MULTIZONE BUILDING WITH VAV AIR-CONDITIONING SYSTEM SIMULATION FOR EVALUATION AND TEST OF CONTROL SYSTEMS

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ABSTRACT

Simulation techniques have been playing a more and more important role in research and development of reliable and energy efficient building automatic control solutions. Furthermore, simulation is appraised as being viable to judge building automation and control solutions. Therefore, to test and evaluate control strategies, Siemens Building Technologies (SBT) developed a building and HVAC (heating, ventilation and air-conditioning) plant model library. In this paper, a Matlab/Simulink building model, which is taken from this library, with a variable air volume (VAV) air conditioning (AC) plant is presented. Different control strategies are applied to this system and tested by connecting the VAV AC plant model with a Simulink model of the control system. All components used for the control represent functionalities being currently available in SBT building automation systems. It is shown that the presented models provide good usability and flexibility for the evaluation and test of control algorithms, especially for innovative building-wide coordinated control strategies.

KEYWORDS

Building automation, Simulation, Control strategy evaluation , VAV air-conditioning system, Building energy performance.

INTRODUCTION

With the increasing awareness of indoor comfort and energy saving in buildings, the evaluation, testing and comparison of building automation control strategies regarding both criteria has become more and more important. At the same time, these investigations rely increasingly on simulation techniques. At Siemens Building Technologies (SBT), heating, ventilation and air-conditioning (HVAC) plant simulation is an integral part of the product development process to evaluate and test the design of control strategies, and provide a virtual environment for testing applications running in building automation systems. It also serves as a fundamental tool for research and innovation.

To investigate the interaction between all HVAC related control loops requires integrated models of buildings and entire HVAC plants, considering transport (aeraulic/hydraulic) as well as thermal aspects. The models should be flexible, consider different building and plant configurations, enable easy implementation of control strategies and provide accurate results for both control behavior and energy performance analysis.

Although many building and HVAC plant simulation programs exist and also several model libraries are provided, none could be found that sufficiently matched all requirements. They focus either on the energy flow (eg. TRANSYS, DOE-2) or system dynamics (eg. SIMBAD), and most of the programs are only applicable to part of the system as building or Air Handling Unit (AHU), but not easy to be extended to simulate entire supply chains, which includes energy distribution from energy producers to energy consumers.

Therefore SBT developed their own test and evaluation environment which contains a Matlab/Simulink-based modular model library and an Excel-based configuration tool for setting up plant models. This paper presents part of the model library with focus on ventilation and air conditioning and its use with exemplary control strategies.

HVAC MODEL LIBRARY AND ITS USE

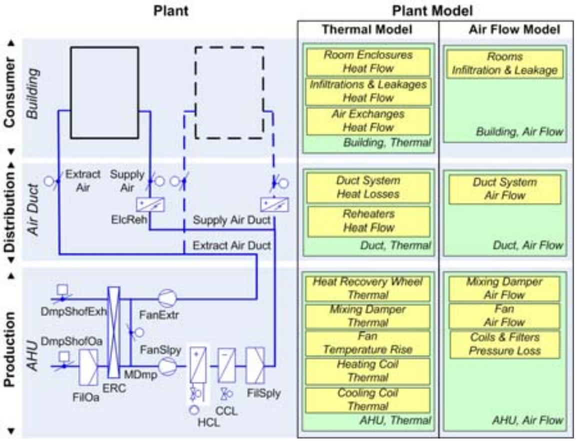


Figure 1 Model library

Figure 1 gives an overview of the ventilation and air conditioning model library. The model of an entire plant is composed of models, each representing parts of the technical building equipment or the building itself, in the Figure shown as yellow blocks. The modular approach facilitates extension and variation of the models.

Thermal behaviour and air flow calculation are decoupled by assuming that air density doesn't change with temperature for air flow calculation. The resulting error is neglectable since temperature changes are rather small in air ducts. This guarantees reasonable speed of simulation with variable time steps and avoids numerical problems which could be caused by high complexity of the whole plant model.

Each model has its own parameters which are specified in Simulink block masks. Most of the parameters can be easily found in the manufacturers' datasheets (e.g. heat exchanger nominal power, air duct nominal flow and pressure drop). This ensures that people without much knowledge of the modelled component's physics are able to easily use them.

Some of the key models (building, heat exchanger, fan, air duct, etc.) have been tested and validated at HVAC laboratory. There it was confirmed that the simulation adequately represents dynamic and static behavior of the building and the technical equipment as well as the setting of the model parameters is reasonable.

In the following part of this chapter, some of the thermal and air flow models (see Figure 1) are briefly introduced and the use of the model library is described.

