CASE STUDY OF ENERGY DIAGNOSIS SIMULATION OF VAV AHU SYSTEM CONTROLS

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ABSTRACT

Advanced control and operation of HVAC systems in buildings is one of the most promising energy efficient technologies. However, there is still significant energy saving potential in these systems. Energy savings can come from correcting deficiencies through building commissioning. This paper focuses on deficiencies in the controls of a variable air volume (VAV) air handling unit (AHU) system. This paper demonstrates how DeST, a building simulation tool, is used to detect faults and to optimize set points in VAV AHU system controls. Through a detailed case study, this research explores the methods and values of simulation in energy performance diagnosis. The case study described in this paper was carried out as part of a commissioning project of campus buildings.

KEYWORDS

VAV AHU control, Building commissioning, DeST, Building simulation

INTRODUCTION

Sophisticated technologies such as direct digital control (DDC) have been introduced into HVAC systems as promising energy saving measures. However, they also increase the complexity of the systems and lead to a higher probability of deviation between system performance and design intent. As a result, few systems perform as intended. Actual systems in real buildings may differ from predicted performance because of flaws in design, construction, operation, and maintenance. The growing awareness of these problems has expanded the use of energy-oriented commissioning in new and existing buildings.

The authors have participated in a commission project of campus buildings in Philadelphia, United States. The project was launched in 2007. The goal of this project is to optimize the performance of energy systems within a building. The work performed in the project focuses on HVAC control systems as well as takes into account the interactions with other systems. The study described in this paper was carried out as part of this commissioning project.

Commissioning can benefit the building owners, operators, and occupants by correcting system performance deviation. The American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) issued an HVAC commissioning guideline in 1989 and updated it in 2007 (ASHRAE 1989 & 2007). Besides, there is a growing body of literature documenting commissioning case studies for different type of buildings. There are also a great number of previous studies that assembled data from multiple commissioning projects. The Cost-Effectiveness of Commercial Buildings Commissioning (Mills, E. et al., 2004) is a quantitative statistical analysis of commissioning projects across 224 buildings in the United States over the period 1984 to 2003. With a detailed and uniform methodology for categorizing the results of commissioning projects, this report facilitated meaningful inter-comparisons to discuss the commissioning costs, energy savings, and non-energy impacts. The statistical analyses of 99 projects show that the simple payback time of commissioning is about two years on average, with one year as the median. This indicates that commissioning can be more cost-effective than expected.

Significant economic benefits of commissioning come from correcting deficiencies in HVAC systems. International Energy Agency has conducted four projects related to fault detection and diagnosis in HVAC systems from 1991 to 2008. These projects are Annex 25 Real Time HVAC Simulation (IEA, 1996); Annex 34 Computer-Aided Evaluation of HVAC System Performance (IEA, 2006); Annex 40 Commissioning of Building HVAC Systems for Improved Energy Performance, which was launched for the period 2001-2004; and Annex 47 Cost Effective Commissioning of Existing and Low Energy Buildings, which is an on-going project. These footprints of IEA projects indicate the trend of using fault detection and diagnosis tools that are implementable in building energy management systems in building optimization and facilitating the automated commissioning process.

According to the previous studies, among the deficiencies found in 85 commissioning studies the problems with the VAV AHU systems were the most prevalent (Mills, E. et al., 2004). In the energy performance diagnosis project that the authors participated in, through on-site measuring, meter tracking, historical data analysis, and simulation, three problems in VAV AHU systems that cause most energy waste were found. These three problems are:

- Unnecessary preheat in AHUs. Leaky valves, faulty sensors, and flawed control sequences cause unnecessary temperature rise after preheat. The downstream cooling coil must remove the unnecessary heat added by the preheating coil. Such energy waste is hard to notice without building commissioning.
- Superfluous reheat in terminal VAVs. Faulty sensors and sub-optimal setpoints are the causes of this problem in this case. An optimum setpoint is the one that reduces energy use as well as ensures a thermal comfort rate higher than 80%. This means taking the thermal comfort level of one zone at one simulation time step as a sample, more than 80% samples have a satisfactory thermal comfort level. Energy consumption for reheat will be lowered after fault detection and setpoint optimization.
- The control sequence that lacks robustness. The existing control sequence does not consider the sensor dysfunction. The complicated control sequence relies on the accuracy of sensors that actually are likely to malfunction. When there is faulty information from sensors, large amounts of energy will be wasted.

