COMPUTER SIMULATION AS A TOOL FOR THE EVALUATION OF AN ADAPTIVE START/STOP STRATEGY FOR HEATING SYSTEMS

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Summary

The potential of energy saving is documented for the heating system of an office building controlled by an adaptive start/stop controller. The influence of the sizing of the heating system components is considered. The investigations are carried out by detailed and dynamic computer simulations of building and plant. The heating system components are simulated by models developed within the IEA projects Annex 10 and Annex 17. A detailed building model is used. The transient heat transfer through walls is treated by a Finite Difference Model. The disadvantages of the Gradient Method for the prediction of optimal start/stop times, especially, the influence of the structure temperatures of the building, are discussed. Optimal start is realized by repeating the simulations several times until comfort temperatures are reached on time. It is demonstrated that an oversized plant allows to start heating later than a nominal sized plant. Compared to continuous heating the energy savings vary between 14% and 17%.

List of Symbols

A	wall area
c	massic heat
d	thickness of wall layer
D	day
G	gradient
Q	energy
T	temperature
η	efficiency
λ	conductivity
ρ	volumic mass
γ	condition (1=on, 0=off)
τ	time

Subscripts

a	air
b	boiler
c	comfort
e	end of heating
g	gain
i	indoor
l	loss
o	outdoor
p	predicted
r	comfort condition reached
rad	radiant
s	start of heating
w	wall

daily energy consumption of the boiler :

$$Q_b = \int \frac{Q_l(\tau) - \eta_g \cdot Q_g(\tau)}{\eta_b} \cdot d\tau \overset{!}{=} min \tag{1}$$

where Q_l is the energy loss due to heat flux through the building envelope and Q_g is the energy gain due to solar radiation and internal heat gains caused by people, machines and lighting. η_g is the degree of utilization of internal and external heat gains and η_b is the efficiency of the boiler. The aim of intermittent heating is to minimize the energy losses Q_l by keeping comfort conditions only during occupation periods.

Algorithms for the prediction of optimal start/stop are based on equations which characterize the response of the building rooms during return from night or weekend shut down. Seem et al. (2) have compared seven relationships in which the start time is given analytically as a linear, quadratic, or exponential function of the indoor temperature or both indoor and outdoor temperature. They show by computer simulation that the use of equations relating start times to both the indoor temperature and the outdoor temperature are more successful than equations which only consider the indoor temperature.

Leimgruber et al. (3) describe the Gradient Method. Although they assume the increase of room temperatures at the beginning and the decrease of room temperatures after the end of heating to be linear, a large computer memory is required for the nummerical algorithm. In the following section this method is described only for the case of optimal start. (Additional energy saving should be achieved with optimal stop, if furthermore, the room temperatures are permitted to be lower than comfort temperature before the end of the occupation time.)

The start gradient for the day D is defined as

$$G_s(D) = \frac{\tau_r(D) - \tau_s(D)}{T_c - T_{s,i}(D)} \tag{2}$$

with τ_s as the time the heating system is started, τ_r as the time the required comfort condition is reached, T_c as the required comfort temperature and $T_{s,i}$ as the indoor temperature at the time of start. Figure 1 shows the scheme of the Gradient Method for optimal start. The optimal start controller consist of a clock, sensors for the actual indoor and outdoor temperature, a memory mainly for the gradient data bank, and a processor for the estimation of the start times of the heating plant. When the heating system is shut down ($\gamma = 0$) the processor calculates in small time intervals the predicted room temperature T_p by using equation 3 for the case that the heating system will be just started. If the predicted room temperature is equal to or smaller than the required comfort temperature, than the heating system is started by the controller ($\gamma = 1$) and the actual time and indoor/outdoor temperatures will be memorized.

$$T_p = T_i + \frac{\tau_c - \tau}{G_s} \tag{3}$$

where T_i is the actual indoor temperature, which is an effective temperature to be composed of the air temperature T_a and the radiant temperature T_{rad} as

$$T_i = \frac{1}{2} \cdot (T_a + T_{rad}) \tag{4}$$

$$T_{rad} = \sum_{j=1}^{n} \frac{A_j}{\sum_{j=1}^{n} A_j} \cdot T_{rad,j} \tag{5}$$

For the first days the value of the start gradient in equation 3 has to be estimated by the building operator as good as possible. After the comfort temperature is reached, the processor calculates the real start gradient for the actual day and stores it to the memory. The memory is organized as a two dimensional field, in which the value of the start gradient is related to the two dimensions indoor temperature and outdoor temperature $G_s = f(T_{s,i}, T_{s,o})$. From the the fifth day on the gradient can be estimated by 3 dimensional linear interpolation as symbolized in Figure 2.

3. Computer Simulation

Computer simulation is applied to evaluate the potential of energy saving for the heating system of an office building controlled by an adaptive start/stop controller. The investigations are carried out by detailed and dynamic computer simulations of building and plant. The used simulation program GERALT is developed at the University of Stuttgart (7). It is designed to allow detailed simulation of dynamic and simultaneous interactions among building, HVAC plant and controllers. To ensure a realistic dynamic behavior of the building model the transient heat transfer through walls is solved by a Finite Difference Method and the heat and mass balance is considered for every wall surface and room air node.

The HVAC plant should be composed of modules describing plant and controller components. These modules consist of mathematical models mainly developed within the IEA projects Annex 10 " System Simulation " and Annex 17 " Building Energy Management Systems ".

The simulated building and plant are completely specified in an Annex 17 working document [7]. The building is assumed as a set of equal units (office rooms) put together in a symmterical matrix system with 4 floors and 14 rows (see Figure 3). It has a north-south orientation and the northern rooms are separated from the southern ones by common corridors. The heat demand of the rooms is calculated for -12°C outdoor temperature. The insulation of fasade, roof and ceiling is chosen as proposed in a german energy saving order (See Table 1). Typical internal loads (lighting, equipment and people) of a commercial building are chosen.

The building should be occupied from 8 am to 5 pm. For the evaluation of optimal start a northern office room on the third floor is chosen as the reference room (room 15). Test runs have shown that the northern room on the last floor are the coldest rooms.

