A New Fuzzy-based Supervisory Control Concept for the Demand-responsive Optimization of HVAC Control Systems

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Summary

In many cases 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 multiobjective 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 multiobjective optimization concept which has been implemented and is being trialled in a test environment at IITB is analyzed and discussed by means of practice-relevant simulation results.

1 Motivation

Due to the energy crisis and legal energy conservation requirements within the last decades in construction engineering 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 untrained users. 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 multiobjective on-line optimization problem at the IITB a new fuzzy-logic supervisory control concept has been developed [1] which can be applied in principle to comparable problems in different industrial areas. Interestingly enough fuzzy-based optimization concepts have been almost exclusively applied to off-line planning and assistance problems in the area of operations research (cf. e.g. [2]). In the HVAC area fuzzy-logic approaches are mainly restricted to heating control problems [3].

The fuzzy-based supervisory control concept considered within this paper is not constrained only to the HVAC applications but can be adapted to various industrial processes. Especially in the steel and glass industry [4] there is an increasing demand to control processes optimally in terms of contradictory performance criteria (e.g. productivity versus product quality).

2 Control Concept

The climate dynamics within offices and living rooms 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 the 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

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rate AER which can be controlled by fans or tilting windows 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. [5]). 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 $(0 < \lambda < 1)$ of his individual comfort and economy requirement. If he/she is only interested in minimizing the heating costs he/she will choose $\lambda \rightarrow 0$. Vice versa he/she will select $\lambda \rightarrow 1$ if he/she prefers a comfortable living climate. Normally he/she tries to achieve a tradeoff within the range $0 < \lambda < 1$.

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 room presence rate (PRES) in the supervisory control system the optimal reference values of inside temperature control ($T^*_{i,ref}$) and of 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 above nominal operation mode depending on special daytimes, seasons or events heuristic control elements can be inserted. E.g. in the absence of persons or during the night time an economy mode can be set automatically.

3 Multiobjective Fuzzy-Optimization

3.1 General Approach

A controlled process will be considered in which the state variables $\mathbf{x}$ are completely controllable by the reference values $\mathbf{w}$. Moreover, it will be assumed that the process will be controlled in terms of two different, sometimes contradictory performance criteria.

The aim is to optimize the reference values $\mathbf{w}$ in a balanced way 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 structured into three steps. For better understanding of the following the optimization of only one reference value w_i in terms of two performance criteria will be considered (cf. box 1).

In the first step two performance criteria PC_1 and PC_2 will be defined by the fuzzy-membership functions μ_{GK1} and μ_{GK2} which depend only on one state variable. Since the performance criteria provide a diffused evaluation of process quality which is especially in climate processes very realistic for solving the multiobjective optimization problem, the theory of fuzzy decision making [7],[8] can be applied. It is based on the idea to consider the nomalized performance criteria as fuzzy membership functions which can be optimized by introducing max-min operators. Physical constraints can be easily considered by setting the membership functions in the "forbidden" value ranges to zero.

