Hybrid ventilation performance assessment using fitness functions

M. El Mankibi and P. Michel
LASH, ENTPE, Rue Maurice Audin, 69518 Vaulx en Velin, France

ABSTRACT

The purpose of this paper is to provide a multicriteria approach in order to develop and to assess several architectures of controllers for hybrid ventilation. Indeed, there is nowadays a great interest in hybrid ventilation as an energy efficient strategy to achieve thermal comfort and indoor air quality. To reach those targets and manage hybrid ventilation systems, advanced control strategies based on hierarchical fuzzy controllers have been therefore developed at the LASH laboratory. In order to allow an objective evaluation of those controllers integrating comfort, indoor air quality, energy and stability criteria, two fitness functions have been defined and tested. The use of this multicriteria approach is also of special importance for the tuning process to refine the fuzzy sets and rules.

The principle of developed functions consist on converting all assessment criteria to financial equivalent ones taking into account occupant productivity, discomfort cost, heating and ventilating cost and operating cycles of equipments. Such inhomogeneous terms are not very easy to asses and the main difficulty is to define equivalences between them. To do so, both static and adaptive approaches of thermal comfort have been taken into account. PMV, adaptive comfort temperature and CO_2 concentrations have been used to evaluate the comfort criteria.

First, several simulations under winter and summer climate have been performed using a numerical model. The relative performances of developed architectures are then studied using a sensitivity study and the selected one has been tested using an experimental test cell (HybCell) conceived to develop and to assess controllers for hybrid ventilation.

1. INTRODUCTION

The basic principle of a Hybrid Ventilation System is to combine the best features of natural and mechanical ventilation in order to provide the best thermal comfort and an acceptable indoor air quality at the lower cost possible. In addition, those targets have to be reached taking the system stability and the device maintenance into account.

Although there were many projects on developing control strategies for hybrid ventilation (El Mankibi, 2003; Heiselberg, 2002) there remains a lack of knowledge concerning either the selection of adapted controller or the assessment of developed ones.

The fitness function is a multicriteria tool that can be used to solve this problem. It aims at providing an objective measure of any controller and its value has to be minimised. Several models of fitness function (Bruant, 1997; Blondeau et al, 2002) have been developed. The easiest way to build such functions is to use a linear function (1) of all criteria (Michel, 2000).

$$F_a=\sum_{i=1}^{n}\alpha_i \cdot C_i \qquad (1)$$

where:

- C_i: individual performance of the i criterion.
- α_i: Coefficient representing the relative weights of the C_i criterion on the global performance.

In most of the time, the main difficulty is to define the relationship between the criteria. This paper deals with this problem and presents an example of two fitness functions applied to three types of controllers for hybrid ventilation (OnOff, PID and Fuzzy controllers) under winter and summer conditions.

2. DESCRIPTION OF THE BUILDING AND THE NUMERICAL TOOL

An experimental test room called HYBCELL (EL Mankibi et al., 2001) located in Lyon (France) (Fig. 1) has been modelled in order to carry out the simulations. It is 5.1 m long, 3.5 m wide, 2.9 m high and represents a small meeting room within a large hall whose temperature can be controlled to create an artificial climate around it. The front of the cell is a slopped wall (70°) that communicate with outdoor climate trough six sash windows. All walls are made from office building materials.

The cell is equipped with an electric heater, a fan, window engines, CO_2 generation and sensible heat supply devices. Various sensors (temperature, pressure, relative humidity, CO_2 concentration, COV) have been installed in the test cell as well as in the hall and outdoors. In addition, wind velocity, wind direction and solar radiation data are provided by a meteorological station located near the cell. The CO_2 generation and sensible heat supply devices simulate occupancy in the experimental cell.

The simulations were carried out using HYBCELL1.0 (El Mankibi, 2003). This tool has been developed under the Matlab/Simulink environment by coupling a thermal model based on finite differences and a pressure air flow model. Indoor air temperature is calculated from various heat transfers phenomena such as heat transfer through the walls and other enclosure structures, air infiltration and ventilation, internal heat gains and auxiliary heating or cooling.

