ELSEVIER

Energy and Buildings 24 (1996) 213–221

ENERGY AND BUILDINGS

Accounting free gains in a non-residential building by means of an optimal stochastic controller

Y. Oestreicher, M. Bauer [1], J.-L. Scartezzini *,[1]

Centre Universitaire d'Etude des Problèmes de l'Energie (CUEPE), University of Geneva, CH-1231 Conches-Geneva, Switzerland

Received 25 March 1996; revised 31 March 1996; accepted 2 April 1996

Abstract

A prototype predictive controller, based on the theory of optimal stochastic control, was developed and installed in a non-residential building in Delémont (Switzerland). This building is very well insulated ($U=0.65$ W/m^{2}K for windows) and, moreover, equipped with an active floor heating and cooling system. Solar and free gains supply more than 50% of its heating energy during winter. The controller determines, with the aid of the predicted free gains, the heat to supply for the next hour in order to optimise comfort and minimise energy consumption over a period of 24 h. The performance of this controller is compared with that of an advanced external temperature controller installed in the same building. A detailed energy balance of the building is presented for both controller types. The maximal energy savings observed in favour of the predictive controller amount to 24% during the cold season (October through April) and even reach 31% during the hot season (May through September). The thermal comfort was evaluated through questionnaires filled in by the occupants, but also thanks to an analysis based on temperature monitoring in the building. The analysis results show that comfort was maintained by the predictive controller.

Keywords: Free gains; Optimal stochastic control; Predictive controller; Active floor; Non-residential buildings; HVAC system

1. Introduction

The optimal energy conception of a building is usually synonymous with thermal insulation (walls, windows) and integration of passive solar (direct gain, sun space) or active solar components (solar collectors) [1]. The control of HVAC systems is still all too often not taken into account, even though the energy consumption and the thermal comfort are directly dependent on it.

Controller efficiency is particularly necessary, when solar and free gains cover a large part of the heating energy needs. The thermal control of buildings is more difficult when the building and/or the HVAC system have a high thermal inertia [15].

A predictive controller, based on the theory of optimal stochastic control [2,17,18], has been developed to bypass these difficulties. It is able to optimise the heat and cold supplies based on:

- the stochastic behaviour of the main meteorological variables (solar radiation, external temperature);
- variable contribution of free gains (lighting, electrical devices, occupants);
- the dynamic evolution of the building (thermal inertia).

A first experimental device was successfully tested in 1989/90 in two direct-gain passive solar office rooms of an experimental building equipped with a heating floor in Lausanne [3–5]: 27% energy savings on a winter season were achieved in comparison to a conventional controller based on the external temperature.

The experiment was renewed recently, in conditions closer to practice [6] in two solar houses with a floor heating system. Again, considerable energy savings could be observed (20% in comparison with a similar conventional controller) in conjunction with an improvement of the thermal comfort.

The aim of this project was to extend the field of application of the predictive controller to:

- the management of cooling in summer;
- the predictive control of more complex buildings characterised by large free gains (non-residential buildings).

The procedure adopted in this project is similar to the one used in previous applications [3,6], the energy performance indicators of the predictive controller being compared to

* Corresponding author.

[1] Present address: Solar Energy and Building Physics Laboratory (LESO-PB), Ecole Polytechnique Fédérale de Lausanne (EPFL), CH-1015 Lausanne, Switzerland.

PII S0378-7788(96)00980-2

those of a conventional one. This paper presents the results of monitoring of the building from Nov. 1992 to Dec. 1994.

2. Description of the building

2.1. Geographic and climatic situation

The building houses the administrative section of a factory (Fig. 1). It is situated in Delémont (latitude 47°20′, altitude 431 m) in the northern part of Switzerland. This area is characterised by an average horizontal solar irradiation of 1126 kWh/m^2 per year (278 kWh/m^2 from Oct. to Mar. [7]) and an average ambient temperature of 7.5°C.

2.2. Thermo-physical characteristics

The building is particularly well insulated: its windows have a U value of 0.64 W/m^{2}K. The entrance has a large glazing area and is only partially heated: it is not taken into account in the thermo-physical characteristics of the building.

The building is occupied daily by forty employees, but is not well situated with regard to solar gains: a factory building obstructs the south-facing glazing area. The following remarks can be made regarding the passive solar gains:

- the windows are distributed in a similar way on all facades;
- high insulation glazing has a poor energy transmission factor ($g = 0.42$);
- the net glazing area represents only 60% of the global area of apertures (thick frame);
- the walls are particularly thick (double brick walls).

Passive solar gains are thus considerably reduced. However, the reduced thermal losses of glazing compensate this to a large extent: the fact that the heating needs of the building are drastically reduced leads to a significant solar saving fraction.

The glazing characteristics are given in Table 1 and Table 2.

