MULTI-OBJECTIVE OPTIMIZATION OF BUILDING CLIMATE CONTROL SYSTEMS USING FUZZY-LOGIC

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Abstract

Frequently the user of multi-variable control systems is interested in operating them in a demand- or event-responsive manner according to various, sometimes opposing performance criteria. E.g. within well isolated low-energy houses there is an increasing requirement to coordinate the control of heating, ventilation and air conditioning systems (HVAC) in such a way that both economy and comfort criteria can be considered with a user-specific tradeoff. In order to find an on-line solution of this multi-objective process optimization problem, a new supervisory control concept has been developed at IITB. By means of a simple slide button the user is enable to choose his individual weighting factors for the economy and comfort criteria which are taken to optimize the reference commands of heating and ventilation controllers. The disturbing influence of external climate changes is considered as well as variations of the room occupancy. The performance of the fuzzy-based multi-objective optimization concept which has been implemented in a test environment at IITB is analyzed and discussed by means of experimental results.

1 Motivation

Within the last decades more and more insulating building materials and construction techniques have been developed and introduced. By these measures a remarkably high energy saving has been achieved, however at the cost of a diminished natural air exchange within the buildings. In order to guarantee a sufficient air quality and living comfort it is compelling to introduce more and more controlled ventilation besides controlled heating facilities.

The demand-responsive coordination of both control loops is a tough problem for the average user. On the one hand he is free to choose the reference commands of heating and ventilation control in such a way that his individual cost and comfort criteria are satisfied. On the other hand the climate state response within the living room in interaction with the outside climate is very complex and nonlinear. Thus the user will hardly comprehend all the consequences of his operations with respect to cost and comfort criteria.

Obviously, there is an increasing demand on the HVAC (heating, ventilating and air conditioning) market for a user - friendly integrated control and monitoring concept of heating and ventilation control systems which is optimizable with respect to the individual comfort and economy requirements of the user.

In order to solve the multi-objective on-line optimization problem at the IITB a new fuzzy-logic supervisory control concept has been developed [1],[2] which can be applied in a modified way to different industrial areas as well. Especially in the steel and glass industry [3] there is an increasing demand for controlling processes optimally in terms of contradictory performance criteria (e.g. productivity versus product quality).

As regards the application of fuzzy methods to multicriterial optimization problems in the area of operations research various fuzzy-based optimization concepts have been successfully applied to off-line planning and assistance problems (cf. e.g. [4]). In the HVAC area fuzzy-logic approaches are mainly restricted to heating control problems [5].

2 Control Concept

The climate dynamics within offices and domestic buildings is more complex as it seems to be at first sight. Thus, both the comfort perception as well as the energy consumption depend on the essential climate state variables such as temperature T_i, relative humidity φ_i and CO_2-concentration $CO2_i$ as reference gas of air quality. The climate state will be disturbed by different measurable or non measurable influences of the outside climate as well as of the room occupancy. Measurable disturbance inputs are e.g. temperature T_o, relative humidity φ_o and CO_2-concentration $CO2_o$ outside as well as the presence of persons within the room. Non-measurable mainly stochastic disturbances are the heating flows, water vapor sources, air draft as well as CO_2-emissions caused by present persons (cf. fig. 1).

For controlling the room climate in terms of T_i, φ_i and $CO2_i$ first of all controllable heating and ventilation facilities have to be installed. However, while T_i can be selectively controlled e.g. by radiators, φ_i and the $CO2_i$ are strongly coupled with each other. Thus, the air exchange rate *AER* which can be controlled by fans or tilting windows has to be introduced as auxiliary control variable.

As regards a feedback-control of T_i as well as φ_i or $CO2_i$ of rooms in the past different efficent concepts or products have been proposed (cf. e.g. [6]). Much less considered has been the supervisory control problem of T_i, φ_i and $CO2_i$.

The supervisory control concept introduced in this paper is based on the approach that the user chooses the performance requirements in terms of "economy" and "comfort" but not, as usual, the reference values of heating and ventilation controllers. By means of a simple slide button ("economy-comfort slider") he/she is enable to select the weighting factor λ of his individual comfort and economy requirement.

