Design and Optimization of Control Strategies and Parameters by Building and System Simulation

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ABSTRACT

Control parameters for HVAC systems are usually set during the Initial Commissioning Process within the Acceptance Phase of buildings. The quality of the Testing, Adjusting and Balancing (TAB) depends primarily on the specifications of the designer and on the knowledge of the constructor (commissioning personnel). Often the TAB and thus the Initial Commissioning is considered as completed after the functionality and performance of the systems are proven. Therefore, further optimization concerning the energy consumption does not take place.

The building and system simulation usually is used during the pre-design of buildings to determine and optimize the influence of the building envelope relating to the energy demand for heating and cooling. Furthermore it is sometimes used for dimensioning the HVAC systems and particular components during the design phase. Additional abilities of the simulation models to predict or even control the building operations are not used.

The purpose of the chosen approach is to use the dynamic building and system simulation to design and verify control strategies and determine the exact setup for the control parameters. Therefore the models from the former design phases have to be adapted and extended so that the control strategies can be considered in the right way. This paper presents an example how to use the dynamic simulation to optimize the characteristic of a heating and cooling system of a school building.

DESCRIPTION OF THE PROJECT

Within the new development of a building for the Gebhard-Mueller-School (GMS), a vocational school center in Biberach (Southern Germany), a very challenging project was created. With limited means a innovative building with a high technical standard and a low energy demand should be built. First meetings with the owner, the future occupants, the architect and the design engineers were held in summer 2001. The building will be ready for occupancy in summer 2004. A depiction and the current state of the building site (August 2003) are shown in Figure 1 and Figure 2.

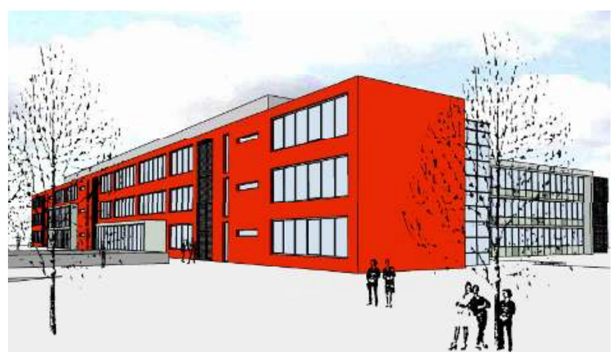

Figure 1. Depiction of Gebhard-Mueller-School.

Figure 2. Current state of building site (August 2003)

General Building Characteristics

The following general building characteristics are given:

- 3-story school building for 1,200 students
- gross floor area 10,000 m² (107,640 ft²)
- mechanical ventilation system for entire building
- heating and cooling by embedded coils in the floors and ceilings

Energy Performance Target Values

Even before any design process had started, the building owner defined a high energy efficiency standard for the building when he published the target of a "2-liter-building". This target of 2 liters of fuel oil per square meter and year means an energy consumption of 20 kWh/(m²·a) for heating, ventilation, and cooling . [1]

Due to the limited budget for the building construction and the heating and ventilation system this target was increased to a value of less than 30 kWh/m²a, what is still an ambitious value. By law, the maximum allowable energy consumption for heating and ventilation for this building is 60 kWh/(m²·a)[1].

Building Envelope

To reduce the heat loss during cold periods of the year, the building features an envelope with high thermal insulation (20 cm). The U-values of all exterior components like walls, ceilings, and floors are less than 0.20 W/(m²·K). The U-values of the windows and exterior doors are 1.20 W/(m²·K). Furthermore, the building envelope is designed for a maximum air tightness and minimum cold bridges. These features will be proven by blower door and thermography measurements.

The windows are equipped with external shading devices to reduce the solar gains when they are not needed. The shading system is controlled by the building control system to ensure proper operation in particularly during unoccupied periods.

HVAC System

Central heating system

The central heating system consists of two heat pumps and one wood-fired furnace. The ground water coupled heat pumps, 120 kW each, supply the basic load for heating at low temperatures of 28 °C (82 °F) to a maximum of 35 °C (95 °F). At these supply temperatures, in combination with ground water temperatures at about 10 °C (50 °F), a maximum COP of about 5 or 6 can be reached.

Higher temperatures are necessary to supply the heat for the air-heating coils at outside air temperatures below 0 °C (32 °F). These supply temperatures are served by a 110 kW boiler with a wood fired furnace.

The division of heat generation into 3 components (2 heat pumps and 1 boiler) gives a high redundancy which is required for school buildings. In case of an outage of the heat pumps or the boiler the heat can be shifted between the systems by means of a bypass.

