Control Of Thermally Activated Building Systems

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SUMMARY

A research project on the control and design of thermally activated building systems (TABS) has been started in May 2004. This paper presents one selected result after three years of work: A comprehensive TABS zone control strategy with a modular concept consisting of maximally four parts which allows creating four different control strategies.
The (mandatory) first part of the comprehensive control strategy is an outside air temperature compensated supply water temperature control based on an unknown-but bounded approach to cope with uncertainties and variations in the heat gains during operation.
The (optional) second part of the comprehensive control strategy is an algorithm for room temperature feedback control. With this part, room temperatures are controlled in an energy-efficient way. The algorithm also corrects wrong parameter settings of the other control parts.
The (optional) third part of the comprehensive control strategy is a pulse-width modulation (PWM) module for intermittent operation of the recirculation pump. The intermittent operation is used to save pump energy, but it is also applied to benefit from low-cost energy sources such as free-cooling during the night or electrical energy in low tariff phases.
The (mandatory) fourth part of the comprehensive control strategy is a standard sequence controller to control the zone supply water temperature within the according setpoint range.
In simulations, all four control strategies are applied to TABS and the simulation results are analyzed regarding comfort criteria and energy efficiency.

KEYWORDS: control, thermally activated building systems (TABS), concrete core conditioning, performance bound

INTRODUCTION

Thermally activated building systems (TABS) have emerged as an energy efficient and economical way for cooling and heating of buildings. They integrate the building structure in the overall energy strategy of the building as energy storage. The dynamic thermal behavior of building elements such as structural floors and slabs is exploited to provide either cooling by radiant and convective energy absorption from the space, or space heating by the release of stored energy. In contrast to radiant cooling by suspended ceiling panels, peaks in energy demand are flattened and the actual cooling is shifted in to the colder night time [1], [2].
So far, control is implemented downstream in the design process. The specification of control algorithms is difficult because of the large thermal inertia of the system and because of the challenge to comply with comfort requirements in different rooms with different heat gains within the same hydraulic zone. Various control approaches are presented (see [3]-[9]), but they often have disadvantages due to different approaches for cooling and heating, too frequent switching between heating and cooling, the need for manual switching between heating and cooling mode as well as the need for manual adjustment of parameters. In [10],

[11], an unknown-but-bounded approach is presented to cope with uncertainties and variations in the heat gains during the design phase. In [12], [13], an integrated design process for TABS and its control is given based on the unknown-but-bounded approach.
This paper presents possible additions to the base control concept described in [12] which leads to a modular control concept. This concept can be adapted to different TABS plants and thereby increase the energy efficiency, the comfort and/or the commissioning and operation effort. The concept has been developed in the frame of a research project on which was reported the first time in [10].

OVERALL CONTROL CONCEPT

The presented control concept is one part of an integrated process that additionally consists of TABS design (planning of HVAC system and its control), commissioning of TABS and optimization during operation. In the TABS design, the base TABS zone control strategy is used (mandatory parts, see [12]). This base control strategy can be extended by optional control parts to improve comfort and/or energy efficiency depending on given requirements and installations. The result is a modular control concept for a TABS zone which – by configuration – can be adapted to different TABS plants. Besides the control of the zones, also the heat and cold generation and the distribution have to be controlled. In this paper, only the TABS zone control is described in detail.
In Figure 1, the overall control concept is shown for a TABS plant with two zones. Two zone controllers (see next chapter) act on the zone circulation pumps and the zone heating and cooling valves. Together with the zone supply water temperature setpoints $\vartheta_{sw,SpH,PWM}$ and $\vartheta_{sw,SpC,PWM}$, these signals can also be used to set up a demand dependent control of the heat and cold generation and distribution as indicated in Figure 1.