Based on the arbitrarily selected cost-comfort weighting, factor λ as well on the measured inside climate state (T_i, φ_i, $CO2_i$), outside climate state (T_o, φ_o, $CO2_o$) and the presence of person in the room (*PRES*) the optimal reference values of inside temperature control ($T^*_{i,ref}$) and air exchange rate AER^*_{ref} are computed (cf. fig. 1). The multiobjective optimization of both reference values is based on a fuzzy-algorithm which will be derived in the following chapter.

In addition to the proposed operation mode above depending on special day times, seasons or events heuristic control elements can be inserted. E.g. in the absence of persons or during the night time an economy mode is set automatically.

3 Multiobjective Fuzzy-Optimization

The evaluation of climate performance in a living room by human users incorporates a natural diffusion which is realistically described by fuzzy optimization methods (e.g. method of fuzzy decision making [7]). It is based on the idea to consider the normalized performance criteria as fuzzy membership functions which can be optimized by introducing max-min operators.

3.1 General Concept

A controlled process will be considered in which the state variables $\boldsymbol{x}$ are completely controllable by the reference value w. Moreover, it will be assumed that the process is controlled in terms of N different, sometimes contradictory performance criteria. To simplify matters, in the followingonly two performance criteria PC_1 and PC_2 are considered.

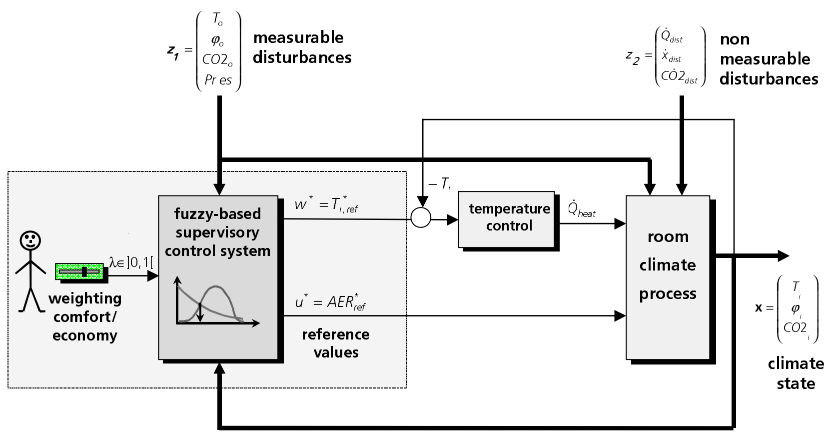
The aim is to optimize in a balanced way the reference value w with respect to both criteria while the user can arbitrarily select his individual weight factor. For solving this multiobjective optimization problem a concept has been developed which can be subdivided into three steps (cf. box 1).

In the *first step* two performance criteria PC_1 and PC_2 will be defined by the fuzzy-membership functions $\mu_1(x_1)$ and $\mu_2(x_2)$ which only depend on one state variable or auxilliary variable x_1 resp. x_2. Constraints can be easily considered by setting the membership functions in the "forbidden" value ranges to zero.

In the *second step* a static or dynamic model is introduced which describes the relation between x_1 resp. x_2 and the reference value w to be optimized. It is assumed that the process behaves quasi-stationarily in the considered optimization interval $[t,t+\Delta t]$. Thus the measured state variables $\boldsymbol{x}$ can be regarded as constant in $[t,t+\Delta t]$.

In the *third step* the weighting factors $\lambda_1 \equiv \lambda$ and $\lambda_2 \equiv (1-\lambda)$ are applied to μ_1 resp. μ_2 and the fuzzy decision $\mu_D(w)$ is computed by using the *min*-operator as a fuzzy *and*-operator. The desired optimal reference value w^* will be obtained as the maximum value of $\mu_D(w)$.