In several campus buildings for which the authors have conducted commissioning, faulty sensors, leaky valves, flawed control sequences and improper set points can cause considerable energy waste. After fixing some of these problems, consumption of steam and chilled water can be lowered by 10% to 30%. This has been validated by metering of steam and chilled water consumption. This paper will focus on the problem of superfluous reheat in VAV systems. A VAV system is an energy-efficient solution to a multi-zone building with different cooling and heating demands. However, some problems in the system will cause energy waste. These problems include improper set points of minimum air flow rate of VAV boxes, improper AHU supply-air temperature set points, and faulty information from air flow rate sensors and CO_2 sensors.

Several fault detection and diagnosis tools that targets AHU controls are currently available (Castro, N.S., Vaezi-Nejad, H. 2005; Schein, J. 2006; Wang, S., Xiao, F. 2004). However, in this case study, on-site measuring, meter tracking, historical data analysis and building simulation were used to detect defficiencies and to find energy saving potential. This approach could potentially benefit the continuous commissioning in a different way. Building and HVAC system simulation can be instrumental in the building commissioning to optimize the system controls. In the following sections, a detailed case study of energy diagnosis in VAV AHU system controls will be described. How simulation helps with detecting faults in the system and finding solutions will be illustrated.

METHODOLOGY

The case study was conducted in an educational building with a total floor area of 30,472m^2. Six AHUs serve the building. The terminal units are mainly VAV boxes with hydronic reheat coils. According to the metering data, during July 2008, the energy input for cooling varied from 65 to 150 W/m^2. The steam consumption, converted to heating power, was 45 W/m^2 on average, which was not normal in summer. The steam was mainly consumed for preheating in AHUs and reheating in VAV boxes. Leaky valve caused large amounts of improper preheating in AHUs. Part of the reheating was necessary even in summer. Because the AHU delivered air to all the zones it served at the same temperature as determined by the control program. In the zones that had less cooling load, if the zone temperatures were still lower than the set points with minimum air flow rate, the air delivered to the zones needed to be reheated by hydronic coil in the VAV box for that zone. However, in this building, reheating in VAV boxes accounted for 23 W/m^2 on average in July. 15% to 35% cooling power was counteracted by reheating in VAV boxes in summer conditions. Excessive energy consumption might be caused by sensor drift or set points that have not been optimized. So simulation was utilized in the building commissioning to solve two problems. The first function of simulation in this case study was to find out how much energy input was superfluous due to the sensor drift. This part of the energy input could be saved after calibrating the sensors. The second function of the simulation was to determine proper set points which could balance between energy cost and thermal comfort.

The energy diagnosis simulation includes four steps, as Figure 1 shows. The first step is populating simulation parameters. The simulation software used in this case study was Designer's Simulation Toolkit (DeST). DeST was developed by Institute of Building Environment and Building Services, Tsinghua University. The second step is calibrating the model. The measured data and simulation results were compared in order to validate the model. The third step is fault detection. The DeST simulation provided data on the amount of necessary reheating. The remarkable difference between the simulation results and actual consumption measurements indicated that there were faults in the system. The fourth step is optimizing the AHU supply-air temperature set points. The existing control sequence could be further optimized. DeST was also used to simulate the hourly optimal AHU supply-air temperature. Through statistical analysis, new AHU supply-air temperature set point for unoccupied modes was determined. Using this supply-air temperature set point as input, another simulation was run to make sure that the thermal comfort level was acceptable.