Thermal models

- Building, Thermal

The multizone building thermal model is based on the heat balance method. It calculates heat transfer through layered walls and windows from and to each room. Room arrangement and properties of building enclosures are given as parameters. Therfore for different size and type of buildings, the simulink model structure doesn't have to be changed. The following differential equation shows the heat balance of air in a room:

$$\frac{d(m_{a,R}h_{a,R})}{d\tau} = V_R \rho_a c_{p,a} \frac{dT_{a,R}}{d\tau} = \dot{Q}_{Encl} + \dot{Q}_{CnvcInt} + \dot{Q}_{AirExg} + \dot{Q}_{Infil}$$

- Duct, Thermal

Duct system heat losses model calculates heat flow between the environment and supply air in every section of the duct through the insulation. It brings in the supply temperature tranport delay effect, which is critical for control. Reheaters heat flow model calculates room supply temperature after electrical reheaters.

- AHU, Thermal

Thermal models of heat recovery, mixing damper and fan are simplified linear models. The heat exchanger model contained in cooling coil and heating coil is based on operating characteristics (Rechnagel, 90/91). The whole heat exchange area is divided into n (one parameter of model) elements. Dynamic water and air temperature and heat transfer of each element is calculated considering heat mass of air, water and tube.

Air flow models

The air flow models calculate pressure and air flow for the whole duct system and for every room. The pressure drop between two places in the air flow system is calculated by:

$$\Delta P = K \cdot \dot{V}^{n}, \qquad K = \frac{\Delta P_{Nom}}{\dot{V}_{Nom}^{\;n}}$$

With n equals to 2 for duct, damper, coils and filters, and equal to 1.5 for windows and doors.

- Building, Air Flow

Rooms Infiltration & Leakages are calculated with room pressures and infiltration coefficients.

- Duct, Air Flow

The air duct model is built up with three elementary modules: air duct, air branch and air zone (including supply and extract air dampers). This makes the model simple to adapt to various duct structures. To eliminate algebraic loops, dynamic states of pressure are introduced by considering the compressibility of air in modelled air volumes (rooms, duct junctions, etc.)

- AHU, Air Flow

The fan air flow model is based on fan performance (head-efficiency) curves, see ASHRAE HVAC 2 TOOLKIT (1993). Models of mixing damper, coils and filters are composed by the same modules as in duct air flow model.

Use of the model library

To demonstrate the use of the model library, a VAV system is chosen with a control strategy that coordinates individual room temperature control, supply air temperature control as well as supply and extract air pressure control.

For investigation of building-wide control strategies, including several control loops working in parallel and influencing each other, the model library provides a good environment as it not only offers specific models for rooms or HVAC plants but also models to simulate the whole building with its entire technical equipment. Moreover, the control function models such as PID control, On-Off control, setpoint determination, ect. contain the same code as function units currently available in SBT building automation systems. Therefore the simulated control performance represents very closely the real situation and allows both, investigation on control stability, room comfort, energy consumption and optimization of control parameters and algorithms.

The simulation procedure including the setup of the model is shown in the following workflow overview in Table 1.

Table 1 Overview of simulation procedure

Step	Description	Tool
Preprocessing		
1	Define building parameters	Excel
2	Calculate room thermal load	Excel, Simulink
3	Plant design	Excel
Processing		
4	Energy demand analysis	Simulink
5	Control behavior analysis	Simulink
Postprocessing		
6	Generate results report	Simulink, Excel

The configuration and modeling work flow described in detail further down as well as the simulation results given later in the results and discussion section are based on the office building (OB) and VAV AC plant shown in Figure 1 and 2. The AUH is equiped with cooling and heating coil, mixing damper and heat recovery wheel.

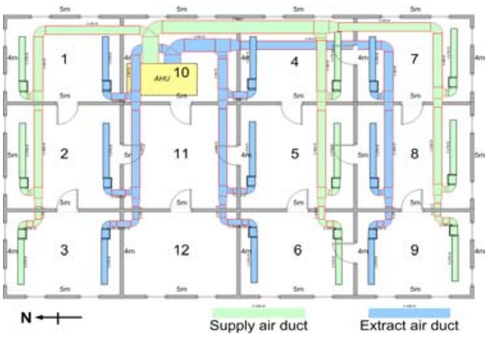


Figure 2 Building & duct design

To guarantee reliable simulation results, it is important to set proper parameters for the studied building and HVAC plant. Therefore, in the first three steps of the simulation procedure, parameters are set up step by step with the help of an Excel-based configuration tool.