Ground water is used as source for the heat pumps as well as for direct cooling of the ventilation and the cooling system. A maximum of 18 l/s is delivered by a well which is located in the basement of the building. An additional well is prepared as backup in case of a decreasing capacity. The ground water is fed back to the aquifer via 2 wells, located 300 m away from the building. The maximum temperature change of the ground water is 4 Kelvin. To protect the aquifer from pollution the ground water is separated from the cooling and heating system with an additional heat exchanger.

General operation of central HVAC systems

The central HVAC systems serve the following operation modes for heating in winter and cooling in summer:

- winter day: heat pumps and wood-fired furnace (if required) deliver warm water to the heating coils of the ventilation system
- winter night: heat pumps serve warm water to the embedded heating system to load the thermal mass for next day
- summer day: cooling coils of ventilation system are served directly with ground water
- summer night: embedded cooling system is served directly with ground water to load thermal mass for next day

Embedded hydronic heating and cooling system

Heating and cooling for the entire building is realized with an embedded hydronic heating and cooling system (EHHC system). This system consists of flexible tubes that are tied down at the reinforcement and embedded in the concrete ceilings (see Figure 3). Depending on heating or cooling demand in the building warm or cold water circulates in the tubes that heats or cools the massive ceilings. The result is a large thermal mass with a moderate surface temperature for comfortable heating and cooling of the rooms.

[1] So far, in Germany only the energy consumption for heating and ventilation is limited by law. Cooling energy is not yet considered.

Figure 3. Flexible tubes of embedded hydronic heating and cooling system tied down at the reinforcement (before set in concrete).

Due to the immense thermal mass of the ceilings the system is very inertial with slow reactions for temperature changes. On the other hand the bulky mass is buffering temporary changes in thermal loads. The "loading process" for the thermal mass takes place during night. Hence, caution has to be taken not to overheat or overcool the system.

Ventilation system

The building is equipped with a mechanical ventilation system. Each classroom can be served with a variable air volume, depending on the current air quality (CO_2 is measured at exhaust air). The maximum air volume rate in the classrooms is 4.5 1/hr what comes up to a guaranteed maximum of 30 m³ per hour and person (corresponding to the maximum value required by official rules).

There are 3 central air handling units (AHU) with an over-all air volume of 100,000 m³/hr located on the attic. The air is supplied through ducts to the rooms. Every room is equipped with a VAV box. The exhaust air from the rooms is led back to the heat recovery at the central AHU's.

There is no individual temperature control for the rooms. All rooms in a single zone (which is related to the central AHU's) are served with the same supply air temperature of 20 to 23 °C (68 to 73 °F).

The air is heated by a pre-heating-coil, served with water from the heat pump with maximum temperatures at 35 °C (95 °F). At higher heating demands, i.e. outside air temperatures less than 0 °C (32 °F) an additional heating coil, operated with water temperatures of 85 °C (185 °F) from the wood fired furnace, heats the air to the desired supply air temperature.

The air is cooled using ground water. For cooling, the pre-heating-coils are used as cooling coils. There is no humidification or dehumidification.

CONTROL OF EMBEDDED HYDRONIC HEATING AND COOLING SYSTEM

Due to the moderate surface temperatures, close to the desired room temperature, the EHHC system features a self-control function for heating and cooling. The heat transfer from the ceiling to the room depends on the temperature of the surface and the temperature of the room. With a surface temperature of the ceilings between 20 and 24 °C (68 and 75 °F) the rooms will be automatically heated when the room temperature falls below this surface temperature, respectively cooled when the room temperatures exceed the surface temperature. The bigger the temperature difference between surface temperature and room temperature the faster the room temperature swings back into the desired range. [2]

Due to the highly inertial behavior and the combination of the EHHC system to spaciously heating circuits there is no individual temperature control for single classrooms. However, the demand for higher or lower temperatures would not affect until several hours later. Nevertheless, the supply temperature has to be controlled to provide the right amount of heating or cooling capacity to the building.

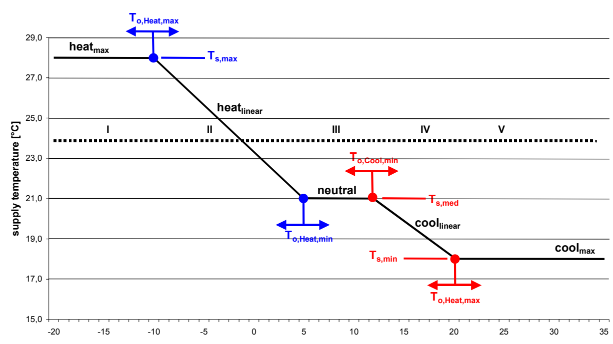

Figure 4. Characteristic of supply temperature for EHHC system.

