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LOCAL OPERATING NETWORKS TECHNOLOGY AIMING TO IMPROVE BUILDING ENERGY MANAGEMENT SYSTEM PERFORMANCE SATISFYING THE USERS PREFERENCES

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The available Building Energy Management Systems (BEMS), although they contribute to a significant reduction of energy consumption and improvement of the indoor environment, they can only be implemented in new buildings. Their installation in existing buildings is far from being cost effective due to the incompatibility of communication protocols between BEMS designed by various manufacturers and unavoidable modifications for data transmission. On the other hand, current research for energy efficient buildings has proved that although the design and the facilities including BEMS aim to satisfy the thermal and visual comfort plus the air quality demands while minimising the energy needs, they often do not reach their goals due to users interference. Latest trends in designing Intelligent Building Energy Management Systems (IBEMS) offer a Man Machine Interface that could store the users preferences and adapt the control strategy accordingly. The objectives of the present paper are to present the advantages of the use of a man machine interface based on a smart card terminal together with fuzzy control techniques in satisfying the users preferences plus to underline the capabilities that the LON network offers to the design. A fuzzy PID controller is developed to reach the first of the above objectives. The monitoring of the energy consumption along with satisfying the users preferences is achieved by the use of

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a suitable cost function for the whole system. All the above parameters as well as the cost function are kept between acceptable limits. The overall control system including the cost function is modeled and tested using MATLAB/SIMULINK. The implementation of the control system in an existing building requires interconnection of sensors and actuators installed across the building, is well served by the LonWorks technology due to its high standards and flexibility features.

Keywords: Fuzzy PID controller; Intelligent Building Energy Management System; Cost function

1. INTRODUCTION

Building Energy Management Systems (BEMS) have been introduced in the late 70's due to the energy crisis combined with the fast development of computers science. Since then, BEMS have been used in a wide range of applications; thus useful experience is available regarding their benefits and drawbacks.

The main issue nowadays, regarding BEMS use, is the fact that although they contribute to significant reduction of energy consumption and improvement of the indoor environment, their installation is cost effective only in new buildings. In existing buildings, due to the incompatibility of communication protocols between BEMS designed by various manufacturers and the unavoidable modifications for data transmission, reduce their attractiveness.

On the other hand, current research for energy efficient buildings has proved that although their design and facilities incorporating BEMS aim to satisfy the thermal and visual comfort plus the air quality demands with simultaneous minimisation of the energy needs, they often do not reach their goals due to the users interference. Users are a dynamic part of the building and they should be treated as such.

The objective of the present paper is to propose the design of a BEMS that takes into account the users preferences as a dynamic part of the system The proposed BEMS will be implemented in three existing buildings using LonWorks (Local Operating Network) technology. In the next sections the software for the satisfaction of the users preferences as well as the cost function is described and simulation results are presented. Finally some implementation issues using LON technology are discussed.

2. SOFTWARE DEVELOPMENT

The software of the system aims to satisfy the following objectives at the zonal level:

(i) To maintain thermal, visual and indoor air quality comfort based on scientific guidelines of related bibliography [1,2].
(ii) To satisfy the users preferences that are inserted to the system through a smart card unit especially designed to support the proposed application.

The objectives are reached by the use of fuzzy PID controller at the zone level of the building while the supervision and minimization of the zones energy consumption for heating/cooling and lighting is based on a suitable cost function.

2.1. The Fuzzy PID Controller

2.1.1. Control Strategy

The aim of the controller is to maintain total comfort. Comfort is a very delicate subject and reflects the subjectivity of the users. The main parameters that influence the users comfort are:

(i) Thermal comfort
(ii) Visual comfort
(iii) Indoor air quality

Each on of the above depends upon various parameters.

The control of the thermal comfort has been limited to temperature and sometimes humidity regulation. Normally thermal comfort depends upon a great number of parameters such as air velocity, mean radiant temperature, people's activity, *etc.* For that reason, in this specific application the controlled parameter for thermal comfort, is the Predicted Mean Vote (PMV) introduced by Fanger [3] which depends upon the temperature of the zone, the relative humidity, the mean radiant temperature, the air velocity, the users activity level and the clothing parameter (clo). The first four parameters are measured while the next two are estimated on the basis of the building type and activities.

The PMV index varies in the range of -3 to $+3$, while the area that represents thermal satisfaction lies between -0.5 to $+0.5$ with the

Percentage of People Dissatisfied (PPD) index, introduced also by Fanger [3], to be less than 10%.

Visual comfort, on the other hand, depends upon a number of parameters (subjective and objective) such as [4] the illuminance levels and their spatial distribution, the glare, the colour rendering, view, *etc.*

The parameter selected for controlling visual comfort is the illuminance level, measured in lux, as all other parameters are strongly subjective and difficult to be measured.

The indoor air quality is mainly influenced by the concentration of pollutants in the controlled space. There is a wide range of indoor pollutants and specific sensors are required to measure each one of them. This forces the selection of the CO_2 concentration (measured in ppm) as the controlled parameter to measure the indoor air quality, as it reflects the presence of users as well as various sources of pollutants in the building.

After having selected the controlled parameters the control strategy is defined. The main issues in controlling all the above parameters is that, on the one hand the limits where the comfort and discomfort lies are fuzzy and subjective, while on the other hand oscillations and overshootings have to be avoided in order to minimise discomfort. A fuzzy PID controller has been selected for the reasons mentioned above, plus the fact that with this type of controller, the set points can be adjusted according to the users preferences and the K_i, K_p, K_d coefficients can be adapted according to the system's response in future research work.

A discrete PID controller consists from the following components:

(i) The P component, proportional to the error between the controlled parameter and the desired set point.
(ii) The I component, as the integration of the above error.
(iii) The D component as the derivative of the error.

Since the number of the fuzzy rules required, taking all three (P, I, D) components as inputs to the controller would be enormous and difficult to manage with, the controller is split to its PI and D component and two fuzzy rule bases are created for the two components [5].

The fuzzy–PI component for each of the controlled parameters (PMV, Illuminance levels, and CO_2 concentration) takes the following inputs:

(i) The error between the desired and the current value of each controlled parameter. This error is expressed as:

- pmve for PMV
- co2e for CO_2 concentration measured in ppm
- ie for illuminance measured in lux

(ii) The rate of the error for each controlled parameter expressed as:

- pmvr for the rate of error of PMV measured in 1/sec
- co2r for the rate of error of CO_2 measured in ppm/sec
- ir for the rate of error in the illuminance level measured in lux/sec

The outputs of the PI component are:

(i) Increase/decrease of heating/cooling (ah).
(ii) Increase/decrease of window opening or ventilator (w).
(iii) Increase/decrease of shading controlling the daylight contribution (s).
(iv) Increase/decrease of electric lighting (al).

The D component features the same outputs with the PI component and has the following inputs for the PMV and the CO_2 concentration:

(i) The difference between the value of the controlled parameter at time nT and its value at time $(n-1)T$. Those inputs are expressed as:

DYpmv for PMV
DYco for CO_2 measured in ppm

(ii) The error.

The outputs of the D component are:

Increase/decrease the window opening signal (dw)
Increase/decrease the heating/cooling (dah)

The use of the D component for the lighting level management is not considered necessary, since the response of the PI controller is satisfactory.

The fuzzy PI component has six inputs and four outputs, while the D component has four inputs and two outputs.

The controller has been modeled using MATLAB/SIMULINK. The simulation time step and the time interval for the evaluation of the parameter's rate of error is 120 sec.

The model of the building has been developed by the University of Athens in the framework of the Joule III Research Programme JOE3–CT 97 0044.

