Integrated Design Of Thermally Activated Building Systems And Of Their Control

Jürg Tödtli[1], Markus Gwerder[1], Beat Lehmann[2], Franz Renggli[1], Viktor Dorer[2]

[1]Siemens Switzerland Inc., Building Technologies Group, Zug, Switzerland
[2]Empa, Swiss Federal Laboratories for Materials Testing and Research, Duebendorf, Switzerland

Corresponding email: markus.gwerder@siemens.com

SUMMARY

A new promising integrated design method for thermally activated building systems (TABS) and their control is presented. In contrast to the conventional iterative design method of TABS, which is based on iterative dynamic model simulation studies, the new approach is a more straight-forward calculation process. The new design method is less time-consuming and enables more insight into the potential of TABS. For example, it shows the limitation of TABS application and points out when additional auxiliary heating or cooling devices have to be installed. It is based on lower and upper bounds for the heat gains that have to be estimated within the design process.

KEYWORDS: control, thermally activated building systems (TABS), concrete core conditioning, integrated design, unknown-but-bounded

INTRODUCTION

A research project on the control and design of thermally activated building systems (TABS) [1], [2] has been started in May 2004 [3], [4]. This paper presents one selected result: A TABS design method for building automation and HVAC design engineers.
It is well known among TABS designers that TABS cannot be designed and sized like other HVAC systems. The design and sizing of an HVAC system and its control is usually done in two steps. In a 1st step the HVAC system is designed and sized using a static model for full load operation. The 2nd step is the design of its control, where sometimes dynamic models are used. If the HVAC system is a TABS this approach is not appropriate. This has two reasons. The temperatures in a TABS usually never achieve steady-state conditions. The dynamic behavior has therefore to be considered. This requires dynamic instead of static models. The second reason is that the dynamic behavior of the temperatures depends also on the control. Therefore the control should be taken into account when designing and sizing the TABS. Thus it should not be designed afterwards in a second step. That’s why a TABS and its control should be designed and sized in an integrated way. This is well known among designers of TABS. A frequently heard argument is that simulations have to be performed to design and size TABS. And for such simulations it is necessary to assume some kind of control.
This paper presents a new promising integrated design method for TABS and their control based on [3], [4]. In contrast to the conventional integrated design method of TABS, which is based on iterative dynamic model simulation studies, the new approach is a more straight-forward calculation process. It is based on lower and upper bounds for the heat gains that have to be estimated within the design process.
The first section of the paper will describe how the new integrated design method has been developed. The second section gives an overview of the resulting new integrated design method. A design example will illustrate the method in the third section.

DEVELOPMENT OF THE INTEGRATED DESIGN METHOD

In this section it is outlined how the integrated design method has been developed. It has been designed together with the control algorithms.

The following questions Q1 to Q4 have guided the design process essentially:

Q1 How to switch automatically between heating and cooling a TABS using the outside air temperature information?
This question has been motivated by often heard statements as: The switching between heating and cooling of TABS must be done by hand. Automatic solutions switch too frequently which causes waste of energy. Or automatic solutions based on outside air temperature dependent switching lead to comfort problems.

Q2 How to control rooms with different specific heating and cooling loads?

Q3 What are the advantages and disadvantages of water flow on/off control and how should it be done?

Q4 Is it possible to use room temperature feedback control, and if yes, how should it work and what is the benefit?
This question has been motivated also by often heard statements as: The self-regulating effect is sufficient to control the room temperature, no conventional room temperature feedback controller is necessary. Conventional room temperature feedback controllers do not work because the system to be controlled does react very slowly.