Because of its massive construction (external walls and floor), the building has a very high thermal inertia. Its time constant calculated from the global heat capacity C_p (MJ/K) and the global heat loss coefficient of the building H_0 (W/K) ($\tau = C_p/H_0$) [8] equals 155 h. The building is thus almost insensitive to temperature perturbations and variations of meteorological conditions.

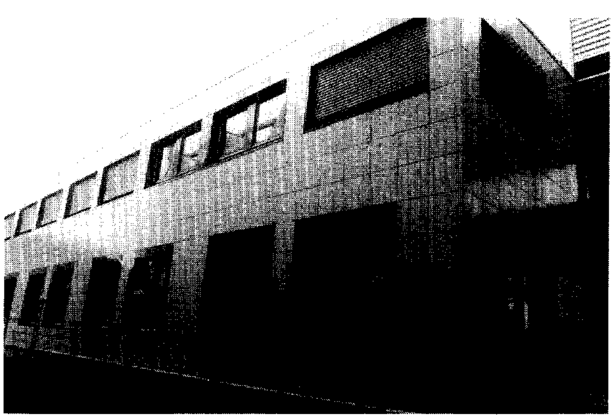

Fig. 1. View of the administrative building.

Table 1
Performance of HIT glazing

Characteristics of glazing	Standard values
Thermal loss coefficient U (W/m^{2}K)	0.66
Luminous transmission τ (–)	0.58
Energy transmission factor g (–)	0.42

Table 2
Heated floor area and volume

Zone	Net glazing area (m^2)	Floor area (m^2)	Volume heated zone (m^3)
East	57	590	1770
West	78	688	2100
Total	135	1278	3870

2.3. Technical installations

The building is built over two levels. The warm and cold water distribution is provided by an 'active floor' (see Fig. 2), which is made up of two hydraulic pipes imbedded in the concrete ceiling of the first and second storey. The hydraulic network consists of two groups of distribution, corresponding to the two distinct parts of the building:

- the eastern group, characterised by significant free gains in 1993 (computer centre);
- the western group, characterised by moderate free gains (people, lighting and electrical devices).

The heat is provided in priority by heat exchangers attached to the factory's air compressors; an additional supply can be provided by an oil-fired boiler. Cooling is provided by a hybrid tower which can cool the circulating water in the floor down to 17°C by watering and/or ventilation.

Two pumps provide the distribution of the water in the two groups. They work permanently throughout the whole year to even out the indoor temperatures in each of the two parts of the building and to evacuate or distribute the heat supplied by users and electrical devices (up to 10 kW in the western zone in 1994). The temperature of the 'active floor' is always set between 17°C (minimum) and 24°C (maximum).

The 'active floor' also works as a thermal tank because of its large thermal capacity; the indoor temperature variations are thus considerably reduced in winter and in summer.

The air renewal rate through air infiltration and opened windows is particularly poor in winter: it was evaluated at 0.15 h^{-1}. The building is, however, equipped with two mechanical ventilation systems working during office hours:

- one is used to ventilate the sanitary air rooms (airflow rate of 800 m^3/h);
- the other is equipped with a heat recovering system (efficiency 70%) and is used in the other rooms (airflow rate of 1700 m^3/h).

The global air renewal rate equals 0.55 h^{-1} when the overall mechanical ventilation system is on.

2.4. Conventional control

The technical installations of the building are driven by 4 numerical controllers (DC 9100 of Johnson control), which can be programmed. They manage respectively:

- the ventilation system;
- the hybrid tower;
- the eastern and western active floor;
- an additional floor heating system.

The conventional controller maintains the temperature setting in the hydraulic networks thanks to heating curves.

The controller is based on the outdoor temperature and defines a return temperature to the water of the 'active floor' (instead of an inlet temperature) as a function of outdoor temperature values. The controller works practically in 'spate': measurements of the active floor and its return temperatures are used to give an inlet temperature order. This method allows taking partially into account solar and free gains absorbed by the thermal mass of the concrete floor. The performance of this conventional controller is expected to be superior to that of a controller giving an inlet temperature order (usual strategy of control).

No night reduction of the temperature orders was needed in winter; the indoor temperature being practically stable, even without heating, during a 12 h period because of the thermal inertia of the building.

The settings of the predictive controller were adjusted to those of the conventional controller: they were chosen for the interior room temperatures to be identical for both controllers on cloudy days with few free gains (night or weekend).

3. Predictive controller

3.1. Principle of working

The working principle of the predictive controller consists in optimising hot and cold supplies over a time horizon (usually 24 h), using expected values of solar and free gains given by stochastic models. For the considered building, this implies:

- predicting and anticipating internal and solar gains;
- being able to describe the dynamic thermal behaviour of the building.

This procedure is carried out by a computer program installed on a 486 PC computer (33 MHz, 4 Mb RAM), whose main algorithms are described below.