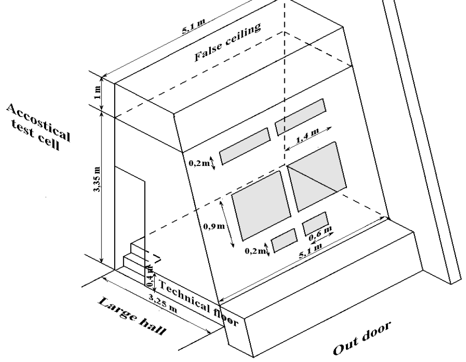

Figure 1: HYBCELL test cell architecture.

Several control strategies for hybrid ventilation based on CO_2, PMV and temperature were implemented in the model. Schedule and occupation patterns were also taken into account in the model. Experimental data provided by the HYBCELL test cell, has been used to adjust this numerical model.

3. DEVELOPED CONTROL STRATEGIES

The developed control strategies concern control of heating and ventilation. The aim was to provide a good thermal comfort and an acceptable indoor quality at the least energy consumption and maintenance coast. Three types of controller were tested:

- On-Off control: its action depends only on the value of the controller parameter and the set point.
- PID control: its action takes into account the history of the controlled parameter.
- Fuzzy control: its action is based on existing empirical knowledge of the system behavior and no mathematical description of the system is required.

3.1 Control parameters

Regarding to the objective of the controllers mentioned above, the selected control parameters are:

- PMV was selected as the daytime thermal comfort index. Occupant’s activity was supposed constant and equal to 1.2 met. Clothing value was considered equal to 0.5 clo in summer and 1 clo in winter.
- Indoor air temperature was considered to control night heating in winter and night cooling in summer.
- CO_2 concentration was chosen as indoor air quality index. The set point fixed for this index was 850 ppm.

Additional parameters called observation parameters was used for fuzzy control (dPMV/dt, dCO_2/dt and Outdoor air temperature).

The controlled variables were the fan speed, the heating power and the windows positions.

3.2 Architecture of the controllers

For each season (winter and summer), two type of control architecture were designed:

- Simple architecture based on On-Off or PID controllers (Fig. 2). The philosophy of this architecture consist on adjusting the status of fan speed, the heating power and the windows position according to the value of the difference between PMV, CO_2 and the indoor air temperature values and their respective set points.
- Fuzzy architecture based on hierarchical fuzzy controller (Fig. 3). The purpose of the first layer of this architecture is to identify the system thermal and ventilation demands. The second layer (Energy preference) defines whether IAQ or thermal comfort should be a priority according to the preferences of the designer. The last level of this architecture was dedicated to the required fun, windows or heating power status according to the history of decisions and the thermal or IAQ demands.

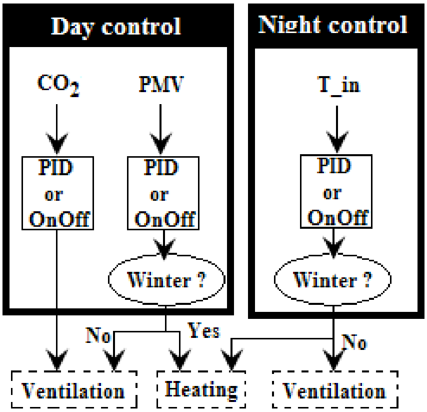

Figure 2: Architecture of simple controllers.

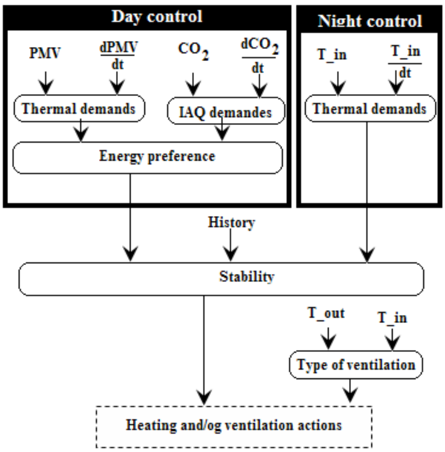

Figure 3: Architecture of fuzzy controllers.

In winter both simple and fuzzy architecture uses mechanical ventilation. On the other hand, in summer, three types of ventilation (natural, mechanical and hybrid) were tested.

4. DEVELOPED FITNESS FUNCTIONS

Two fitness functions F_a and F_b were developed according to five main criteria. The definition of weights for the selected criteria was based on finding financial equivalents for them.

4.1 Hot and cold sensations criteria

As a measure of thermal comfort, PMV was used for F_a and adaptive comfort temperature T_{comf} (Kathryn et al., 2002) was used for F_b.