2.1.2. *The Fuzzy Rule Base*

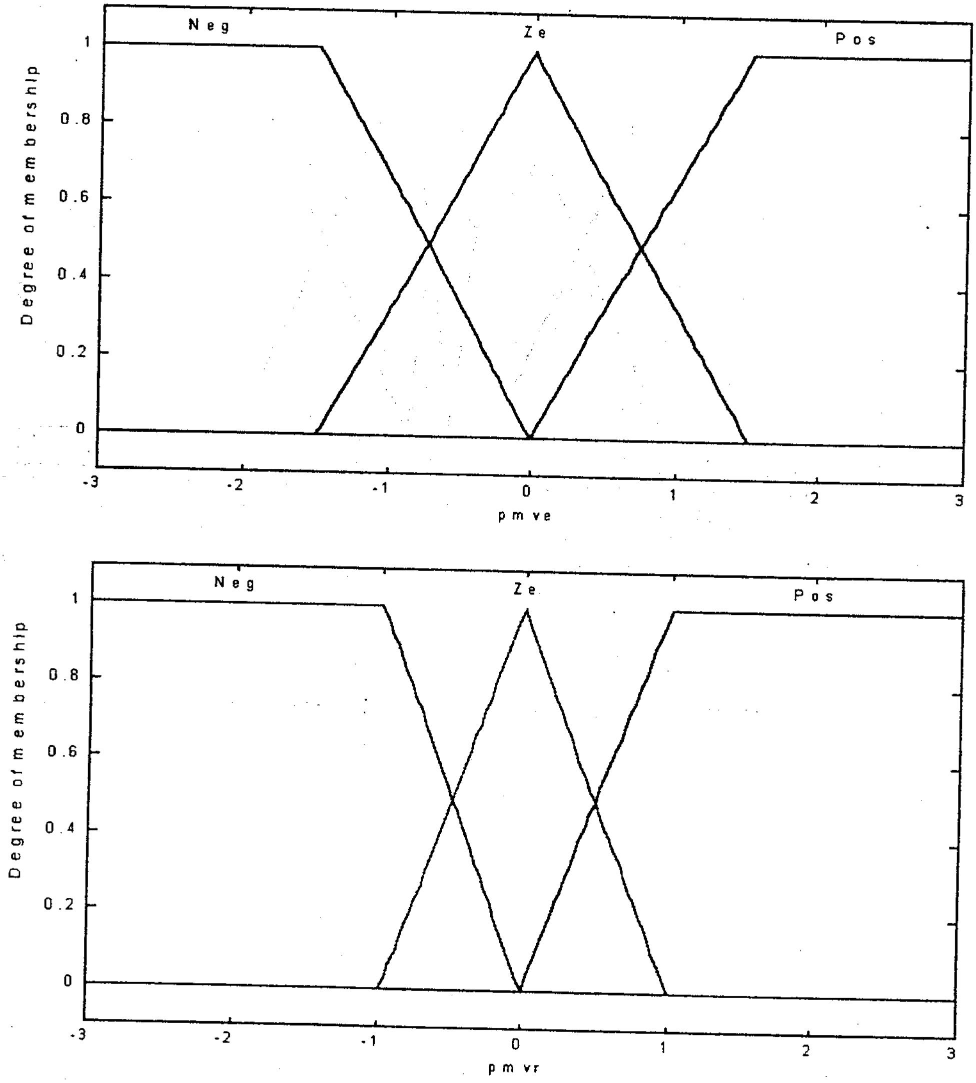
Before the description of the membership functions and the rule base, the following should be noted:

(a) The K_i, K_p and K_d coefficients are all selected equal to 1.
(b) The coefficients of the control signals (K_{upi}) for the fuzzy PI component are one scale higher than the coefficients of the fuzzy D component, indicating the stronger influence of the PI component to the control strategy.
(c) The membership functions used for this application for each controlled parameter are of triangular and trapezoidal type as these membership functions are the most widely used and demand less computational time [6], [7]. Furthermore, by applying other types of membership functions (*e.g.*, gaussian), there is no significant change in the controlled parameters response.
(d) The rules take into account the influence of the ventilation to the thermal comfort and *vice versa*.
(e) The influence of the daylighting to the thermal comfort is considered negligible.

Three membership functions were selected per input for each of the controlled parameters around the regions zero (Ze), negative (Neg) and positive (Pos).

Five membership functions are used per output (Zero, Small Positive, Small Negative, Positive, Negative).

The membership functions of the PMV (pmve) and its rate (pmvr) are illustrated in Figures 2.1.2.a and 2.1.2.b. The membership functions for heating/cooling are illustrated in Figure 2.1.2.c.



FIGURES 2.1.2.a, b Membership functions for ‘pmve’ and ‘pmvr’.

The rules controlling the PMV are the following:

If (*pmve is Neg*) *and* (*pmvr is Neg*) *then* (*ah is Neg*) (1)
If (*pmve is Neg*) *and* (*pmvr is Ze*) *then* (*ah is Neg*) (1)
If (*pmve is Neg*) *and* (*pmvr is Pos*) *then* (*ah is SN*) (1)
If (*pmve is Ze*) *and* (*pmvr is Neg*) *then* (*ah is SN*) (1)
If (*pmve is Ze*) *and* (*pmvr is Ze*) *then* (*ah is Ze*) (1)
If (*pmve is Ze*) *and* (*pmvr is Pos*) *then* (*ah is SP*) (1)
If (*pmve is Pos*) *and* (*pmvr is Neg*) *then* (*ah is SP*) (1)
If (*pmve is Pos*) *and* (*pmvr is Ze*) *then* (*ah is Pos*) (1)
If (*pmve is Pos*) *and* (*pmvr is Pos*) *then* (*ah is Pos*) (1)

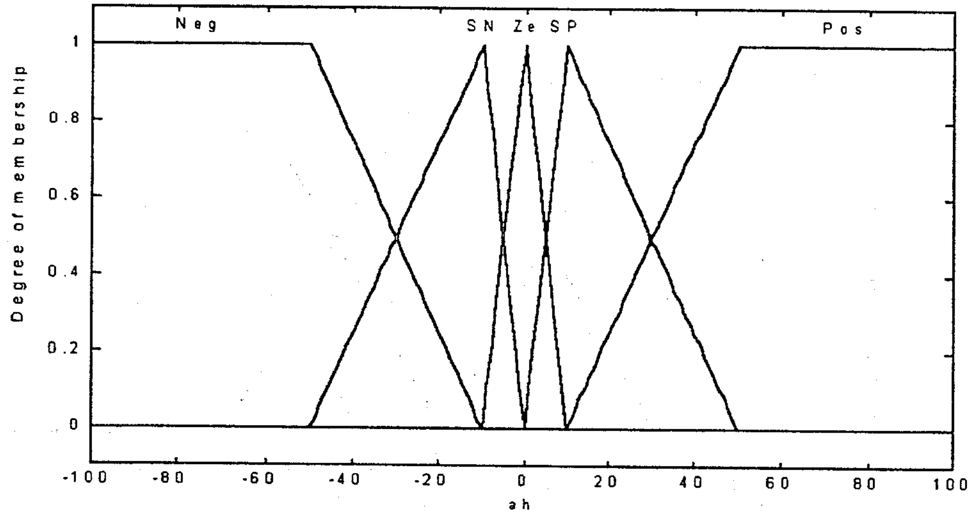


FIGURE 2.1.2.c Membership functions for heating/cooling change of the PI controller.

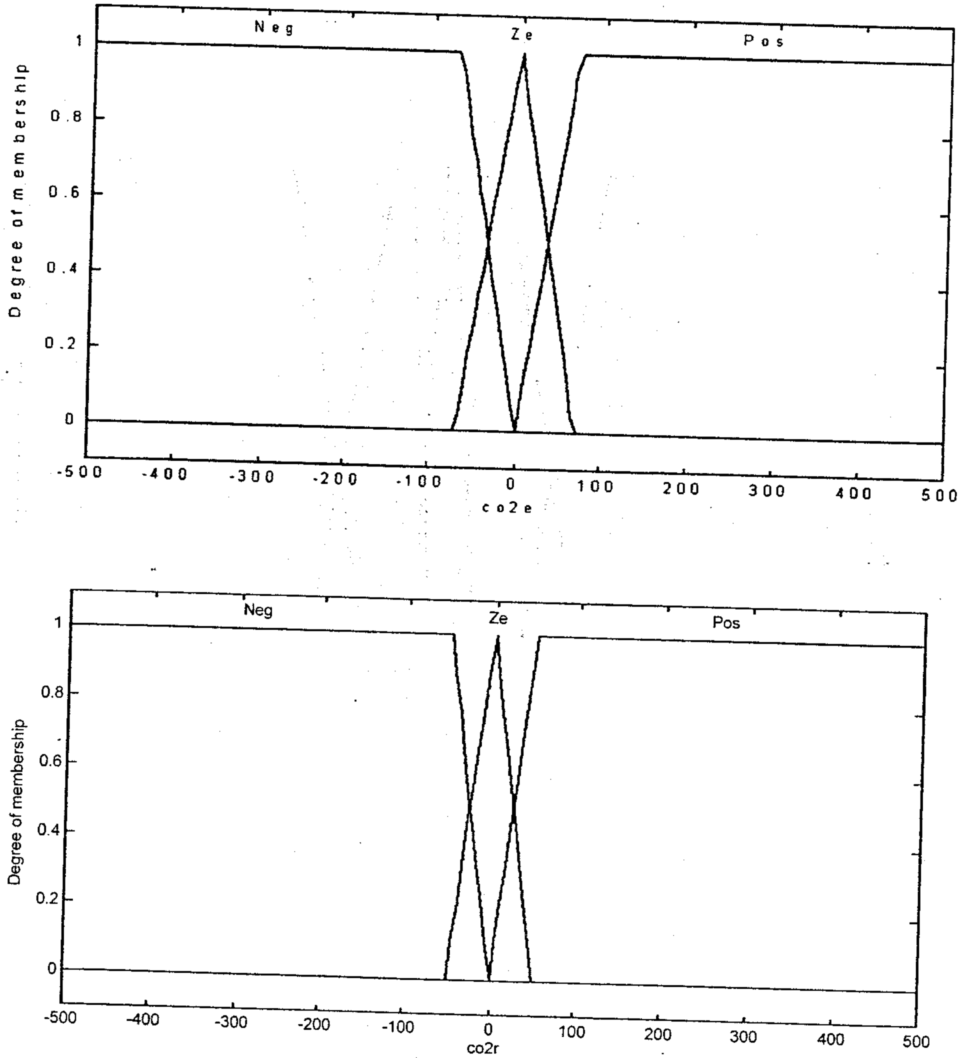
The membership functions of the CO_2 concentration error (co2e) and its rate (co2r) are shown in Figures 2.1.2.d and 2.1.2.e. The membership functions for the output are shown in Figure 2.1.2.f.