With $\lambda = 0.5$ both performance criteria PC_1 and PC_2 are supposed to have the same priority. In the special cases $\lambda \to 0$ and $\lambda \to 1$ only one of both performance criteria PC_1 and PC_2 is optimized, but even in this cases the "forbidden" value ranges, in which μ_1 or μ_2 are equal zero, are valid and the corresponding values of w are excluded.



T_o, T_i:	outside/inside temperature [°C]
$T^*_{i,ref}$:	optimal reference temperature [°C]
φ_o, φ_i:	outside/insude relative humidity [°C]
$CO2_o$, $CO2_i$:	outside/insude CO_2-concentration [ppm]
AER^*_{ref}:	optimal reference air exchange rate [1/h]
PRES:	presence of person [0/1]
λ:	weighting factor [0...1]
Q_{heat}:	heating power [W]
Q_{dist}:	disturbing heating sources [W]
x_{dist}:	disturbing water vapour sources [g/kg/h]
$CO2_{dist}$:	disturbing CO_2-sources [ppm/h]

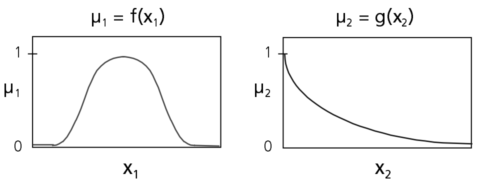
fig. 1: Scheme of the fuzzy based supervisory control and monitoring system.

In the case of strongly nonlinear processes the modelling may sometimes be difficult. However, for the fuzzy description containing some uncertainty in the majority of cases it is sufficient to use a simplified physical model in terms of few significant parameters.

The multiobjective optimization approach for one output w^* outlined above can be easily enlarged to several outputs $\boldsymbol{w}^*$ if a weakly coupled MIMO process is considered. In the case of HVAC systems a rather weak coupling of heating and ventilation control loops can be assumed.

Box 1: General concept of demand-responsive fuzzy optimization

Step 1: Definition of performance criteria



x_1, x_2: state variables
μ_1, μ_2: membership functions of the performance criteria

Step 2: quasi-static model

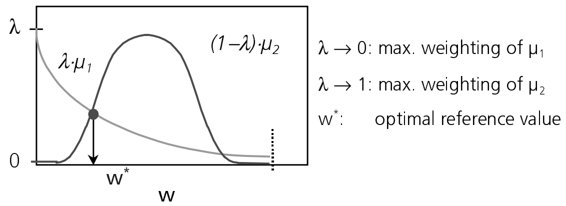
$\mathbf{x} \approx$ const. in $[t, t+\Delta t]$

$$x_1 = P(\mathbf{x},w) \qquad \mu_1 = f(P(\mathbf{x},w)) \equiv f(w)$$
$$\Rightarrow$$
$$x_2 = Q(\mathbf{x},w) \qquad \mu_2 = g(P(\mathbf{x},w)) \equiv g(w)$$

x: state vector, t: actual time, Δt: intervall of optimization

Step 3: computing of w^*

$$\mu_D(w) = \min_w(\lambda \cdot \mu_{PC1}(w), (1-\lambda)\cdot \mu_{PC2}(w))$$
$$\mu_D(w^*) = \max_w(\mu_D(w))$$



3.2 Application to HVAC Control Systems

3.2.1 Comfort Criteria

According to the gerneral concept (cf. box 1) in a first step useful performance criteria of comfort and economy depending on climate state variables T_i, φ_i, $CO2_i$ have to be defined.

Obviously, there are no universal models which can realistically describe the human comfort perception. In the HVAC technology, however, the limits of comfort in terms of temperature and air quality are well defined [8].

According to these standards the temperature T_i should be within the range 20 ... 24 °C, the relative humidity φ_i between 30 % and 70 % and the CO_2-concentration $CO2_i$ down to 1000 ppm. The heat flow of the air which causes draught q_d should not be much greater than 40 W/m^2.

Since these parameters are only blurred recommendations it is useful to represent them by fuzzy-membership functions e.g. according to fig. 2. Obviously, the shown fuzzy-membership functions μ_{comf} in terms of T_i, φ_i $CO2_i$ and q_d represent the human-like comfort evaluation much better then step - like membership functions (dotted lines) of the classical binary logic. Moreover, the characteristic parameters of the membership functions can be easily matched to individual user criteria.

