HVAC SYSTEM SIMULATION AND ANALYSIS BASED ON UNCERTAIN INNER HEAT GAINS

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ABSTRACT

For large scale commercial buildings, the inner heat gains acts in an uncertain way in time serial and space. Presently, fixed schedule is generally used to describe the inner heat gains in the state of arts HVAC system simulation which couldn't reflect the uncertain characteristic of inner heat gains. Therefore the simulation is required to use a range rather than just a certain point as the simulation input of the inner heat gains. This paper presents a new mathematic methodology to deal with the region operation, which including the definition, the operation rules, and the theoretical proving of region operation. This new mathematic methodology could be used to calculate the results under the interaction between uncertain factors and controlling means. By applying this region operation methodology into HVAC system simulation analysis, this paper presents a new HVAC system simulation method under uncertain inner heat gains. In order to testify the validity of this method, this paper provides a series of validation between new method and Monte Carlo method. With the applications of the HVAC system simulation method under uncertain heat gains, it shows the advantage of this new method.

KEYWORDS

Uncertain analysis, Region operation, Building simulation

INTRODUCTION

Building energy simulation tools play an important role in modern building design processes. They provide a wide range of functions for building designers with incredible speed and repeatability(Clarke J A. 2001) (Hong TZ. 2000). For large scale commercial buildings, inner heat gains are the most important factor that affects the building thermal environment. And for the inner heat gains are greatly affected by a lots of complex and uncertain factors, which including occupancy, climate, holiday, etc., it is very hard to forecast the quantity and rule of transformation of the inner heat gains.The figure 1 shows one Japanese office's 8 days measured equipment electricty consumption in 2004, the maxium inner heat gains are almost 2 times of the minium.

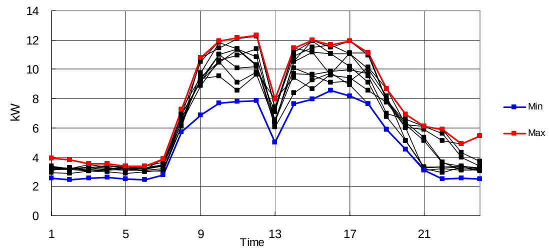

Figure 1 A Japanese office's 8 days measured equipment electricty consumption in 2004

Since the inner heat gains acts in an uncertain way in time serial and space, the uncertain property of the inner heat gains is the main reason to result in the problem of inhomogeneous temperature distribution in the HVAC system operation. Presently, fixed schedule is generally used to describe the inner heat gains in the state of arts HVAC system simulation. However, this description couldn't reflect the uncertain characteristic of inner heat gains, therefore the simulation couldn't accurately estimate the possible conditions which may happen in the real system operation, and even worse, it may result in the designer's error decisions in some cases. In order to make the simulation more close to the real condition, it is required to use a range rather than just a certain point as the simulation input of the inner heat gains. In this way, the simulation would conduct not only the comprehensive verification of climate but also the comprehensive analysis of inner heat gains, so as to completely check out the possible problems in real system operation, and to achieve the optimization and improvement of design.

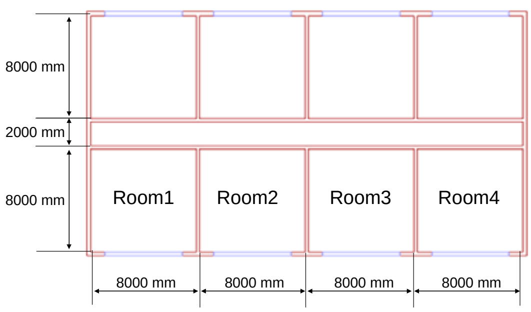

Figure 2 Layout plan of an office building

In order to illuminate how the inner heat gains uncertainty affect on HVAC system simulation, one case has been performed. As figure 2 shows, one HVAC system is dealing with four office rooms. The inner heat gains setting and system type settings are as shown in table 1. For the Case3 and Case6, the inner heat gains are gerenate by using Monte Carlo method to simulate the uncertain process.

Table 1 Case settings and system types

Case	Inner Heat Gains	System	Air Volume
Case1	40 W/m2	CAV	6 ACH
Case2	10 W/m2	CAV	6 ACH
Case3	10～40 W/m2	CAV	6 ACH
Case4	40 W/m2	VAV	3～6 ACH
Case5	10 W/m2	VAV	3～6 ACH
Case6	10～40 W/m2	VAV	3～6 ACH

Figure 3 shows the system unsatisfied hour's simulation results in different cases in full year. We can see that, in the certain inner heat gain's cases, for the four office rooms' thermal conditions vary in a same way, the system almost could meet the requirement all over a year. However, in the uncertain cases, for the rooms' thermal conditions vary in a different step, it will produce greatly unbalance between each room, and finally lead into thousand hours unsatisfied hours.