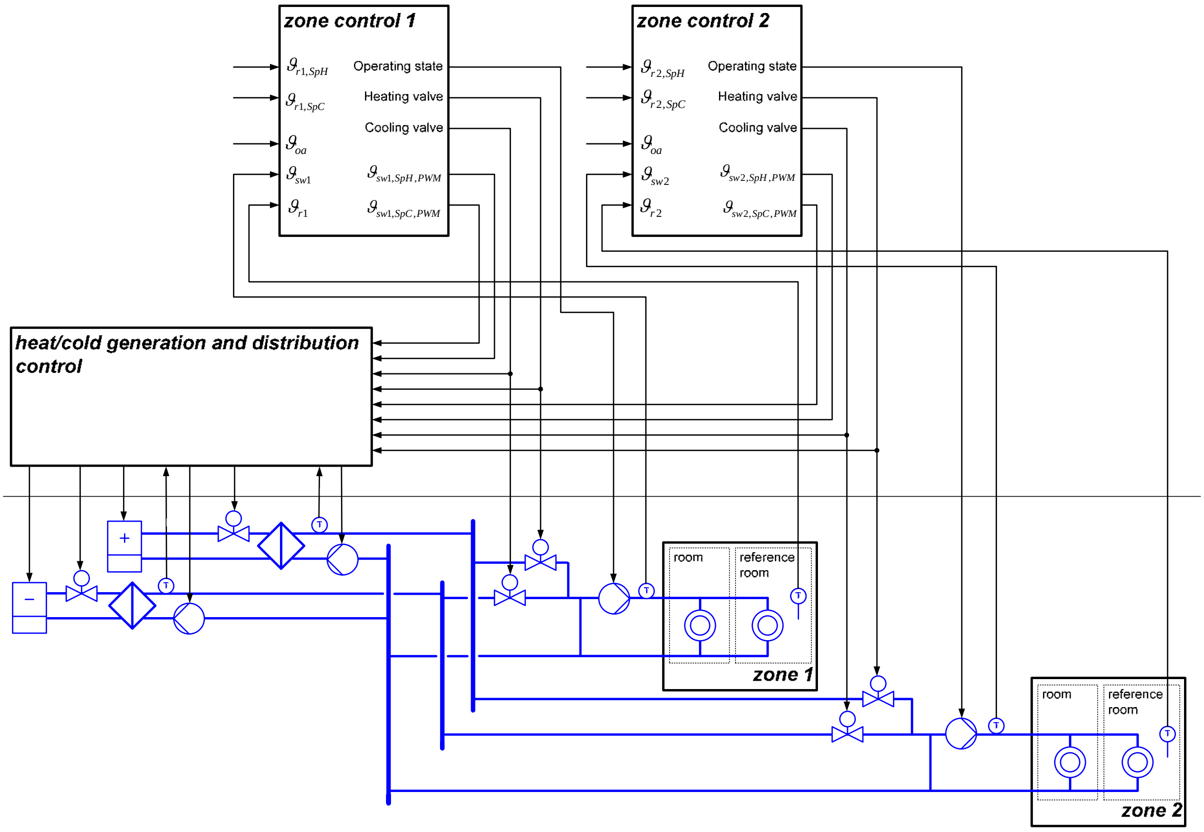

Figure 1: The overall TABS control concept, including heat/cold generation and distribution

ZONE CONTROL

In Figure 2, the modular TABS zone control is given in more detail. If an optional part is not needed or required, only the feed-through indicated by dotted arrows in the corresponding control part function block has to be realized. The functionalities of the four control parts are explained below.

1. Outside temperature compensated supply water temperature control (mandatory)

This core control part determines a supply water temperature setpoint range [$\vartheta_{sw,SpH}$, $\vartheta_{sw,SpC}$] as a function of the mean outside air temperature of the last 24 hours $\overline{\vartheta}_{oa}$ and the current room temperature setpoint range [$\vartheta_{r,SpH,FB}$, $\vartheta_{r,SpC,FB}$]. For that purpose, the so called heating and cooling curves are used. The heating and cooling limits serve to identify the operating mode depending on $\overline{\vartheta}_{oa}$ (see e.g. Figure 2). In order to define initial parameters of this control part, an unknown-but-bounded design process can be used [12].