3.2. Optimal stochastic control algorithms

Two distinct processes are carried out by the predictive controller in the course of time. The matrix of optimal commands is calculated at the beginning of each optimisation period, i.e. at midnight for a duration of 24 h. The optimal command is then retrieved from the matrix every hour in the course of the second process. A pointer is used into the matrix to retrieve the commands; it consists of the measurement of:

- the meteorological variables (solar radiation and outdoor temperature);
- the thermal state of the building (indoor air and building element temperatures);
- the hour of the day.

A thermal nodal model of the building allows a determination of its dynamic evolution based on its actual thermal state and the possible values of the meteorological variable and free gains. Thanks to this model, the controller can determine the optimal control strategy over 24 h (adopted time horizon).

The building model is a linear set of equations of the form,

$$T(t+\Delta t) = f(T(t), y(t), u(t)) = A \cdot T(t) + B \cdot y(t) + D \cdot u(t)$$

where the thermal state of the building system $T(t+\Delta t)$ depends on the previous thermal state $T(t)$, the driving variables $y(t)$ (solar radiation, outdoor temperature and internal gains) and the heating command $u(t)$ (heating or cooling energy). The matrices A, B, D depend on the characteristics of the building and the heating system (thermal capacity, heat exchange coefficients, etc.). Refs. [3] and [4] give a detailed presentation of the mathematical aspects of this approach.

In the administrative building in Delémont, two nodal models, illustrated in Fig. 2, have been used separately for the eastern and the western zone. Table 3 describes the four nodes used during the 2 years of operation of the controller.

The temperatures of the nodes with a larger thermal inertia ('massive' and 'active floor') were determined as follows:

- temperature of the 'active floor' (node 'active floor'): through the measurement of two sensors placed on the floor;
- temperature of the 'massive part' (node 'massive'): through the average, balanced by the respective thermal capacity of the building elements, of the air temperature (approximate temperature of the interior walls) and the

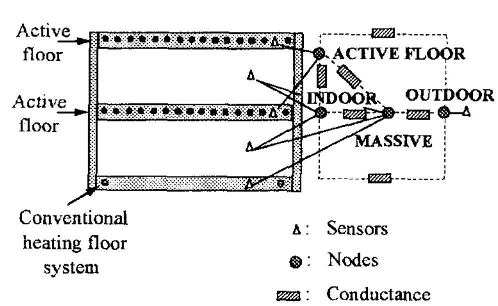

Fig. 2. Simplified nodal model.

Table 3
Nodal model of the building

Nodes of the model
Indoor air (Node 1)
Massive parts (Node 2)
• windows (glazing and frame)
• indoor and exterior walls
• ground floor (without hydraulic network managed by the predictive controller)
• furniture
Active floor (Node 3)
• active floor imbedded in the ceilings of the first and second floor managed by the predictive controller
Exterior air (Node 4)

temperature of the non-heated part of the ground floor at midnight.

The heat exchange coefficients were evaluated regardless of the energy performance analysis which was based on temperature monitoring.

3.3. Meteorological stochastic model

Among the meteorological variables able to influence the dynamic behaviour of a building, the solar radiation and the outdoor temperature were identified as dominant [9].

Hourly weather data for the location of Fahy (latitude 47°25′, altitude 596 m), collected by the Swiss Meteorological Institute, were used to construct the stochastic models of the meteorological variables. This model has been described in detail in Ref. [3] and will not be presented here.

Passive solar gains in the administrative building can then be calculated, thanks to these models, for predefined classes of horizontal solar irradiation. Vertical irradiation on every face of the building (calculated itself from the horizontal irradiation) is used for this purpose, taking into account the energy transmission of glazing ($g = 0.42$) and the shading effects of the window frames, the wall thickness, as well as the adjacent building [14].

3.4. Deterministic model of free gains

A deterministic model of free gains was adopted in order not to increase the complexity of algorithms and the time of calculation. It was developed separately for the eastern and the western part of the building and is based on the following elements:

- hourly measurement of the total electrical consumption of the building;
- punctual statement of the consumption of the main electrical equipment (hybrid tower, computer centre, air conditioning, pumps, etc.)
- census of electrical devices and artificial lighting in the offices (place, electrical consumption, working duration);

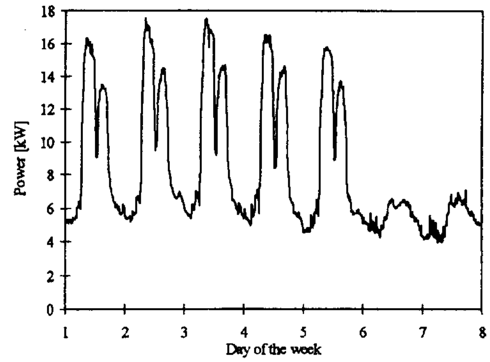

Fig. 3. Average profile of global electricity consumption of the building monitored during the cooling season 1994 (1 May to 30 Sept. 1994).