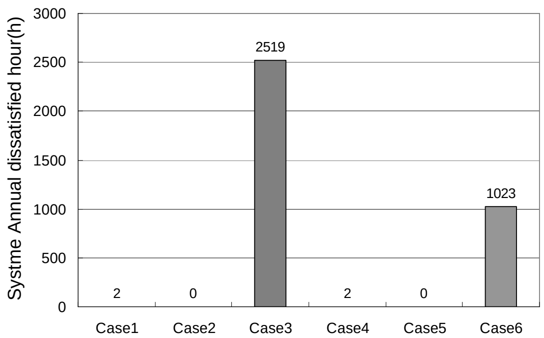

Figure 3 Annual dissatisfied hour comparison

Differential Sensitivity Analysis and Monte Carlo Analysishave been used to analyze the uncertainty of repetitive manual changing of the input parameters in simulation (Iain Macdonald and Paul Strachan, 2001), and describe how uncertainty analysis has been incorporated into ESP-r. These methodologies are quite easy to implement in building simulation program, and do not needed to modify the program. However, these two methodologies are too time-consumed, and need to forecast the distribution of all the uncertain factors. Annual twin load curves analysis which simulate the full year load under maximum and minimum inner heat gains, has been used to determine the reasonable number and size of chillers in design stage (Zhu, 1998). This method could reflect the effect of uncertainty in load part. Nevertheless it could not reflect the effect of uncertainty in indoor temperature unbalance and system control.

In order to make the simulation more close to the real condition, it is required to use a range rather than just a certain point as the simulation input of the inner heat gains. In this way, a new mothodology of simulation is needed to completely check out the possible conditions while the inner heat gains act in a range value.

REGION OPERATION METHODOLOGY

To solve the above problems, a new mathematic methodology is needed to deal with the region operation, which including the definition, the operation rules, and the theoretical proving of region operation. In order to simulate the range which is caused by the interaction between uncertain factors and controlling means, the new mathematic methodology should solve the following problem:

- The mathematic methodology need define and reflect uncertain factors and controlling mean's different characters.
- The mathematic methodology need solve the result which is interacted by uncertain factors and controlling means.
- The result range should both shows the range which reflect all the uncertain factors and controlling means could reach, and also the range which the controlling mean could control uncertain factors into it.

If the uncertain factors x is belong to the range $[x_1, x_2]$, and the controlling mean y is belong to the range $[y_1, y_2]$. So we define,

$$z_1 = \min_{x\in[x_1,x_2]} \min_{y\in[y_1,y_2]} f(x,y)$$

Where z_1 means, when x is belong to the range $[x_1, x_2]$, y is belong to the range $[y_1, y_2]$, the minimum value which $f(x, y)$ could be. The physical meaning of z_1 is the minimum value which uncertain factors and controlling means could meet。

$$z_2 = \max_{x\in[x_1,x_2]} \max_{y\in[y_1,y_2]} f(x,y)$$

Where z_2 means, when x is belong to the range $[x_1, x_2]$, y is belong to the range $[y_1, y_2]$, the maximum value which $f(x, y)$ could be. The physical meaning of z_2 is the maximum value which uncertain factors and controlling means could meet.

$$z_3 = \max_{x\in[x_1,x_2]} \min_{y\in[y_1,y_2]} f(x,y)$$

Where z_3 means, when y is belong to the range $[y_1, y_2]$, the minimum value which $f(x, y)$ could be when change x (belong to the range $[x_1, x_2]$) to make the $f(x, y)$ value to maximum at the same time. The physical meaning of z_3 is the minimum value which controlling means could control when uncertain factors lead the value to maximum.

$$z_4 = \min_{x \in [x_1, x_2]} \max_{y \in [y_1, y_2]} f(x, y)$$

Where z_4 means, when y is belong to the range $[y_1, y_2]$, the maximum value which $f(x, y)$ could be when change x (belong to the range $[x_1, x_2]$) to make the $f(x, y)$ value to minimum at the same time. The physical meaning of z_4 is the maximum value which controlling means could control when uncertain factors lead the value to minimum.