The heating system is assumed as a " low temperature heating system " (design temperatures 70/60°C). It consists of flat plate radiators (nominal power between 986 W and 1366 W) in each of the office rooms controlled by ordinary thermostatic valves (set point temperature 23°C). A modern high efficiency boiler is chosen (nominal useful power 130 kW). Next to the boiler a three way mixing valve is available to control the supply temperature. The boiler is controlled by on off operation of the burner to keep the supply temperature as a linear function of the outdoor temperature (80 to 20°C supply temperature related to -12 to 20°C outdoor temperature). The control function for the supply temperature of the three way mixing valve is the same as the function for the boiler control, but shifted 5 K lower. Bypass valves in each vertical coulumn

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provide a better hydraulic behaviour of the system. Only the two middle sections of the whole building are simulated. Figure 4 shows the scheme of the heating plant for the section to be simulated.

The period of 4 weeks from February 1st to 28th is simulated, using the meteorological data of the german test reference year (8). This month represents a heating period with a very wide range of outdoor temperatures (see Figure 5).

At the beginning of the investigations optimal start/stop control was realized by introducing a controller module, in which a control algorithm, based on the Gradient Method described in chapter 2, was implemented. But the simulation results show that the method does not provide the best forecasts. Figure 6 gives an example for the predicted start times and the times at which the comfort temperature of 20°C is reached at the required time 7 am on each day. It can be seen that even after 3 month the algorithm is not always successful.

To find out the reason of the bad estimations, which the algorithm had made, and to evaluate the maximum potential of energy saving by adaptive start/stop controllers it was decided to realize the simulation of optimal start by iteration:

The simulations are repeated several times, until comfort temperature is reached every day on time at 7 am (one hour before the occupants return) in the reference room 15. After each simulation run these values are corrected by looking at the plots for the temperature in the reference room. After 4 to 6 repetitions the optimal start times are found.

The simulations are carried out on a CRAY2 computer using a time step of 300 seconds. The simulation run time for the whole period of 4 weeks takes about 10 minutes (10 minutes elapsed time, 2.5 minutes cpu time). Most of this time is needed to compute mass balance and pressure drop in the hydronic network (70%). The rest of the time is shared between the building and the heating system components for heat transfer calculations.

4. Sizing of the Heating System Components

The influence of the sizing of the heating system components is shown by the combination of 4 sizes of boilers (see Table 2) and two sizes of radiators (100% and 200% nominal performance). Furthermore, in combination with thermostatic valves the big radiators cause higher level of the room temperatures. This provides higher transmission losses of the building. To investigate this influence, a special case with 1 K reduced set point temperature of the thermostatic valves is simulated for the oversized plant (200% radiator and 200% boiler power).

5. Results and Discussion

Figure 7 shows the room temperatures of the reference room in the case of nominal sized boiler and radiators. The room temperature is composed of the air temperature and the radiant temperatures as described in equation (4) and (5). Figure 8 shows the room temperatures for the big plant with 200 % oversized boiler and radiators. It can be seen that the larger plant allows to start the heating system later than the nominal plant.

The total energy consumptions for all simulated cases is given in Figure 9 and Table 2. There are only small differences in the network useful energy between the various boilers, if optimal start is applied. Furthermore, the oversizing of the radiators leads to higher energy consumtions caused by higher room temperatures. For both control modes the consumption falls, if the set point temperature of the thermostatic valves is reduced 1 K .

In Figure 10 the energy saving of optimal start, if compared with continuous heating, is shown. The energy saving is defined as to be for the same boiler and radiator sizing the quotient of the total energy consumption with optimal start control to the total energy consumption when the heating system runs continuously. It can be seen, that the energy savings vary between 14.5% and 17.6% for the boiler fuel consumption, and 14% and 17.3% for the network useful energy. Furthermore, due to the higher energy consumption in the case of oversized radiators, the energy saving is about 2% lower than the case of nominal sized radiators. It is frequently discussed that the oversizing of the heating system is done especially to introduce intermittent heating. In this case all results of the optimal start cases should be related to the result for the heating system with nominal sized (100%) radiator and boiler in the continuous case. Then the maximum value of fuel saving will be 19.6% (See Table 2, case 7: 200% oversized boiler and radiators, set point temperature of thermostatic plants 1 K reduced).

Furthermore, it can be demonstrated that if the Gradient Method is applied for the prediction of optimal start times, the influence of the structure temperatures should not be neglected. Within the Gradient Method the structure temperatures are not considered directly. They are weakly represented by the radiant temperatures (see Equation (5)). The optimal start times, found by the repetition of the simulations, and the daily indoor temperatures at the moment of start can be used to calculate the daily gradients of start by using equation 2. These values are plotted by relating them to their indoor/outdoor temperatures in a 3 dimensional field. The result is shown in the right part of Figure 11. The Finite Difference Method for the modelling of the building allows to investigate the layer temperatures in all walls, too. By using the layer temperatures as an indication, the irregular peaks in the right part of Figure 11 can be identified as the gradients of those days, on which the outdoor temperatures have returned from a cold season back to warmer days, but the building structure is still "cold". If the gradients of these days are not considered in the plot, the picture of a much smoother plane will be achieved (see Figure 11, left part). The Gradient Method with only two dependences ($G_s = f(T_{s,i}, T_{s,o})$) will not provide good forecasts, if the effect mentioned above is neglected. Within the Gradient Method the thermal inertia of the building should be considered in a better way. A possible solution would be to equip the optimal start/stop system with an additional sensor which measures the structure temperature in a suitable location. Then the daily gradients should be stored in a three dimensional field $G_s = f(T_{s,i}, T_{s,o}, T_{structure})$. The disadvantage of this method would be the long installation time of the controller, in which the empty sections of a 3-dimensional memory matrix have to be charged. Another way would be to permit optimal start/stop on days only on which the outdoor temperature is not too cold, and to heat the building continuously on extremely cold days. This would keep the average temperature of the building structure in a small range and provide similiar thermal response on different cold days.