Figure 4 shows the general model of the characteristic of the supply temperature for the EHHC system depending on the outdoor temperature. Below a mean outdoor temperature $T_{o,heat,max}$ there is a range with a constant supply temperature for maximum heating load of the EHHC (range I). From $T_{o,heat,max}$ to $T_{o,heat,min}$ there is a range II with a linear dependence of the supply temperature from the medial outdoor temperature. Range III indicates a neutral range where neither heating nor cooling is required. According to the heating ranges the cooling is divided in

2 ranges with a linear dependence of the supply temperature between $T_{o,cool,min}$ and $T_{o,cool,max}$ (range IV), and a constant supply temperature for maximal cooling load above a medial outdoor temperature $T_{o,cool,max}$ (range V).

The medial outdoor temperature used with the characteristic is calculated as a mean value of the outdoor temperature of the last 3 days, where the last 24 hours count twice. This value gives a sufficient damping of the instantaneous outdoor temperature without suppressing relevant changes. Different kinds of medial outdoor temperatures have been tested and analyzed within simulation calculations.

SIMULATION MODEL

Building Model

The part of the building considered for this study is modeled using the TRNSYS Type 56 multi-zone building model [3]. The model consists of 13 different thermal zones which contain all relevant kinds of rooms and spaces in the building. This number results from different problems which were analyzed within the design phase like thermal behavior of classrooms with different occupancy, dimensioning of embedded tubes, influence of the not heated underground parking below the first floor, thermal behavior of halls and atrium, thermal behavior of internal classrooms etc. The high number of thermal zones effects long simulation times (about 6 minutes for one year simulation) which are not optimal for the following optimization calculations with hundred or even more runs.

The embedded hydronic heating and cooling system is modeled by using a model generated by EMPA which is integrated into the TRNSYS building model [4].

System Model

The detailed model of the peripheric systems, the occupancy and load schedules of the building and the control strategies is built using the appropriate types from the model library of TRNSYS. Also equations are used to model the described characteristic with the free parameters for the optimization.

For further optimization calculations the detailed heating and cooling equipment (heat pump, heat exchangers, pumps, etc.) will be modeled using existing TRNSYS types. Also, additional models in EES (detailed model of heat exchanger) and SIMULINK (model for heat pumps) will be implemented in the TRNSYS model.

Optimization Calculations with GenOpt

GenOpt is a generic optimization program for multi-dimensional minimization of an objective function that is computed by a coupled simulation program. It automatically finds the values of selected free parameters that minimize the objective function [5]. Within these studies GenOpt is used in combination with TRNSYS.

The definition of an optimization problem consists of:

1. a set of free parameters (the independent variables or design parameters),
2. some constraints that bound the domain of the free parameters and dependent variables, and
3. an objective function (the function to be minimized) that depends on the free parameters.

Free parameters

The free parameters within this problem are the searched temperature settings of the characteristic of the supply temperature. To access these parameters the characteristic shown in Figure 4 has to be defined exactly in the simulation model. Equation (1) shows the code to describe the characteristic within the TRNSYS simulation model.

$$
\begin{aligned}
T_s &= lt\left(T_o^*, T_{o,Heat,\max}\right) \cdot T_{s,\max}\,\mathrm{K} \\
&+ and\left(ge\left(T_o^*, T_{o,Heat,\max}\right), lt\left(T_o^*, T_{o,Heat,\min}\right)\right) \cdot \frac{T_{s,\max} - T_{s,neutral}}{T_{o,Heat,\max} - T_{o,Heat,\min}}\mathrm{K} \\
&+ and\left(ge\left(T_o^*, T_{o,Heat,\min}\right), lt\left(T_o^*, T_{o,Cool,\min}\right)\right) \cdot T_{s,neutral}\,\mathrm{K} \\
&+ and\left(ge\left(T_o^*, T_{o,Cool,\min}\right), lt\left(T_o^*, T_{o,Cool,\max}\right)\right) \cdot \frac{T_{s,neutral} - T_{s,\min}}{T_{o,Cool,\min} - T_{o,Cool,\max}}\mathrm{K} \\
&+ ge\left(T_o^*, T_{o,Cool,\max}\right) \cdot T_{s,\min}
\end{aligned}
\tag{1}
$$

where

T_s	=	supply temperature [°C]
T_o^*	=	medial outdoor temperature [°C], medial value of the last 3 days is used, where the last 24 hours count twice
$T_{o,Heat,max}$	=	threshold value of medial outdoor temperature for maximum heating supply temperature [°C]
$T_{o,Heat,min}$	=	threshold value of medial outdoor temperature for minimum heating supply temperature [°C]
$T_{o,Heat,min}$	=	threshold value of medial outdoor temperature for minimum cooling supply temperature [°C]