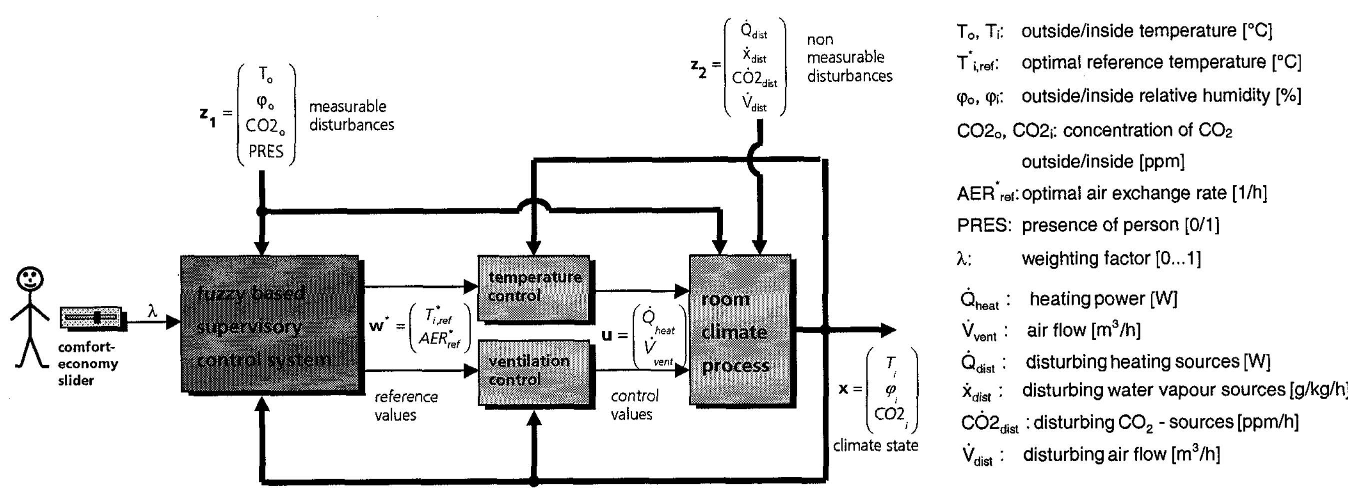
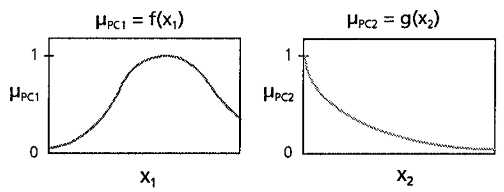


fig. 1: The fuzzy based supervisory control and monitoring system for indoor temperature and air exchange rate is superimposed to the temperature and ventilation control loops.

In the second step a static or dynamic model is introduced which describes the relation between state variables **x** depending on both performance criteria and the reference value w_i to be optimized. Assuming the approximation that the process behaves quasi-stationarily in the considered optimization interval both performance criteria can be described in terms of the reference value w_i to be optimized.

Box 1: General concept of demand-responsive fuzzy optimization

Step 1: Definition of performance criteria



x_1, x_2: state variables
μ_{PC1}, μ_{PC2}: membership functions of the performance criteria

Step 2: quasi-static model

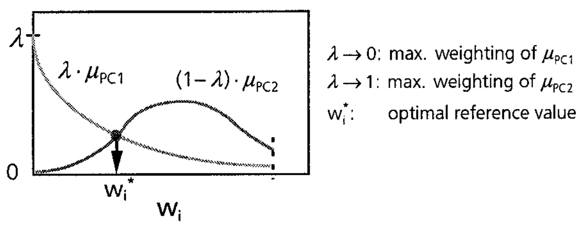
$x \approx$ const. in $[t, t+\Delta t]$

$$x_1 = P(x, w_i) \qquad \mu_{PC1} = f(P(x,w_i)) \equiv \tilde{f}(w_i)$$
$$\Rightarrow$$
$$x_2 = Q(x, w_i) \qquad \mu_{PC2} = g(P(x,w_i)) \equiv \tilde{g}(w_i)$$

t: actual time; Δt: intervall of optimization

Step 3: computing of w^*_i

$$\mu^*(w_i^*) = max\{min(\lambda \cdot \mu_{PC1}(w_i)),(1-\lambda)\cdot \mu_{PC2}(w_i))\}, \quad 0<\lambda<1$$



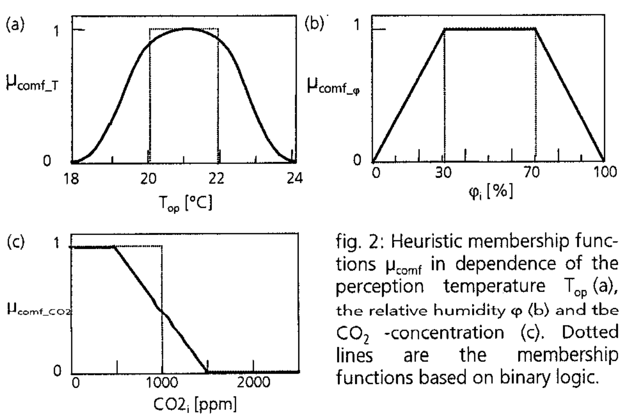


fig. 2: Heuristic membership functions μ_{comf} in dependence of the perception temperature T_{op} (a), the relative humidity φ (b) and the CO_2 -concentration (c). Dotted lines are the membership functions based on binary logic.