The rules controlling the CO_2 concentration are:

If (*co2e is Neg*) *and* (*co2r is Neg*) *then* (*ah is SP*)(*w is Pos*) (1)
If (*co2e is Neg*) *and* (*co2r is Ze*) *then* (*ah is SP*)(*w is Pos*) (1)
If (*co2e is Neg*) *and* (*co2r is Pos*) *then* (*w is SP*) (1)
If (*co2e is Ze*) *and* (*co2r is Neg*) *then* (*w is SP*) (1)
If (*co2e is Ze*) *and* (*co2r is Ze*) *then* (*w is Ze*) (1)
If (*co2e is Ze*) *and* (*co2r is Pos*) *then* (*w is SN*) (1)
If (*co2e is Pos*) *and* (*co2r is Neg*) *then* (*w is SN*) (1)
If (*co2e is Pos*) *and* (*co2r is Ze*) *then* (*w is Neg*) (1)
If (*co2e is Pos*) *and* (*co2r is Pos*) *then* (*w is Neg*) (1)

It is noticed that the control of the indoor air quality is taken into account for the heating/cooling operation to avoid fast increases and decreases of the PMV index when handling the openings/ventilators. The window opening varies from −30 to +30 (Fig. 2.1.f) assuming that the window cannot be opened more than 30% in most cases.

The same applies for the illuminance levels, where the membership functions are shown in Figures 2.1.2.g, 2.1.2.h, 2.1.2.i, 2.1.2.j. The



FIGURES 2.1.2.d, e Membership functions for 'co2e' and 'co2r'.

rules for the illuminance error (ie) and its rate (ir) are:

If (*ie is Neg*) *and* (*ir is Neg*) *then* (*al is Neg*)(*s is Pos*) (1)
If (*ie is Neg*) *and* (*ir is Ze*) *then* (*al is Neg*)(*s is Pos*) (1)
If (*ie is Neg*) *and* (*ir is Pos*) *then* (*al is SN*)(*s is SP*) (1)
If (*ie is Ze*) *and* (*ir is Neg*) *then* (*al is SN*)(*s is SP*) (1)
If (*ie is Ze*) *and* (*ir is Ze*) *then* (*al is Ze*)(*s is Ze*) (1)
If (*ie is Ze*) *and* (*ir is Pos*) *then* (*al is SP*)(*s is SN*) (1)
If (*ie is Pos*) *and* (*ir is Neg*) *then* (*al is SP*)(*s is SN*) (1)
If (*ie is Pos*) *and* (*ir is Ze*) *then* (*al is Pos*)(*s is Neg*) (1)
If (*ie is Pos*) *and* (*ir is Pos*) *then* (*al is Pos*)(*s is Neg*) (1)

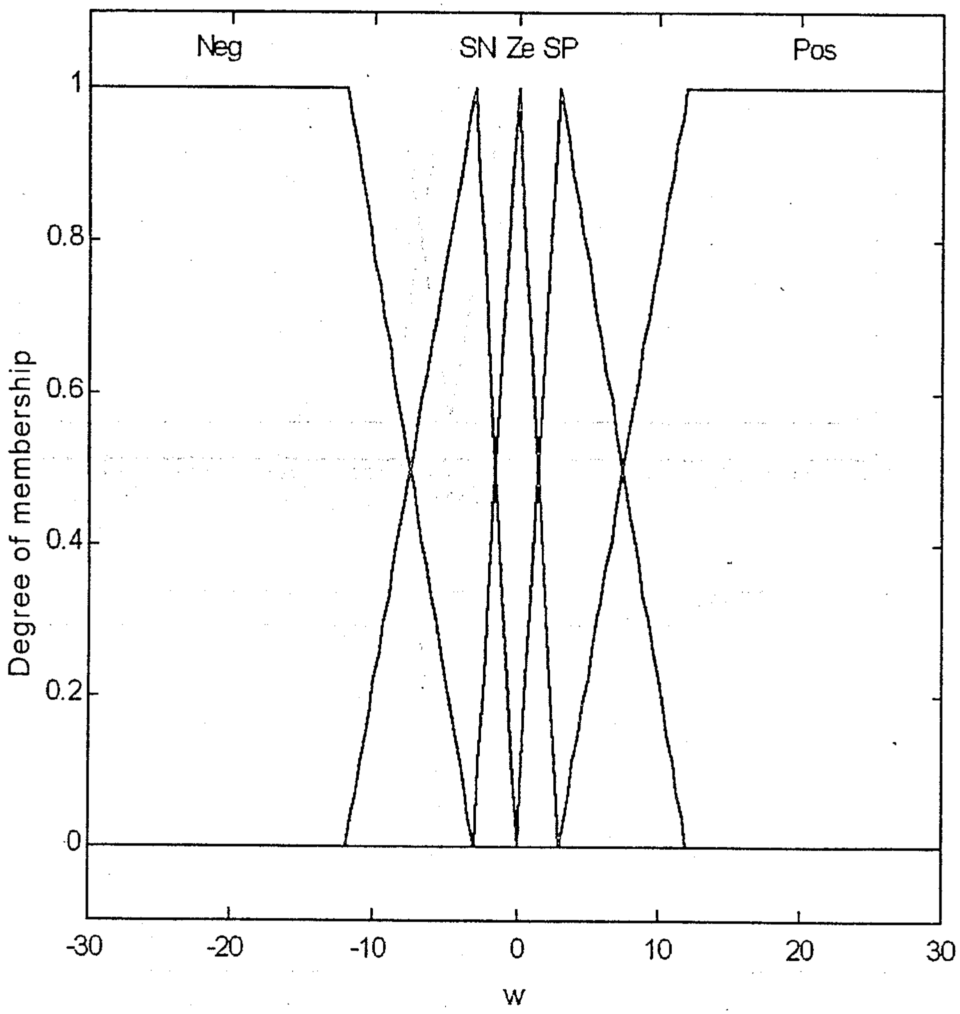
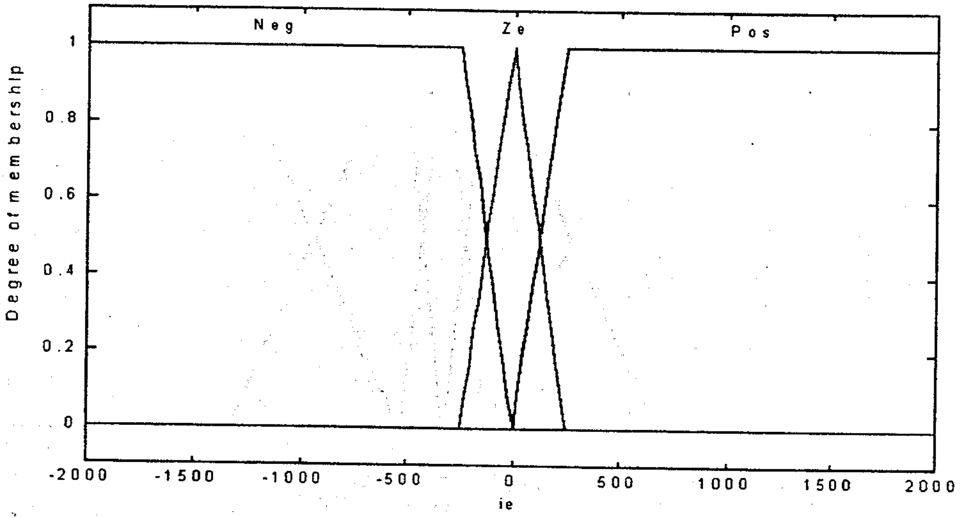
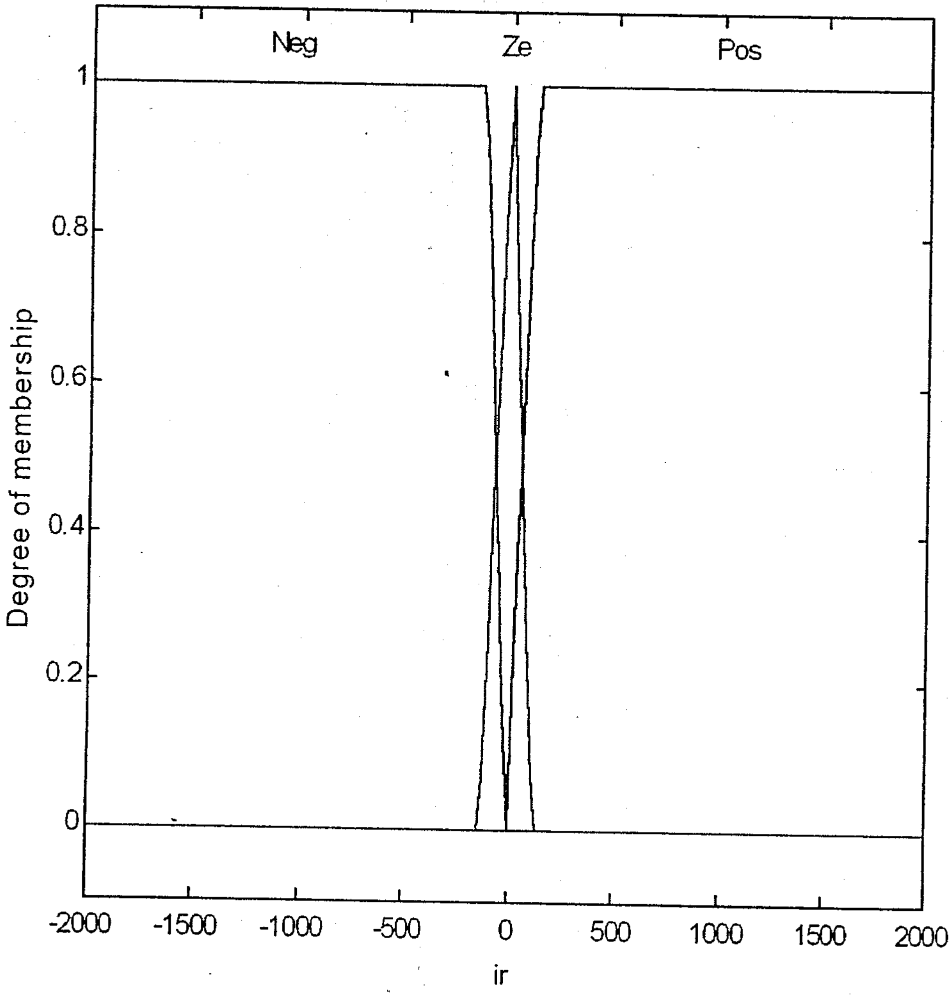