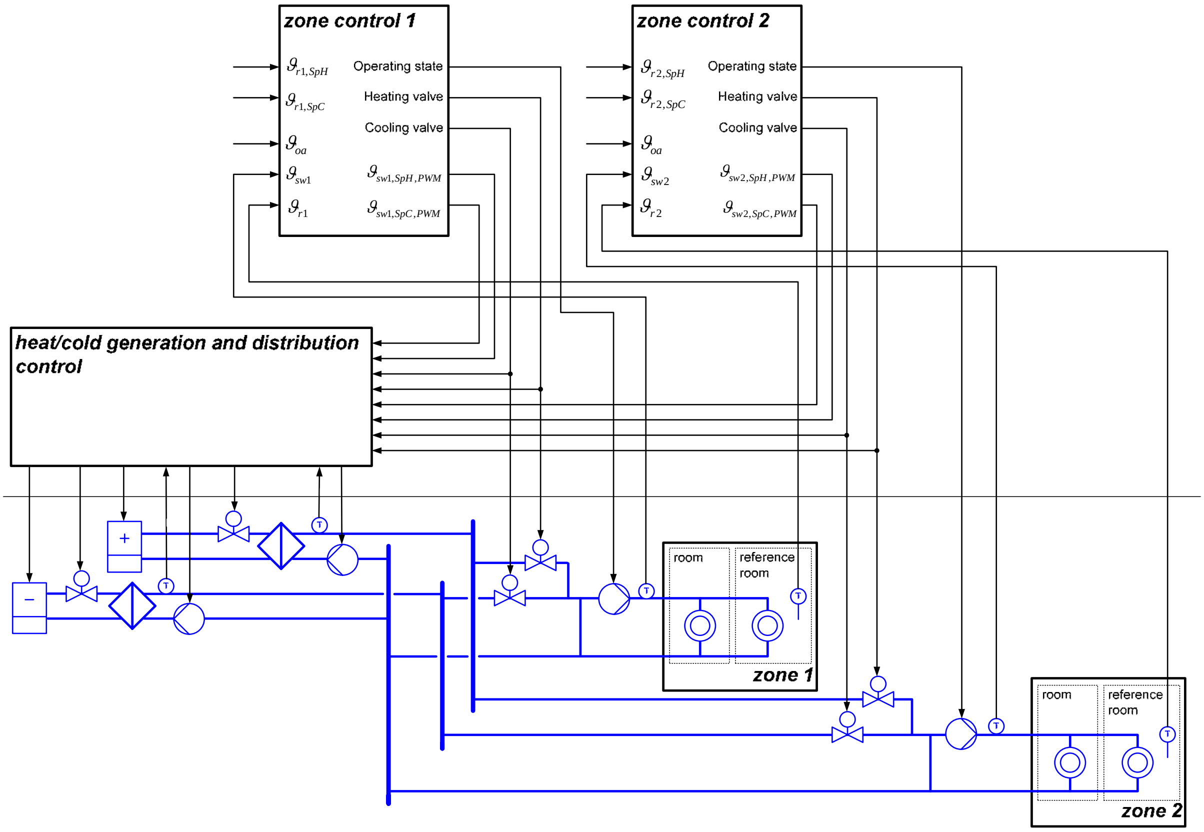


Figure 1: The overall TABS control concept, including heat/cold generation and distribution

Development step 1:

Question Q1 has been addressed first. It led also to an answer of question Q2. In order to find an answer to Q1 only one zone has been considered, e.g. zone 1 in Figure 1. It has been assumed that no room temperature sensor in a reference room is available. Thus the zone controller (Zone control 1 in Figure 1) has only two sensor inputs, the supply water temperature ϑ_{sw} (also called flow temperature) and the outside air temperature ϑ_{oa}. The zone controller acts on the zone heating and the zone cooling valve and it includes a supply water temperature feedback controller with the set-points $\vartheta_{sw,SpH}$ for heating and $\vartheta_{sw,SpC}$ for cooling. The zone controller has also the room temperature heating set-point $\vartheta_{r,SpH}$ and the room temperature cooling set-point $\vartheta_{r,SpC}$ as inputs, which define together the room temperature comfort range.