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.

In the third step by using a max-min operation the desired optimal reference value w^*_i will be obtained. By introducing the weighting parameter λ the individual importance of both performance criteria is considered. In the special cases $\lambda \rightarrow 0$ and $\lambda \rightarrow 1$ only one of both performance criteria PC1 and PC2 is optimized.

The multiobjective optimization approach for one output w^*_i outlined above can be easily enlarged to several outputs $\mathbf{w}^*$ 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.

3.2 Optimization of HVAC Control Systems

3.2.1 Comfort Criteria

For solving the optimization problem in a first step useful performance criteria of comfort and economy depending on $T_{i,ref}$ and AER_{ref} 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 [6]. According to these standards the perceived temperature T_{op} should be within the range 20 ... 22 °C, the relative humidity φ_i between 30 % and 70 % and the CO_2-concentration $CO2_i$ down to 1000 ppm. 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_{op}, φ_i and $CO2_i$ represent the human-like comfort evaluation much better then step – like membership functions (dotted lines) of the classical binary logic. Moreover, the Fuzzy-parameters can be easily matched to individual user criteria.

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 inside temperature and air exchange rate as well as of decreasing outside temperature.

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

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

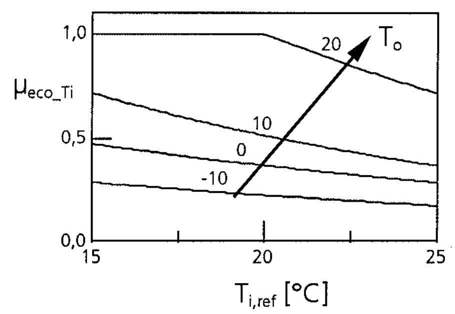
$\dot{Q}_{heat}$: heating power, $\dot{Q}_{norm}$: nominal power

For the inside temperature T_i:

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

$$\dot{Q}_{nom} = k \cdot A \cdot \Delta T_{nom} = const.$$

$$\Rightarrow \quad \mu_{eco\_Ti}(T_{i,ref}) = e^{-(T_{i,ref} - T_o)/\Delta T_{nom}}$$



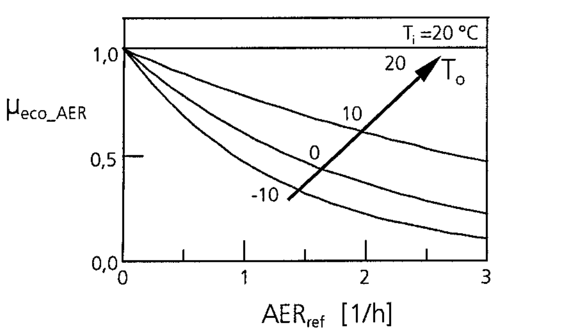
$\dot{Q}_{trans}$: heating losses by transmission [W]
ΔT_{nom}: nominal temperature - difference [K]
k: coefficient of heat transission [W / m²K]
A: wall surface [m²]

For the air exchange rate AER:

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

$$\dot{Q}_{nom} = c \cdot \rho \cdot V \cdot AER_{nom} \cdot \Delta T_{nom}$$

$$\Rightarrow \quad \mu_{eco\_AER}(AER_{ref}) = e^{-AER_{ref} \cdot (T_{i,actual} - T_o)/AER_{nom}/\Delta T_{nom}}$$



$\dot{Q}_{vent}$: heating losses by ventilation [W]
AER_{nom}: nominal air exchange rate [1/h]
c: heat capacity of the air [J / kg / K]
ρ: air density [kg / m³]
V: room volume [m³]

3.2.3 Optimization of Temperature Control

After the definition of 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} (cf. fig. 2). The optimizable relation between the economy membership function μ_{eco} and $T_{i,ref}$ can be derived from the model-equations (cf. box 2). Based on $\mu_{comf}(T_{i,ref})$ and $\mu_{eco}(T_{i,ref})$ the optimization of $T^*_{i,ref}$ is obtained by min-max operations. The resulting dependence of the optimized reference temperatures $T^*_{i,ref}$ on the weighting factor λ and the outside temperature T_o is shown in fig. 3.