FIGURE 2.1.2.f Membership functions for window/ventilator opening of the PI controller.

The membership functions of the inputs of the D component are derived similar to those of the PI component. The rules of the D component are:

If $(-pmve$ *is pos*$)$ *and* $(DYpmv$ *is neg*$)$ *then* $(dah$ *is zero*$)$ (1)
If $(-pmve$ *is ze*$)$ *and* $(DYpmv$ *is pos*$)$ *then* $(dah$ *is pos*$)$ (1)
If $(-pmve$ *is ze*$)$ *and* $(DYpmv$ *is ze*$)$ *then* $(dah$ *is zero*$)$ (1)
If $(-pmve$ *is ze*$)$ *and* $(DYpmv$ *is neg*$)$ *then* $(dah$ *is neg*$)$ (1)
If $(-pmve$ *is neg*$)$ *and* $(DYpmv$ *is pos*$)$ *then* $(dah$ *is zero*$)$ (1)
If $(-co2e$ *is pos*$)$ *and* $(DYco$ *is pos*$)$ *then* $(dw$ *is zero*$)$ (1)
If $(-co2e$ *is ze*$)$ *and* $(DYco$ *is pos*$)$ *then* $(dw$ *is neg*$)$ (1)





FIGURES 2.1.2.g, h Membership functions of 'ie' and 'ir'.

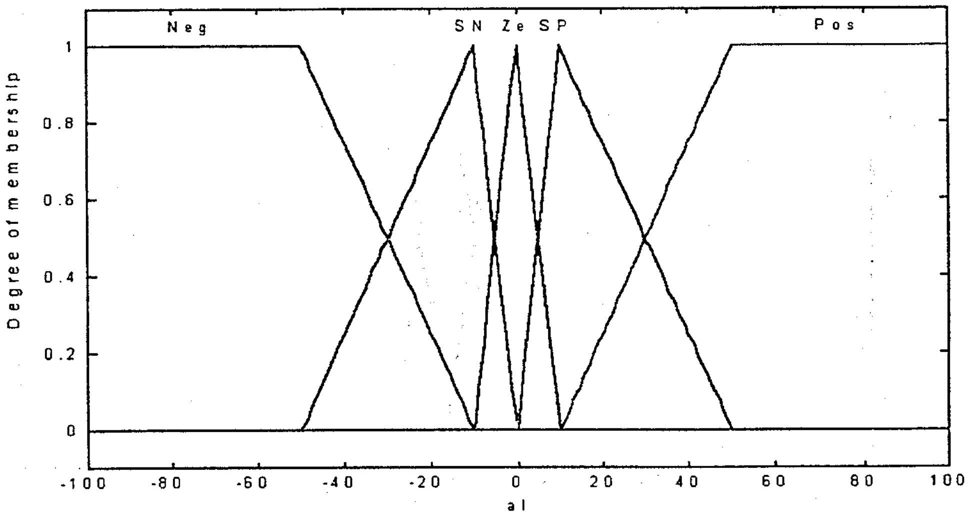


FIGURE 2.1.2.i Membership functions of electric lighting change.

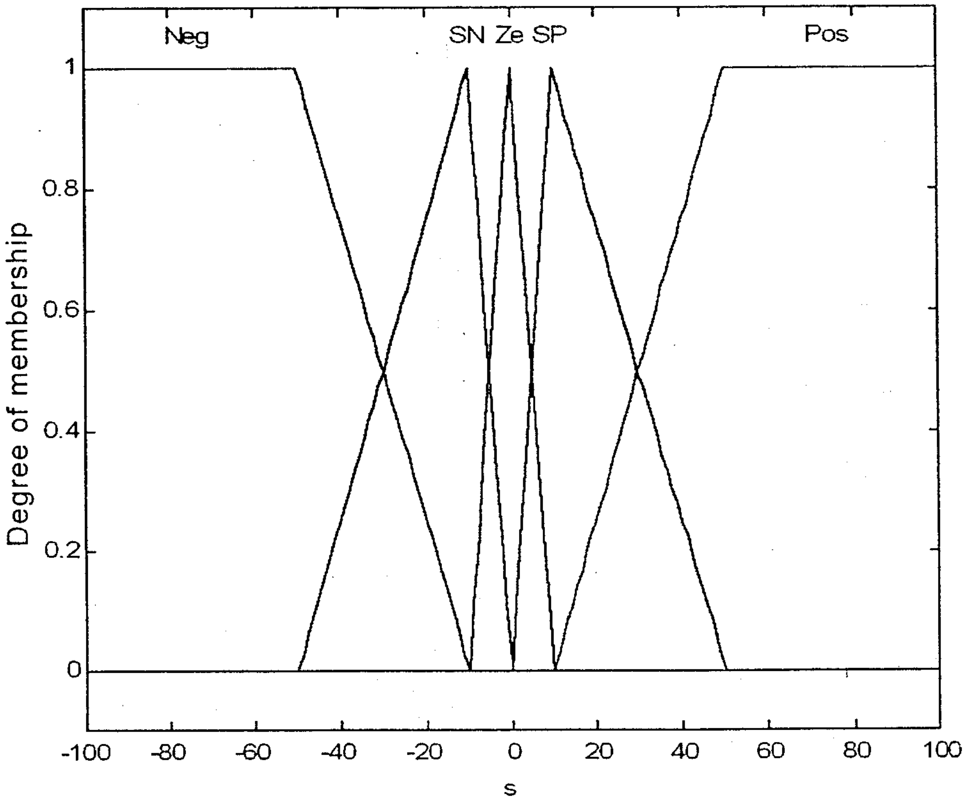


FIGURE 2.1.2.j Membership functions for shading and control of daylighting.

If $(-co2e$ *is* $ze)$ *and* $(DYco$ *is* $ze)$ *then* $(w$ *is* $zero)$ (1)
If $(-co2e$ *is* $ze)$ *and* $(DYco$ *is* $neg)$ *then* $(dw$ *is* $pos)$ (1)
If $(-co2e$ *is* $neg)$ *and* $(DYco$ *is* $pos)$ *then* $(dw$ *is* $zero)$ (1)

The rules of the D component are fired when the errors are approaching zero, in order to minimise the overshootings.

2.1.3. Simulation Results

The specified PID controller is tested using MATLAB/SIMULINK. The response of the three controlled parameters are shown in Figure 2.1.3.a for three typical winter days. The set point in Figure 2.1.3.a is PMV = 0, [CO_2] = 800 ppm and illuminance = 500 lux.