MODEL BUILDING

The first step of simulation was to build the 3-D model and to input the parameters. The parameters included hourly weather data, building envelope information, internal load, and corresponding schedules. HVAC parameters consisted of hourly AHU supply-air supply, return-air temperature and air flow rate, room temperature set points, VAV box maximum and minimum air flow rates. These HVAC parameters were acquired from the digital control platform of the system and on-site measuring.

MODEL CALIBRATION

The model was verified by comparing on-site measured data and simulation results of the building load. By measuring the AHU supply-air temperature, return air temperature, and air flow rate, the amount of the cooling could be calculated. With the data showing heating water supply and return temperature for reheating, and its flow rate, how much heat was added to the zone could be calculated. Then the actual building load approximately equaled to cooling input minus the reheating. Figure 2 describes this process.

The calibration of simulated building performance to measured performance has been previously studied (Haberl et al., 1993). Graphic tools such as signatures of heating and cooling energy consumption for AHUs help researchers make quick and rational decisions when calibrating models (Wei et al., 1998). The calibration in this case study was performed by modifying simulation inputs until the results approximately agree with the measured data. Critical elements that affect HVAC energy use pointed out in the previous studies were considered in the model calibration in this study. Adjusting the occupancy schedule played an important role in model calibration in this case.

Figure 3 shows that by comparing the simulation results with the on-site measurements in a week, the relative error was within the acceptable range, so the model was ready for further study.

FAULT DETECTION

The next step was to run the VAV system model in DeST to simulate the necessary reheat in the conditions of the existing control sequence. Comparison between simulation results and actual consumption could indicate whether there were faults in the system.

Inputs and Outputs

Figure 4 is a block diagram of the fault detection process in detail. Besides the building information, the HVAC parameters including AHU supply, air temperature, and air flow rate were input according to existing conditions. The simulation output in this phase showed how much reheating was needed if all the actuators and the sensors functioned well according to the existing control sequences. The difference between actual and simulated amounts of reheating was the superfluous reheating which was an important indicator of whether the existing system was functioning well.

Results

Figure 5 shows the necessary reheating for zones served by one of the six AHUs in this building according to the set points in the existing control sequences. This figure also displays the superfluous reheating and the zone cooling load. The superfluous amount of reheating indicated that there were faults in the system. And this amount of energy consumption can be saved after correcting the faults.

Analysis

Through further investigation, the faults that accounted for superfluous reheating were sensor drift in VAV air flow measuring and CO_2 concentration measuring. Faulty sensor measurements caused large amounts of superfluous reheating.

It was found that in several systems, the actual air flow rate was much larger than the readings given by the sensors. Two facts supported this finding. First, the sum of terminal VAV box air flow rate was smaller than that of AHU. The sum of the sensor readings of VAV box air flow rate was about 65% of that of the AHU. This meant that some sensors under-measured the air flow, and/or some air from the AHU did not go through the VAV box due to duct leakage. Second, on-site measurement of individual VAV boxes also showed that the actual air flow rate of VAV boxes was far from the sensor readings, as shown in Table 1. When the control system got the signal from the sensor that air flow rate of the VAV box had reached the minimum air flow, instead of further closing the air damper, the system opened the reheat valve to meet the room temperature set point. This caused superfluous reheating.

Another concern was that if CO_2 sensors detected that the CO_2 concentration was higher than the set point, it would make the air damper open further to increase the air flow rate. If sensors over-measured CO_2 concentration, then they demanded more reheating due to larger air flow rate. This fault was also responsible for large energy waste in this building. If the sensors could be calibrated more often, significant amounts of energy could be saved.

As Figure 4 shows, less than half of the current reheat was necessary according to the simulation results. The superfluous reheating could be saved.