Development step 2:

In order to find a solution to the problem expressed in question Q1 it has been started with a related problem which is easier to solve, as it is recommended by G. Polya in his famous little book on how to solve problems [8]. The related problem is a special case: the outside air temperature dependent switching between heating and cooling for a system where the *outside air temperature and the heat gains vary only slowly*. This allows us to use a static model to solve the problem. It has additionally been assumed that all rooms of the zone are identical and have the same heat gain $\dot{q}_g$, which allows us to assume that all rooms have the same room temperature ϑ_r. This problem can be formulated mathematically as follows (**problem 1**):

Static model (cf. Figure 2):

$$\dot{q}_w = \frac{1}{R_{l,f}} \cdot (\vartheta_r - \vartheta_{oa}) - \dot{q}_g \qquad (1)$$

where $\dot{q}_w$ is the TABS heating or cooling power and $R_{l,f}$ the thermal resistance of the façade.

$$\dot{q}_w = \begin{cases} 0 & \text{if no heating and no cooling is required} \\ \frac{1}{R_t + \tilde{R}} \cdot (\vartheta_{sw} - \vartheta_r) & \text{if there is heating or cooling demand} \end{cases} \qquad (2)$$

where $R_t + \tilde{R}$ is a thermal resistance characterizing the TABS between the supply water temperature and the room temperature.

Known:

$R_{l,f}$, $R_t + \tilde{R}$, $\vartheta_{r,SpH}$, $\vartheta_{r,SpC}$, ϑ_{oa} and $\dot{q}_g$.

Determine:

When is it required to heat and when is it required to cool, and if either of them is required, what is the required supply water temperature ϑ_{sw}, such that $\vartheta_{r,SpH} \le \vartheta_r \le \vartheta_{r,SpC}$ and $|\dot{q}_w|$ is minimal.

Result:

Heating is required if $\vartheta_{oa} \le \vartheta_{oa,LmH}$ where $\vartheta_{oa,LmH}$ is the heating limit and

$$\vartheta_{oa,LmH} = \vartheta_{r,SpH} - R_{l,f} \cdot \dot{q}_g \qquad (3)$$

$$\vartheta_{sw} = \vartheta_{sw,SpH} = \vartheta_{r,SpH} + \frac{R_t + \tilde{R}}{R_{l,f}} \cdot (\vartheta_{r,SpH} - \vartheta_{oa}) - (R_t + \tilde{R}) \cdot \dot{q}_g \qquad (4)$$

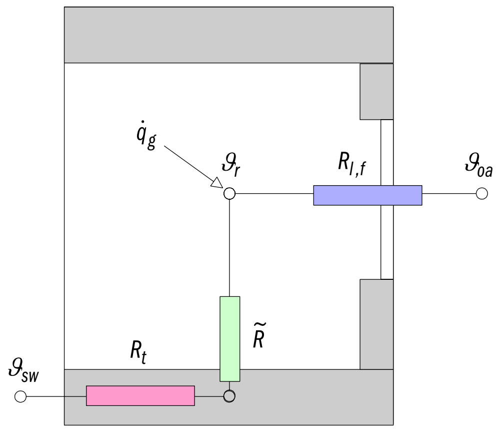
Cooling is required if $\vartheta_{oa} \ge \vartheta_{oa,LmC}$ where $\vartheta_{oa,LmC}$ is the cooling limit and

$$\vartheta_{oa,LmC} = \vartheta_{r,SpC} - R_{l,f} \cdot \dot{q}_g \qquad (5)$$

$$\vartheta_{sw} = \vartheta_{sw,SpC} = \vartheta_{r,SpC} + \frac{R_t + \tilde{R}}{R_{l,f}} \cdot (\vartheta_{r,SpC} - \vartheta_{oa}) - (R_t + \tilde{R}) \cdot \dot{q}_g \qquad (6)$$

Neither heating nor cooling is required if $\vartheta_{oa,LmH} \le \vartheta_{oa} \le \vartheta_{oa,LmC}$.