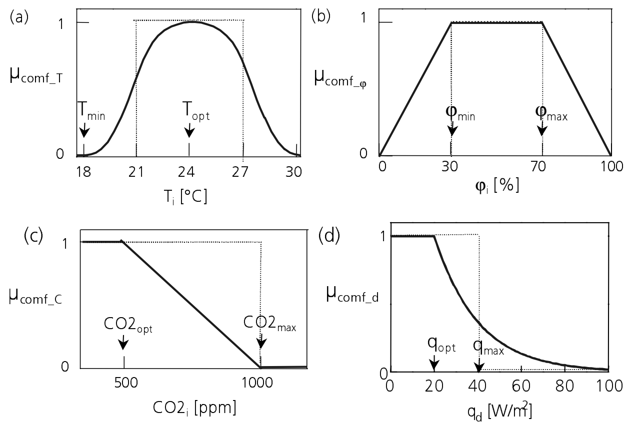


fig. 2: Heuristic membership functions μ_{comf} in dependence on the temperature T_i (a), relative humidity φ (b), CO_2 -concentration (c) and heat flow of the air draught q_d (d).

3.2.2 Economy Criteria

The cost of inside temperature and air exchange rate results directly from the required heating power. Thus, a membership function is required which describes the economy rate of the HVAC in terms of heating power. A decreasing exponential function which can be easily parameterized by simple model equations is sufficient (cf. box 2).

In accordance with reality the membership functions show a decrease of economy in terms of increasing T_i and *AER* as well as of decreasing outside temperature T_o.

3.2.3 Optimization of Temperature Control

Having defined the comfort and economy criteria according to chapter 3.2.1 and 3.2.2 the reference inside temperature $T_{i,ref}$ can be optimized. As regards the comfort criterium the direct dependence on $T_{i,ref}$ is defined by the membership function μ_{comf_T} (cf. fig. 2). The optimizable relation between the economy membership function μ_{eco_Ti} and $T_{i,ref}$ can be derived from the model-equations (cf. box 2).

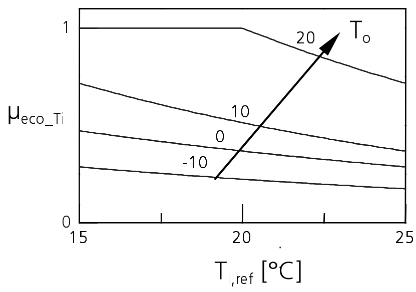
Box 2: Calculation of economy membership functions μ_{eco} in terms of T_i und AER

General approach: $\boxed{\mu_{eco} = e^{-\dot{Q}_{heat}/\dot{Q}_{nom}}}$

$\dot{Q}_{heat}$: heating power, $\dot{Q}_{norm}$: nominal power

For the inside temperature T_i:

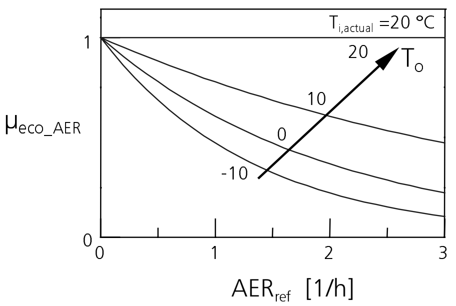
$$\dot{Q}_{trans} = k \cdot A \cdot (T_{i,ref} - T_o)$$



$\dot{Q}_{trans}$: heating losses by transmission [W]
k : coefficient of heat transission [W/m^2/K]
A : wall surface [m^2]

For the air exchange rate AER:

$$\dot{Q}_{vent} = c \cdot \rho \cdot V \cdot AER_{ref} \cdot (T_{i,actual} - T_o)$$



$\dot{Q}_{vent}$: heating losses by ventilation [W]
c : heat capacity of the air [J/kg/K]
ρ : density of the air [kg/m^3]
V : room volume [m^3]

influence of the characteristic parameters of μ_{comf_Ti} can be clearly seen. For $\lambda \rightarrow 0$, this corresponds to "max. economy", it holds $T^*_{i,ref} = T_{min}$ = 18 °C and for $\lambda \rightarrow 1$, this corresponds to "max. comfort", $T^*_{i,ref} = T_{min}$ = 24 °C (cf. μ_{comf_T} in fig. 2a).