The target is to maintain PMV in the bounds [-0.5; 0.5] as defined by ISO 7730 in order to keep the number of unsatisfied people under 10%. There is no standard concerning the bounds of comfort around T_{comf}. So in this study, we used variable bounds to have the equivalent unsatisfied people calculated using PMV (El Mankibi, 2003) (Fig. 4). Thermal criteria were calculated as follows:

$$
\begin{aligned}
C_{pmv}^{th-}(t) &= C_{pmv}^{th-}(t-dt) + \max(0; -PMV - 0.5) \\
C_{pmv}^{th+}(t) &= C_{pmv}^{th+}(t-dt) + \max(0; PMV - 0.5) \\
C_{Tcomf}^{th-}(t) &= C_{Tcomf}^{th-}(t-dt) + \max(0; T_{comf} - T_{LB} - T_{in}) \\
C_{Tcomf}^{th+}(t) &= C_{Tcomf}^{th+}(t-dt) + \max(0; -T_{comf} - T_{UB} + T_{in})
\end{aligned}
\quad (2)
$$

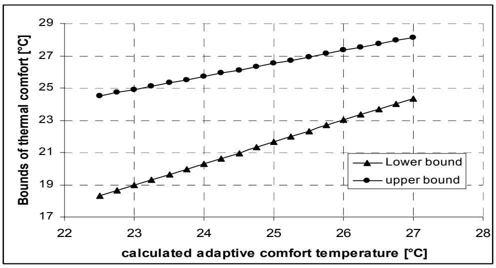

Figure 4: Bounds of adaptive comfort zone.

where:

C(t): Thermal criteria at time t [-/°C]
T_{UB}: Upper thermal comfort bound [°C]
T_{LB}: Lower thermal comfort bound [°C]
dt: Step time of the simulation [s]

4.2 Indoor air quality criterion

The same strategy was adopted for indoor air quality. The chosen assessment set point is equal to 850 ppm. Thus the IAQ criterion is defined as follows:

$$C^{IAQ}(t) = C^{IAQ}(t-dt) + \max(0; CO_2 - 850) \quad (3)$$

4.3 Stability criterion

To increase life cycle of devices and reduce maintenance or replacement cost, the stability criterion take into account each change in their status as follows:

If status(t) ≠ status (t-dt)
If (status(t-1) = device stopped)
Then $C^{Stab}(t) = C^{Stab}(t-dt) + 10$
Else $C^{Stab}(t) = C^{Stab}(t-dt) + 1$
Else $C^{Stab}(t) = C^{Stab}(t-dt) + 0$

The 10 to 1 ratio is due to the cost difference for the concerned device only or whole system replacement.

4.4 Energy criterion

The energy criterion is the easiest one to measure. At any step time, the total electric power required was evaluated. Consequently, the function characterising this criterion is:

$$C^{E}(t) = C^{E}(t-dt) + P(t) \quad (4)$$

where:

P(t): electric power [kWh^{-1}].

4.5 Thermal comfort weights

Two financial equivalences were adopted for thermal criteria. The weight used for the function F_a allows to link thermal comfort to occupants productivity. Bergland have produced a simple model to relate occupants' performance decrement with temperature (18% change in thermal satisfaction corresponds to 3% change in productivity) (Bergland et al., 1999). The thermal comfort weight for F_a criteria is therefore:

$$\alpha_{th}^{F_a} = \frac{PL \cdot SC \cdot FA \cdot ND}{Nbts \cdot PMV^{*} \cdot 365} \quad (5)$$

with:

Nbts: Number of simulation step time [-]
PL: Productivity loss for 18% of unsatisfied (0.03) [-]
PMV*: Corresponding PMV (0.55) [-]
SC: Staff cost/year/floor area [€.m^{-2}]
FA: Floor area [m²]
ND: Number of simulated days [-]

For the function F_b the thermal weights were calculated in order to evaluate the required energy cost to establish a situation of thermal comfort. The applied formula is:

$$\alpha_{th}^{F_b} = \frac{\rho \cdot V \cdot c}{3600 \cdot 1000} \cdot Ec \quad (6)$$

with:

ρ: air density [kg.m^{-1}]
V: Test cell volume [m^3]
c: Specific heat [J.kg^{-1}.K^{-1}]
Ec: Energy coast [€.(Kwh^{-1})$^{-1}$]