2. Room temperature feedback control (optional)

If one or several room temperatures ϑ_r are measured in the controlled zone, a room temperature feedback control part can be added to the zone control. Room temperature feedback control has the following advantages (+) and disadvantages (–):

+ Comfort can be improved if heating and cooling curves are wrong placed or if the intermittent zone pump operation is inaccurate due to modeling errors (see part 3).
+ Energy efficiency can be increased when room temperatures are controlled making full use of the room temperature comfort range. This also leads to less frequent switching between heating and cooling demand of the zone.
+ Commissioning and tuning effort can be reduced since the feedback control corrects settings that are wrong (to a certain extent).
− Since TABS react slowly, only a day-to-day compensation is promising, an instant correction can not be achieved through the TABS.
− The placement of the room temperature sensor is critical: The measured temperature should be meaningful during the whole operation.
− If the zone consists of more than one room, the measured temperature has to be a reference temperature for the whole zone or several sensors in different rooms are used.

Since TABS react slowly, only day-to-day room temperature compensation is promising, an instant correction can not be achieved with TABS. A possible implementation of room temperature feedback control by two standard PID controllers is outlined here: The task of controller 1 is to keep the room temperature ϑ_r above the lower room temperature setpoint $\vartheta_{r,SpH}$ and the task of controller 2 is to keep the room temperature below the upper room

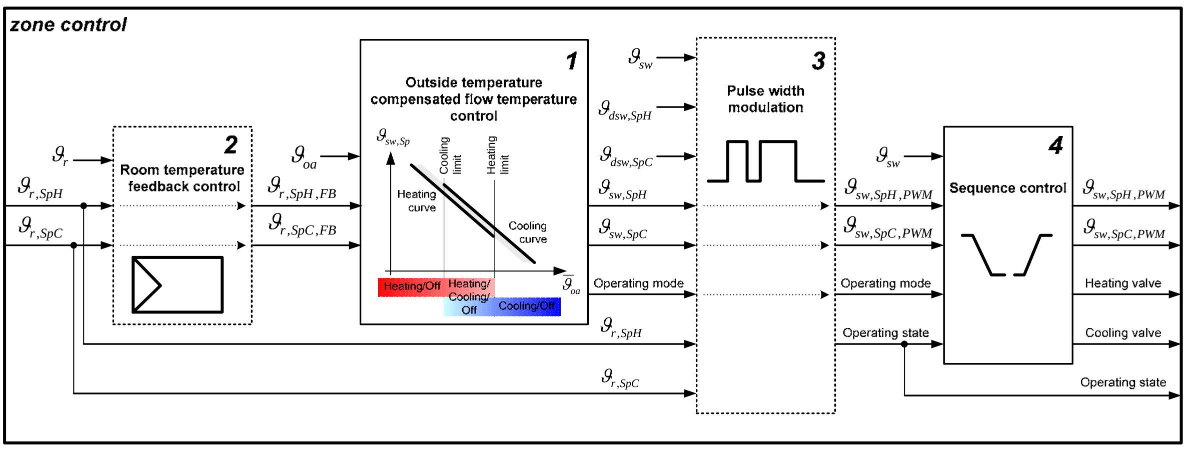

Figure 2: Scheme of the modular zone control (mandatory parts with solid frame, optional parts with dotted frame)

temperature setpoint $\vartheta_{r,SpC}$. The controlled variable for the P- and I-part of the controllers are the minimal (for controller 1) and maximal (for controller 2) room temperature of the last 24 hours. The controlled variable for the D-part of the controllers is the average room temperature of the last 24 hours. The controller outputs are limited (e.g. [-5K, 5K]) and added to $\vartheta_{r,SpH}$ and $\vartheta_{r,SpC}$ so that a corrected room temperature setpoint range [$\vartheta_{r,SpH,FB}$, $\vartheta_{r,SpC,FB}$] results. Controller 1 operates with $\vartheta_{r,SpH}$ while the setpoint of controller 2 is modified to cope with exceptional days when less internal heat gains are present (e.g. weekend).