$T_{o,Heat,min}$ = threshold value of medial outdoor temperature for maximum cooling supply temperature [°C]

$T_{s,max}$ = maximum supply temperature (28 °C)

$T_{s,neutral}$ = neutral supply temperature (21 °C)

$T_{s,min}$ = minimum supply temperature (18 °C)

$T_{o,Heat,max}$, $T_{o,Heat,min}$, $T_{o,Cool,min}$, and $T_{o,Cool,max}$ are the free parameters of the objective function. The maximum and minimum supply temperatures for heating and cooling ($T_{s,max}$ and $T_{s,min}$) have been defined within former simulations for the dimensioning of the EHHC system. The objective function is not the equation of the characteristic but the calculation of the annual energy demand for heating and cooling within the entire simulation model.

Dependent variables

Optimization in GenOpt is considered as minimizing a function. Hence, all dependent variables have to be positive with the optimum at zero. The dependent variables for the problem at hand are the energy demand for heating and cooling. Furthermore, the reduction of energy consumption must not impair the thermal comfort in the classrooms.

The annual energy demand for heating and cooling is calculated by using outputs from the simulation program using following equations:

$$Q_{Heat} = \sum_{1}^{8760} \left(\frac{c_{p,water} \cdot m \cdot (T_S - T_R)}{3.6} \right) \quad \text{for} \quad T_S > T_R \qquad (2)$$

$$Q_{Cool} = \sum_{1}^{8760} \left(\frac{c_{p,water} \cdot m \cdot (T_R - T_S)}{3.6} \right) \quad \text{for} \quad T_S < T_R \qquad (3)$$

where

Q_{Heat} = annual heating demand for EHHC system [kWh/a]

Q_{Cool} = annual cooling demand for EHHC system [kWh/a]

$c_{p,water}$ = specific heat capacity of water [kJ/(kg·K)]

m = mass flow [kg/h]

T_S = supply temperature [°C]

T_R = return temperature [°C]

The heating and cooling demand is then divided by the gross room area of the used building model to get more common and comparable specific values [kWh/(m²·a)].

The influence on the thermal comfort is considered in form of degree-hours for overheating (*HDH*) and overcooling (*CDH*) of the building. Overheating can be accepted for few hours of the year whereas overcooling must not occur at any time. In this case only the temperatures during occupancy are considered.

$$HDH = \sum_{1}^{8760} \left(T_R - T_{R,\max} \right) \quad \text{for} \quad T_R \geq T_{R,\max} \qquad (4)$$

$$CDH = \sum_{1}^{8760} \left(T_{R,\min} - T_R \right) \quad \text{for} \quad T_R \leq T_{R,\min} \qquad (5)$$

where

HDH = overheating degree hours [Kh]

CDH = overcooling degree hours [Kh]

T_R = room temperature [°C]

$T_{R,max}$ = max. allowable room temperature (26 °C / 79 °F)

$T_{R,min}$ = min. allowable room temperature (21 °C / 70 °F)

Constraints

Natural constraints are given by the used weather data:

$T_{o\ min}$	=	-18.6 °C	(-1.5 °F)
$T_{o,max}$	=	31.4 °C	(88.5 °F)
$T_{o\ ,min}^{*}$	=	-13.3 °C	(8.1 °F)
$T_{o\ ,max}^{*}$	=	22.7 °C	(72.9 °F)

Therefore, the following constraints are set for the free parameters (also used as constraints for the parametric runs):

$T_{o,Heat,max}$	=	-10 … -1 °C	(14 … 30 °F)
$T_{o,Heat,min}$	=	0 … 10 °C	(32 … 50 °F)
$T_{o,Cool,min}$	=	8 … 15 °C	(46 … 59 °F)
$T_{o,Cool,max}$	=	16 … 22 °C	(61 … 72 °F)

Execution

Optimization calculations are executed in several steps to limit the free parameters and thus for a better understanding of the results. Parametric runs are used to show the results for the entire array of the free parameters within their constraints. Further optimization calculations will be executed by using the optimization algorithms of GenOpt.

In a first step only the free parameters for the "heating side" of the characteristic of the supply temperature are considered as free parameters. Hence, the results can be shown in diagrams depending on 2 parameters. The same procedure is then executed for the "cooling side" of the characteristic.