4.6 IAQ weights

Sick building syndrom can reduce staff productivity by 2 up to 100% (Bruant, 1997) but there is no equivalence between CO_2 concentration and productivity unlike thermal comfort. However, using the relation linking CO_2 concentration to the number of unsatisfied (Michel, 2000), the IAQ weight for F_a was calculated following the same philosophy as for thermal weights:

$$\alpha_{IAQ}^{Fa} = \frac{PL \cdot SC \cdot FA \cdot ND}{Nbts \cdot CO_2^{*} \cdot 365} \quad (7)$$

CO_2^* is the CO_2 increase corresponding to 3% productivity (1000 ppm in our case).

The IAQ weight for F_b is calculated evaluating the needed fun energy to establish a CO_2 concentration equal to 850 ppm. Thus the formula for this weight is:

$$\alpha_{IAQ}^{F_b} = \frac{P \cdot \rho \cdot V}{\left(850 - C_{CO_2}^{Ext}\right) \cdot 3600 \cdot 1000} \cdot Ec \quad (8)$$

with:

$C_{CO_2}^{Ext}$: External CO_2 concentration [ppm]
P: Fun power [W]

4.7 Energy and stability weights

F_a and F_b have the same weights for energy and stability. The energy weight represents the cumulated electric power as follows:

$$\alpha_E = \frac{dt \cdot Ec}{3600 \cdot 1000} \quad (9)$$

The weight for stability was defined according to the life cycle of each device and it replacement cost:

$$\alpha_{Stab} = \frac{Cost}{Life \quad cycle} \quad (10)$$

The defined functions are then:

$$F_a(t) = F_a(t-dt) + \alpha_{th}^{F_a} \cdot \left(C_{pmv}^{th-} + C_{pmv}^{th+}\right) + \alpha_{IAQ}^{F_a} \cdot C^{IAQ} + \alpha_E \cdot C^E + \alpha_{Stab} \cdot C^{Stab} \quad (11)$$

$$F_b(t) = F_b(t-dt) + \alpha_{th}^{F_b} \cdot \left(C_{Tconf}^{th-} + C_{Tconf}^{th+}\right) + \alpha_{IAQ}^{F_b} \cdot C^{IAQ} + \alpha_E \cdot C^E + \alpha_{Stab} \cdot C^{Stab} \quad (12)$$

For the test cell (volume of 40 m^3) with an energy cost equal to 0.107 € per Kwh^{-1} and a staff cost equal to 2500 $€.m^{-2}.year^{-1}$:

$\alpha_{th}^{F_a}$ =4.3 10^{-3} €; $\alpha_{IAQ}^{F_a}$=2,365.10^{-6} $€.ppm^{-1}$

$\alpha_{th}^{F_b}$ =1.5 10^{-3} $€.°C^{-1}$; $\alpha_{IAQ}^{F_a}$=2,14.10^{-6} $€.ppm^{-1}$

α_E=1.7833 10^{-6} €;

Fan	α_{Stab}=6.333.10^{-4} €
Heating	α_{Stab}=3.75 10^{-4} €
Windows	α_{Stab}=9.205 10^{-4} €

5. RESULTS AND DISCUSSION

Two periods of 30 days (winter and summer) were simulated under the climate of Lyon (France). The winter simulations aimed at comparing the performance of the developed controller and selecting adequate type of ventilation for each of them. Table 1 presented the performed simulations for this season.

The summer simulations aimed at comparing natural, mechanical and hybrid ventilation performances for each controller (Table. 2).

The winter simulations results are shown in Table 3. The F_a and F_b values for the tested architecture revelled that global cost were reduced by 11% up to 15% with fuzzy control when compared to simple strategies according to the type of ventilation. This profit was due to energy consumption (3% to 5%), thermal comfort (70% to 75%) and stability (65% to 72%). The simulations also showed that fuzzy controllers performances depends less on the type of ventilation whereas simple controllers performances are tributary of ventilation type and only OnOff presented th+ discomforts.

Differences were also noticed between the developed functions of performance, in particular for thermal comfort criteria. Thus, F_b describes better lower temperatures especially for OnOff control.

Alike winter results, summer ones (Fig. 5) shows that global performances for On-Off control was 1% up to 3% better than those of fuzzy architecture. Whoever, detailed analysis of individual criteria showed that fuzzy architecture is quit better in terms of thermal comfort and IAQ with a high level of instabilities. For all tested

Table 1: Winter simulations.