Table 1Examples of comparison between sensor reading and on-site measurement of air flow rate of VAV boxes

CASE	SENSOR READING (CFM)	ON-SITE MEASUREMENT (CFM)
1	1910	2828
2	1978	7250
3	252	1170

SAT OPTIMIZATION

As shown in Figure 5, during the unoccupied periods, when the cooling load was less, the zones required more reheating compared with occupied periods. This issue was related to the AHU supply-air temperature. The existing control program sets the supply-air temperature (SAT) as 55°F(13℃) throughout the year in this building.

This is an appropriate set point for summer cooling in occupied mode. But this low SAT set point can cause VAV boxes to expend more energy than necessary reheating air to reach the required zone temperature in the winter and the unoccupied mode, when there is less internal load. This problem can be improved if the AHU manages a higher supply temperature by adjusting the ratio of fresh air to return air or by using a glycol heat recovery system. The higher supply-air temperature will save heating water used for reheat in VAV boxes. Thus, the operation cost will be reduced.

However, raising the AHU supply-air temperature might also increase the risk of thermal discomfort in the zones in which cooling load is high. So simulation should be involved to find optimal set points that will save energy without decreasing comfort level.

Inputs and Outputs

Figure 6 describes the inputs and outputs in SAT optimization.

In the DeST model, the AHU supply-air temperature was allowed to change hourly within the range from 50°F(10℃) to 70°F(21℃) as the ambient temperature, internal load, and occupancy rate varied. The output was hourly optimal supply temperature, which could best meet all zone temperature set points and meanwhile requires least reheating within the given range.

However, the existing control system could not predict the internal load as simulation did. The algorithm to decide AHU supply-air temperature such as "voting method" (Kasahara, 2001) was not programmed in the existing control system. Thus, one most implementable solution was to choose two set points for occupied and unoccupied modes for summer conditions respectively through statistics analysis. Another set of temperature set points will be required for each season.

It was necessary to run another simulation to check the thermal comfort level. DeST was used again to simulate the zone temperatures when new SAT set points were applied. Based on the zone temperatures, whether thermal comfort level was acceptable could be evaluated.

Results and Analysis

Figure 7 shows the simulated hourly optimum AHU supply-air temperatures in summer conditions. Data was plotted with outdoor temperature as the X-axis value. Different colors represent six AHUs in the building. During the occupied mode, the optimum supply-air temperature varied from 52°F(11℃) to 62°F(17℃), while in unoccupied mode, the range was offset slightly higher, from 55°F(13℃) to 65°F(18℃).

The hourly optimum AHU supply-air temperature setpoint is the result reset for the warmest zone by the simulation program. So this setpoint is the highest temperature that can ensure the thermal comfort of all zones at each simulation step. In other words, it is the temperature that can minimize energy use without compromising thermal comfort level. As far as the feasibility is concerned, one setpoint needs to be chosen for each mode (occupied and unoccupied). Categorizing all hourly optimum setpoints into three temperature ranges, as Figure 8 shows, it is suggested that in occupied mode the supply-air temperature should still be 55°F(13℃), while in unoccupied mode it should be changed to 60°F(16℃). According to the temperature distribution as Figure 8 shows, in unoccupied mode, there will be less than 26% of the total time that the thermal comfort of the warmest zone might be compromised. So the thermal comfort rate after changing the supply-air temperature setpoint is examined. Less than 20% of the thermal comfort of all samples in unoccupied mode is compromised. The unoccupied mode refers to 9pm to 6am, when there are fewer people in this 24-hour accessible building.

In the similar way, it was recommended that the set points are 60°F(16℃) in occupied mode and 65°F(18℃) in unoccupied mode in winter conditions. These optimized AHU supply-air temperature set points could further reduce the "necessary" reheating.