Step 1. Define building parameters such as material of building envelopes, room arrangement, infiltration coefficients, ect. Two simulation cases were set up: a better insulated heavier office building (OB1) located in Basel, Switzerland and a well insulated lighter office building (OB2) located in Beijing, China. Construction of both buildings fullfill the local energy saving standard (see Appendix). The first floor of the building is simulated. The whole floor is divided into 12 zones of which 9 are offices equipped with VAV. An AHU supplies air to the whole floor. Internal load is defined according to Swiss norm (SIA, 1992).

Step 2. Calculate room thermal load. Define room temperature setpoints in Excel (for the given example 21°C for winter and 26°C for summer). Following Swiss standard (SIA, 1992), static heating load is calculated in Excel, and dynamic cooling load is calculated with Matlab/Simulink using setpoints, building and weather data read from Excel. The thermal load calculation results are then written in Excel and used for plant design.

Step 3. Plant design. Define the dimension of the air ducts and capacity of fans, heating and cooling coils, based on thermal loads and design criteria according to Swiss standard (SIA, 1992).

Step 4. Energy demand analysis. Only the physical building model is simulated for investigation of building energy performance. It is assumed that the room temperatures are ideally controlled within heating and cooling setpoint (21°C and 26°C). Thermal room energy demand and thermal ventilation energy demand are calculated for a whole year.

Step 5. Control behavior analysis. A specific control strategy is implemented by adding models of control functions, sensors and actuators to the physical building and plant model.

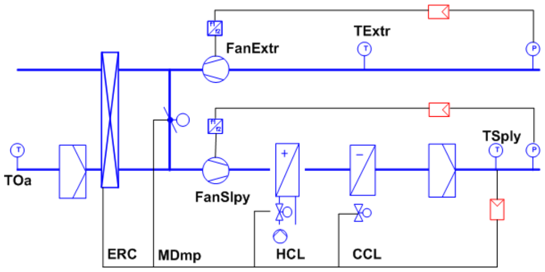


Figure 3 Primary control loops

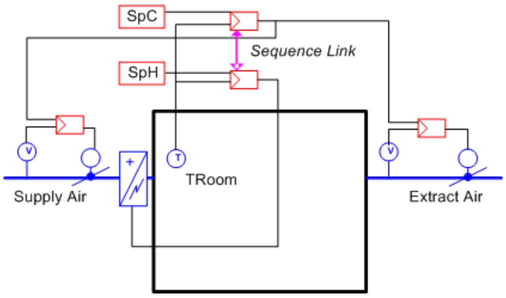


Figure 4 Secondary control loops

The primary and secondary loops in the studied case are shown in Figure 3 and 4. In the primary loop, supply and extract air fan are controlled by PI controllers to maintain the supply and extract air static pressure at the setpoints; heating coil, mixing damper, heat recovery and cooling coil are controlled by PI controllers and working in a sequence to maintain the supply air temperature within a setpoint range. In the secondary loop, pressure-independent VAV boxes and electrical reheaters are controlled by PI controllers and work in sequence to maintain the room temperatures within the setpoint range (26°C for VAV and 21°C for reheater). Operation time of the building is from 8:00 to 20:00 at work days. The plant is turned down during night and weekends.

The following different algorithms of primary loop control are implemented:

a. BM (Benchmark): A common strategy applied in existing running systems, regarded as a benchmark for evaluating advanced strategies. The setpoints of pressure and supply air temperature control are fixed. Supply and extract air pressure setpoints are set according to design conditions; supply temperature setpoint is 15°C for heating and 16°C for cooling.

b. HP (Head Pressure coordination): In oder to save energy of air fans, setpoints of supply and extract air pressure are lowered to achieve VAV damper position (average of three maximum) of 90%.

c. STfl (Supply Temperature coordination, air flow used as cooling demand): Supply air temperature setpoint of heating coil varies with room heating demand (average of three maximum), the more the demand the higher the value; and for cooling vice versa. The control commands of electrical reheaters are used as heating demand and nomalized room supply air flows as cooling demand.

d. STseq (Supply Temperature coordination, signal from room sequence controller used as cooling demand): Different from STfl, an additional PI controller with setpoint of 26°C (same as room cooling sequence) is inserted in room control sequence between heating and cooling, to generate the cooling demand signal.

e. PT (Pressure Temperature coordination): combination of HP and STseq.

f. NgtC (Night Cooling): The extract fan is turned on at night when the room temperature is higher than the cooling setpoint (26°C) and the outside air temperature has a cooling potential.

g. NT (Night cooling and supply Temperature coordination): combination of NgtC and STseq.

h. NPT (Night cooling and Pressure Temperature coordination): combination of NgtC and PT.