The result is illustrated by Figure 3. HC is the heating curve and CC the cooling curve.



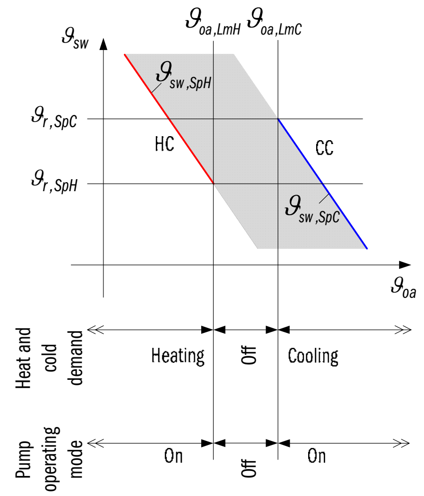


Figure 2 (left): Static building and TABS model

Figure 3 (right): Heating curve (HC) and cooling curve (CC) for known heat gain $\dot{q}_g$

Development step 3:
A next step was to solve another related problem which is a little more difficult. It has been assumed that the heat gain $\dot{q}_g$ in the room is not known but only a lower bound $\dot{q}_{g,lb}$ and an upper bound $\dot{q}_{g,ub}$ of it are known. That means $\dot{q}_{g,lb} \le \dot{q}_g \le \dot{q}_{g,ub}$. This reflects one of the following situations:

- the designer of a controller is uncertain on the value of the heat gain,
- the heat gain in a room is varying very slowly, in a non predictable way and cannot be measured
- the rooms of the zone have different specific heat gains

This more difficult problem (**problem 2**) can also be solved with a static model.
Depending on $\Delta\dot{q}_g = \dot{q}_{g,ub} - \dot{q}_{g,lb}$, which we call the heat gain span, three cases can be distinguished, as can be seen in Figure 4. Case (a): if the heat gain span $\Delta\dot{q}_g$ is small, the solution is similar to that of problem 1. There exists an outside air temperature interval in which certainly neither TABS cooling nor TABS heating power is required. Case (b): for medium heat gain span $\Delta\dot{q}_g$, the heating and the cooling curve overlap, i.e. there exists an outside air temperature interval in which – with knowing only the outside air temperature – it is not possible to determine whether there is heating or cooling demand or no power demand at all. Nevertheless, the supply water temperature feedback controller is able to automatically do the correct action (lowering ϑ_{sw} if it lies above the cooling curve, rising ϑ_{sw} if it lies below the heating curve or water circulation only if ϑ_{sw} lies between heating and cooling curve). Case (c): for large heat gain span $\Delta\dot{q}_g$, it is not possible anymore to maintain comfort for all heat gain situations as the heating curve lies above the cooling curve! In certain cases, the integration of a control loop (with room temperature sensors) may solve the problem. But in most cases, this situation can only be handled by using auxiliary heating or cooling systems and/or additional sensors (not outlined here).
The solution of the problem 2 supplies us with formulas which can be used to calculate the parameters of the heating and cooling curves. The solution leads also to a switching algorithm which can be used in the zone controller to switch between heating and cooling.
The model used so far, where the uncertainty of the heat gains is characterized by bounds, in system theory is called an unknown-but-bounded model. That's why the resulting method to design the TABS and its control has been called **unknown-but-bounded method**.