3.2.4 Optimization of Air Exchange Rate

The optimization of the air exchange rate AER_{ref} is somewhat more complex than the temperature optimization. While the economy criterium depends in a straightforward way on AER_{ref} to be optimized (cf. box 2) the comfort criterium is defined only in terms of CO_2-concentration $CO2_i$, relative humidity φ_i and draught q_d, but not directly in terms of AER_{ref}. The dynamic behaviour of $CO2_i$ and φ_i in terms of AER_{ref} which is disturbed by humidity- and CO2-sources (e.g. men) has to be considered in the optimization procedure.

In order to obtain *one* comfort membership function, the comfort criteria have to be combined. This can be achieved in a realistic way by applying a fuzzy *and*-operator (e.g. *min*-operator):

$$\mu_{comf}(AER_{ref}) = \mu_{comf\_C}(CO2_i) \wedge \mu_{comf\_\varphi}(\varphi_i) \wedge \mu_{comf\_d}(q_d) \quad (1)$$

Equation (1) can only be computed, if there are models which describe $CO2_i$, φ_i, q_d in terms of AER_{ref}:

$$\begin{aligned} CO2_i &= f(AER_{ref}) \\ \varphi_i &= g(AER_{ref}) \\ q_d &= h(AER_{ref}) \end{aligned} \quad (2)$$

Contrary to the static *feedforward optimization* of $T_{i,ref}$ in the optimization of AER_{ref} the transition dynamics of $CO2_i$ and φ_i have to be additionally considered, i.e. a dynamic *feedback optimization* is applied to obtain AER^*_{ref}.

By means of an internal predictive model with a reference trajectory the time response of $CO2_i$ and φ_i is simulated and optimized at each sampling instant, e.g. every minute, over a prediction horizon, e.g. 20 minutes (cf. box 3).

The internal model describing the dynamics of $CO2_i$ and φ_i in terms of AEF_{ref} and internal disturbances, is represented by a nonlinear differential equation (cf. box 3 for $CO2_i$). Since the disturbances $\dot{CO2}_{dist}, \dot{\varphi}_{dist}$ can not be measured directly they have to be estimated. By means of that internal model for a desired dynamic response (e.g. low pass first order, time constant τ)

Box 3: Principle of dynamic feedback optimization with internal predictive model (e.g. CO_2 behaviour)

system behaviour:

$$\dot{CO2}_i = -AER_{ref} \cdot (CO2_i - CO2_o) + \dot{CO2}_{dist}$$

required dynamic response (low pass):

$$\dot{CO2}_i = -\tfrac{1}{\tau} \cdot (CO2_i - CO2_{i,ref})$$

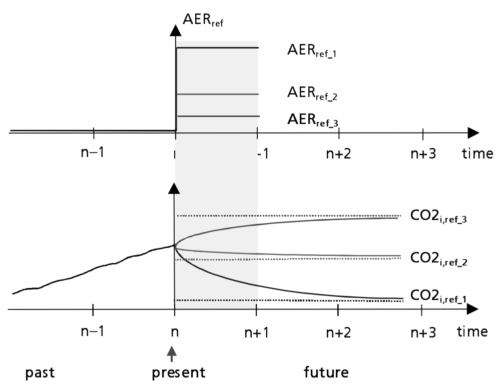
$$\Rightarrow \quad CO2_{i,ref} = CO2_i + \tau \cdot (-AER_{ref} \cdot (CO2_i - CO2_o + \dot{CO2}_{dist}))$$

$$\Rightarrow \quad CO2_{i,ref} \equiv f(AER_{ref})$$

$CO2_{i,ref}$: internal reference value

τ: time transition constant from $CO2_i$ to $CO2_{i,ref}$

prediction of system behaviour:



the desired function $CO2_i = f(AER_{ref})$ is obtained. In an analogous way the function $\varphi_i = g(AER_{ref})$ is achieved. This method is similar to the concept of predictive functional control [9].