Simulations for different strategies are executed after implementation. The time steps are variable and less than 10 seconds.

Step 6. Generate results report. Energy consumption and room comfort data are exported to Excel for further data processing and analysis.

RESULTS AND DISCUSSION

Table 2 gives the overview of executed simulations.

Table 2 Overview of simulations

Building	Location	Simulations
OB1	Basel, Switzerland	1. Control behavior analysis for 2 weeks in 3 seasons with 8 strategies explained in the previous section (see Figure 5 to 8). 2. Control behavior analysis for a whole year with BM, PT and NPT (see Figure 9 and 10).
OB2	Beijing, China	

The following results are generated:

- Dynamic control behavior

The controlled variables and operation state of every component at every minute during the whole day can be ploted out. Figure 5 presents the control behavior of primary and secondary loops in one typical day of three seasons with Benchmark for building OB1.

- Strategy comparison of three seasons

The percentage of room comfort satisfactory time (room temperature between heating and cooling setpoints) and energy consumptions of different strategies for both buildings are compared and shown in Figure 6 and Figure 7. In order to make energy consumptions from different sources comparable, an electrical energy equivalent is calculated. It is assumed that heating and cooling energy are produced by a heat pump and a chiller with a system Coefficient Of Performance (COP) of 2 (1 kWh electricity generate 2 kWh heating or cooling energy).

- Strategy comparison of whole year

The whole year energy consumptions and electrical energy equivalent of different strategies are compared and shown in Figure 8 and Figure 9.

Comparison between control strategies

- BM (Benchmark)

With BM strategy the room comfort is mostly satisfied (over 90%). However in cold seasons with OB2, room temperature goes below comfort range usually in the morning because of the cooled down effect during the night. In reality the plant will be turned on earlier to deal with the cold morning problem. Advanced control systems also provide optimal start control function in conformity with european standard EN-ISO-16484-3 (2005) to optimize operation time. For easier comparison, in the simulation operation time is kept the same.