3. Intermittent operation of zone water circulation pump (optional)

The control parts presented so far are based on continuous operation of the zone water circulation pumps. An additional third control part (see Figure 2) can be added to operate the zone water circulation pump intermittently which has the following advantages (+) and disadvantages (–):

+ Energy efficiency can be increased by reducing the operation time of the zone circulation pumps.
+ Energy efficiency can be increased by moving zone circulation pump on-times to time intervals where heat and cold can be delivered efficiently, e.g. free-cooling during nights.
+ Energy costs can be reduced by moving the on-time of the zone circulation pumps to time intervals where energy can be delivered at lower cost, e.g. using low tariff of the electrical energy to operate chillers and heat pumps.
+ Investment costs can be reduced by smaller dimensioning of the chiller when using it during the day for the air conditioning system and during the night for the TABS.
− The achievable comfort level generally decreases with intermittent operation of the zone circulation pump. During off-times, no heat is exchanged to the water circuit. This has to be compensated by lower or higher supply water temperatures during on-times, respectively, which reduces the self-regulating effect.
− The control of zone supply water temperatures for intermittent operation is more critical since turning the zone pumps on and off is heavily disturbing the control system.
− Intermittent operation can lead to more switching between heating and cooling demand than necessary.

A possible implementation of the intermittent operation control part is presented here: A pulse width modulation (PWM) approach is used to determine pump on- and off-times depending on the current operating mode. The pump operating mode (on or off) and the according supply water temperature setpoint range [$\vartheta_{sw,SpH,PWM}$, $\vartheta_{sw,SpC,PWM}$] are calculated based on a physical TABS model (see Figure 3). The same model then can be used to shorten or prolong pump on-times whenever the supply water temperature ϑ_{sw} is not kept within its setpoint range due to control errors or limitations of the heating/cooling system. Before starting an active heating or cooling process, an idle running operation is applied (the water circulates in the zone with zone valves closed). If after a specified idle operation time, the measured supply water temperature is within the range [$\vartheta_{sw,SpH}$, $\vartheta_{sw,SpC}$], the model based calculation is redone so that – whenever possible – no active heating or cooling process is necessary. To increase energy efficiency (or to reduce energy costs), on-time intervals are placed where heat or cold is expected to be delivered more efficiently (or less expensive).

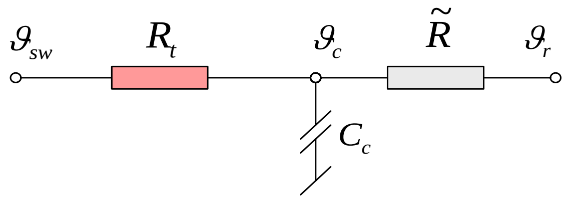

Figure 3: TABS first order model used for control of intermittent operation of zone water circulation pump

The values of the fictitious TABS thermal resistance R_t (between ϑ_{sw} and the concrete core temperature ϑ_c of the concrete core thermal capacity C_c) and the thermal resistance $\tilde{R}$ (between ϑ_c and ϑ_r) of the model in Figure 3 can be calculated according to [12]. The model then allows calculating turn-on ratios between on-time Δt_1 and the period length Δt for given supply water temperature setpoints. The simplified result for the turn-on ratio in the heating cases is given in (1), a similar equation is found for the cooling case. To calculate a non-simplified result, a calculation procedure as described in [15] can be applied.

$$\frac{\Delta t_1}{\Delta t} = \frac{1}{1 + \dfrac{\vartheta_{sw,SpH,PWM} - \vartheta_{sw,SpH}}{\dfrac{R_t}{R_t + \tilde{R}}\left(\vartheta_{sw,SpH} - \vartheta_{r,SpH}\right)}} \qquad (1)$$

A simplified result for the turn-on ratio in the heating case for varying supply water temperatures is given in (2). This equation is used to shorten or prolong pump on-times whenever the supply water temperature is not controlled within its setpoint range.

$$\frac{\Delta t_1}{\Delta t} = \frac{\dfrac{1}{\Delta t}\displaystyle\int_{t=t_0}^{t_0+\Delta t_1} \vartheta_{sw}(t)dt - \dfrac{R_t}{R_t + \tilde{R}} \cdot \left(\vartheta_{sw,SpH} - \vartheta_{r,SpH}\right)}{\vartheta_{sw,SpH} - \dfrac{R_t}{R_t + \tilde{R}} \cdot \left(\vartheta_{sw,SpH} - \vartheta_{r,SpH}\right)} \qquad (2)$$

4. Sequence control of zone supply water temperature (mandatory)
A standard sequence controller that controls the supply water temperature ϑ_{sw} (the according setpoint range is [$\vartheta_{sw,SpH,PWM}$, $\vartheta_{sw,SpC,PWM}$]) is acting on the heating and cooling valves. Depending on operating mode and operating state one or both sequences are disabled and the respective valve is closed.