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5. Conclusion

For the application of optimal start/stop controllers in buildings with hydronic heating systems the disadvantages of the Gradient Method for the prediction of optimal start times and the influence of sizing on intermittent heating are discussed. The Gradient Method cannot provide good forecasts, if the influence of the structure temperatures on the dynamic behavior of the building is neglected. By computer simulation it is proved that an oversized plant allows to start heating later than a nominal sized plant. Compared to continuous heating the energy savings for intermittent heating with optimal start vary between 14% and 17% for the given example.

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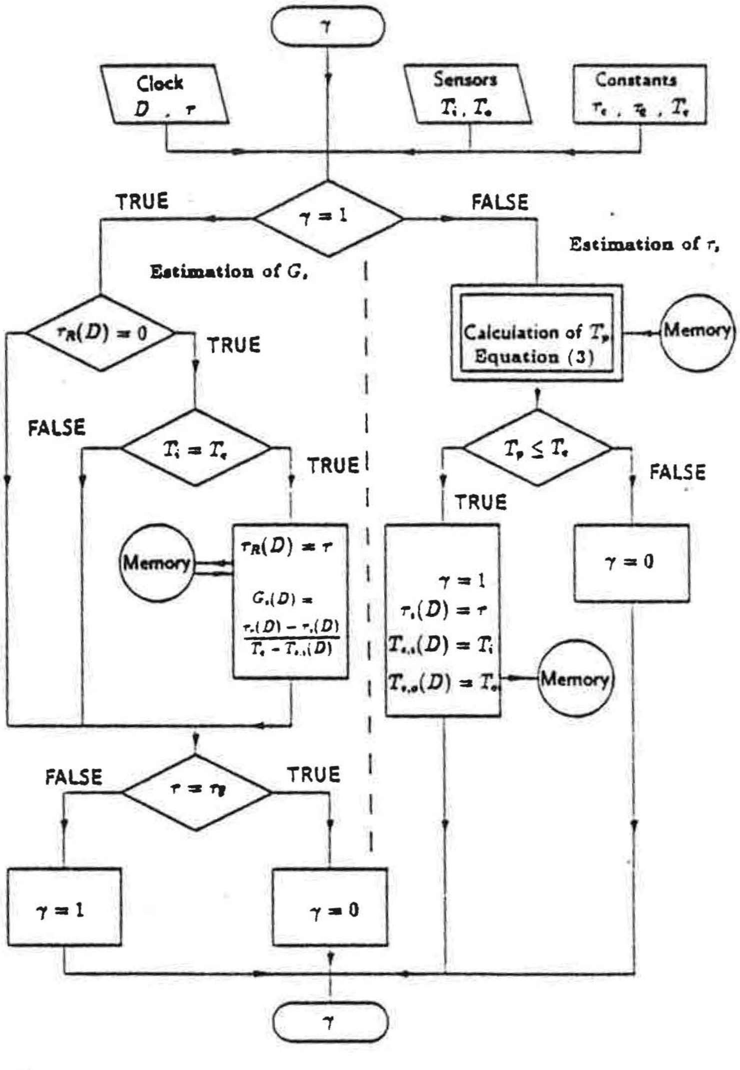
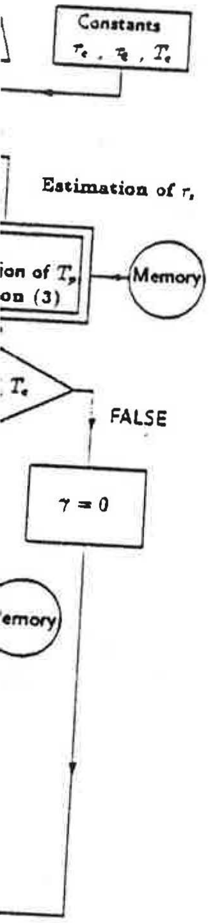


Figure 1 : Control algorithm for predicted start



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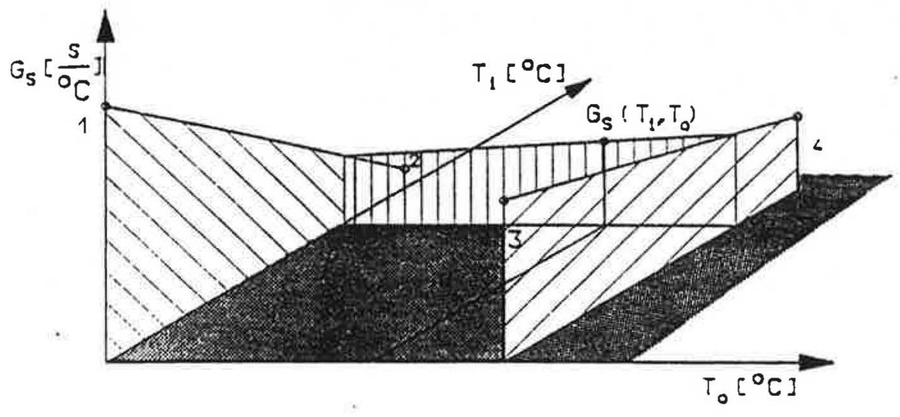

Figure 2 :

Prediction of the start gradient $G_s = f(T_{s,i}, T_{s,o})$) by linear interpolation. (The points 1.2.3, and 4 represent memorized gradients of previous days. The values for T_i and T_o of these days have the smallest distance to the actual point (T_i, T_o) on the $G_s = 0$ plane.)