The users preferences are modelled using random generators that provide various set points for the PMV, CO_2 concentration and illuminance levels within the acceptable limits. The PMV set point is

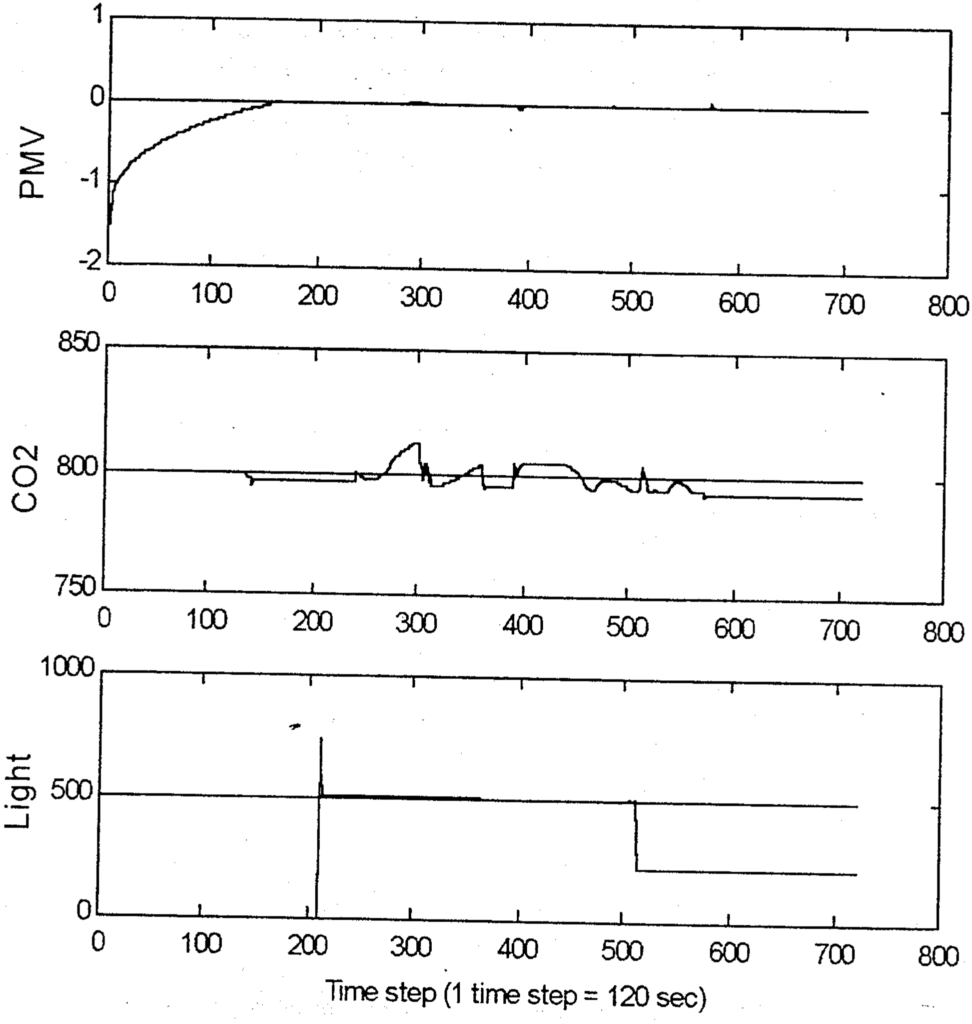


FIGURE 2.1.3.a PID controller response for fixed set points.

changing once every 3 hours while the [CO_2] set point once every 7 hours, considering that if the pollutants concentration is kept within the acceptable limits, people are satisfied.

The acceptable limits considered in order to model the controller are:

$-0.5 \leq \text{PMV} \leq 0.5$ [1]
600 ppm $\leq [CO_2] \leq$ 800 ppm [1, 2]
300 lux $\leq$ Illuminance $\leq$ 1000 lux [1, 2]

The simulation results are illustrated in Figure 2.1.3.b where the dashed line represents the users preferences (set points) and the solid line the system's response. The PMV is approaching the set point smoothly and without any overshootings or oscillations.

The [CO_2] level oscillates due to variant occupancy of the space. Although the controlled parameter follows the desired one quite successfully, this is achieved by opening and closing the window/ventilator very frequently (Fig. 2.1.3.c). Considering the fact that the window should not be opened and closed often because it is very likely

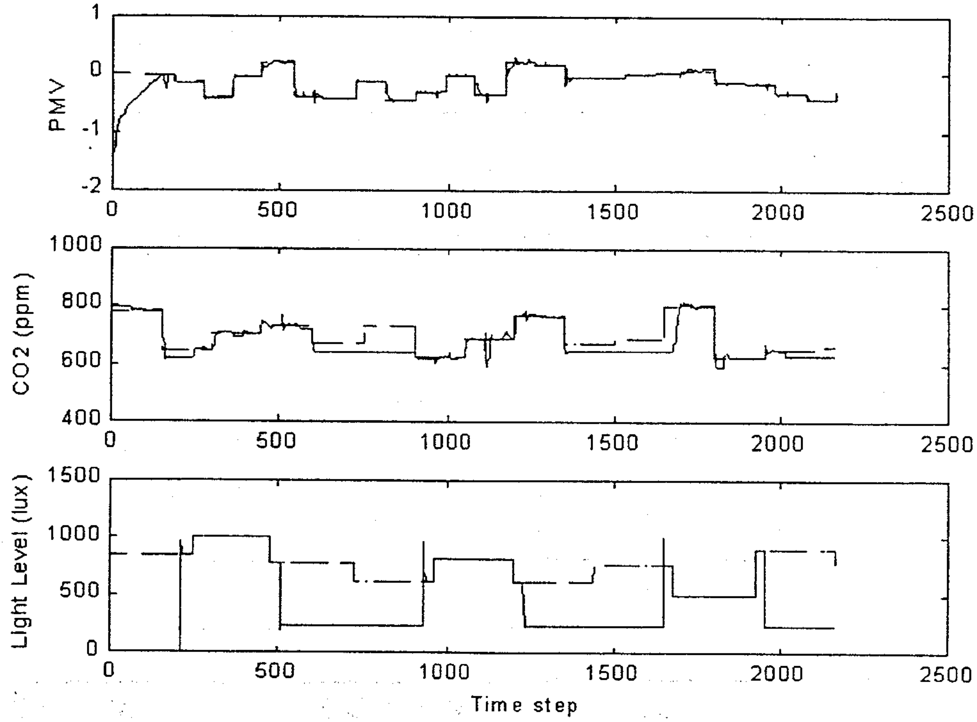


FIGURE 2.1.3.b PID controller response for users preferences.

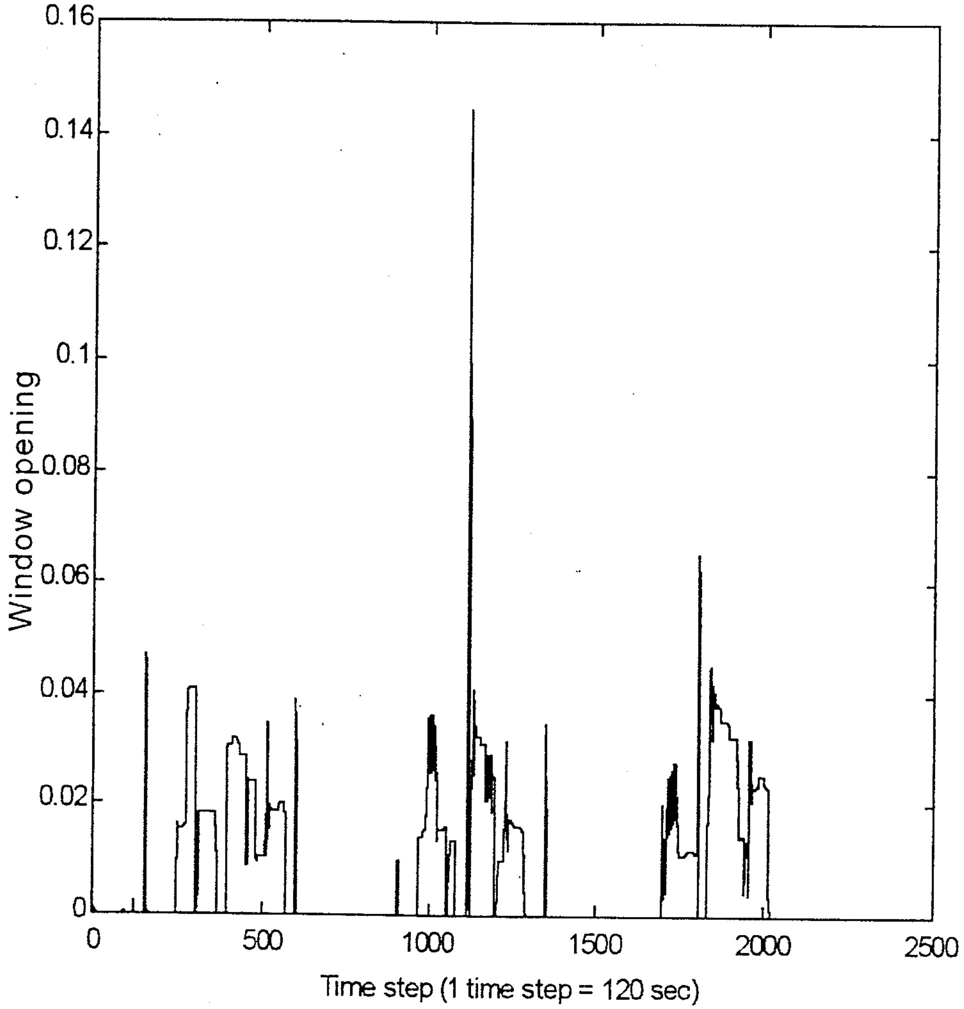


FIGURE 2.1.3.c Control signal for window opening.

that it causes annoyance to the occupants, the controller is simulated setting the K_i, K_p, K_d components of the [CO_2] concentration equal to 0.1 and without taking into account the influence of the window opening to the thermal comfort, because the control signal is small. The results are shown in Figure 2.1.3.d while the control signal is shown in Figure 2.1.3.e (window opening).