RESULTS: CASE STUDY WITH DIFFERENT ZONE CONTROL TYPES

A simulation case study was made to compare four different TABS zone control strategies:
- control strategy 1 includes control parts 1, 4
- control strategy 2 includes control parts 1, 2, 4
- control strategy 3 includes control parts 1, 3, 4
- control strategy 4 includes control parts 1, 2, 3, 4

The simulated zone only contains one room; key figures of the room and the TABS configuration are given in Table 1 and Table 2 (see reference building in [12]).
Whole-year simulations for all four control strategies were carried out in a Matlab/Simulink simulation environment. Outside air temperature and solar heat gains were derived from local meteorological data for Zurich/Switzerland. The used individual heat gains of persons, equipment and lighting are based on the Swiss standard [14]. Room temperature setpoints $\vartheta_{r,SpH}$ = 21 °C and $\vartheta_{r,SpC}$ = 26 °C were used for the whole year. Other main control parameter values were determined in an unknown-but-bounded design process for the defined zone as described in [12], [13]. Here two major heat gain situations were differentiated: workdays and weekends; for both situations dynamic lower and upper heat gains were specified. This ultimately leads to the heating and cooling curve parameter values for weekdays and weekends. The design process also produces parameter values for the heating limit (13.1 °C) and the cooling limit (-1.2 °C).
In Figure 4, an example of the TABS zone control is shown for control strategy 4 for one week in summer: In the top diagram, it can be seen that $\vartheta_{r,SpC}$ is increased by control part 2