For describing the air draught q_d inside a room in terms of AER_{ref} the static model

$$q_d = \gamma \cdot AER_{ref} \cdot (T_{i,actual} - T_o) \qquad [\mathrm{W/m^2}] \qquad (3)$$

can be assumed. The heuristic constant γ can be estimated experimentally. In the IITB test rooms e.g. the value $\gamma \approx 3$ Wh/m²/K has been determined.

In fig. 3 the influence of the weighting factor λ and the outside temperature T_o to AER^*_{ref} can be seen. In contrast to the optimization of $T_{i,ref}$ the resulting AER^*_{ref} depends not only on λ and T_o, but on the actual inside state of $CO2_i$, φ_i, T_i, $\dot{CO2}_{dist}$ and $\dot{\varphi}_{dist}$ as well (cf. fig. 3).

Since both the relative humidity φ_i and the draught q_d depend strongly on T_o the saturation limit of AER^*_{ref} depends on T_o as well. Just this dependence demonstrates the advantage of the proposed supervisory control concept over the non-coordinated operations of a user which hardly assesses all the consequences of his heuristic control actions with respect to economy and comfort. The minimal value $AER^*_{i,ref}$ = 0,6/h in the case of highest economy ($\lambda \rightarrow 0$) results from the limit value $CO2_{max}$ = 1000 ppm recommended for comfortable air quality in living rooms [8] (cf. μ_{comf_C} in fig. 2).

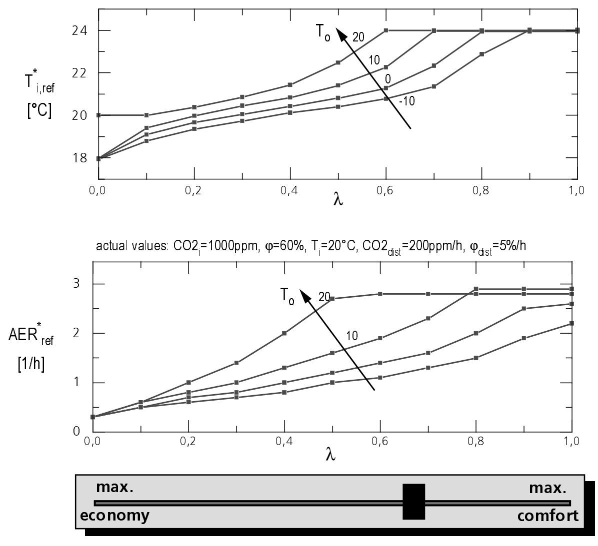


fig. 3: Dependence of the optimal indoor temperature $T^*_{i,ref}$ and the air exchange reference AER^*_{ref} on the slider position λ and the outdoor temperature T_o.

4 Results

In order to investigate system behaviour of the room and performance of the fuzzy-based supervisory control concept under almost realistic conditions a simulation model has been generated in a MATLAB/SIMULINK software environment (cf. [1],[10]).

Furthermore, the fuzzy-based supervisory control concept has been applied to two office rooms at IITB. In order to demonstrate the robustness of the concept, different sensor-actor configurations and fieldbus systems have been installed in these rooms.

For the room ventilation controllable fans (room 1) and tiltable windows (room 2) have been introduced. The air quality is measured by CO_2 sensor (room 1) and by a mixed gas sensor (room 2) capable to detect oxidizable components of the air (e.g. smoke). First expermental results of room 1 have been presented meanwhile [2].

The measurement results shown in fig. 4 have been obtained on 2. March 1999 in room 2. The diagram shows the time responses of weighting factor λ, temperature inside (actual/reference) $T_{i,act}$, $T_{i,ref}$ and outside T_o, the presence of persons in the room *Pres*, the comfort membership μ_{comf_d} in terms of draught q_d, the air exchange rate (actual/reference) AER_{act}, AER_{ref} and the sensor signal of the mixed gas sensor MG_i in arbitrary units.