RESULTS

Variation of Heating Parameters

The parametric run of the variation of $T_{o,Heat,max}$ and $T_{o,Heat,min}$ is executed within the above-named constraints. The values for the "cooling side" of the characteristic are set as constant, where

$T_{o,Cool,min}$ = 12°C (54 °F)

$T_{o,Cool,max}$ = 20°C (68 °F)

Figure 5 shows the resulting heating demand for this parametric run. The bottom axis of the diagram shows the values of $T_{o,Heat,max}$, the right axis shows the values of $T_{o,Heat,min}$. The calculated heating demand is shown by different colors (gray shades) at a scale from 10 to 30 kWh/m²a. The highest values appear at the highest values for the parameters $T_{o,Heat,max}$ and $T_{o,Heat,min}$ (upper right corner of the diagram).

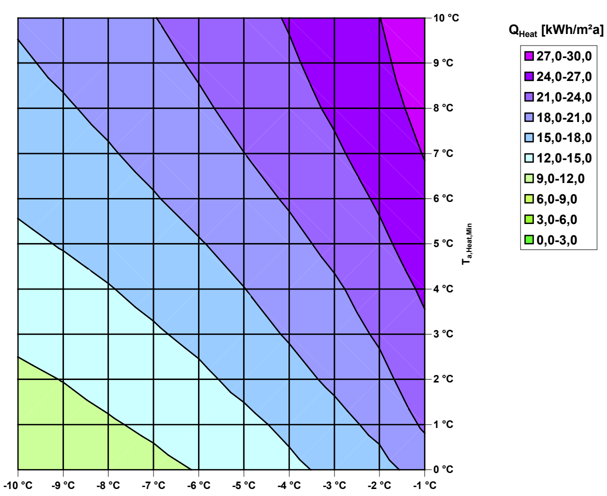

Figure 5. Variation of $T_{o,Heat,max}$ and $T_{o,Heat,min}$ – heating demand (Q_{Heat}).

Figure 6 shows a diagram with the overcooling degree hours for the same parametric run. There is overcooling in the rooms only at low values of $T_{o,Heat,max}$ and $T_{o,Heat,min}$ (lower left corner of the diagram).

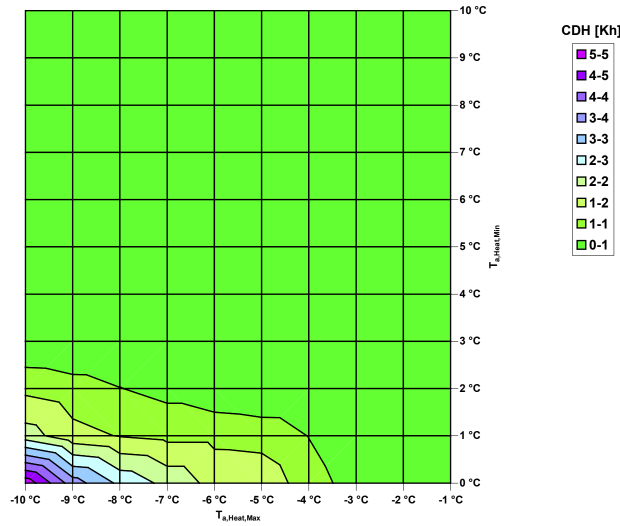

Figure 6. Variation of $T_{o,Heat,max}$ and $T_{o,Heat,min}$ – overcooling degree hours (*CDH*).

It is practicable to analyze the results not with the absolute values of the calculated parameters but with normalized values. Therefore each value is divided by the maximum value within the entire calculated array (e.g. $Q_{Heat}/Q_{Heat,max}$). Hence, the highest normalized value is defined as 100 % as it is shown in Figure 7. In this diagram the possible energy savings are readable at once. Each color (gray shade) shows a change in energy demand of 10 %.

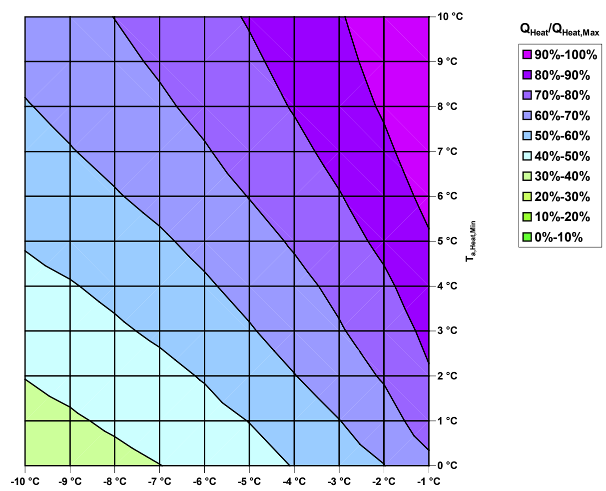

Figure 7. Variation of $T_{o,Heat,max}$ and $T_{o,Heat,min}$ – normalized heating demand ($Q_{Heat}/Q_{Heat,Max}$).