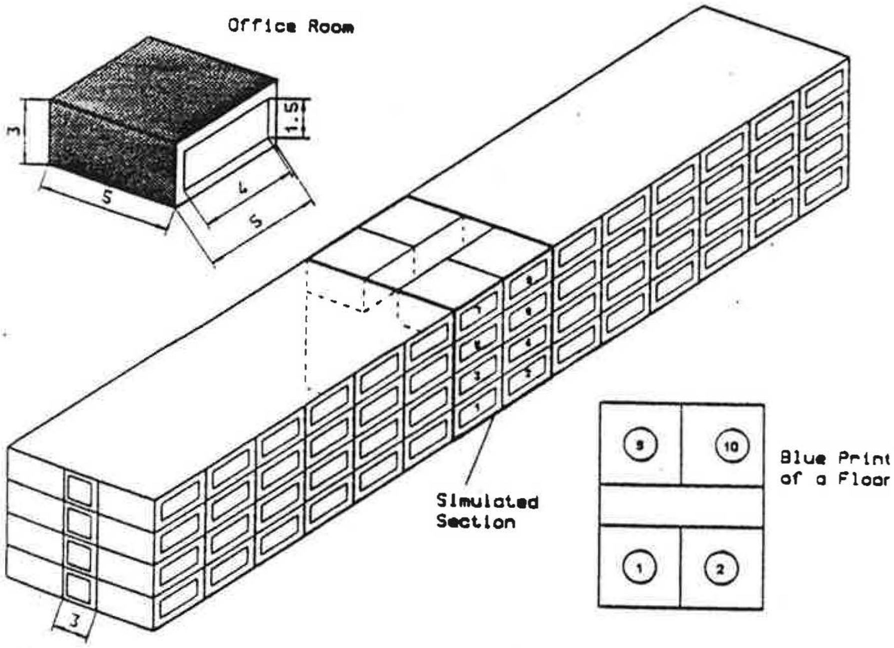

Figure 3 : Office building with blue print of a floor section. dimensions in meters

Table 1 : Thermal data of building structure

SECTION	CONSTRUCTION	d m	λ W/(mK)	c kJ/(kgK)	ρ kg/m³
FLOOR TO CELLAR	PAVEMENT	0,03	0,87	1,05	1800
	CONCRETE	0,12	1,05	1,05	2000
	INSULATION	0,08	0,04	1,38	50
FLOOR AND CEILING	PAVEMENT	0,03	0,37	1,05	1800
	CONCRETE	0,12	1,05	1,05	2000
EXTERNAL WALLS	ASBESTOS CEMENT	0,03	0,45	1,05	1300
	INSULATION	0,05	0,04	1,38	50
	CONCRETE	0,10	1,05	1,05	2000
INTERNAL WALLS	GAS. CONCRETE	0,12	0,40	1,05	1200
ROOF	BALLASTING	0,04	0,58	0,89	1800
	INSULATION	0,08	0,05	1,88	200
	CONCRETE	0,20	1,05	1,05	2000

Table 2: Boiler data based on the german industry standard (9)

sizing [%]	75	**100**	150	200
nominal useful power [kW]	98	**130**	195	260
standby loss [W]	600	**740**	1010	1260
full load efficiency [%]	91.44	**91.51**	91.59	91.64

c kJ/(kgK)	ρ kg/m³
1,05	1800
1,05	2000
1,38	50
1,05	1800
1,05	2000
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1,38	50
1,05	2000
1,05	1200
0,89	1800
1,38	200
1,05	2000

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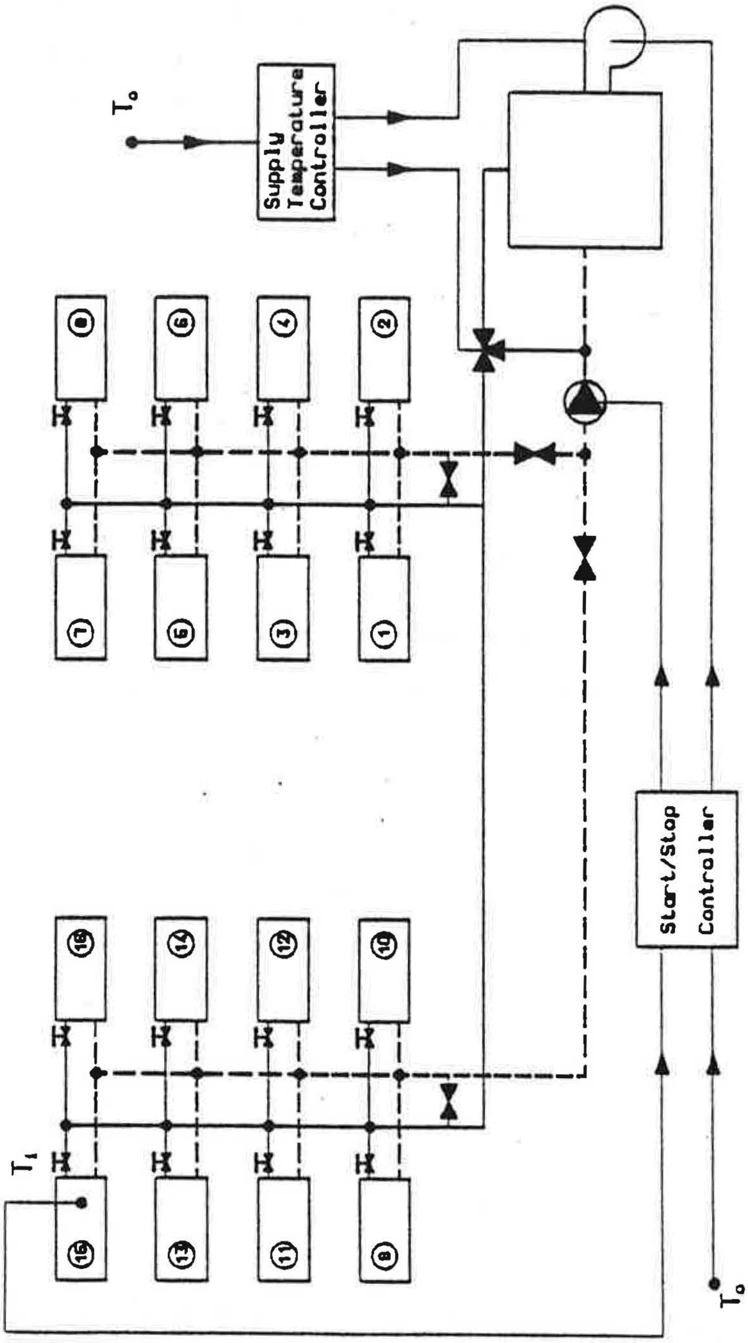