- inquiry as to the occupancy of the offices.

The electricity consumption observed during summer 1994 is given in Fig. 3.

Profiles of free gains were built with these data for every zone; they are a function of the time and day of the week. The electrical consumption, due to appliances which do not contribute to free gains inside the building (hybrid tower, external lighting, etc.), was not taken into account. The analysis of the distribution of the gains was carried out principally through a census of electrical devices and lighting fixtures. The gains due to people were evaluated thanks to office occupancy data (100 W emitted by each person [10]).

The installation of an air conditioning device in the computer centre and the substitution of a main frame computer by a low consumption computer have made compulsory the modification of these models. Separate measuring of the electrical consumption of every zone would have simplified the creation of these models. The overcost linked to a sectorisation of the electrical network made this procedure impossible, however.

3.5. Cost function

The objective of the control algorithm is to minimise the expected cost function of thermal performance indicators over the optimisation period. For a given time step, the cost function is given by:

$$J(u, \boldsymbol{T}) = C_1 |u| + C_2[\exp(\mathrm{PMV}^2(\boldsymbol{T})) - 1]$$

where: $\boldsymbol{T}$ (°C) is the vector of temperatures ($T_{\text{indoor air}}$, $T_{\text{active floor}}$); $|u|$ (W) is the absolute value of the thermal power to be supplied to the building; PMV (–) is the predicted mean vote, calculated with the model of Fanger [10].

The Fanger theory of comfort was used to express thermal comfort conditions inside the building as indicated by this equation.

3.6. Discretisation of control variables

The insulation and the thermal inertia of this administrative building make it almost insensitive to external perturbation (irradiation or ambient temperature). The scale of variation

Table 4
Discretisation of variables

Parameters of discretisation	Indoor air temperature	Active floor temperature	Solar radiation	Supplies by the heater or the hybrid tower
Number of discrete states	28	21	10	7
Interval defined by a discrete state	0.2°C	0.1°C	$I_0/10$	$(P_{max}-P_{min})/7$
Domain covered by the set of states	19–24.6°C	T_d(24 h) − 1°C to T_d(24 h) + 1°C	0 to I_0	P_{min} to P_{max}

I_0 (W/m^2): solar radiation by clear sky.
T_d(24 h): temperature at midnight of the active floor.
P_{max} (W): maximal heating power supplies by the heater for a given month.
P_{min} (W): minimal cooling power supplies by the hybrid tower for a given month.

of temperatures representative of the thermal state of the building (indoor air, massive parts, active floor) was thus limited during one day. The discretisation of these temperatures (state variables), which is required by the optimal stochastic control theory [3], should be extremely fine in order to allow the predictive controller to work accurately; at the same time, it should not lead to excessive computation time. Table 4 gives an overview of the discretisation.

3.7. Hardware implementation

The following strategy was adopted to come near practical conditions:

- the number of sensors needed by the controller was reduced to a minimum (reduction of implementation cost);
- sensors with moderate prices were used.

The predictive controller needs the measurement of 5 state values, performed every hour of the day:

- the indoor air and active floor temperatures (characterising the thermal state of the building);
- solar radiation and outdoor air temperature (meteorological variables);
- the amount of energy supplied by or retrieved from the active floor (commands).

The heat supplies to the heating and the active floor are determined with the help of thermocouples and flow-meters, measuring the inlet and return temperature of the hydraulic distribution network. The water flows in the networks are practically constant (they depend on the characteristics of the hydraulic networks): energy supplies could be evaluated by measuring only the inlet and return water temperatures.

The solar radiation sensor is a photovoltaic cell (1 cm × 1 cm) generally used to control venetian blinds (relative uncertainty: 10%). All sensors used by the predictive controller were connected to a data logger.

The predictive controller software was conceived to control either the eastern or the western part of the building, or the whole building. Usually, one part of the building was managed by the predictive controller, and the other by the conventional controller; the two modes of control were interchanged every 15 days, to avoid bias in the energy performance due to user behaviour.

The sluices and pumps of the active floor were managed by the predictive controller with the help of electronic relays; the control device worked satisfactorily during both years.

4. Monitoring results

4.1. Energy analysis method

An original method analysis ('Eta' method), based on the so-called 'H-m method' [11], was developed for the purposes of the project; it allows two particularities of the building to be taken into account:

- the large contribution of free gains to the building heating supplies (more than 35%);
- the capacity of the active floor to provide both heat and cooling.

A detailed description of this method is given in Ref. [12]. It provides an equation similar to:

$$H' = H_0 - \eta \cdot m_{tot}$$

The parameter m_{tot}, including average solar and free gains $\bar{G}$ (W) calculated for a two-day period, is given by:

$$m_{tot} = \frac{\bar{G}}{(\bar{T}_i - \bar{T}_e)}$$

where $\bar{T}_i$, $\bar{T}_e$ are the indoor and outdoor average temperatures during the same period.