To simplify the reading and interpretation of the results it is useful to join the results to get a single objective value. The primary value for the optimization of the "heating side" of the characteristic is the heating demand. But the thermal comfort has to be considered too, hence no overcooling will be accepted in the rooms.

A combined optimization factor can be calculated with the following equation by using the heating demand Q_{Heat} and the overcooling CDH.

$$Opt_{Heat} = Q_{Heat} \cdot \left(1 + \left(\frac{CDH}{Min(CDH)+1} \right)^n \right) \qquad (6)$$

where n is an exponent to emphasize the importance of the overheating. An analogous equation can be set up for the cooling demand Q_{Cool} and the overheating HDH.

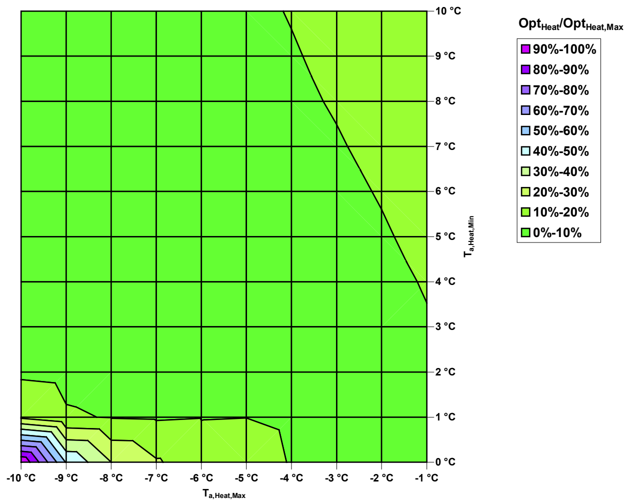

Figure 8. Variation of $T_{o,Heat,max}$ and $T_{o,Heat,min}$ – normalized combined optimization factor (Opt_{Heat}) on a scale from 0 to 100 %.

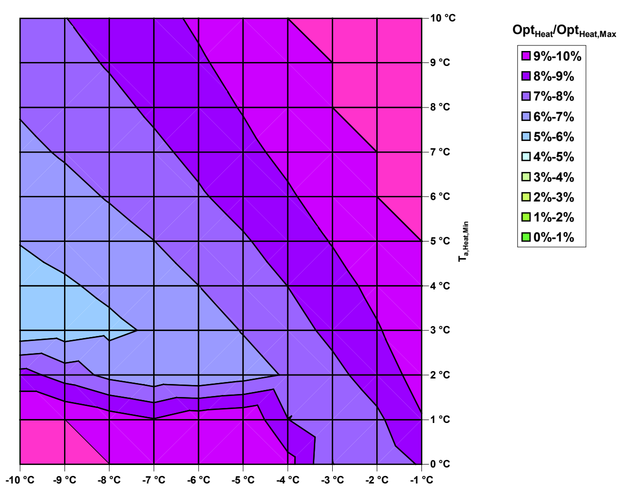

Figure 9. Variation of $T_{o,Heat,max}$ and $T_{o,Heat,min}$ – normalized combined optimization factor (Opt_{Heat}) on a scale from 0 to 10 %.

Figure 8 shows the optimization factor Opt_{Heat} for the full range from 0 to 100 %. Figure 9 shows the same diagram with a scale from 0 to 10 % to get a better resolution of the area of interest.

Within this diagram the optimized parameter settings for the lowest energy demand without overcooling can be estimated as:

$T_{o,Heat,max}$ = -10 °C (14 °F)
$T_{o,Heat,min}$ = 3 °C (37 °F)

Variation of Cooling Parameters

Corresponding calculations are executed with the "cooling side" of the characteristic of the supply temperatures for the EHHC system.

The temperatures of the "heating side" are set constant to

$T_{o,Heat,max}$ = -10 °C (14 °F)
$T_{o,Heat,min}$ = 8 °C (46 °F)

Figure 10 shows the normalized energy demand for cooling. Since there is only a small change of the values over the calculated array, the scale is set from 80 to 100 %. Each color (gray shade) shows a change in energy demand of 2 %. The absolute values range from 60 to 65 kWh/(m²·a). Whereas, the calculated overheating degree hours have a significant change from 75 to 250 Kh as shown in Figure 11.