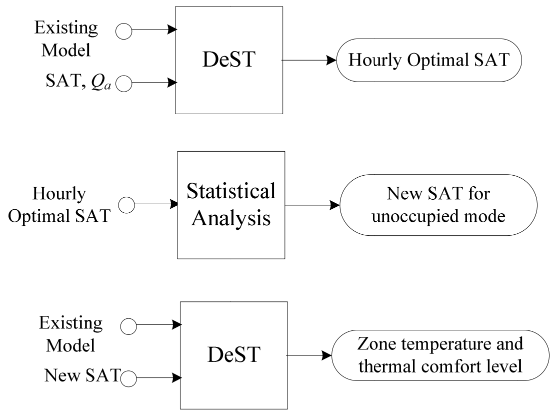

Figure 6 Inputs and outputs in SAT optimization

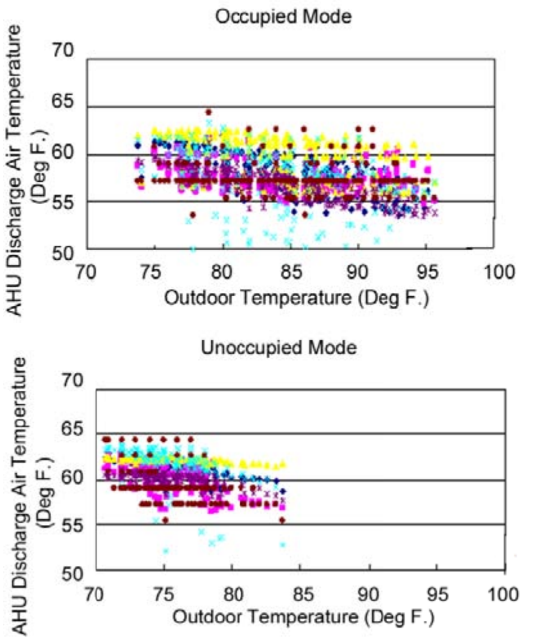

Figure 7 Optimal AHU supply-air temperature by simulating

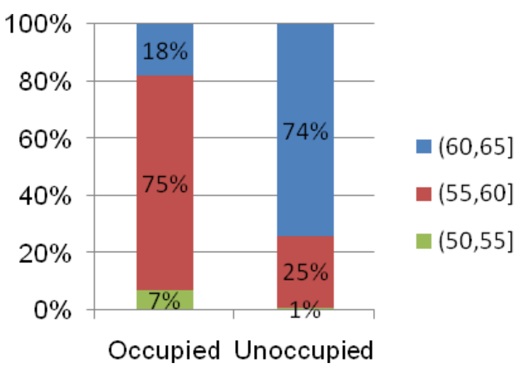

Figure 8 Analysis of AHU supply-air temperature in summer conditions

DISCUSSION

From this case study, we have learned that in the phase of model building, understanding of key factors that affect energy consumption is crucial. This will decide what input parameters are worth the time and effort to make them as detailed and as close to reality as possible. In this case study, the building is internal load dominant. So the information related to people, lighting, equipment and their schedules affects the building cooling load and reheating energy consumption significantly. Many efforts were made to collect this information in order to calibrate the model.

In building commissioning, on-site measured data can be utilized in simulation in three aspects. First, these data can serve as inputs. For example, in this case study measured AHU supply-air temperature and air flow rate were input parameters in reheating simulation. Second, on-site measured data can also help to verify the reliability of the model and to ensure that the further simulation makes sense. What's more, comparing on-site measurement with simulation results, deficiencies in systems and energy saving potentials can be found. As described in fault detection section, if the measured reheat is unreasonably larger than the simulated results, it is recommended to check the sensor accuracy and the function of actuators. This is based on the assumption that the simulation is as accurate as possible. In this case study, the degree of error was within ±20%, which should be considered.

Since it is time consuming to build this model that is close to real conditions, it is necessary to find the most important factors that affect fault detection and set point optimization in VAV AHU system controls. Further research can focus on how to accelerate the process after understanding these key factors. Besides, based on the accumulated data and case studies, simplified measures and models should be developed to detect faults, to optimize set points, and to estimate energy savings.