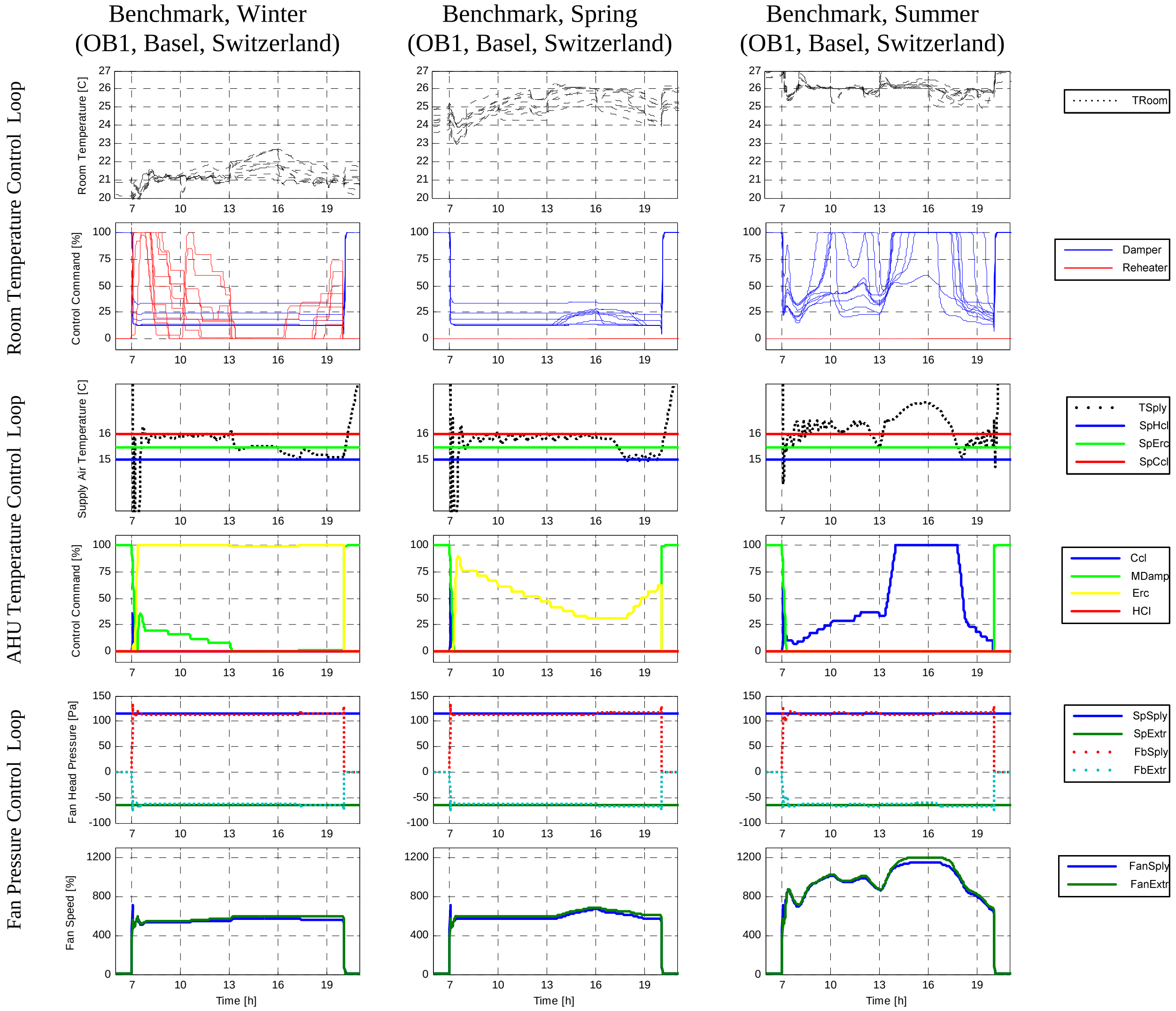


Figure 5 Control behavior with Benchmark in typical days (OB1, Basel)

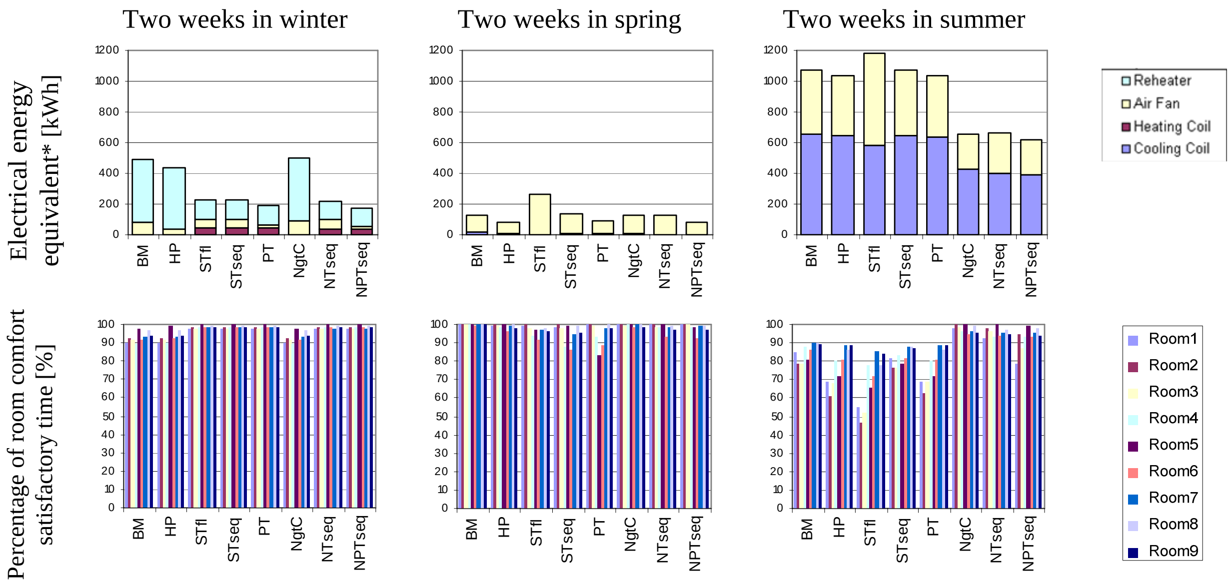


Figure 6 Comparison between control strategies (OB1, Basel)

* Electrical energy equivalent of cooling coil and heating coil = heating and cooling energy consumption / COP (COP=2)