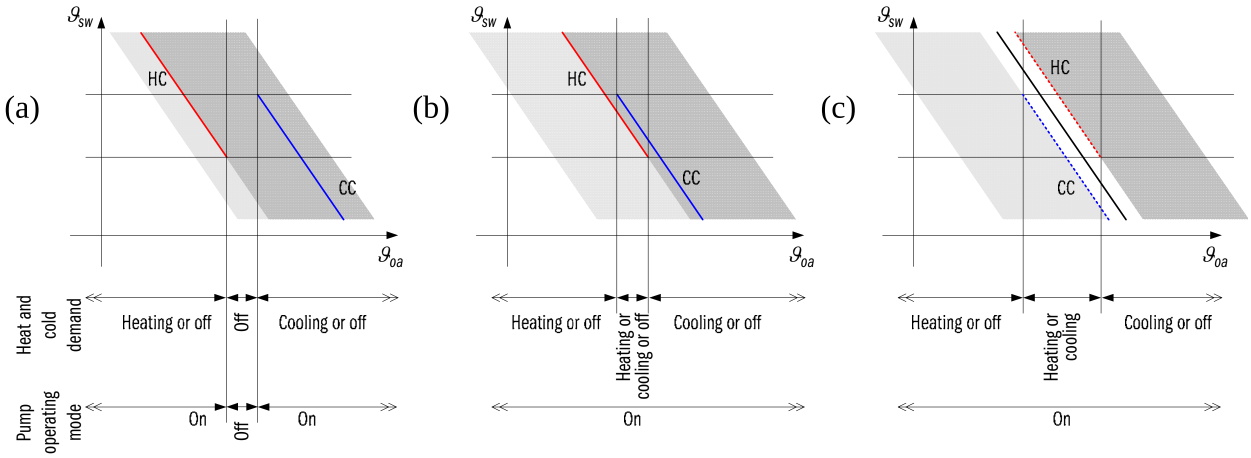


Figure 4: Heating curve (HC) and cooling curve (CC) for different heat gain spans $\Delta\dot{q}_g$

Development step 4:
The problem solved so far differs from the real situation mainly in two points:

- Daily variation of the outside air temperature
- Daily variation of the heat gains. For example considerable internal heat gains during the occupancy time from 08:00 until 18:00 in an office building at weekdays. This usually leads to daily variation of the lower and the upper bound of the heat gains.

It is easy to cope with the first point. Because of the large thermal inertia of TABS it is reasonable that the zone controller takes the average $\overline{\vartheta}_{oa}$ of the past 24 hours of the outside air temperature instead of the actual value ϑ_{oa} to determine the supply water temperature set-point. This averaging of the outside air temperature leads to a slowly varying variable.
To cope with the second point – the daily variation of the heat gain bounds – is more difficult. It has been solved by calculating an equivalent lower bound $\dot{q}_{g,elb}$ and an equivalent upper bound $\dot{q}_{g,eub}$ of the heat gains, which replace $\dot{q}_{g,lb}$ and $\dot{q}_{g,ub}$ in step 3 and which can be used instead of $\dot{q}_g$ in the formulas (4) and (6) to calculate the heating and the cooling curves. To calculate these equivalent bounds a linear dynamic model of TABS and room is used, which represents the dynamic thermal behavior . Further details are given in [5].
What has been done so far in the four steps is the derivation of a first base control strategy for a zone controller – called in analogy to EN 12098-1 "outside temperature compensated flow temperature control" – and of a method to calculate its parameters. Additionally a solution of how to group and assign rooms to zones has been found. Also a method to tune the heating and cooling curves during the first phase of operation has been developed, based on [9].
Development step 5:
Looking for an answer to question Q3 has lead to an option of the base control strategy – called "pulse width modulation" – and looking for an answer to question Q4 has lead to a second option – called "room temperature feedback control". Finally other base control strategies – e.g. the "outside temperature compensated return temperature control" – have been derived, again with the two options mentioned above. The base control strategies together with the two options altogether lead to a set of control strategies among which a designer may choose [6]. Additional control strategies have been derived for the case where additional auxiliary heating or cooling devices are used.

OVERVIEW OF THE INTEGRATED DESIGN METHOD

The integrated design method is represented by the flow chart in Figure 5. Steps 1 to 6 in this chart represent the straight forward design part. Step 7 is recommended to be performed, when the result of step 6 leaves doubts whether the resulting comfort will be accepted (see example in the next section). A prototype of a design tool which supports to design a TABS and its control according to this method has been developed.