The [CO_2] concentration follows the desired set point less accurately but the control signal is smoother. The oscillations of the [CO_2] concentration are due to the users presence.

As far as the lighting levels are concerned, the controlled parameter follows the desired values, quite satisfactory. The overshooting observed at time step 200 occurs due to the immediate increase of

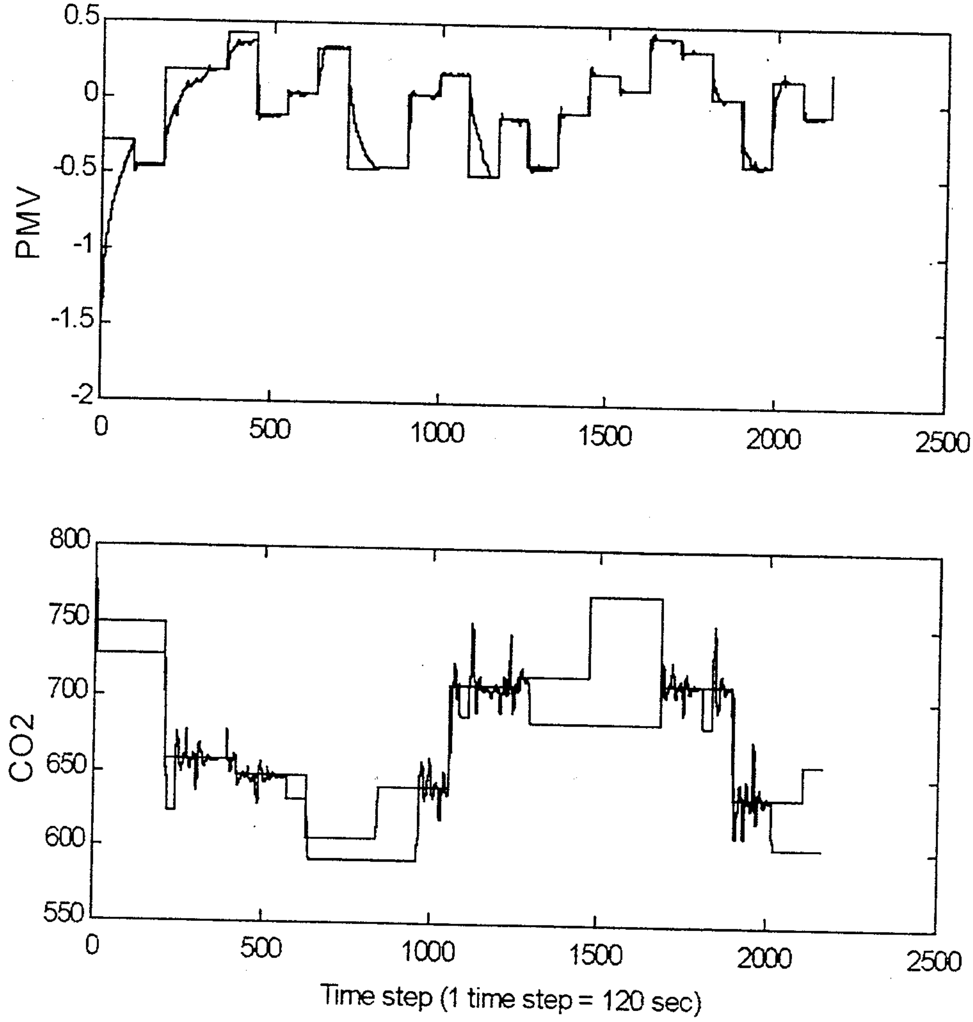


FIGURE 2.1.3.d PID controller response with respect to the window opening.

lighting levels due to daylight contribution. During the night, the desired lighting levels cannot be reached due to low levels of electric lighting used by the model. By keeping the lighting levels within the limits the glare index is acceptable [4] as shown in Figure 2.1.3.f.

2.2. Cost Function

2.2.1. The Role of the Cost Function

The aim of the system, as mentioned before, is to achieve minimisation of the energy consumption while maintaining comfort. Thus, the second important task of the controller is to monitor and control the

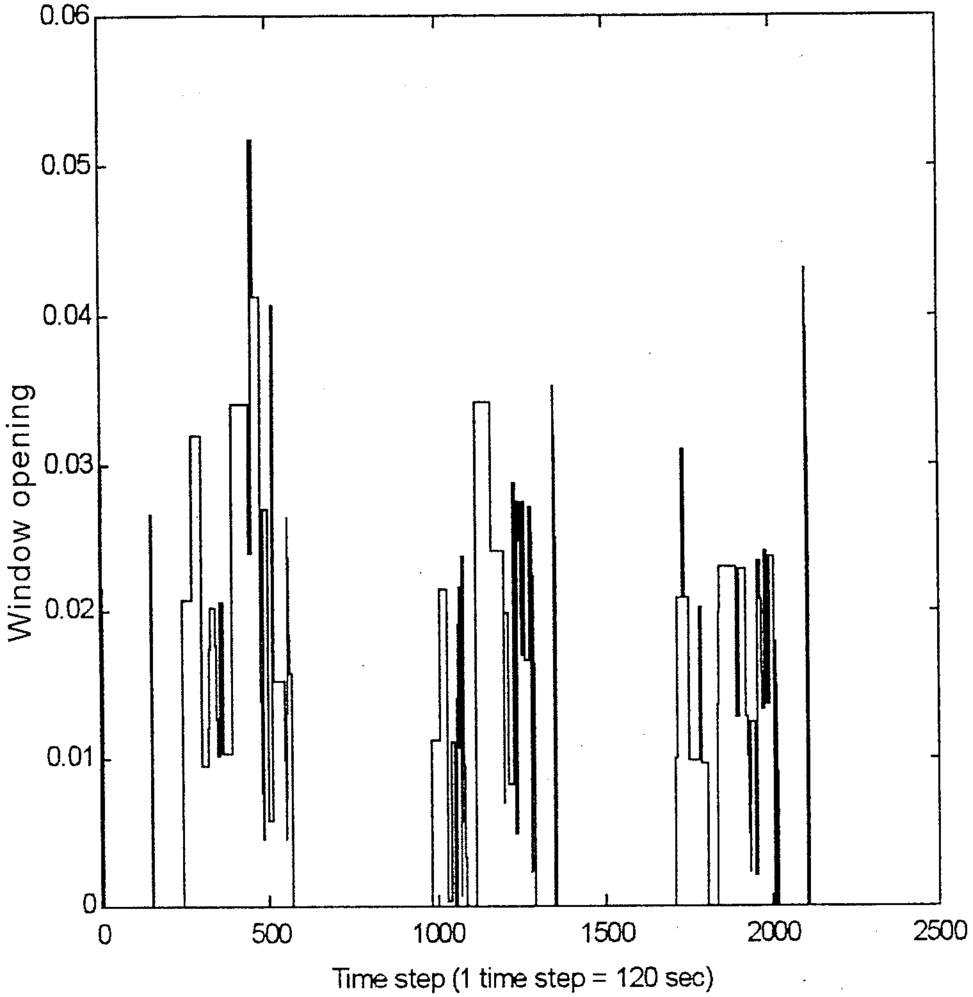


FIGURE 2.1.3.e Window opening.

energy consumption. This is achieved introducing a suitable cost function of the form:

$$\text{Cost } F = w_1 \cdot f_1 + w_2 \cdot f_2 + w_3 \cdot f_3 + w_4 \cdot f_4 + w_5 \cdot f_5 \qquad (2.2.1)$$

where f_1, f_2, f_3, are the normalised parameters for:

(a) PMV
(b) $[CO_2]$
(c) Illuminance levels

f_4, f_5 are the energy consumption for heating/cooling and the energy consumption for electric lighting respectively and w_1, w_2, w_3, w_4, w_5 are the weights of each parameter.