The parameter H' takes into consideration the energy stored in the building structure to correct its influence on the building temperature. During the heating season, only heat supplies to the active floor $\bar{P} > 0$, are considered, giving:

$$H' = \frac{\frac{C}{\Delta t}\Delta T_i + \frac{1}{\Delta t}\int_0^{\Delta t} P(t)\,\mathrm{d}t\Big|_{P(t)>0}}{(\bar{T}_i - \bar{T}_e)}$$

During the cooling season, only cold supplies to the active floor $\bar{P} < 0$, are considered, giving:

$$H' = \frac{\frac{C}{\Delta t}\Delta T_i + \frac{1}{\Delta t}\int_0^{\Delta t} P(t)\,\mathrm{d}t\Big|_{P(t)<0}}{(\bar{T}_i - \bar{T}_e)}$$

where: P (W) is the back-up power supplied to the building; Δt (s) is the integration interval (48 h); C (J/K) is the thermal capacity of the building. ΔT_i (°C) is the indoor temperature variation during Δt, H_0 (W/K) is the building heat loss coefficient.

This equation can be interpreted as follows:

During the heating season (defined as $\bar{P} > 0$)

$(1-\eta)$ represents the fraction of free gains evacuated from the building; a value $\eta = 1$ points out that the controller performs very well and uses all the free gains perfectly.

During the cooling season (defined as $\bar{P} < 0$)

η represents the fraction of free gains remaining in the building and not evacuated by the occupants (venetian blinds, solar protections, windows openings) or by means of passive cooling strategies (night ventilation); a value $\eta \cong 0$ points out that the controller performs very well and that heat is efficiently evacuated by the occupants or by passive cooling strategies.

4.2. Comparison of performances

The aim is to quantify rigorously the energy consumption achieved by the predictive controller in relation to that of the conventional one. As a direct comparison was not possible (orientation and occupation mode of the building parts are different), an indirect comparison, based on the 'Eta' method, was used.

The parameters Ho (W/K), η_h (–) (for the heating season) and η_c (–) (for the cooling season) are, in a first step, determined thanks to correlation diagrams. Supposing that these correlation characteristics are representative of the energy-related behaviour of the building and its technical installations during the whole heating and cooling period, a reasonable estimation of the specific power H^* (W/K) can be obtained using monitored values of the parameter m_{tot}* in the former equation, given by:

$$m^*_{tot} = \frac{\bar{G}^*}{T_{io} - \bar{T}^*_e)}$$

with $\bar{G}^*$ (W) monitored solar and free gains; $\bar{T}_e$* (K) monitored outdoor air temperature; T_{io} (K) indoor temperature setting.

5. Thermal performances indicators

5.1. Utilisation factor of free gains

Measurements carried out from May 1993 to Dec. 1994 were used for this analysis. Diagrams based on the 'Eta' method were then produced for the eastern and the western zone and the four heating and cooling periods. Eight sets of correlation diagrams were produced for each control mode, some of them being given here (Fig. 4 and Fig. 5). Table 5 gives the values of coefficients H_0 (W/K), η_h (–) and η_c (–) determined that way.

The following comments can be made:

During the heating season

the utilisation factor of free gains is up to twice as high in predictive mode than in conventional mode (0.57 instead of 0.25 in the western zone in 1994).

Between seasons

a better efficiency of the predictive controller is observable as well; the resilient power H' (W/K) being weaker in predictive mode than in conventional mode.

During the cooling season

the better performance of the predictive controller leads to a decreasing factor η_c (0.42 instead of 0.58 for the western zone in 1993); this is due to a better management of free gains over a 24 h period (no heating and cooling on the same day, as observed with conventional control).