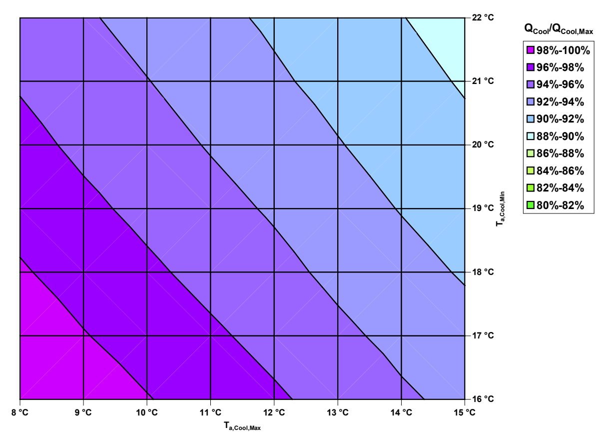

Figure 10. Variation of $T_{o,Cool,min}$ and $T_{o,Cool,max}$ – normalized cooling demand ($Q_{Cool}/Q_{Cool,Max}$).

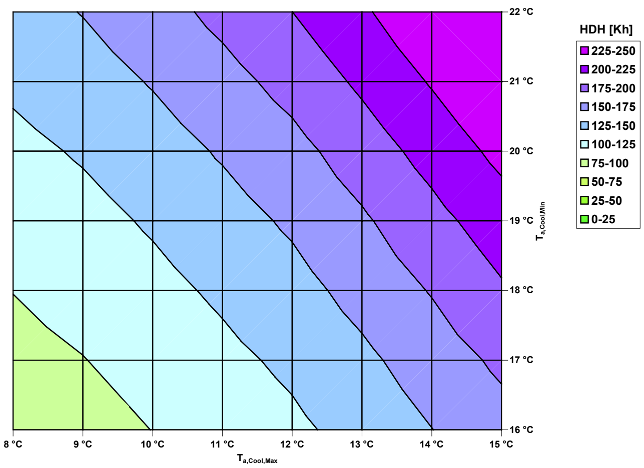

Figure 11. Variation of $T_{o,Cool,min}$ and $T_{o,Cool,max}$ – overheating degree hours (*HDH*).

The obtained results for the setting of the cooling parameters are not clear and thus not satisfying. The user has to decide how much overheating to accept. Therefore the dynamic results of the simulation have to be analyzed to appraise the consequences for the user. Since there is only a small change in the energy demand the parameters could be set to low threshold temperatures (e.g.. $T_{o,Cool,min}$ = 10 °C / 50 °F; $T_{o,Cool,max}$ = 18 °C / 64 °F) to get less overheating degree hours without an acceptable energy demand.

<u>Variation of Minimum Supply Temperature for Cooling</u>

Another way to get better results is to check other parameter sets for the control of the characteristic or even another control strategy. The previous simulations were executed with a maximum supply temperature for heating $T_{s,max}$ = 28 °C (82 °F) and a minimum supply temperature for cooling $T_{s,min}$ = 18 °C (64 °F). The dynamic results of the simulation show overheating for days with high temperatures, i.e. high thermal loads. At the same time the surface temperatures are at 22 °C (72 °F) or higher. During cooling periods, surface temperatures down to 20 °C (68 °F) can be allowed without negative effects for the thermal comfort or condensation. Therefore, further simulations were executed with a minimum supply temperature for cooling at $T_{s,min}$ = 16 °C (61 °F). The results of the parametric run are shown in Figure 12 and Figure 13.

Figure 12 shows the normalized energy demand for cooling on a scale from 80 to 100 %. In comparison to the former energy demand for cooling with $T_{s,min}$ = 18 °C (64 °F) in Figure 10 there is a more distinctive change in energy demand. The absolute values now range from 60 to over 70 kWh/m²a. It is remarkable that the lower value for energy demand is still the same than with the higher minimum supply temperature $T_{s,min}$.

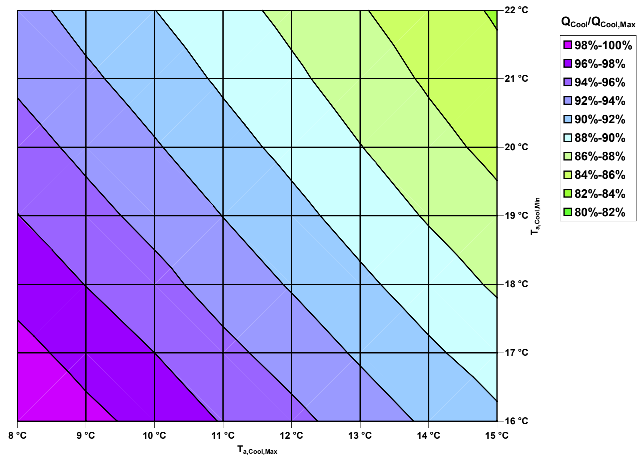

Figure 12. Modified supply temperature ($T_{s,min}$ = 16 °C / 61 °F); Variation of $T_{o,Cool,min}$ and $T_{o,Cool,max}$ – normalized cooling demand ($Q_{Cool}/Q_{Cool,Max}$).