By changing the weighting factor λ (slider position) from $\lambda \rightarrow 0$ ("max. economy") to $\lambda = 0.5$ ("medium") and finally to $\lambda \rightarrow 1$ ("max. comfort") the corresponding optimal inside temperatures $T^*_{i,ref}$ = 18 °C, ≈ 21 °C and 24 °C will be controlled. In the special case of an empty room (*Pres* = 0) a constant set point $T^*_{i,ref}$ = 15 °C is selected.

The optimized air exchange rate AER^*_{ref} depends not only by the user controlled λ but by disturbences like cigarette smoking as well. The diagram shows that after cigarette 1 is smoked, AER^*_{ref} is equal to zero because $\lambda \rightarrow 0$ ("max. economy").

When the person leaves the room at 10:00 a.m. the system switches into an absence mode which is characterized by $T^*_{i,ref}$ = *15 °C* and the internal slider position "max. comfort" with respect to AER_{ref}. As a consequence no heating power caused by the enforced ventilation will be consumed.

At 12:00 a.m. cigarette 2 is smoked, AER_{ref} increases and the window opens. Because of the low outside temperature μ_{comf_d} is decreasing and a tradeoff between comfort with respect of air quality and comfort in respect of draught is found. During absence at 12:30 a.m. the window opens again and closes when the defined level of optimal air quality MG_{opt} is reached.

At 2:30 p.m. and 4:00 p.m. when cigarettes 3 and 4 are smoked, the window is opened for a longer period due of the weighting factor $\lambda \rightarrow 1$ ("max. comfort"). Again a tradeoff between the opposing comfort criteria air quality and draught is found which results that the window is closing before optimal air quality is achieved.

After clearing the room at 5:00 p.m. the window opens as long as the air quality is equal to MG_{opt}.

5 Conclusions

In this paper a new fuzzy-based supervisory control concept for the optimization of dynamical systems with respect to fuzzy performance criteria is presented. The concept has been applied to the optimization of HVAC systems. It enables the untrained user to easily and optimally operate his/her home heating and ventilation control facilities according to his/her individually weighted comfort and economy objectives. The performance with respect to energy saving and comfort improvement is demonstrated by experimental results. On-going R&D activities deal with the implementation of the fuzzy concept in a marketable building automation and control system. The modification of the fuzzy-based supervisory control concept to completely different multivariable industrial processes will be the subject of further research.