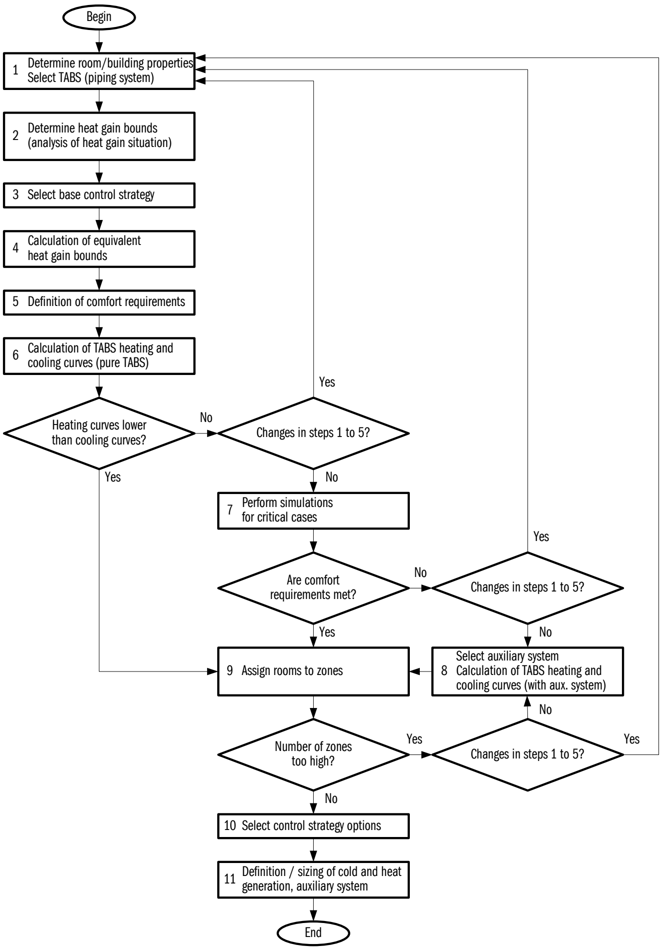


Figure 5: Flow chart of the integrated TABS design method

AN EXAMPLE (Design steps according flow chart in Figure 5)

Design step 1: "Determine room/building properties, select TABS (piping system)"

Table 1. data of the rooms

		Room 1 (normal office)	Room 2 (corner office)
Space length, width, height		6 m x 6 m x 3 m	6 m x 6 m x 3 m
Façade	Orientation	West	West / South
	Area	18.0 m^2	36.0 m^2
	Overall U-Value	0.65 W/m^2K	0.65 W/m^2K
	Glazing fraction façade	42 %	42 %
Additional internal Wall (light)		36 m^2	36 m^2
Natural air change		0.1 h^{-1}	0.2 h^{-1}
Ventilation according to indoor air quality requirements (no cooling/heating by ventilation assumed)			

Table 2. data of the TABS configuration (valid for room 1 and 2)

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

Design step 2: "Determine heat gain bounds (analysis of heat gain situation)"