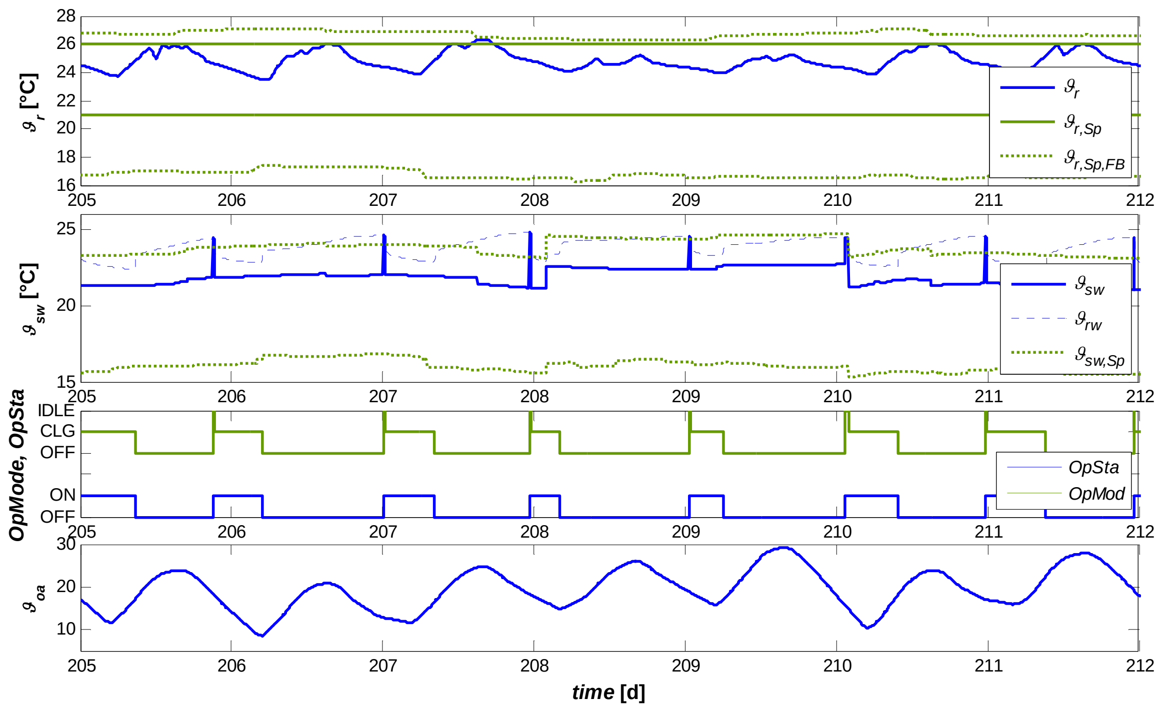

Figure 4: Example of zone control for control strategy 4 in summer

due to heat gains lower than the specified upper bound. The upper supply water temperature setpoint is then calculated by control part 1. Control part 3 lowers this setpoint and reduces pump on-time. The turn-on times are moved within the cooler nighttime. At the beginning of each cooling period, the zone is operated in idle operation to check if cooling is necessary. The resulting room temperatures for all control strategies are given in Figure 5. Figure 6 shows the heating and cooling energy demand, zone water circulation pump turn-on times as well as hours where the needed supply water temperature was lower than the outside air temperature. Figure 6 also contains performance bound energy demands which are calculated by optimal control with full knowledge of the controlled model and actual and future inputs.

Table 1. data of the simulated room

Space length, width, height		6 m x 6 m x 3 m
Façade	Orientation	West
	Area	18.0 m^2
	Overall U-Value	0.65 W/m^2K
	Glazing fraction façade	42 %
Additional internal Wall (light)		36 m^2
Natural air change		0.1 h^{-1}
Ventilation according to indoor air quality requirements (no cooling/heating by ventilation assumed)		

Table 2. data of the simulated TABS configuration

TABS covering fraction (floor area)	80 %
Thickness concrete slab	250 mm
Pipe spacing	200 mm
External/internal pipe diameter	20/15 mm
Specific supply water mass flow rate [a)]	15 kg/(h m^2)
Fictitious TABS thermal resistance (R_t) [a)]	0.08 (m^2 K)/W
Thermal resistance of flooring (carpet)	0.125 (m^2 K)/W

[a)] in terms of floor area covered by tabs

DISCUSSION

Since the parameter values of the control strategies are based on the exactly known simulated zone and since the boundaries of the heat gains have been specified reasonably, the open-loop room temperature control of strategy 1 is almost ideally in terms of comfort (see Figure 5). An added room temperature feedback control (strategy 2) is reducing the energy demand a little, but also – in a tolerable amount – the comfort. In this scenario, the main advantage of the feedback control is not apparent.

Application of PWM control (strategy 3) results in less pump turn-on times (47 %, see Figure 6), but increased heating and cooling energy demand. That is because the self-regulating effect is lower compared to a continuous operation (where supply water temperatures are closer to the room temperature), and therefore the control tends to compensate more than necessary (room temperatures stay within the comfort range for the whole year). Control strategy 4 with PWM and room temperature feedback control is able to avoid this: heating and cooling energy demand is similar to strategy 2 with similar comfort. Here, the PWM is done in a way so that during summer the on-times are moved to the colder night time in order to benefit more from free cooling (i.e. use of a dry cooling tower). To illustrate the resulting control behavior, Figure 6 shows the numbers of hours for which the outside air temperature was larger than the supply water temperature. During that time, the cooling demand cannot be satisfied by a dry cooling tower alone.

The presented control concept is one part of an integrated process consisting of TABS design (planning of HVAC system and its control), commissioning of TABS and optimization during operation. A modular control concept is used to handle different requirements and installations in a simple manner. Further details of the method can be found in the design and commissioning handbook which will be published in the frame of our work.