3.2.4 Optimization of Air Exchange Control

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 $CO2_i$ and relative humidity φ_i 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.

Contrary to the static optimization of $T_{i,ref}$ in the optimization of AER_{ref} the transition dynamics have to be additionally considered. By means of an internal predictive model the time response of $CO2_i$ and φ_i is simulated and optimized at each sampling instant (e.g. every 5 minutes) over a prediction horizon (e.g. 15 minutes) in terms of the control variable AER_{ref} and the initial values of the measured variables $CO2_i$ and φ_i.

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):

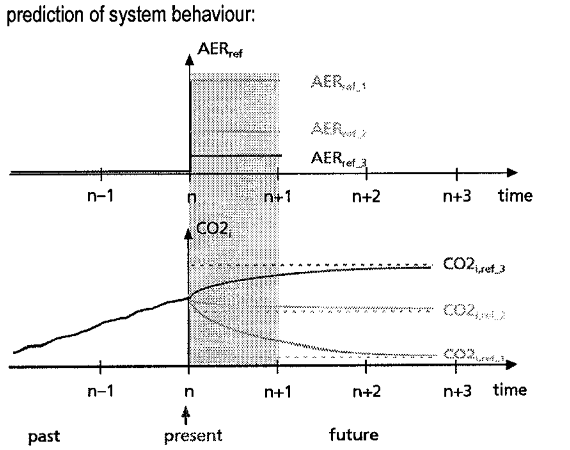
$$\dot{CO2}_i = -\tfrac{1}{\tau} \cdot (CO2_i - CO2_{i,ref})$$

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

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

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

prediction of system behaviour:



Thus, contrary to the feedforward optimization of $T_{i,ref}$ (cf. chapter 3.2.3) a dynamic feedback optimization is applied to obtain AER^*_{ref} according to the concept of predictive functional control [9]. The internal model used for the feedback optimization which describes the dynamics of $CO2_i$ and φ_i in terms of AEF_{ref} and internal disturbances, represents a nonlinear differential equation (cf. box 3). By means of that internal model for a desired dynamic response (e.g. low pass first order, time constant τ) the comfort membership function μ_{comf} can be described in terms of AER_{ref}.

In order to combine μ_{comf} ($CO2_i$) and μ_{comf} (φ_i) a resulting membership function can be achieved by applying a min-operator. Finally the optimal value AER^*_{ref} results from a max-min operation of $\mu_{comf}(_{AERref})$ and $\mu_{eco}(_{AERref})$.

From the resulting nonlinear function of AER^*_{ref} in terms of the weighting factor λ the strong influcence of outside temperature T_o can be seen (fig. 3). Since the outside humidity φ_o depends strongly on T_o the saturation limit of AER^*_{ref} depends on T_o as well. Just this dependence demonstartes the advantage of the proposed supervisory control concept over the non-coordinated operations of a user who hardly comprehends 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 ($\lambda = 0$) results from the limit value $CO2_i \leq 1500$ ppm recommended for comfortable air quality in living rooms [6].