Simulation	Architecture	Ventilation
W1	Simple (OnOff)	Natural
W2	Simple (OnOff)	Mechanical
W3	Simple (PID)	Natural
W4	Simple (PID)	Mechanical
W5	Fuzzy	Natural
W6	Fuzzy	Mechanical

Table 2: Summer simulations.

Simulation	Architecture	Ventilation
S1	Simple (OnOff)	Natural
S2	Simple (OnOff)	Mechanical
S3	Simple (OnOff)	Hybrid
S4	Simple (PID)	Natural
S5	Simple (PID)	Mechanical
S6	Simple (PID)	Hybrid
S7	Fuzzy	Natural
S8	Fuzzy	Mechanical
S9	Fuzzy	Hybrid

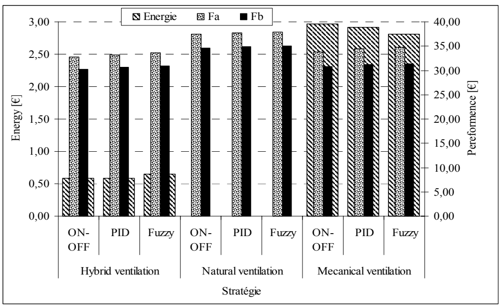

Figure 5: Summer simulations results.

Table 3: Winter simulations results.

	Global		Th+		Th-		IAQ		Stability	Energy
	F_a	F_b	F_a	F_b	F_a	F_b	F_a	F_b		
W1	124.77	127.43	0	0.86	0.38	2.16	0.45	0.48	14.94	108.99
W2	125.01	125.79	0	0.56	0.31	0.48	0.63	0.67	14.95	109.13
W3	125.35	126.43	0	0	0.83	1.91	0.01	0.01	13.86	110.65
W4	122.60	122.67	0	0	0.63	0.69	0.12	0.13	11.87	109.98
W5	109.27	109.08	0	0	0.73	0.53	0.17	0.18	4.11	104.26
W6	110.93	110.64	0	0	0.78	0.47	0.41	0.43	5.55	104.19

architectures, the use of hybrid ventilation reduced the energy cost by 75% while providing the same thermal comfort level as mechanical ventilation.

Under summer conditions neither F_a nor F_b were able to sense the good performance of fuzzy controller concerning the PMV values revelled by the simulations. Indeed, the maximum of PMV for simple strategies was 0.9 point higher than for fuzzy architecture while the used fitness functions indicated an insignificant difference between the three architectures. This is due to definition of weights for thermal criteria which depend linearly on PMV value whereas the variation of percentage of unsatisfied people doesn't vary linearly with PMV.

6. CONCLUSION

This study showed the aptitude of multicriteria fitness functions to assess different architectures of control strategies. It also revelled higher performances either for fuzzy controllers or for hybrid ventilation under summer and winter conditions. However, the definition of weights is of special importance for the interpretation of the assessment results.

REFERENCES

Bergland, L., R. Gonzales and A. Gagge, 1999. Predicting human performance decrement from discomfort and ET*, proceeding, Indoor air 1999, Ottawa, Canada.

Blondeau, P., M. Spérandio and F. Allard, 2002. Multicriteria analysis of ventilation in summer period, Building and Environment, Vol 37.

Bruant, M., 1997. Développement et paramétrage de contrôleurs flous multicritères de confort d'ambiance, Phd, Lyon, Institut National des Sciences Appliquées de Lyon.

El Mankibi, M., P. Michel and G. Guarracino, 2001. Control Strategies for hybrid ventilation development of an experimental device. Proceedings, The 22nd Annual AIVC Conference, Bath.

El Mankibi, M., 2003. Développement et évaluation numérique et expérimentale de stratégies de gestion de la ventilation hybride, Phd, Lyon, Institut National des Sciences Appliquées de Lyon.

Heiselberg, P., (ed), 2002. Principle of Hybride Ventilation, Aalborg, Aalborg University.

Kathryn, J., McCartney and J.F. Nico, 2002. Developing an adaptive control algorithm for Europe, Energy and Buildings, Vol 34, n° 6.

Michel, P., 2000. Fuzzy controllers and smart tuning techniques for energy efficiency and overall performance of HVAC systems in building, Final report, European projet Genesys.