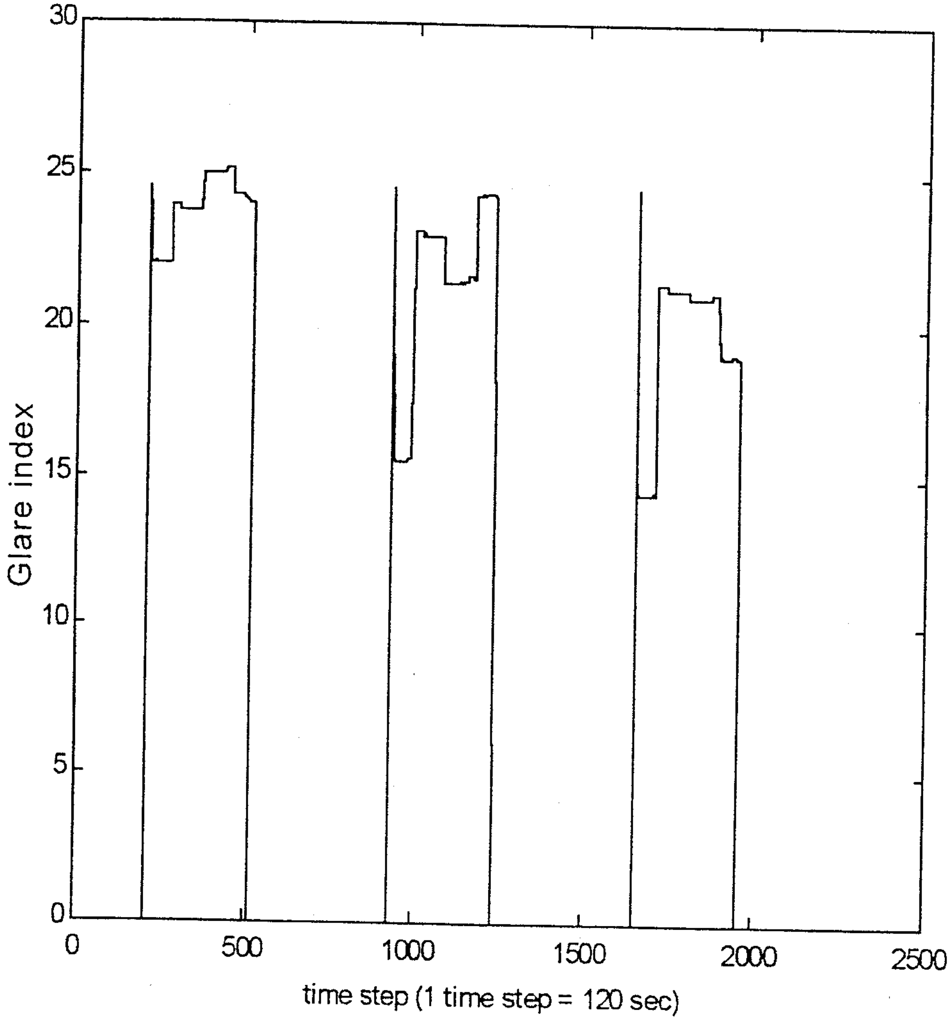


FIGURE 2.1.3.f Glare index.

The weights of the parameters are calculated using the Principal Component Analysis method (PCA) [7] where the largest weights are addressed to the parameters with the highest variation. Therefore the most important parameter for the user has the highest weight.

Having determined the acceptable limits of the parameters f_1, f_2, f_3 in the previous section, random generators are used to generate values within the acceptable limits. The optimum energy use per day is modelled using MATLAB/SIMULINK. For heating/cooling an optimum energy consumption of 200 kWh/m^2 per year is considered, while for electric lighting the level is 100 kWh/m^2 per year

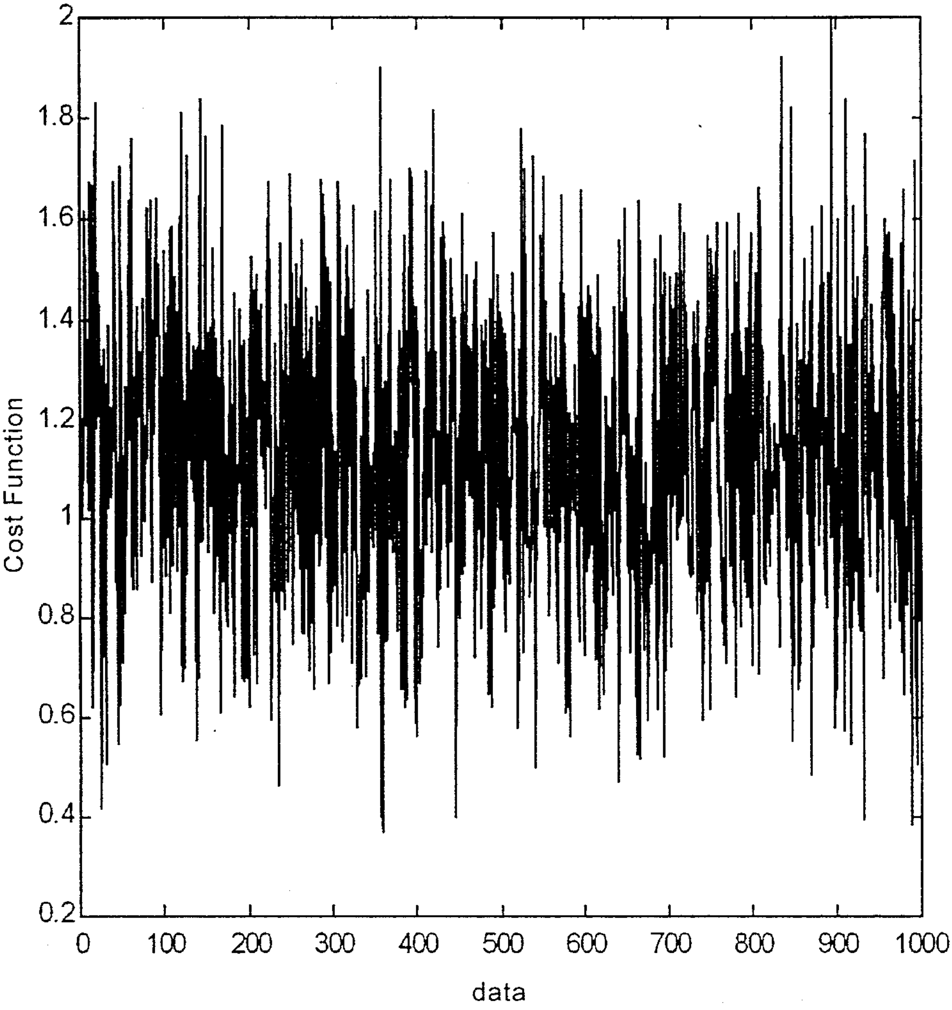
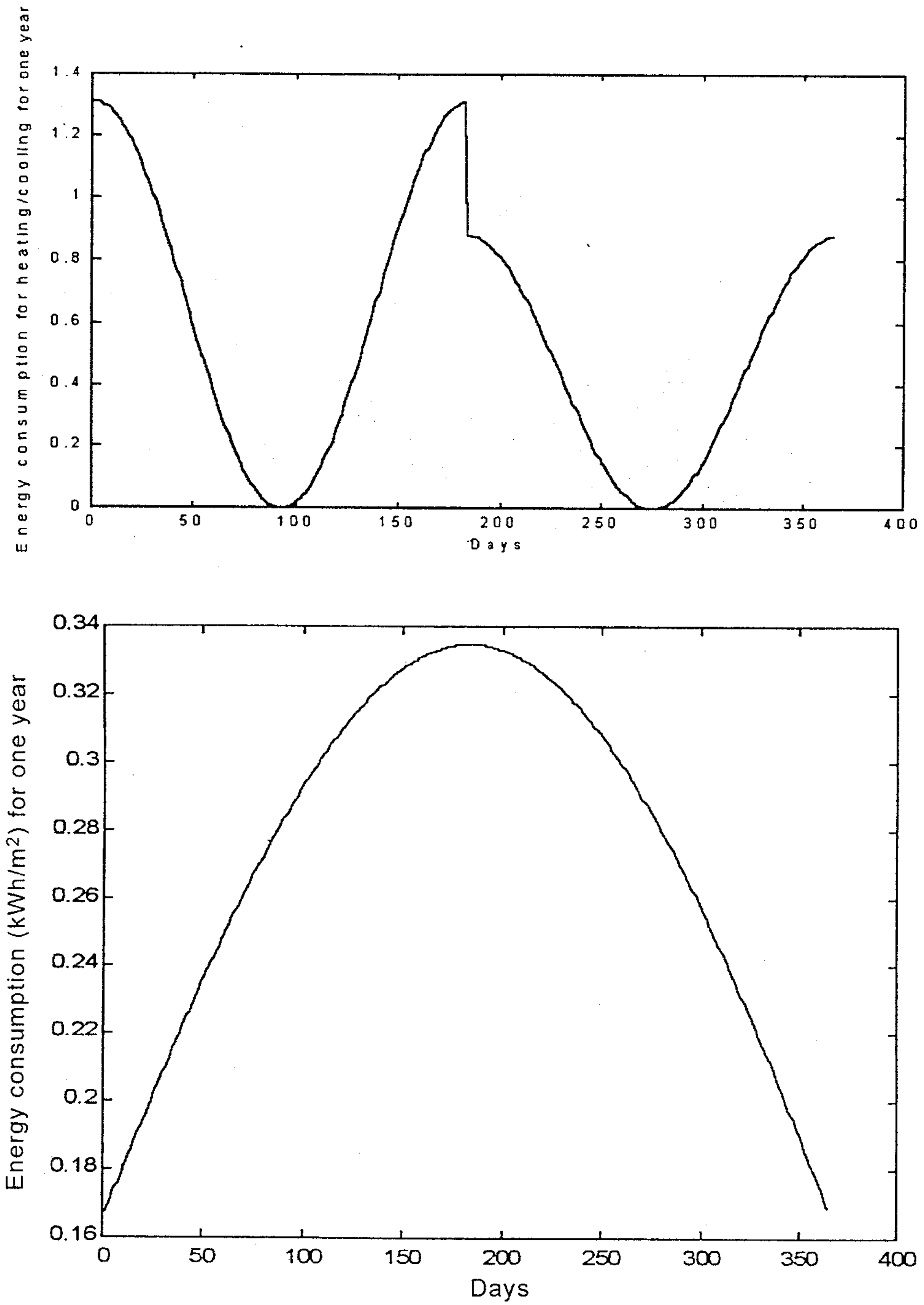


FIGURE 2.2.1.a Optimum values of the cost function.