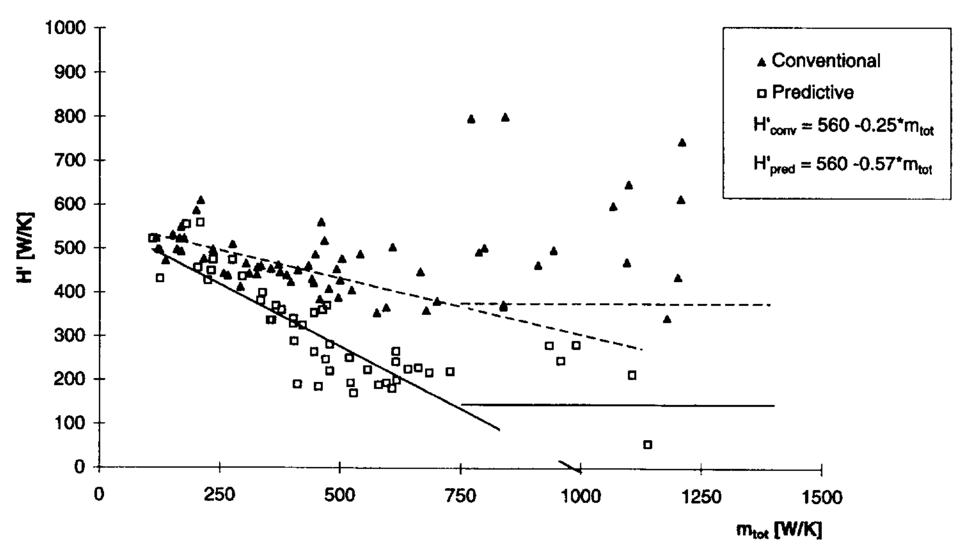

Fig. 4. 'Eta' correlation diagram of the western zone (heating season 1993, predictive and conventional mode of control).

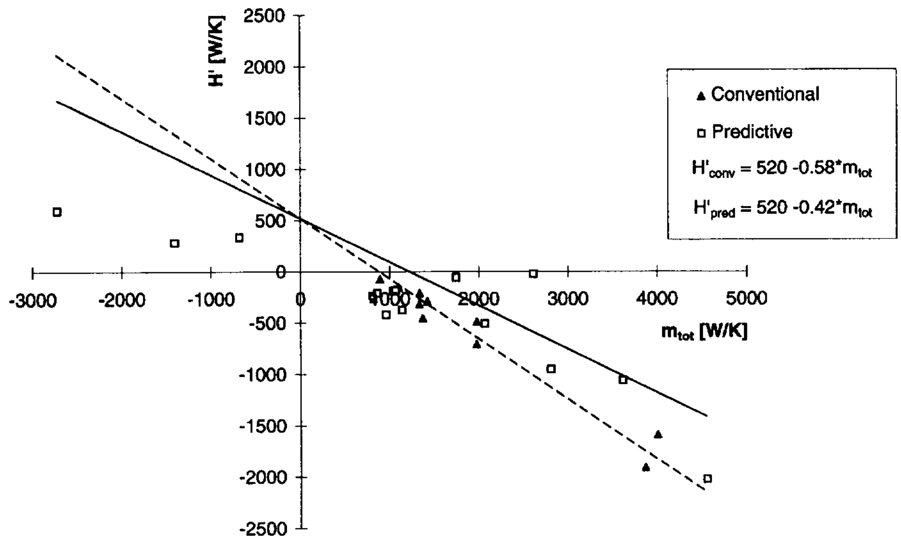

Fig. 5. 'Eta' correlation diagram of the western zone (cooling season 1993, predictive and conventional mode of control).

Table 5
Heat loss coefficient and utilisation factor of free gains obtained by correlation (the slope of correlation straight lines η_h and η_c has been determined by forcing their way by $\bar{H}_0$)

	H_0 (W/K)	$\bar{H}_0$ (W/K)	η_h (–)	η_c (–)
Eastern zone, 1993		310		
predictive	330 ± 35		0.51 ± 0.14	0.51 ± 0.05
conventional	287 ± 12		0.37 ± 0.03	0.51 ± 0.05
Western zone, 1993		520		
predictive	516 ± 35		0.57 ± 0.08	0.42 ± 0.05
conventional	525 ± 23		0.45 ± 0.06	0.58 ± 0.04
Eastern zone, 1994		330		
predictive	351 ± 24		0.40 ± 0.07	0.67 ± 0.04
conventional	316 ± 17		0.35 ± 0.06	0.78 ± 0.05
Western zone, 1994		560		
predictive	581 ± 25		0.57 ± 0.05	0.65 ± 0.07
conventional	541 ± 15		0.25 ± 0.04	0.61 ± 0.03

5.2. Energy consumption

The performance of both systems was compared every year during two distinct periods: the usual winter heating season (Oct.–Apr.) and its complement (May–Sept.). Indoor temperatures were assumed identical for both modes of control; average values measured during one period for every zone, were used.

The virtual consumption values, obtained by extrapolation of 'Eta' correlation figures for the different periods, building zones and modes of control, are given in Table 6. The heat (E_h (MJ)) and cold (E_c (MJ)) supplies are both counted positively. Relative energy savings, obtained by the predictive controller in comparison with the conventional controller, are given in Table 7.

Energy savings reached a maximum value of 31% during summer 1993 and 24% during winter 1994. The savings are, in absolute value, more important in winter because of higher heating degree days in comparison with the cooling degree days. These relative energy savings were mainly achieved through:

- a more efficient use of free gains in winter and between seasons (anticipation of free gains);
- better management of heat and cold supplies between seasons or during the cooling season (evaluation of supplies on a time horizon).