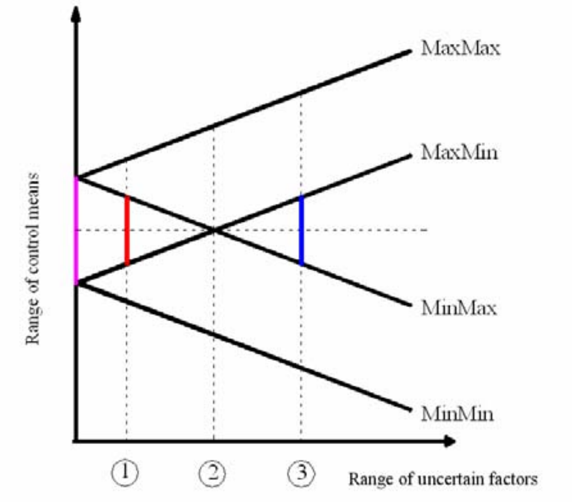

Figure 4 sketch map of the interaction between uncertain factors and controlling means

As the figure 4 shows, the result range $[z_1, z_2]$ stands for the minimum and maximum value which uncertain factors and controlling means could meet.

When the uncertain factors is relative smaller than that controlling means are, which is $z_3 < z_4$, as figure 5 shows, that is mean wherever is uncertain factors x is in the range $[x_1, x_2]$, by the controlling means y in the range $[y_1, y_2]$, could control $f(x, y)$ into any special point of the range $[z_3, z_4]$.

When the uncertain factors is relative larger than that controlling means are, which is $z_3 > z_4$, as figure 6 shows, that is mean wherever is uncertain factors x is in the range $[x_1, x_2]$, by the controlling means y in the range $[y_1, y_2]$, could only control $f(x, y)$ into the range of $[z_4, z_3]$, however, it could not be controlled into any special point in this range.

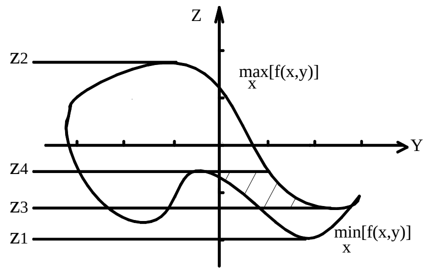

Figure 5 example of Z_3<Z_4

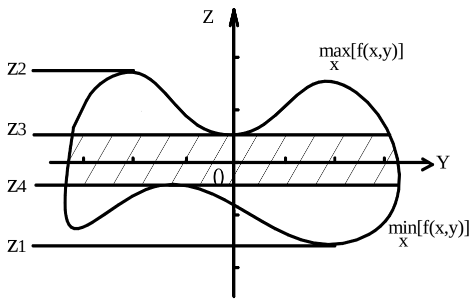

Figure 6 example of Z_3>Z_4

By defining these ranges, we could finally calculate the range which is caused by the interaction between uncertain factors and controlling means. It is really interested that the final result would be two kinds of results. One kind of result shows that the uncertain factors is relative smaller than that controlling means are, so we could control the system into any special point of the result range. In another hand, when the uncertain factors is relative larger than that controlling means are, so we could just control into the result range, however, it could not be controlled into any special point in this range.

For example, for the function $z = (x - y)^2$, $x \in [0,1]$, $y \in [0,1]$, then as the figure 7 shows.

$$\begin{cases} z_1 = \min_{x \in [x_1, x_2]} \min_{y \in [y_1, y_2]} f(x, y) = 0 \\ z_2 = \max_{x \in [x_1, x_2]} \max_{y \in [y_1, y_2]} f(x, y) = 1 \\ z_3 = \max_{x \in [x_1, x_2]} \min_{y \in [y_1, y_2]} f(x, y) = 0 \\ z_4 = \min_{x \in [x_1, x_2]} \max_{y \in [y_1, y_2]} f(x, y) = 0.25 \end{cases}$$

Thus means,

1. For the function $z = (x - y)^2$, $x \in [0,1]$, $y \in [0,1]$, the value of function should be content into the range [0,1].
2. If we select one point z in the range of [0,0.25] as the target value of the function, wherever $x \in [0,1]$, we could find a $y \in [0,1]$, to make $z = (x - y)^2$.

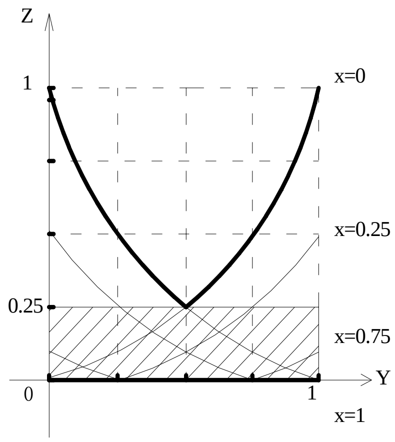

Figure 7 sketch map of function example

By defining the new range operation mathematic methodology, which including the definition, the operation rules, and the theoretical proving of region operation, then we could calculate the range which is caused by the interaction between uncertain factors and controlling means.

