conductivity coefficient: 0.03 W/m.K, indoor and outdoor convection coefficients 10 and 30 $W/m^2.K$, respectively, air density: 1.177 kg/m^3 and air specific heat: 1.006 kJ/kg.K. Open loop simulations were performed using real external temperature measurements and constant and equal powers (396W). Figure 5 presents the simulation results, using real external temperature data. Note that walls play the role of linear filters, which explains the stability of the indoor temperature profile. Energy consumptions of the warmers were constant and equal to 792 Wh/m^2.

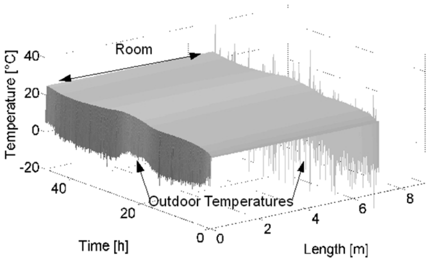

Figure 5: Room Temperature Profile with Open-Loop Control.

4.2 Model Predictive Control

Model Predictive Control (García, 1989) is a process control method that uses: (i) a dynamic model of the process, (ii) past control history and (iii) cost optimization over a prediction horizon H_p, as shown in Figure 6.

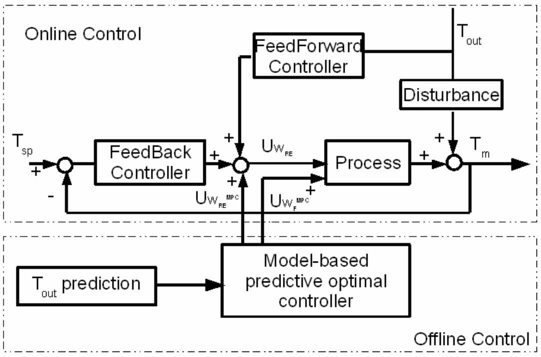

Figure 6: Mixed FB/FF and Predictive Control Scheme.

Such an approach was already tested in this context, but using static modelling, (Kalagasidis, 2006). The corresponding optimization problem is formulated as follows:

$$\begin{aligned} &\min_{U_{WF},U_{WRE}^{MPC}}\left(\sum_{k=1}^{Hp}(U_{WF}(k))^2\right)\\ &\text{s.t.:}\quad \text{Equations (2) - (3)}\\ &\qquad U_{W_F}^{\min} \le U_{W_F}(t) \le U_{W_F}^{\max}\\ &\qquad U_{W_{RE}}^{\min} \le U_{W_{RE}}(t) \le U_{W_{RE}}^{\max}\\ &\qquad \left|T_m(H_p)-T_{sp}(H_p)\right| = 0\\ &\qquad \left|T_m(H_c)-T_{sp}(H_c)\right| = 0 \end{aligned} \tag{4}$$

Where U_{W_F} and $U_{W_{RE}}^{MPC}$ are the power applied to W_F and an extra-power applied to W_{RE}. The idea herein is to use W_{RE} upon saturation before using W_F. Hence, ∀t, $U_{W_{RE}}(t)=U_{W_{RE}}^{PI+FF}(t)+U_{W_{RE}}^{MPC}(t)$, where $U_{W_{RE}}^{PI+FF}$ is the contribution to the power applied to W_{RE} computed by the on-line controller. The advantage of this formulation is that, while $U_{W_{RE}}(t) \le U_{W_{RE}}^{\max}, U_{W_F}=0$ for optimality. It is imposed that the room temperature reaches its setpoint at H_c and H_p while minimizing U_{W_F} (Equation 4). W_{RE} is controlled through online Feedback/Feedforward Control, while W_F power increments are computed by MPC, using $H_p=2\text{h}$ and $H_c=1\text{h}30$. The optimization problem uses biased external temperatures predictions by means of a 1°C oscillating prediction error.

Figures 7 and 8 show the temperatures time profiles and the powers applied to the warmers, respectively, and Table 1 summarizes energy consumption for the investigated scenarios. Feedback/Feedforward (FB/FF) of the two warmers, for which priority is given to W_{RE}, was also investigated for comparison purposes. It seems that most of the reduction is due to the use of time-varying setpoint (see FB/FF results), while setpoint tracking is efficiently achieved. However, this table shows that MPC allows a 7% additional fossil energy consumption reduction when compared to FB/FF.

Table 1: Performance Indicator Values for the Different Control Strategies.

	Open-loop	FB/FF	FB/FF+MPC
W_{RE}	792	1223.3	1227.6
W_F	792	100.9	93.5

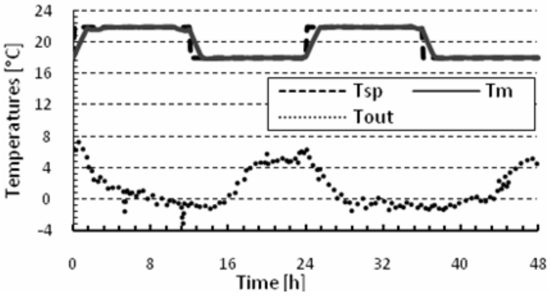

Figure 7: Room, Setpoint and Outdoor Temperatures for FB/FF+MPC Control.

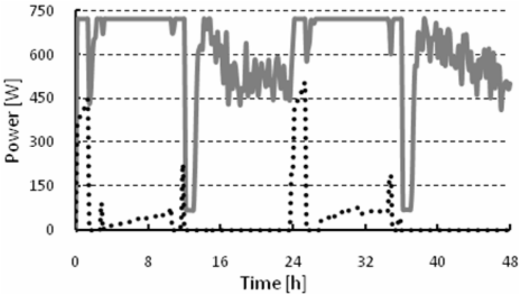

Figure 8: Power Profiles Applied to the Warmers for FB/FF+MPC Control (W_{RE}: solid line; W_F: dotted).

5 CONCLUSIONS

This article presents the results of a study dealing with the improvement of energetic performance of renewable energy buildings. A performance indicator (kWh/m^2/yr) was chosen that allows comparisons between buildings of different areas and localizations. A processor-based prototype was developed, to perform on-line acquisition, monitoring and control of heat consumption in renewable energy buildings. The potential for the fossil energy consumption reduction is illustrated by the simulation of temperature control of University's offices. Mixed online and model-based predictive control using both external temperature predictions and real measurements with time-varying temperature setpoint leads to a very large fossil energy consumption reduction.

Future work will include the improvement of the dynamic model, so as to test the developed control algorithms on larger and more complex dynamic systems. Furthermore, in-situ application of the prototype has already begun in our partner's headquarters. It is planned to include control algorithms in addition to real-time data-acquisition and performance indicator monitoring.

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