The thermal intensity of the whole building amounts to 140 MJ/m^{2}a; the intensity corresponding to the cold supplies equals 40 MJ/m^{2}a (absolute value). The global electrical intensity equals 183 MJ/m^{2}a, of which 27 MJ/m^{2}a are consumed by the hybrid tower and the ventilation system, as well as 25 MJ/m^{2}a by the pumps.

5.3. Thermal comfort

The thermal comfort was evaluated with the help of questionnaires (filled in regularly by the occupants) and through temperature measurements (indoor air, floor and roof areas).

Table 6
Virtual consumption of the two control modes for the different building zones in 1993 and 1994

	Winter season		Summer season	
	E_h (MJ)	E_c (MJ)	E_h (MJ)	E_c (MJ)
Eastern zone, 1993				
predictive	47854	1244	8940	10865
conventional	59311	1244	11738	10861
Western zone, 1993				
predictive	104641	403	9034	10606
conventional	116094	1120	11033	17372
Eastern zone, 1994				
predictive	58097	1824	4192	22036
conventional	61546	2478	4711	26824
Western zone, 1994				
predictive	95085	1061	5184	26256
conventional	125854	803	8368	24029

Table 7
Relative energy savings (%) of the predictive controller (at the same comfort level and under equivalent building utilisation conditions)

Period	Western zone	Eastern zone
1993	14	17
Winter season	10	19
Summer season	31	12
1994	20	10
Winter season	24	6
Summer season	3	17

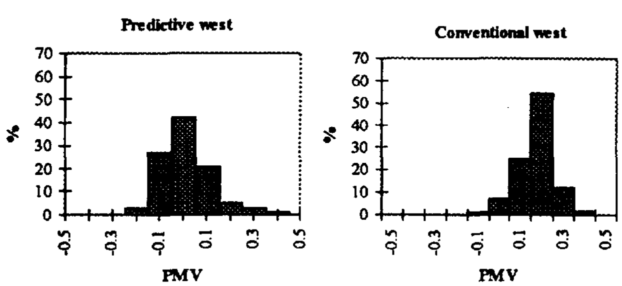

Fig. 6. PMV distribution obtained for the western zone based on the monitored temperature in 1994 (indoor air, active floor and ground floor).

Questionnaires of comfort were given to five occupants in the western zone and two in the eastern zone, chosen as a function of their working place, in order to have votes representative of each part of the building. No information was given to the users as to the mode of control.

The expression of votes following Fanger's scale was used to compare thermal comfort conditions offered by the two control modes. These histograms did not allow a differentiation of the comfort conditions of the two modes of control.

In the whole building, the variations of the indoor air temperature between heating and cooling seasons was very low (reaching 0.8°C at the most for the western ground floor). The occupants' clothing changed considerably between these two seasons; it is therefore not surprising that the histograms of comfort indicate some discomfort during the cooling season (light clothing worn indoors). Thermal comfort can also be evaluated by measuring the temperatures in each part of the building, the PMV Fanger equation being used to assess thermal comfort indicators [10].

The radiative temperature of the office is determined with the help of the temperatures of the walls (supposed equal to the air interior temperature) and of the active and ground floor.

The parameters of the Fanger model for metabolic activity (madu = 64 W/m^2), and the clothing factor (ricl = 0.17 m^{2}k/W), were those used in the program of the predictive controller, chosen in order to keep up an interior temperature of 22°C. The same parameters were used to evaluate the thermal comfort.

A PMV distribution, determined during the working hours, is given in Fig. 6 for the western part of the building for 1994; the measurements in the eastern part give similar results.

The statistical distributions, of 'predictive' and 'conventional' votes are symmetrical and centred on zero. Moreover, they are contained, for the two modes of control, in the [−0.5; 0.5] interval, which corresponds to practically adequate thermal comfort conditions (less than 10% of unsatisfied people [10]).

5.4. *Influence of free gains*

The annual average electricity consumption of electrical devices and lighting equalled 5.8 W/m^2 in the western part of the building (between 6 and 10 W/m^2 during the heating season). The heat dissipation by building occupants was evaluated at 1 W/m^2 [13,16].

Three categories of internal gains were considered to determine the influence of internal gains on heating needs.

The auxiliary heating needs of the western part of the building were determined for the whole heating season with the help of these evaluations on the internal gains; for this the following hypotheses were made:

- the correlation of the predictive and the conventional controller (H_0, η) was supposed identical for other free gain values;

Table 8
Thermal intensity and relative energy savings obtained with the predictive controller for different rates of internal gains (western part of the building)

Virtual consumption heating season		Control modes		Relative savings (%)
(MJ/m^2)	Gains (W/m^2)	Predictive (MJ/m^2)	Conventional (MJ/m^2)	
'Low' internal gains	5.7	188	204	8
'Medium' internal gains	9.7	148	172	14
'High' internal gains	13.7	104	135	23

- the indoor temperature was supposed independent of the site.