CONCLUDING REMARKS

This study demonstrated how building simulation can be used to detect sensor drift and to optimize set points in VAV AHU systems. Through a detailed case study, this research described the process of using simulation in building commissioning.

This paper pointed out that sensor drift could cause large amount of superfluous reheating in VAV systems. Besides, it provided an implementable solution for the existing control system to optimize AHU supply-air temperature. This study also explored the methods and values of utilizing on-site measured data in energy diagnosis simulation.

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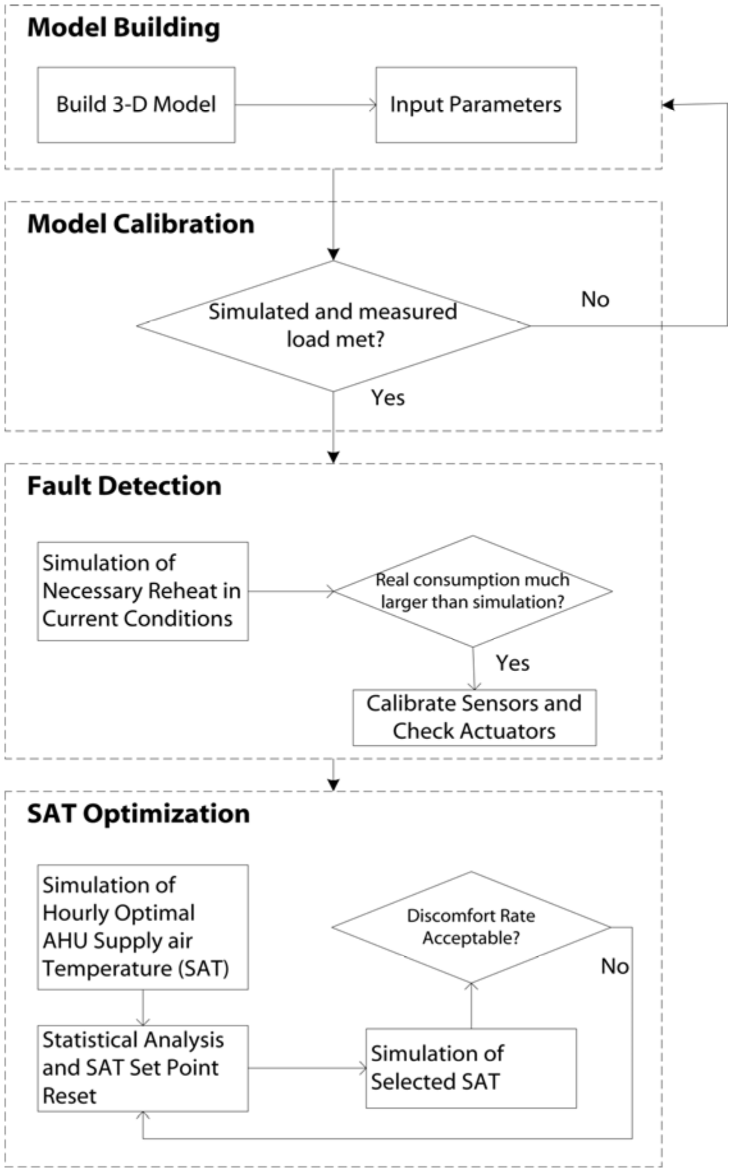