(Figs. 2.2.1.b, 2.2.1.c). The daily energy consumption computed by the model is divided by the optimum energy consumption per day to provide the parameters f_4 and f_5. The objective is the determination of the optimum limits of the cost function as a whole. The weights are estimated using PCA and the resulting values are:

$w_1 = 0.4462$
$w_2 = 0.4432$
$w_3 = 0.4541$
$w_4 = 0.4396$
$w_5 = 0.4527$



FIGURES 2.2.1.b, c Energy consumption in kWh/m^2 for heating/cooling and electric lighting per day for one year.

The weights of the cost function are almost equal since the random generators do not show any preference to any particular parameter. The calculated weights and the optimum values of the normalized

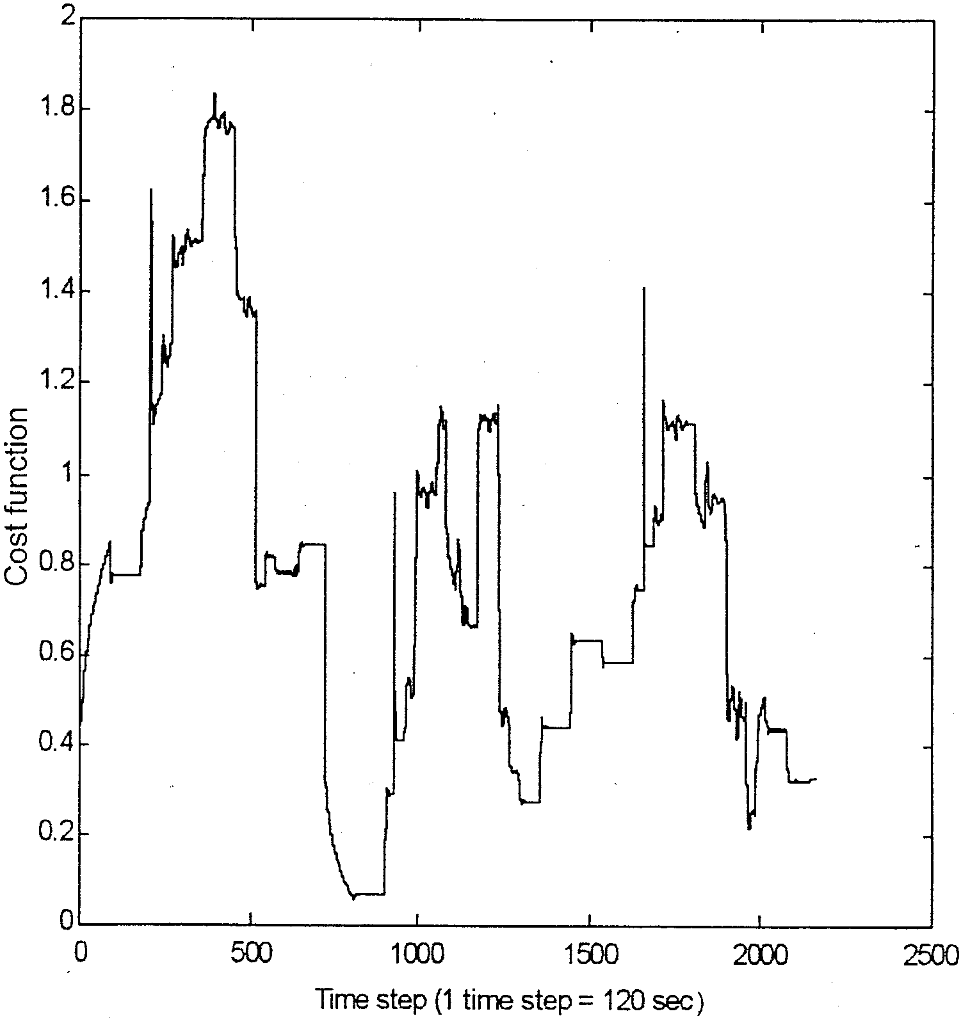


FIGURE 2.2.1.d Cost function for three days simulation of the PID controller.

parameters are used to estimate the range of the optimum cost function. The optimum cost function lies between 0 and 2 as shown in Figure 2.2.1.a. The maximum value of the cost function occurs while the system is operating at its highest limits for all environmental parameters and the energy consumption while the minimum cost function represents an average user and low energy consumption.

During real time operation the weights are tuned according to the users preferences, with the parameters characterized by the strongest variation to have the highest weights. The weights can be minimized but in any case cannot be zero.

The simulation results for the cost function for three winter days are shown in Figure 2.2.1.d. It is noticed that it is well within the acceptable limits with maximum value equal to 1.8. Therefore, the system is operating with acceptable energy use and within the comfort zone.

2.2.2. Action of the Cost Function

The role of the cost function is system supervision. As mentioned in Section 2.2.1 the cost function is kept within the acceptable limits. This may not be the case when the system is in actual operation. For that reason, after the installation of the system and during the on line operation, the cost function is estimated every 1/2 hour. When the cost function is out of the acceptable limits, the following actions will take place:

3. CONCLUSION

The described system ensures the satisfaction of the users preferences and energy savings. The reduction of the energy use is monitored by the cost function while the users is the dynamic part of the system.

The implementation of the control system in an existing building requires interconnection of sensors and actuators installed across the building, together with computational support for the control algorithm. This dual task is well served by the LonWorks technology due to its high standards and flexibility features. The integration of the Man Machine Interface is supported by a smart card unit. The proposed hardware architecture, offering the maximum degree of flexibility and expandability, is shown in Figure 3.1.

The data transmission throughout the system is performed by the Local Operating Network system (LON). The hardware of the system is fully interconnected. The LonWorks and LonTalk products of the ECHELON Inventor Company ensure communications networks realizations featuring a worldwide common protocol with high interoperability and interchangeability properties.

The LON Network is a solution suitable for building control due to its advantages. More specifically the LONTALK protocol has been designed for applications involving sensing, monitoring, control and

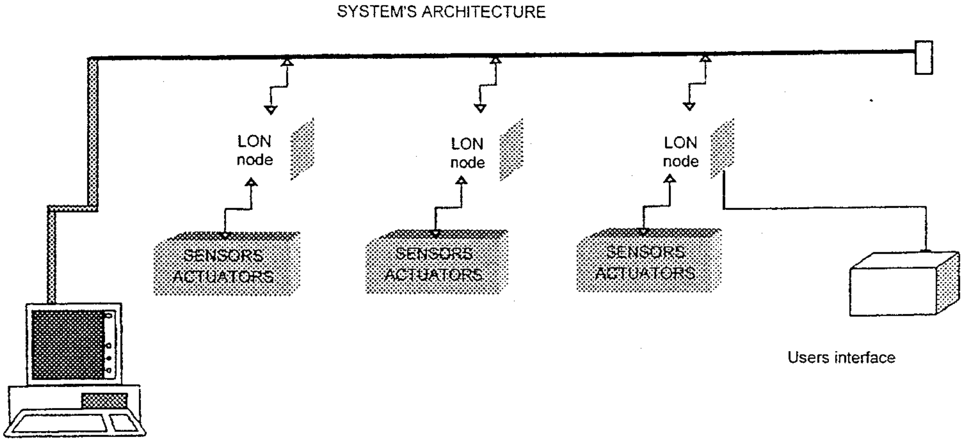


FIGURE 3.1 System's architecture.

identification function. The main features are:

(i) Free topology connection (ring, bus or star and all the combinations of the above) is allowed.

(ii) End-to-end acknowledgments with automatic retries are supported.

(iii) The nodes are "intelligent", due to the Neuron Chip microcontroller.

(iv) The LONTALK protocol supports communications on a wide range of wired and wireless media, including twisted pair, power lines, radio frequency, coaxial cabling, fiber optics, *etc.*

Especially for buildings applications, the existing power lines can be used, so no modifications are necessary.

The LON network provides the alternative of applying the IBEMS to existing buildings under low cost installation where the energy consumption is high. The cost of construction modifications is in a good compromise with the energy consumption minimization.

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