The gains from lighting were increased by 50%, in order to take into account the weak level of daylighting in winter.

Table 8 shows the influence of these gains. The administrative building of Delémont belongs to the second category, with a medium level of internal gains: energy savings are obviously superior if gains are higher.

6. Conclusions

A prototype predictive controller, based on the theory of optimal stochastic control, was developed and installed in an administrative building in Delémont (Switzerland). This building benefits from highly insulated glazing ($U = 0.65$ W/m^2K) and is equipped with an active floor heating and cooling system; a considerable part of the energy needs are thus met by free gains (solar radiation and internal heat dissipation).

The predictive controller was used successfully from Nov. 1992 to Dec. 1994 to drive the active floor system in the building. A comparison of its thermal performances with those of an advanced outdoor temperature based control device was undertaken simultaneously, showing energy savings in favour of the predictive controller amounting to 15% in the winter season as an average (Oct. through Apr.) and to 16% in the summer season (May through Sept.). An analysis of thermal comfort, based on questionnaires filled in by building users, as well as temperature monitoring in the building, showed that a high thermal comfort level was obtained with both control strategies.

These very positive results confirm the previous experiments carried out applying the optimal stochastic control theory to the energy management of direct gain solar office rooms (27% savings during a winter period) and active solar dwellings (20% savings on a winter season).

The extrapolation of these results to a wider use of this new control strategy must however be examined under the constraints of building practice. Even though high priority was given, during this work, to reducing the cost and the complexity of the hardware of this control device, a serious effort is still needed to avoid excessive commissioning charges and possible technical misunderstanding of the working principles of the optimal stochastic controller. Already addressed in this work in so far as well-known engineering rules were applied for the building parameters used by the control device, this aspect of the implementation of a new building technology will be considered in more detail in the upcoming development of an industrial product.

References

[1] A. Faist et al., Chaleur et lumière dans le bâtiment, *Document SIA D056*, LESO-PB EPFL, Switzerland, 1990.
[2] D. Bertsekas, *Dynamic Programming and Stochastic Control*, Academic Press, New York, USA, 1976.
[3] M. Nygard-Ferguson, Predictive thermal control of building systems, *Thèse No. 876*, Dept. de Physique, EPFL, Switzerland, 1990.
[4] M. Nygard-Ferguson and J.-L. Scartezzini, Evaluation of an optimal stochastic controller in a full-scale experiment, *Energy Build., 18* (1992) 1–10.
[5] J.-L. Scartezzini, F. Bochud and M. Nygard-Ferguson, *Applying Stochastic Methods to Building Thermal Design and Control*, Project NEFF 349, EPFL, Switzerland, 1991.
[6] M. Bauer, J.-L. Scartezzini and Y. Oestreicher, Régulation prévisionnelle appliquée à une installation solaire active, *Publication CUEPE No. 60*, Université de Genève, Switzerland, 1994.
[7] Bundesamt für Energiewirtschaft, *Meteonorm: Daten für den Solarplaner*, BEW Bern, Switzerland, 1985.
[8] *Thermal Performance of Buildings — Calculation of Energy Use for Heating*, European Committee for Standardization, Brussels, Belgium, 1994.
[9] J.-L. Scartezzini, F. Bottazzi and M. Nygard-Ferguson, *Application des Méthodes Stochastiques: Dimensionnement et Régulation*, Project NEFF 349/FNRS 2.331-0.86, EPFL, Switzerland, 1990.
[10] P.O. Fanger, *Thermal Comfort*, R.E. Krieger, Malabor, USA, 1981.
[11] Groupe de Recherche en Energie Solaire, *Guide Solaire Passif*, LESO EPFL, Switzerland, 1985.
[12] M. Bauer, A thermal analysis model for heated and cooled buildings, *Solar Energy*, to be submitted for publication.
[13] R. Dehausse, *Energétique des Bâtiments*, Vol. 3: *Les Bâtiments et leurs Équipements*, PYC, Paris, France, 1989.
[14] B.Y.H. Liu and R.C. Jordan, The interrelationship and characteristic distribution of direct, diffuse and total solar radiation, *Solar Energy, IV* (1960) 1–19.
[15] P. Parent and P. Morand, Application of optimal control theory to building energy management systems, *Proc. Third Int. Conf. Building Energy Management ICBEM 87, Lausanne, Switzerland, 1987.*
[16] L'énergie électrique dans le bâtiment, *Recommendation SIA 380/4*, SIA, Zurich, Switzerland, 1992.
[17] R. Weber, La régulation de chauffage prévisionnelle, *J. Suisse des Maîtres Ferblantiers et Appareilleurs, 18* (1993).
[18] R. Weber, Eine prophetische Heizungssteuerung, *St-Galler Tagblatt*, 16.5.1993.