Figure 1 Process of using simulation in diagnosis of AHU VAV system

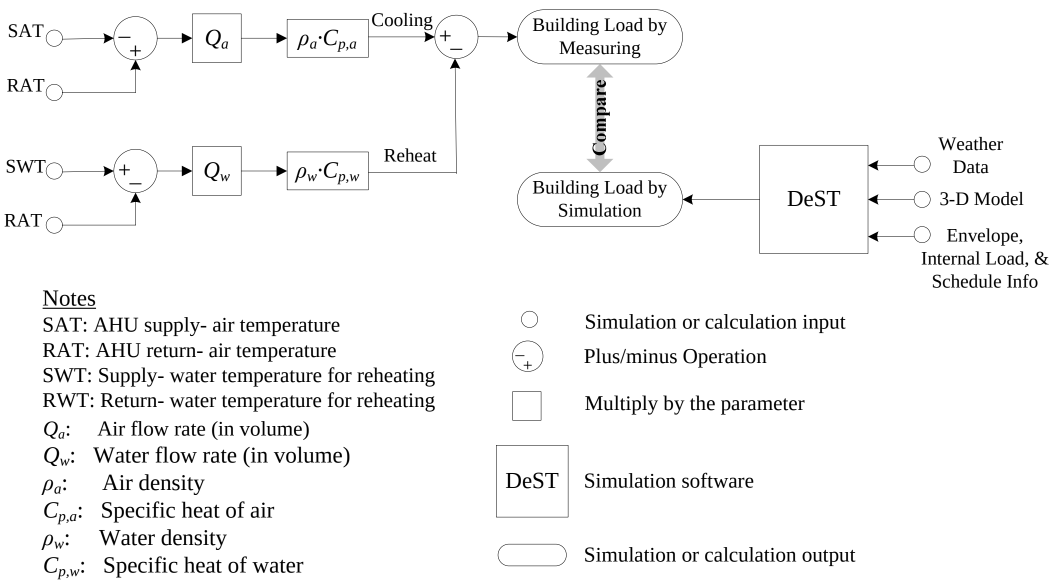

Figure 2 Block diagram of model calibration

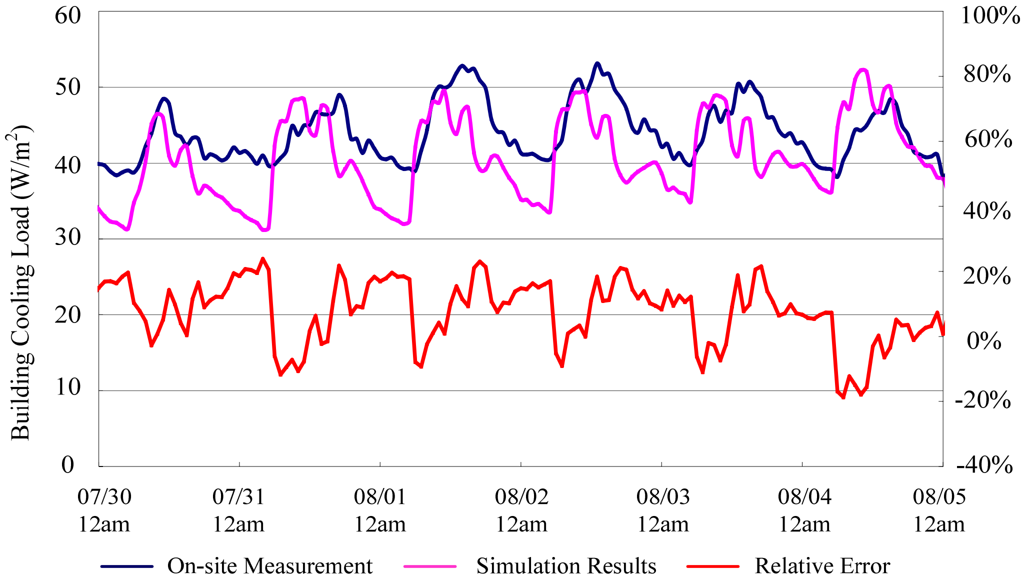

Figure 3 Comparison of building cooling load of on-site measurements and simulation results