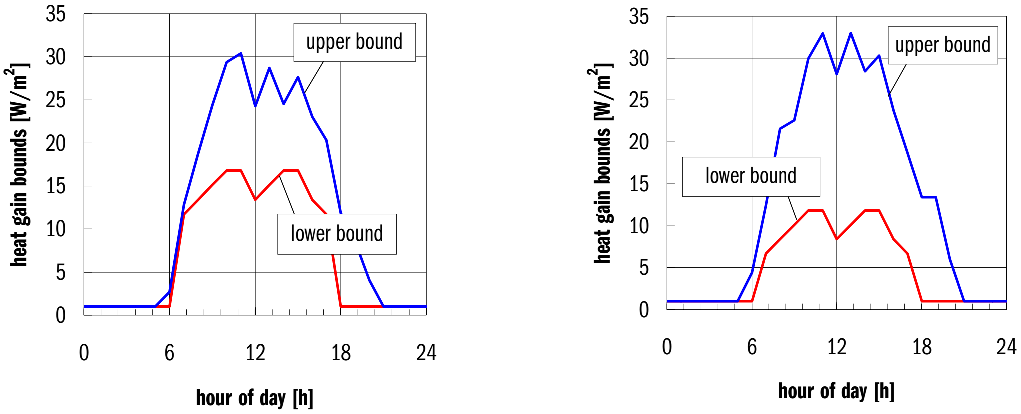


Figure 6: Heat gain bounds for room 1 (left) and room 2 (right), valid for week days

Design step 3: "Select base control strategy"

Here, "outside temperature compensated flow temperature control" is selected.

Design step Step 4: "Calculation of equivalent heat gain bounds"

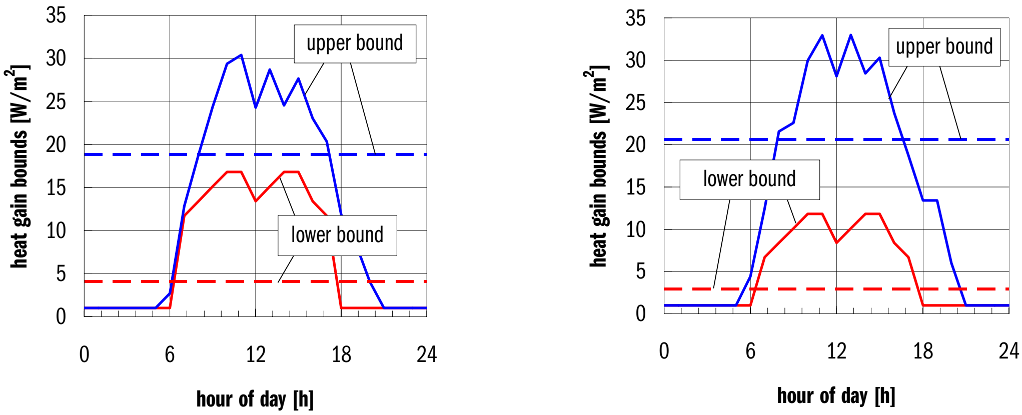


Figure 7: Equivalent heat gain bounds for room 1 (left, dotted lines) and room 2 (right, dotted lines), valid for week days

Design step 5: "Definition of comfort requirements"

Here, a comfort according to [7] is defined (see comfort range in Figure 9).

Design step 6: "Calculation of TABS heating and cooling curves (pure TABS)"

Results (Figure 8) show that room 2 is just at the limit to the critical case (c) in Figure 4.

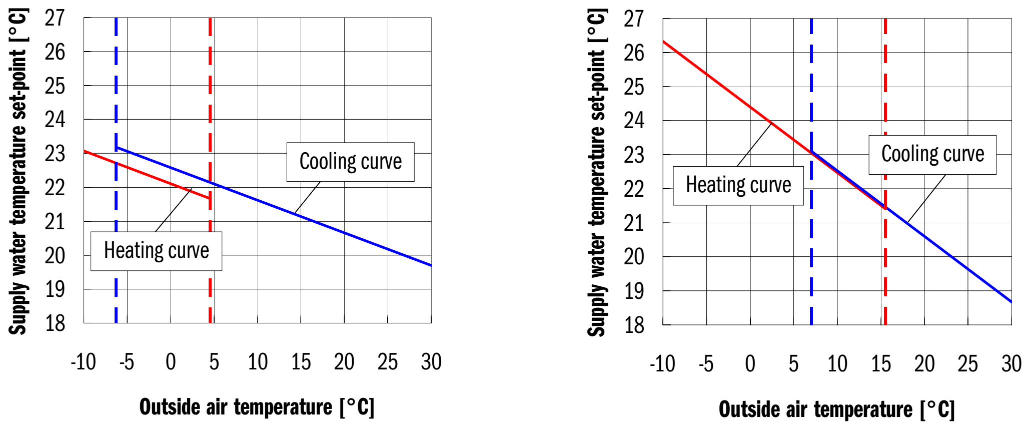


Figure 8: Heating and cooling curves for room 1 (left) and room 2 (right), valid for week days