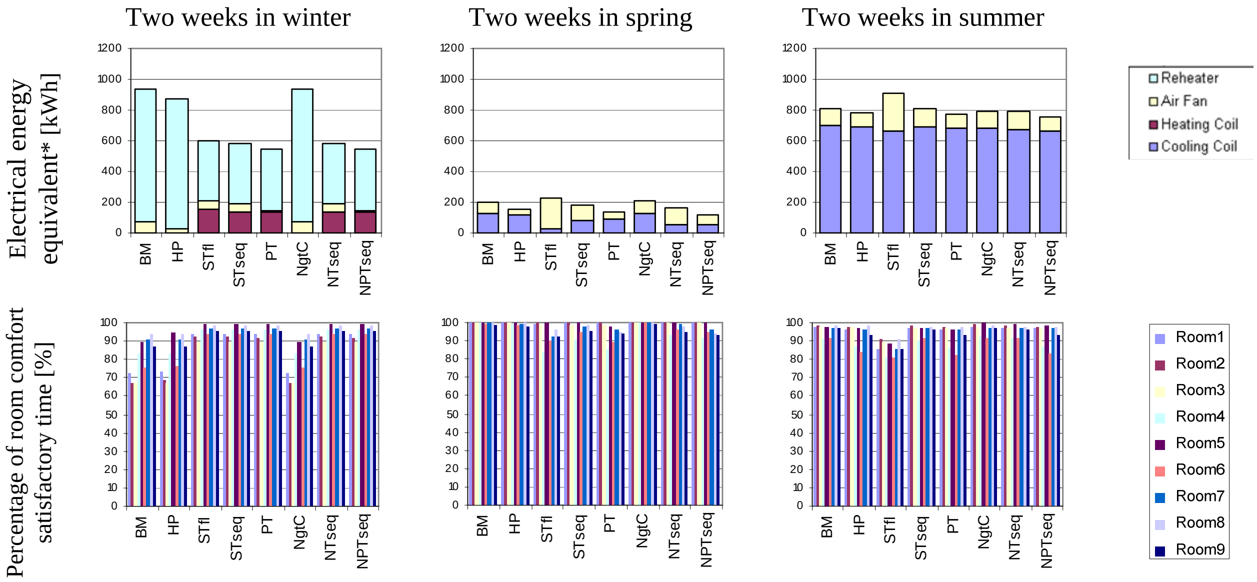


Figure 7 Comparison between control strategies (OB2, Beijing)

* Electrical energy equivalent of cooling coil and heating coil = heating and cooling energy consumption / COP (COP=2)

- HP (Head Pressure Coordination)

The HP strategy saves significant fan energy in cold seasons, but not much in summer. Also the room comfort is worse. It is mainly caused by the unbalanced cooling loads of the rooms. During one summer day some VAV dampers are fully opened while the others are opened only around 50%.

- ST (Supply Temperature Coordination)

Both ST strategies save much energy in cold seasons. Since the supply temperature setpoint is increased, much energy consumed by electrical reheater is saved. In addition more free energy from heat recovery and mixing air is utilized. The room comfort is also improved, since room heating demand is high in the morning, supply temperature is increased which helps to heat the room faster. However in warm and hot seasons, it is found that to use room supply air flows as cooling demand (STfl) causes more energy consumption and worsens room comfort. Because supply air temperature is not low enough when there is cooling demand in rooms, more air has to be transported and therefore the fans consume much more ener gy. A better solution is to have an additional control sequence between VAV damper and reheater to generate a cooling demand signal (as implemented in strategy STseq), so that when the VAV box starts to supply more air in the room, the cooling demand is already 100% and the supply air temperature setpoint is reduced to minimum value. As shown in Figure 5, different from STfl, STseq doesn’t consume more energy than BM.

- NgtC (Night Cooling)

NgtC strategy provides good energy saving in summer, and improve the room comfort at the same time.

- Combination strategies

The combined strategy PT saves more energy than single HP and ST in cold seasons, but in summer there is not much potential. After combined with NgtC (stragety NPT), energy consumption is decreased in summer, the simulation results show an electricity saving of one half for OB1 and one third for OB2, as shown in Figure 10.

Comparison between building OB1 and OB2

Although the winter in Basel is not much warmer than in Beijing, OB1 consumes much less energy in winter because of the better insulation. Room comfort is also better since the building’s heat capacity is larger and the building will not cool down too much during the night as in OB2. In summer the NgtC strategy doesn’t save as much energy in OB2 as in OB1, because the summer night is generally cooler in Basel than in Beijing.