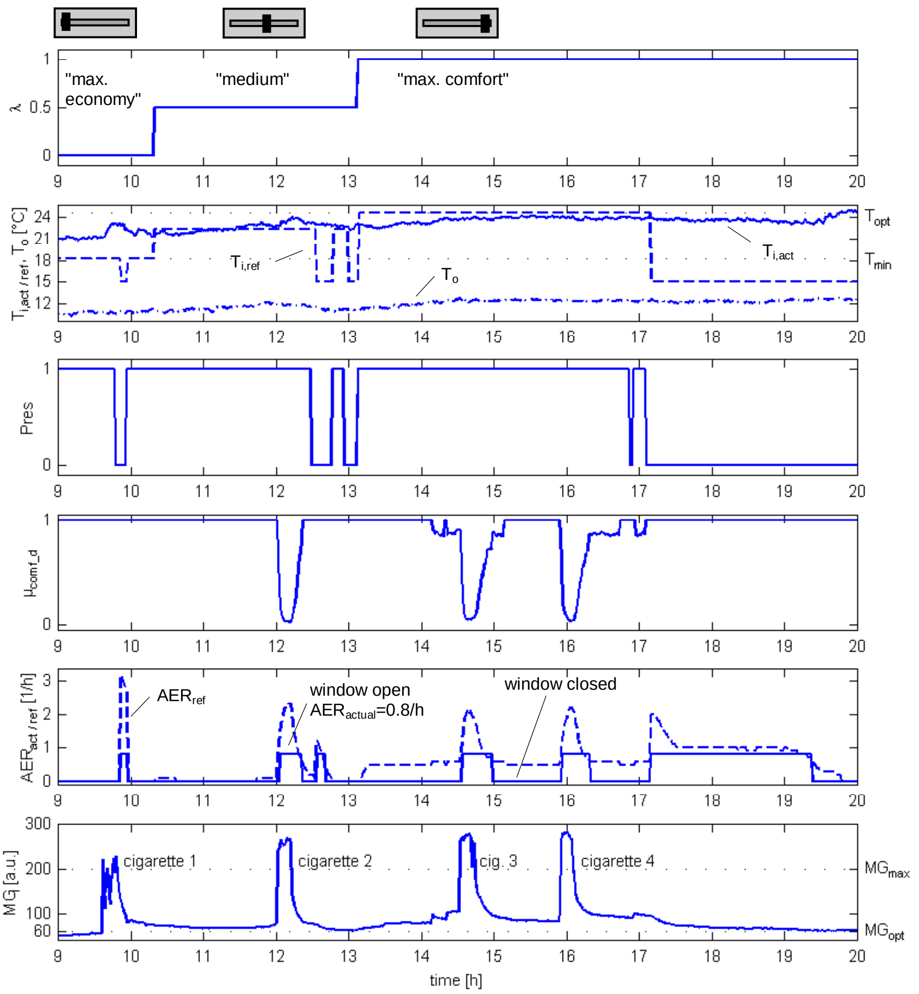


fig. 4: Experimental results in an IITB office room (02.03.99)

References

[1] Bernard, Th; Kuntze, H.-B.: "Ein neues fuzzy-basiertes Leitkonzept zur bedarfsgewichtet optimierten Führung von Klimaregelkreisen", *Automatisierungstechnische Praxis* ***40*** *(1998) 7*, pp. 23 - 25

[2] Bernard, Th.; Kuntze, H.-B.; Nirschl, G.: "Fuzzy-basierte Raumklimaregelung", *Heizung, Lüftung/Klima, Haustechnik (HLH)* ***50*** *(1999) 1*, 38 - 45

[3] Sajidman, M.; Kuntze, H.-B.: "Integration of Fuzzy Control and Model Based Concepts for Disturbed Industrial Plants with Large Dead-Times", *Proceedings of the sixth IEEE Int. Conf. on Fuzzy Systems (FUZZ IEEE'97)*, Barcelona, Spain, July 1997

[4] Zimmermann, H.-J.: "Fuzzy Sets, Decision Making, and Expert Systems", *Kluwer Academic Publishers, Boston 1987*

[5] v. Altrock, C.; Arend, H.-O.; Krause, B.; Steffens, C.; Behrens-Römmler, E.: "Customer-Adaptive Fuzzy Control of Home Heating System", *IEEE Conf. on Industrial Fuzzy Control Inteligent Systems*, 1993, pp. 115-119

[6] Recknagel, Sprenger, Schramek: "Taschenbuch für Heizung und Klimatechnik", *67. Auflage, Oldenbourg Verlag, München 1995*, pp. 1247-1299

[7] Bellman, R.E.; Zadeh, L.A.: "Decision making in a Fuzzy environment", *Management Science,* ***17*** *(1970)*, pp. 141-163

[8] ASHRAE, "Ventilation for Acceptable Indoor Air Quality", *ASHRAE Standard 62-1989*

[9] Kuntze, H.-B. Richalet, J. et. al.: "On the predictive functional control of an elastic industrial robot", *Proceedings of 25th IEEE Conference on Decision and Control CDC'86*, Athen, Greece, December 1986

[10] Bernard, T.; Kuntze, H.-B.: "A New Fuzzy-based Supervisory Control Concept for the Demand responsive Optimization of HVAC Control Systems". *Proceedings of 37th IEEE Conference on Decision and Control CDC'98*, Tampa, Florida, December 1998, Vol. 3, pp. 4258 - 4263