Figure 4 : Radiator heating system of the office building

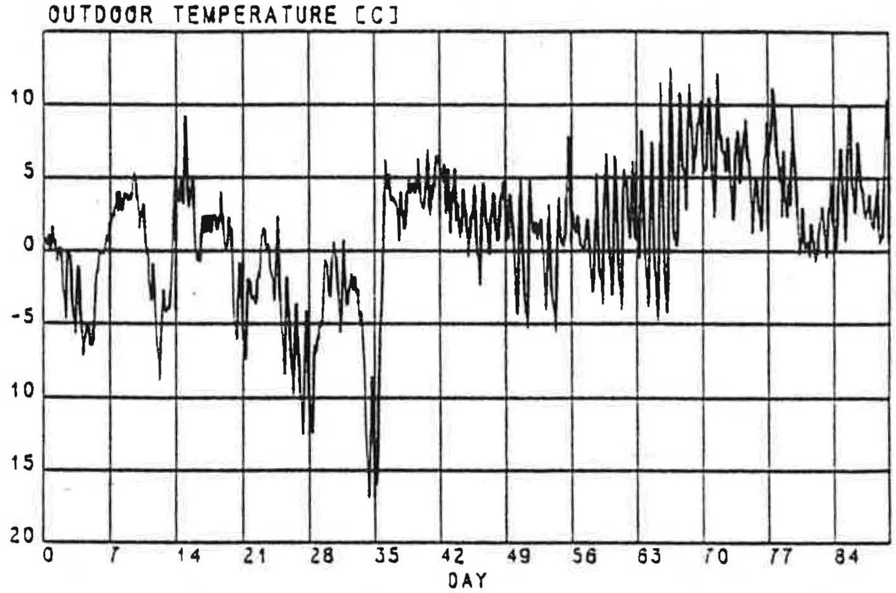


Figure 5 : Outdoor temperatures based on the german test reference year TRY05, January 1st to March 31th (8)

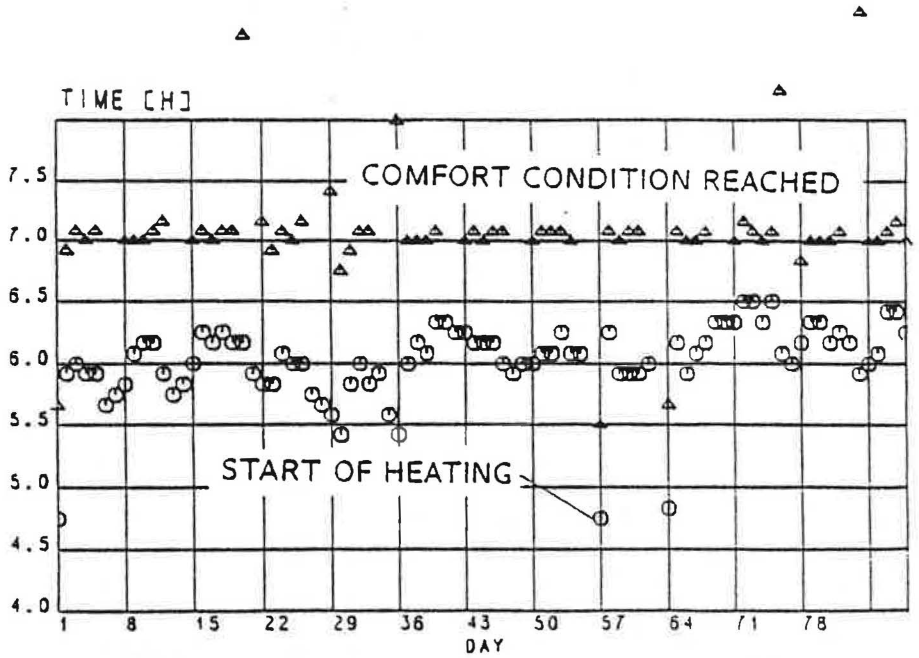
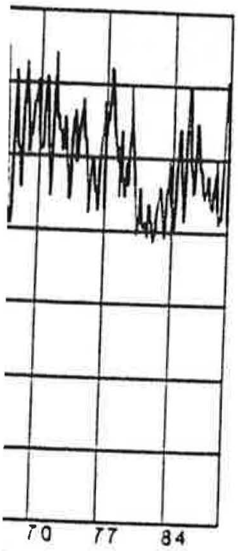


Figure 6 : Start Times calculated with the gradient method.



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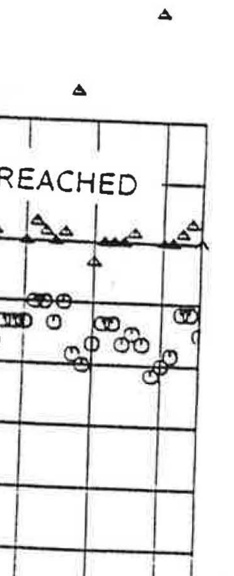


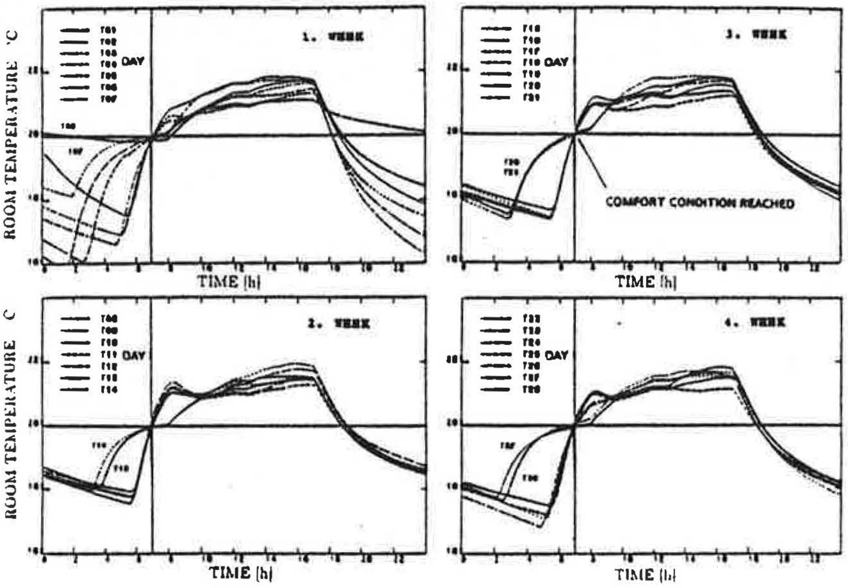


Figure 7 : Room temperatures of the reference room, February 1st to 28th, boiler and radiators nominal sized