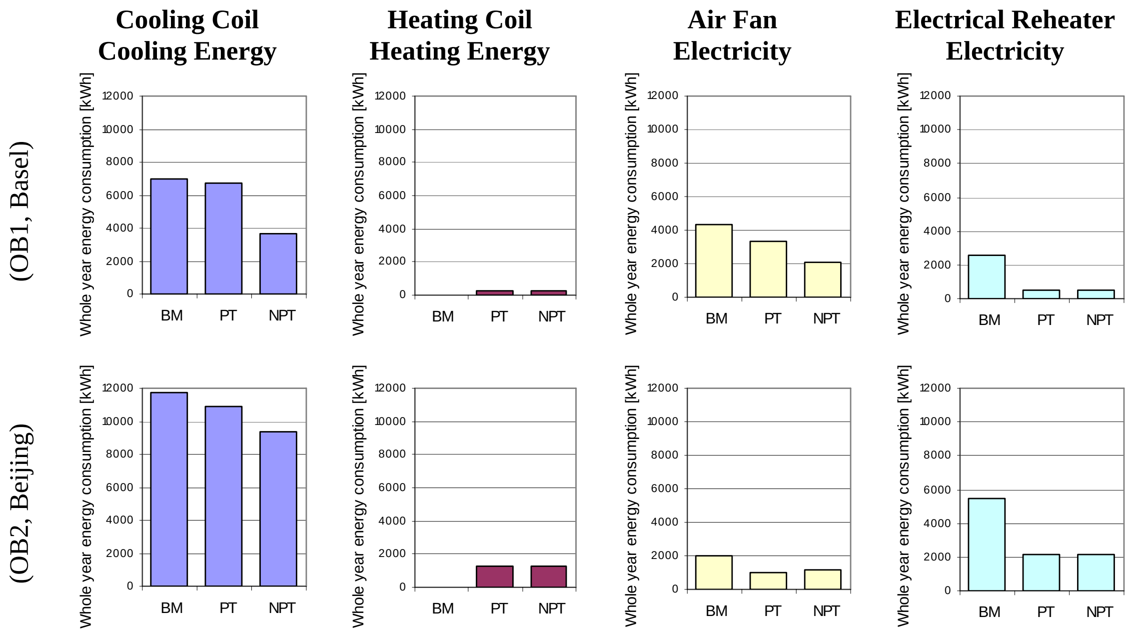
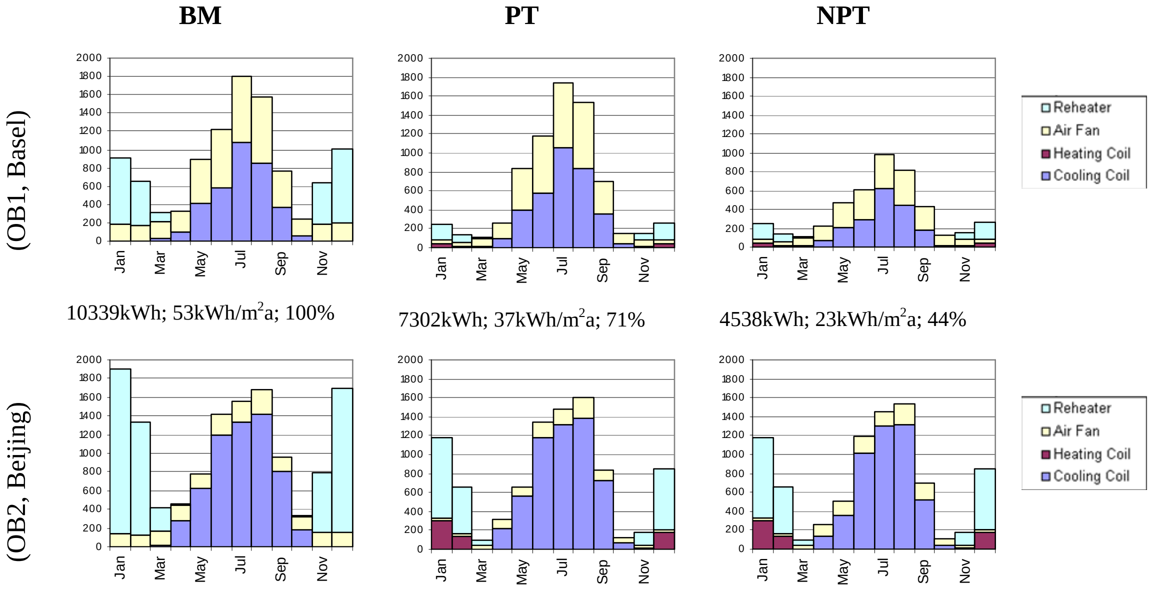


Figure 8 Comparison of whole year energy consumption between control strategies



10339kWh; 53kWh/m^{2}a; 100%

7302kWh; 37kWh/m^{2}a; 71%

4538kWh; 23kWh/m^{2}a; 44%

13322kWh; 68kWh/m^{2}a; 100%

9314kWh; 48kWh/m^{2}a; 70%

8712kWh; 45kWh/m^{2}a; 65%

Figure 9 Comparison of whole year electrical energy equivalent between control strategies*

*Electrical energy equivalent of cooling coil and heating coil = heating and cooling energy consumption / COP (COP=2)

CONCLUSION

This paper presents a simulation model of a VAV AC plant, which is part of a model library for a Matlab/Simulink-based building automation and control test and evaluation environment. This library is used in the product development as well as in research. Providing a managed library on the one heand leads to better models as models are used from more people and in a wider context, on the other hand reduces development effort since not every developer has to build his own simulation models.