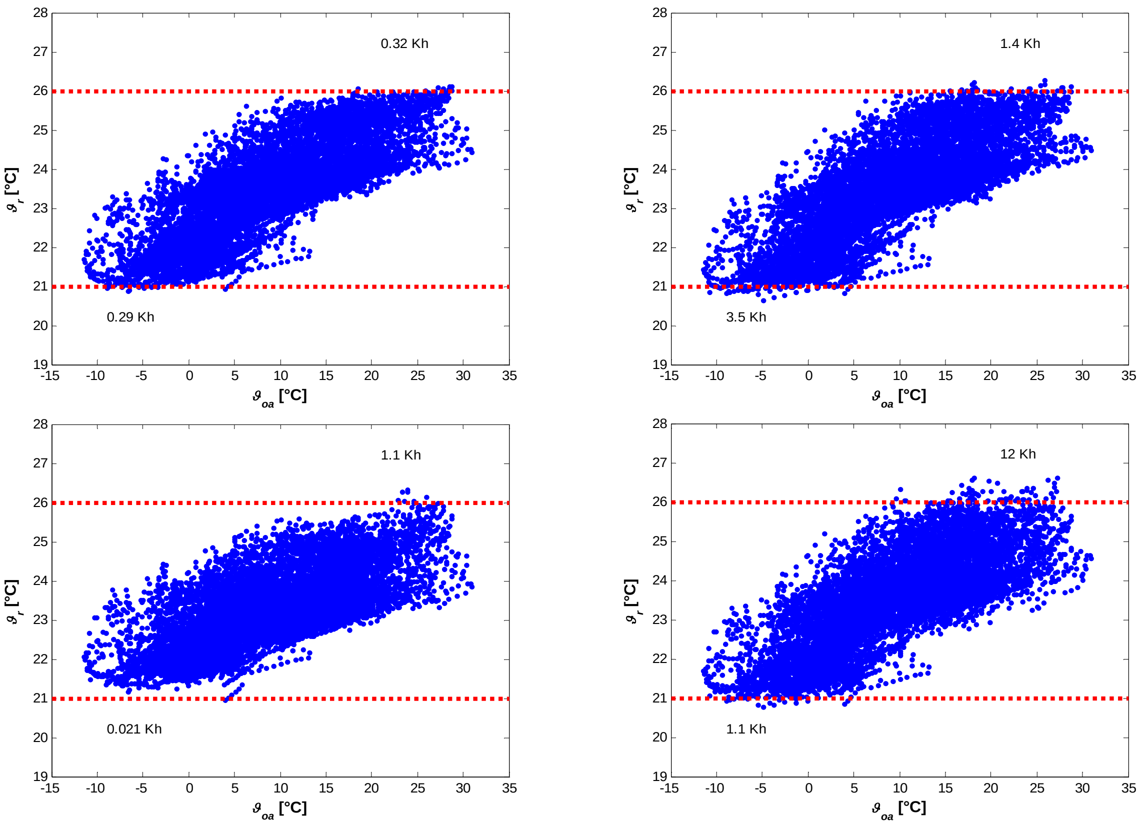

Figure 5: Whole-year simulation room temperatures (hourly values) for control strategies 1 (above left), 2 (above right), 3 (below left) and 4 (below right), room temperature setpoint violations are given within the figures

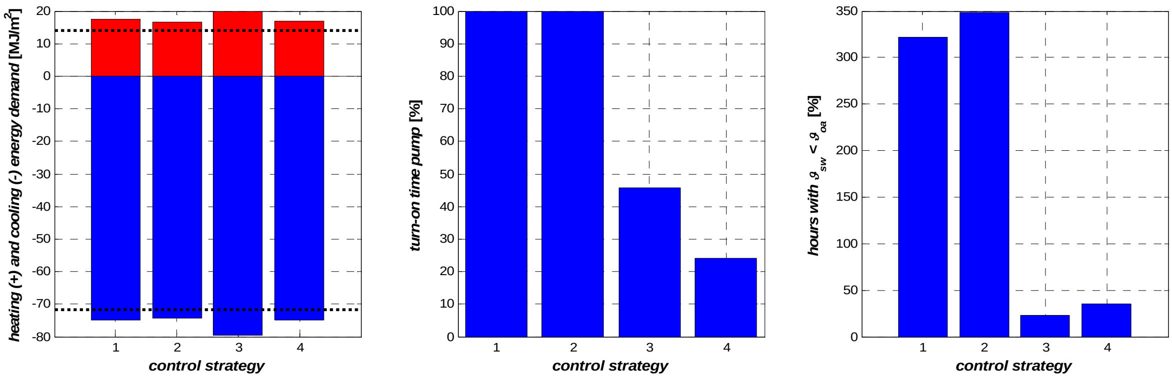

Figure 6: Whole-year simulation heating and cooling energy demand (left) with performance bound (dotted lines), pump operation time (middle) and hours where the supply water temperature was lower than the outside temperature (right)

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