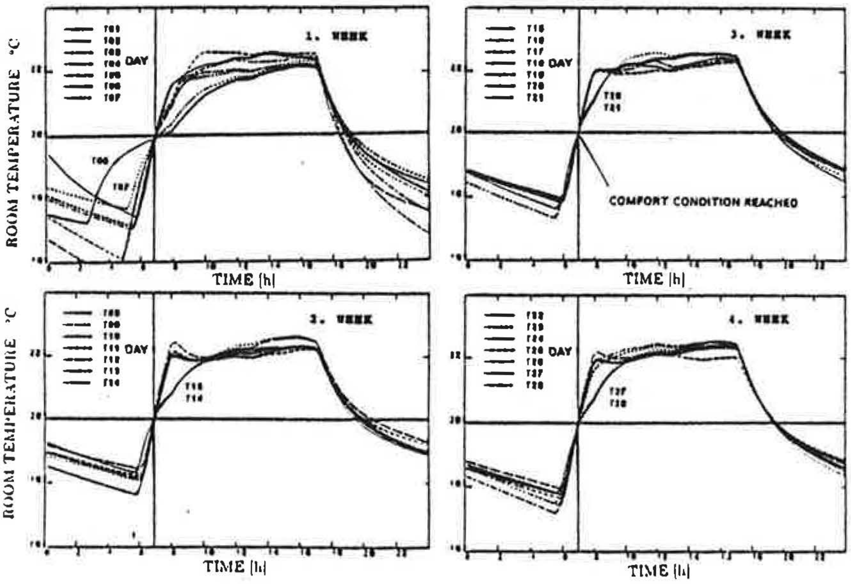


Figure 8 : Room temperatures of the reference room, February 1st to 28th, boiler and radiators 200% oversized

Table 3: Total energy consumption, February 1st to 28th

(LS : set point temperature of thermostatic valves 1 K reduced)

continuous case :

simulation case	1	2	3	4	5	6	7
boiler sizing	75	100	150	200	100	200	200 (LS)
radiator sizing	100	100	100	100	200	200	200 (LS)
boiler consumption [10^{10} J]	16.14	16.52	16.58	16.65	16.63	16.87	15.72
boiler heat output [10^{10} J]	14.89	15.08	15.11	15.12	15.28	15.32	14.26
boiler efficiency [%]	92.28	91.27	91.17	90.83	91.88	90.81	90.71
network useful heat [10^{10} J]	14.46	14.62	14.65	14.66	14.83	14.87	13.69
distribution efficiency [%]	97.13	96.98	96.99	96.94	97.05	97.06	96.00

optimal start case :

simulation case	1	2	3	4	5	6	7
boiler sizing	75	100	150	200	100	200	200 (LS)
radiator sizing	100	100	100	100	200	200	200 (LS)
boiler consumption [10^{10} J]	13.80	13.76	13.71	13.73	14.07	14.23	13.29
boiler heat output [10^{10} J]	12.81	12.73	12.63	12.61	13.09	13.13	12.26
boiler efficiency [%]	92.88	92.54	92.09	91.84	93.00	92.29	92.22
network useful heat [10^{10} J]	12.45	12.33	12.20	12.12	12.67	12.60	11.73
distribution efficiency [%]	96.93	96.66	96.45	96.02	96.62	95.81	95.50