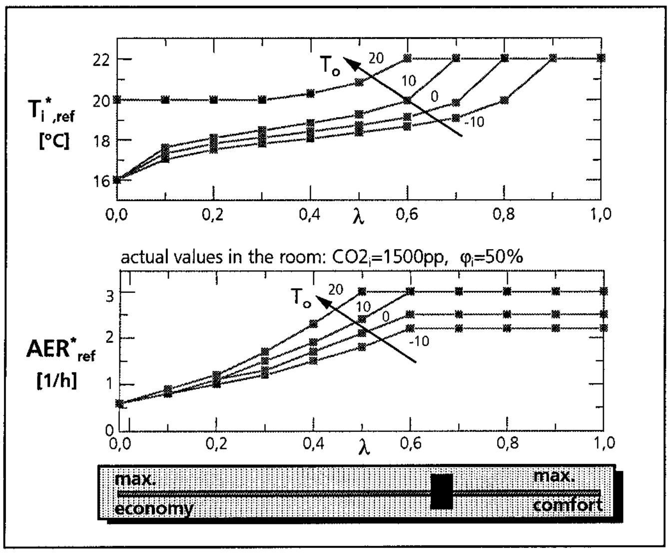


fig. 3: Dependence of the optimal indoor temperature $T^*_{i,ref}$ and the air exchange reference AER^*_{ref} on the slider position λ and the outdoor temperature T_o.

4 Results

In order to investigate system behaviour and performance of the fuzzy-based supervisory control concept under almost realistic conditions as regards the building physics or the climate scenario a simulation model has been generated in a MATLAB/SIMULINK software environment. The physical main structure as well as the essential influence variables are provided by fig. 1. The conventional ventilation and heating control loops which are subordinated to the fuzzy control system are assumed to have PI-behaviour. A sampling interval of $\Delta t = 6$ minutes was chosen. The considered building physics are characterized by a room volume of $V = 50\ m^3$, a discretization of walls by five layers, an outside wall of a 20 cm brick layer and an isolation layer of 5 cm ($k = 0.54\ W/m^2k$), inside walls of 15 cm brick layers ($k = 1.82\ W/m^2k$) as well as one window ($k = 2.0\ W/m^2k$). As regards disturbances internal heating sources $Q_{int} = 100$ W/Persom, a CO_2 generating source of $CO2_{dist} = 10$ Liter/h/person, a water vapour source of $x_{dist} = 40$g/kg/h/person as well as a constant temperature of neighbouring rooms $T_{neighbour} = 15$ °C have been assumed.

From a great manifold of various simulation scenarios one example which represents the course of a typical winter day assuming three different adjustments of the fuzzy-based comfort-cost slider is considered in fig. 4. In order to demonstrate the fuzzy system response with respect to changing room occupancy and to the corresponding disturbances beginning at 8:00 a.m. the room presence is successively increased by 1 person per 2 hour cycle. At 6:00 p.m. all five persons leave the room.

The time response of inside temperature in fig. 4 underlines the strong influence of different adjustments of the comfort-cost slider on the temperature reference value $T^*_{i,ref}$. It varies within a range which was defined by the chosen comfort membership function. For the slider positions "max. comfort", "medium" and "max. economy" it means $T^*_{i,ref} = 22$ °C, about 20 °C and 18 °C respectively. Moreover, the influence on the actual room presence PRES can be clearly seen. If the room is empty the fuzzy-optimization is deactivated, a constant set point $T^*_{i,ref} = 15$ °C is chosen.

From the time response of the air exchange rate AER_{ref} an automatic adaption with respect to altering room occupancy is visible. In the slider position "max. comfort" the ventilation is activated soon after the presence of the first person in order to maintain the defined CO_2-comfort level of 500 ppm. The strong dependency between temperature and relative humidity can be seen as well. The cold inflowing air from outside becomes considerably less humid when heated. Therefore the slider position "max. comfort" represents a tradeoff between the comfort demand with respect to CO_2-concentration and relative humidity while the CO_2-rate increases up to 700 ppm. Vice versa in the slider position "max. economy" the ventilation is not activated before the CO_2-concentration achieves the defined threshold of 1500 ppm. Then the relative humidity remains in an uncritical range.

Based on numerous simulations of various realistic scenarios of building physics and climate it could be proved that a considerable reduction of energy costs can be achieved by the optimally coordinated fuzzy-supervisory control of heating and ventilation systems. In the considered case in fig. 4 the required heating energy of 13.3 kWh at slider position "max comfort" can be reduced by more than 70 % at 3.7 kWh if the slider position "max. economy" is chosen.