In Figure 13 overheating is significant lower than with the setting of $T_{s,min}$. = 18 °C (64 °F) in Figure 11. The diagram is shown on the same scale. The minimum overheating degree hours now is 35 Kh. The maximum value is 200 Kh.

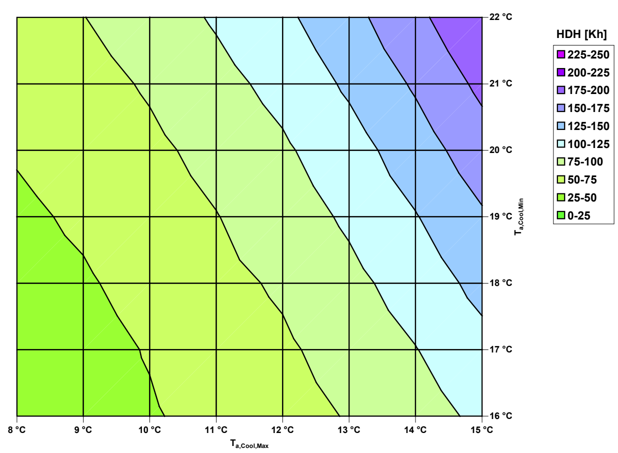

Figure 13. Modified supply temperature ($T_{s,min}$ = 16 °C / 61 °F); Variation of $T_{o,Cool,min}$ and $T_{o,Cool,max}$ – overheating degree hours (*HDH*).

With a disappearing neutral range of the characteristic, the cooling side influences the heating demand and reversed. Therefore, one has to regard that the threshold values bordering the neutral range of the characteristic are not too close. Considering the analysis of the heating demand the optimal parameters can be estimated to

$T_{o,Cool,min}$ = 18 °C (64 °F)

$T_{o,Cool,max}$ = 10 °C (50 °F)

With the same parameter settings for the threshold values, the lower supply temperature $T_{s,min}$ causes a significant decrease of the overheating by 50 % (from 118 Kh to 57 Kh) with a marginal rise of the energy demand from 63 to 68 kWh/(m²·a). It is noted that the cooling water is provided by ground water, thus a bigger heat exchanger is necessary to ensure lower temperatures.

Since the minimum supply temperature $T_{s,min}$ has a significant influence on the overheating of the building, this parameter should be also considered as a free parameter within further optimization. The constraints are given indirectly by the minimum allowable surface temperature of the ceilings.

ADDITIONAL ANALYSIS

Further analysis can be done to optimize following operation of the building:

- Entire heating and cooling system with heat pump, well pump, heat exchangers, pumps to consider COP of heat pumps and run-times of pumps to calculate the overall electrical energy demand for heating and cooling.
- Central heating and ventilation systems with heat pumps, boiler and heating coils to estimate the optimal breakeven point when to add high temperature load from the boiler instead of rising the supply temperature of the heat pump what affects a lower COP.
- Threshold values for jalousie for optimal use of daylight with maximum savings of artificial light and minimum overheating (considering effects to cooling side of characteristic).

CONCLUSIONS

The analysis of the characteristic of the supply temperature for the EHHC system shows a savings potential for heating of about 50 % without affecting the thermal comfort. It is doubtful that the optimal parameter setting would be found within the testing and balancing phase of the building without the optimization calculations. Most likely, the setting would be deemed sufficient if there is no significant failure in the required room temperatures.

The optimization on the cooling side of the characteristic refers to the reduction of overheating. Using knowledge gained during optimization, overheating can be reduced by more than 50 % without an excessive rise in energy demand.

To study the accuracy of the model, it is necessary to conduct a sensitivity analysis with different assumptions for occupancy, internal loads, weather data, etc. The most important influence is the appropriate modeling of the system and the selection and calculation of the right objective functions. The results can be influenced and even falsified by inadequate or incorrect weighting factors.

After estimating the optimized parameter setting, the detailed dynamic results of the simulation should be analyzed to see the impact of the settings to the dynamic behavior of the building and the systems.

The simulation calculation can be used to validate control strategies and establish the correct setting for the control parameters. In unusual HVAC systems, this method is particularly appropriate to get the right setting for a proper and optimized operation without the method of trial and error, which often takes 2 or more years.

The mapped simulation results also can be used to estimate the impact of changes of the parameter setting if it is needed during operation for fine tuning or changes of the use of the building or parts of the building.

The new building of the Gebhard-Mueller-School will be monitored by the Fachhochschule Biberach (Biberach University of Applied Sciences) to evaluate the design targets and the energy optimizations. Monitoring will start after completion of the building in July 2004.

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