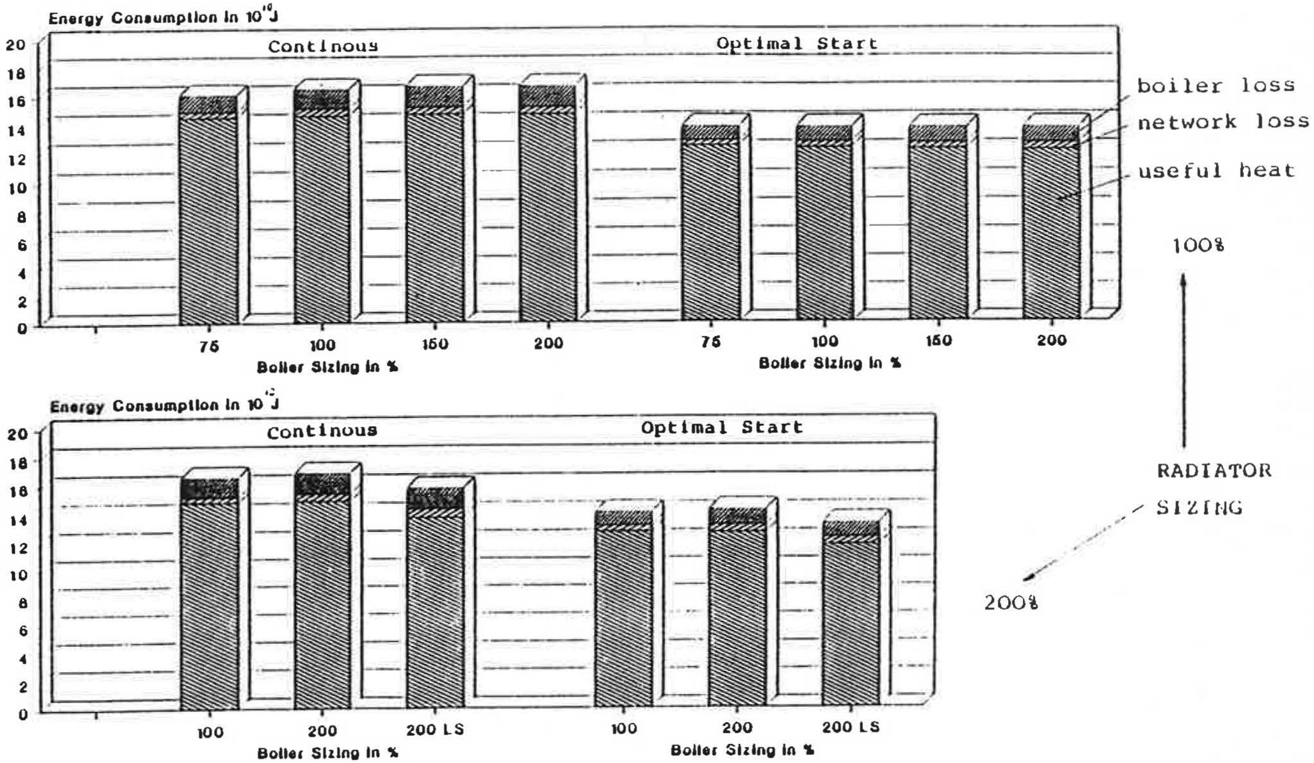


Figure 9 : Energy consumption, results of the heating period February 1st to 28th, (LS : set point temperature of thermostatic valves 1 K reduced)

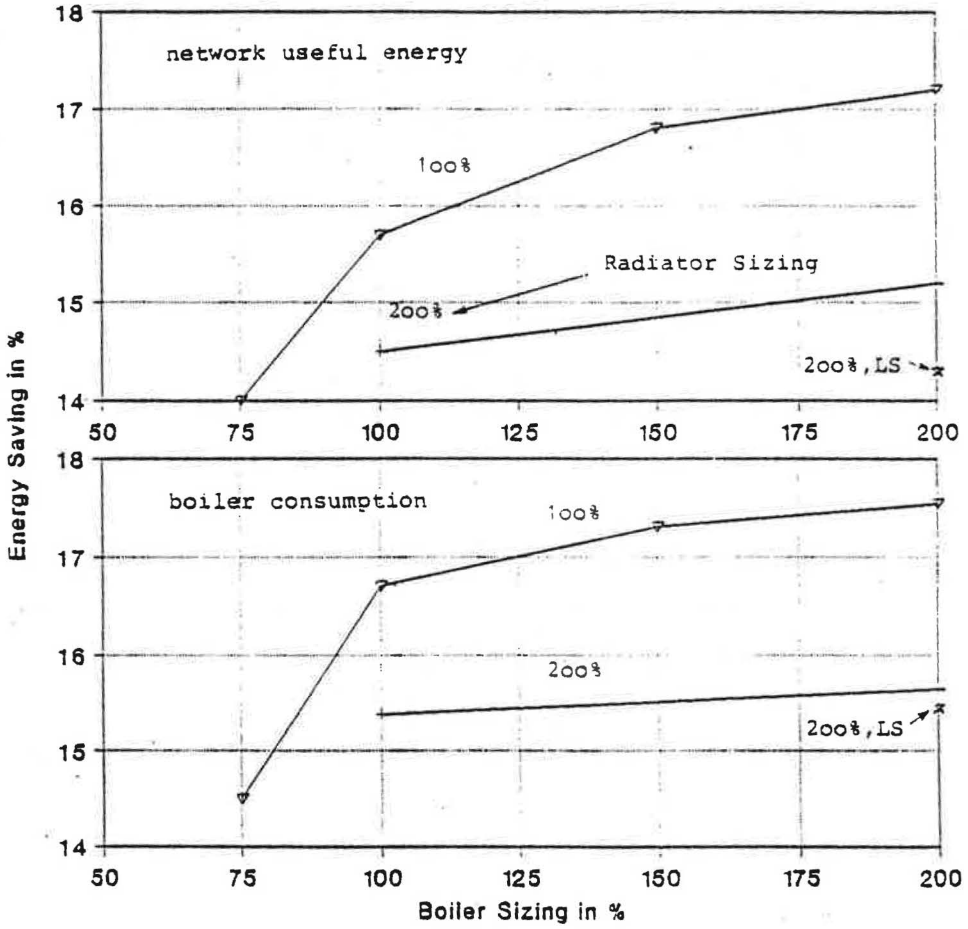
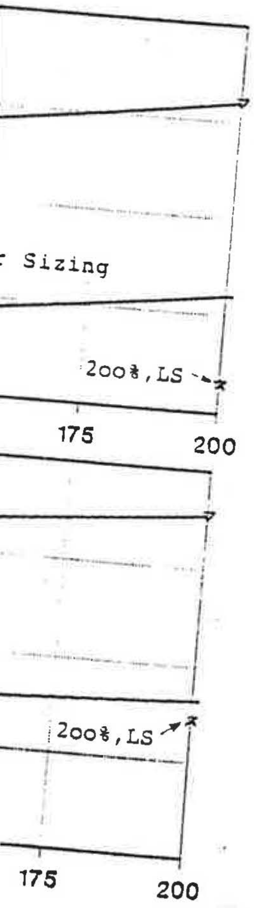


Figure 10 :

Energy saving by optimal start control as a function of boiler and radiator sizing, simulation results of the heating period February 1st to 28th. (LS : set point temperature of thermostatic valves 1 K reduced). The energy saving is defined as to be for the same boiler and radiator sizing the quotient of total energy consumption for intermittent heating to total energy consumption for continous heating