5. Conclusions

In this paper a new fuzzy-based supervisory control concept for HVAC systems is presented. 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 different realistic simulations. On-going R&D activities deal with the implementation of the fuzzy concept in a marketable building automation and control system and with the experimental investigation in a demonstration center at the IITB. The modification of the fuzzy-based supervisory control concept to completely different multivariable industrial processes will be the subject of further research.

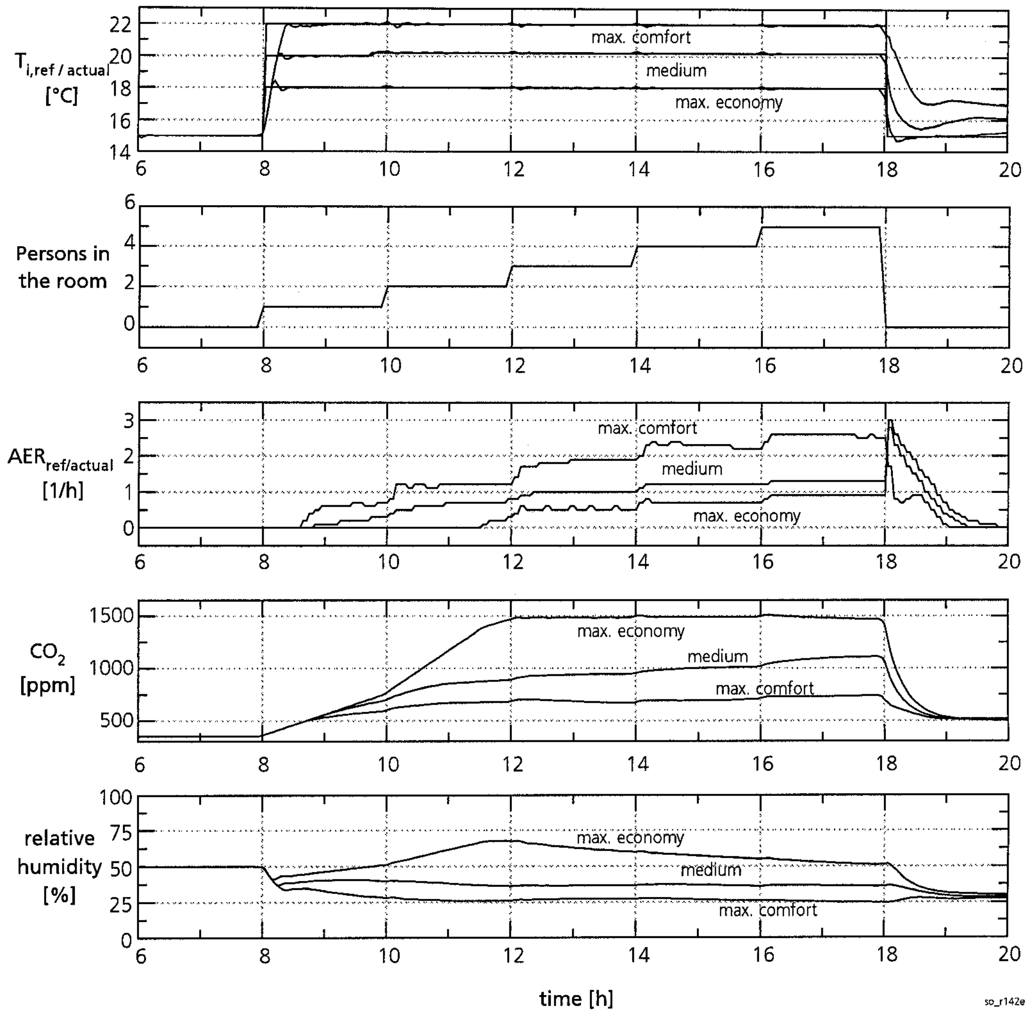


fig. 4: Simulations at slider positions „max economy“ ($\lambda = 0.01$), „medium“ ($\lambda = 0.5$) and „max comfort“ ($\lambda = 0.99$)

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