With the presented model, simulations were carried out for two office buildings, one in Switzerland and one in China. The energy performance and control behavior depends not only on the control strategy but also on the building construction, operation, plant design, and weather conditions. Building and plant simulation helps to investigate issues such as influence of building’s thermal dynamic properties on control and energy consumption, coordination between primary and secondary control loops, and allows more reliable statements of the energy saving capacity of specific control strategies.

From the simulation results it is found that, although the construction and plant design of both buildings are very energy efficient according to local energy saving standard, there is still a large energy saving potential by optimizing plant control.

Further work will include the development and extension of the model library, additional investigation of control strategies such as online optimization and predictive control and analysis of the influence of plant design on control behavior and to find out the limitation of control when a plant is not properly designed.

ACKNOWLEDGMENT

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REFERENCES

Rechnagel. 1991. Taschenbuch für Heizung und Klimatechnik

ASHRAE. 1993. ASHRAE HVAC 2 TOOLKIT, Section 3.1 Detailed Fan/Pump (ASHRAE: American Society of Heating, Refrigerating, and Air-Conditioning Engineers)

SIA. 1992. SIA 382, Kühlleistungsbedarf von Gebäuden (SIA: Schweizerischer Ingenieur- und Architekten-Verein)

SIA. 2001. SIA 380/1, Thermische Energie im Hochbau

EU. 2005. EN-ISO-16484-3, Building automation and control systems (BACS) – Part 3: Functions

CABR. 2006. Design Standard for Energy Efficiency of Public Buildings (CABR: China Academy of Building Research)

NOTATIONS AND ABBREVIATIONS

$m_{a,R}$	Mass of air, kg
$h_{a,R}$	Enthalpy of air, J/kg
$V_{a,R}$	Air Volume, m^3
$\dot{Q}_{Encl}$	Heat flow transferred through room enclosures, including thermal radiation, W
$\dot{Q}_{CnvcInt}$	Convective internal heat gain, W
$\dot{Q}_{AirExg}$	Heat flow caused by air exchange due to mechanical ventilation, W
$\dot{Q}_{Infil}$	Heat flow due to air infiltration through leakages, W
$\dot{V}$	Air flow, m^3/h
$\dot{V}_{Nom}$	Nominal air flow, m^3/h
ΔP	Pressure drop, Pa
ΔP_{Nom}	Pressure drop at nominal flow, Pa
U	Heat transfer coefficient, W/m^2K
A	Area, m^2
Erc	Energy recovery
MDmp	Mixing Damper
Hcl	Heating Coil
Ccl	Cooling Coil
Spd	Speed
T	Temperature
SP	Setpoint
Fb	Feedback
Sply	Supply
Extr	Extract
BM	Benchmark
HP	Heat Pressure coordination
ST	Supply Temperature coordination
PT	Pressure and Temperature coordination
NgtC	Night Cooling
NPT	Combination of NgtC and PT

APPENDIX

The overall heat transfer coefficient is calculated by:

$$U_{Overall} = \frac{\sum_{i=WallExt,WinExt,Roof,Ground} U_i \cdot A_i}{\sum_{i=WallExt,WinExt,Roof,Ground} A_i}$$

In Figure 11, the overall heat transfer coefficient of both simulated building are compared with Swiss building energy saving standards SIA 380/1 (1988, 2001) and Chinese building energy saving standards (CABR, 2006). Both fullfill the listed local standards.

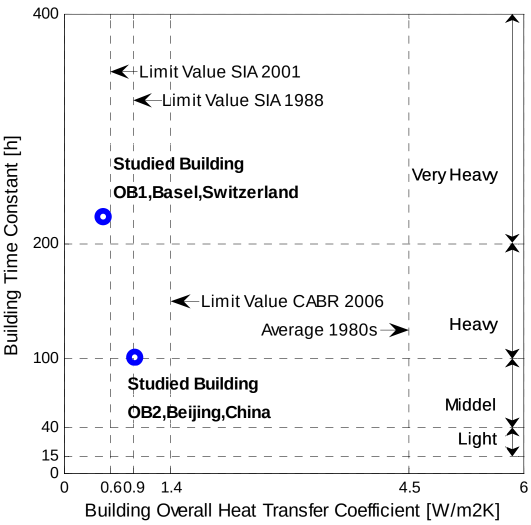

Figure 11 State of art of simulated buildings