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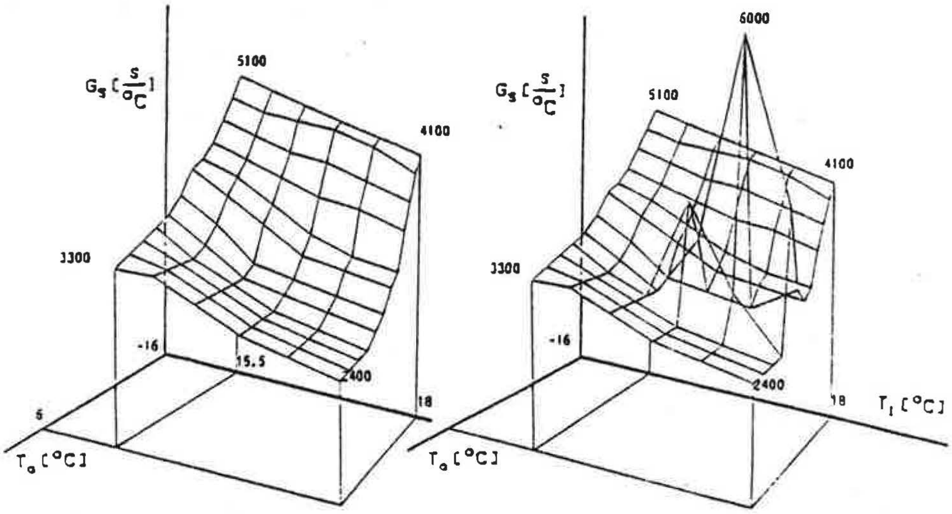

Figure 11 :

Dependences of the start gradient ($G_s = f(T_{s,i}, T_{s,o})$); left side: the gradients of the days, on which the outdoor temperatures have returned from a cold season back to warmer days are not considered; right side: the gradient of all days are considered

DISCUSSION

HAVES Ph. (UK)

Can you comment on the criteria for the selection of weather data for use in evaluating adaptive optimum start/stop controller ? How did you select the weather data used in your test ?

ANSWER :

Artificial weather data, which may be combinations of different real data, could be helpful if the evaluation of adaptive controllers was the point of interest. But we think that there are still some efforts necessary to introduce rules how the data should be chosen and how the combination has to be done.

In order to get simulation results as soon as possible, available weather data were chosen for this study. The selected weather period includes few "cold days" (e.g. -16 C) distributed between rather "warm seasons" (0 to 8 C). This irregularity was our only criterion for the selection of weather data and we discovered that it made our optimal start algorithm busy enough during the simulation.

Although the two-dimensional gradient method (with a memory matrix for measured gradients) is not adaptive (in the classical sense of the control theory), it gives the supervisory controller the ability of self learning. We think that our simulations already give us a quite good picture on the abilities (or disabilities) with this kind of "adaption".

LARET L. (France)

If you oversize the heating system, you increase the closed loop gain during regulation periods (constant comfort inside temperature for occupancy periods). When rather good thermostatic valves are used, the gain may be so high that instabilities (oscillations) can be reached. I observed this behaviour, did you observe it too ?

ANSWER :

No, we didn't observe this effect in the presented studies. But the effect you describe happens, if the thermostatic valves are forced to close on warm days or during periods with high internal gains.

VISIER J.C. (France)

Did you take into account the difference of behaviour between short unoccupancy periods (night) and long (week-end) ones ? The behaviour of the building will be quite different for these two types of periods.

ANSWER :

We agree with you, if the adaptation quality of the optimal start controller is the main point of interest, the "weekend effect" should be taken into account.

Bigger energy savings but also additional problems with the optimal start controller are expected, if weekend shut down is considered.

But to find out the influence of component sizing on the energy saving potential of intermittent heating, we think that there is no need to introduce weekends in the simulations. The tendency of the evolution of the energy consumption for different plant sizes can be also shown with simplified assumptions according to the occupation time schedule, internal loads and weather period.

LOVEDAY D.L. (UK)

Regarding replacing a correctly sized boiler + optimum start controller with an oversized boiler and "cheap" on/off controller, have you any estimates of the cost effectiveness of this approach ?

ANSWER :

No. But we are not going to recommend oversizing the heating systems. We only conclude : if the heating system is already oversized then there may be no need to use a controller which optimizes the daily start times. Certainly there are no further costs for the optimal start function in an already installed BEMS.

SOWELL E.F. (USA)

Perhaps the invariability of start time for oversized equipment is because the limiting factor is the rate at which building mass can absorb energy. If this is so, your results will be sensitive to room treatment, e.g., carpets and false ceilings, do you plan to investigate these factors?

ANSWER :

For this study the heat input to rooms is almost convective. Radiators with higher radiative heat emission would change the thermal response of the room. Similar effects can be shown if we change the structure of walls, ceiling, etc. But we are not going to extend our studies with investigations on this research field.

JIANG Y. (China)

1. The mean temperature with a 200% oversizing is higher than that of the normal size boiler with 8 radiators. How can the energy of the oversized system be saved by 14% ≈ 17% ?

2. Have you considered the operating cost of pumps in the oversized system when you give the data of energy saved?

3. To save energy a good controller is needed even when oversizing the boiler because during the daytime the room temperature should be controlled just at the demand point. With a simple controller on an oversized boiler, it will hardly be achieved.

ANSWER :

1. We compare the energy consumption obtained by optimal start heating with the energy consumption obtained by continuous heating always for the same plant size.

2. No, because the savings in electricity are negligible when compared to the savings in fuel.

3. For comparing different systems, the same comfort conditions in the rooms should be achieved. If thermostatic valves are used, the size of the radiators and the supply temperature change the room temperature level. Therefore the set points of the valves have to be adapted.

WALLENBORG A. (Sweden)

It may not be relevant to compare the cost of oversizing the boiler/radiators to the extra cost of an optimal start/stop controller, since optimal start/stop control is a standard function in many modern BMS systems, and does not necessarily add extra cost to the system.

ANSWER :

We don't compare the cost of oversizing with the extra cost of an optimal start/stop controller. Certainly there are no further costs for the optimal start function in an already installed BEMS.

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MUERAU J. (Germany)

Assumption : room schedules for the entire building are identical. Therefore, the figures showing relations between go ON/OFF VS OSS control have to be modified if you consider individual room schedules, specifically by using commonly installed load demand requests to the HVAC system.

ANSWER :

Yes. The energy saving also depends on the occupation period of the building. As an example, the tendency of the evolution of the energy consumption for different plant sizes is only shown for one time schedule (7 am to 5 pm).

KOHONEN R. (Finland)

Our experience is that oversizing of the heating system influences on the room air temperature distribution and on the "timing-error" but not very much on energy consumption/savings.