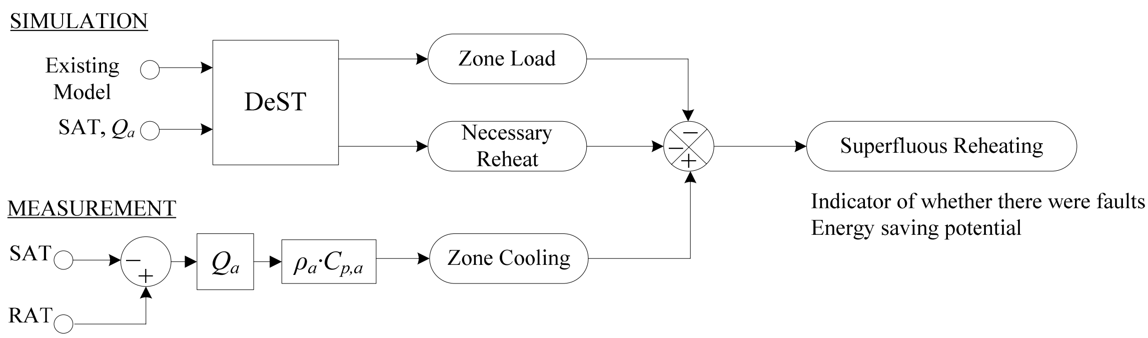

Figure 4 Block diagram of fault detection

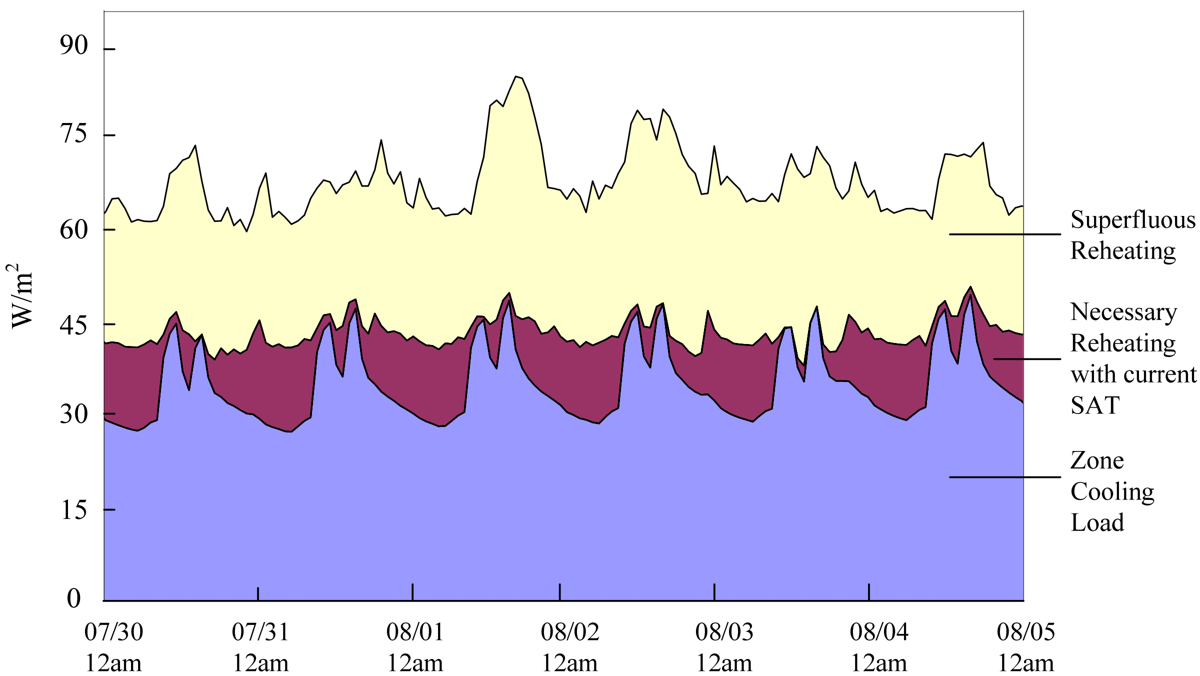

Figure 5 Simulation results of zone cooling load, necessary reheating with current SAT and superfluous reheating of one AHU