Design step 7: "Perform simulations for critical cases"

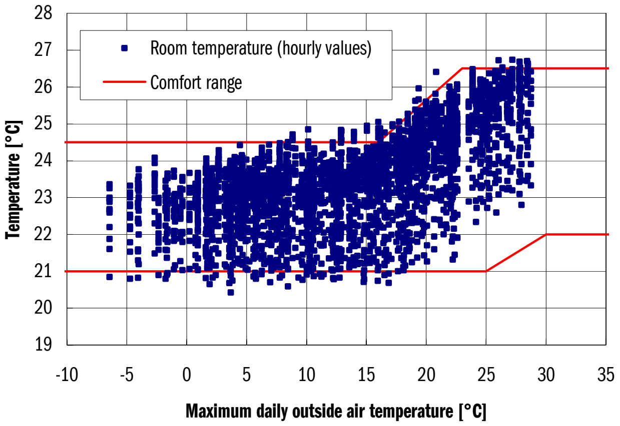


Figure 9: Simulated room temperatures for room 2 (whole-year simulation)

CONCLUSIONS

The new design method is less time-consuming and enables more insight into the potential of TABS. For example, it shows the limitation of TABS application and points out when to install additional auxiliary heating or cooling devices. Additional to the conventional iterative TABS design, the new design process also includes the direct calculation of the parameter values for the underlying base control strategy.
Further details of the method can be found in the design and commissioning handbook which will be published in the frame of our work.

ACKNOWLEDGEMENT

The partial funding of the project by the Swiss Confederation's innovation promotion agency CTI and the input of the project steering committee are gratefully acknowledged.

REFERENCES

[1] Lehmann, B, Dorer, V, Koschenz, M. Application range of thermally activated building systems tabs. Energ Build (2006), doi:10.1016/j.enbuild.2006.09.009.
[2] Koschenz ,M, Lehmann, B. Thermoaktive Bauteilsysteme tabs. Dübendorf (Switzerland): Empa; 2000. ISBN 3-905594-19-6 [in German]
[3] Güntensperger, W, Gwerder, M, Haas, A, et al. Control of concrete core conditioning systems. In: Proceedings: 8th REHVA World Congress Clima (2005), Lausanne (Switzerland).
[4] Tödtli, J, Lehmann, B, Gwerder, M, et al. TABS-Control: Regelung und Steuerung von thermoaktiven Bauteilsystemen. In: Proceedings: 14. Schweizerisches Status-Seminar, Energie- und Umweltforschung im Bauwesen (2006), Zürich (Switzerland) [in German]
[5] Gwerder, M, Lehmann, B, Tödtli, J, et al. Control of thermally activated building systems tabs. Submitted to Applied Energy (2006)
[6] Gwerder, M, Tödtli, J, Renggli, F., Lehmann, B, Dorer,V., Control of thermally activated building systems. In: Proceedings: 9th REHVA World Congress Clima (2007), Helsinki
[7] SN 546 382/1, Lüftungs- und Klimaanlagen – Allgemeine Grundlagen und Anforderungen. SIA, Swiss Association of Engineers and Architects, Zürich Switzerland; 2006 [in German]
[8] Polya, G, "How to Solve It", 2nd ed., Princeton University Press, 1957.
[9] Tödtli, J, Manual Adjusting and Self-Adaptation of Heating Curves, Proceedings: 4th REHVA World Congress CLIMA 2000, Sarajevo, 1989