ROOM HEAT BALANCE MODEL

Based one state-space method, for a room *k*, the room temperature at a time could be written as (Jiang Y. 1982) (Hong TZ. 1997):

$$\begin{aligned} t_k(\tau) = t_{bzk}(\tau) + \sum_j \Phi_{j,0,k} t_j(\tau) + \Phi_{hvac,k} q_{hvac,k}(\tau) \\ + \Phi_{hvac,k} C_p \rho G_{out,k}(\tau)\left(t_{out}(\tau) - t_k(\tau)\right) \\ + \sum_j \Phi_{hvac,k} C_p \rho G_{jk}(\tau)\left(t_j(\tau) - t_k(\tau)\right) \\ + \Phi_{hvac,k} q_{inner,k}(\tau) \end{aligned} \qquad (1)$$

where

$t_k(\tau)$ = temperature of room *k*,

$t_{bzk}(\tau)$ = base temperature of room *k* (it excludes the effects of hvac systems, natural ventilation, ventilation and heat transfer from adjacent rooms),

$t_j(\tau)$ = temperature of room *j*,

$\Phi_{j,0,k}$ = the lumped factor for affecting the temperature of room *k*,

$q_{hvac,k}(\tau)$ = cooling or heating power input to room *k*,

$\Phi_{hvac,k}$ = the lumped factor for affecting the temperature of room *k*,

$q_{inner,k}(\tau)$ = the inner heat gains of room *k*,

$G_{out,k}(\tau)$ = Outdoor air ventilation rates,

$t_{out}(\tau)$ = Outdoor air temperature,

$G_{jk}(\tau)$ = Ventilation rates from adjacent room *j* to room *k*.

If the design conditions of supply air temperature, supply air volume and terminal reheat rates can be determined, the hvac system cooling or heating loads for system *l* of room *k* can be expressed as:

$$q_{hvac,k}(\tau) = C_p \rho G_{s,k}(\tau)\left(t_s(\tau) - t_k(\tau)\right) + q_{term,k}(\tau) \qquad (2)$$

where:

$C_p \rho G_{s,k}(\tau)\left(t_s(\tau) - t_k(\tau)\right)$ = cooling or heating loads of system *l* for room *k*,

$G_{s,k}(\tau)$ = supply air volume for room *k*,

$t_{s,l}(\tau)$ = supply air temperature for system *l*,

$q_{term,k}(\tau)$ = cooling or heating rates of terminal reheater for room *k*.

Substituting equation (2) into equation (1), gives:

$$\begin{aligned} t_k(\tau) = t_{bzk}(\tau) + \sum_j \Phi_{j,0,k} t_j(\tau) + \Phi_{hvac,k} Cp\rho G_{s,k}(\tau)(t_s(\tau) - t_k(\tau)) \\ + \Phi_{hvac,k} q_{term,k}(\tau) + \Phi_{hvac,k} C_P \rho G_{out,k}(\tau)(t_{out}(\tau) - t_k(\tau)) \\ + \sum_j \Phi_{hvac,k} C_P \rho G_{jk}(\tau)(t_j(\tau) - t_k(\tau)) + \Phi_{hvac,k} q_{inner,k}(\tau) \end{aligned}$$

(3)

Then in the equation 1, for the VAV system with reheater, $G_{s,k}(\tau)$ and $q_{term,k}(\tau)$ are controllable range, however, $q_{inner,k}(\tau)$ is a uncertain range. The next procedure is, for all working conditions, using the range operation methodology to simulation the room temperature range.

VALIDATION

In order to validate the room termperature range operation methodology under uncertain inner heat gains in HVAC system simulation, one serial of cases has been performed. As figure 8 shows, there is one VAV HVAC system with six office rooms. The supply air volume is from 4 ACH to 8 ACH. The room set point is 22~24℃. In Case 1, the setting inner heat gains is 0~25W/m^2, and in Case2, the setting inner heat gains is 0~50W/m^2. And Monte Carlo method is used to simulate the uncertain process to compare with the result of range calculation.

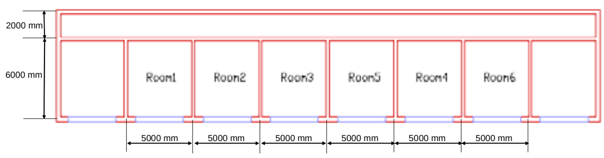

Figure 8 Layout plan of the validation case

In Case 1, as figure 9 shows, the 4 red lines stand for the results of 4 times' Monte Carlo method simulation results. And purple line and blue line stand for the simulation results of range calculations. All the red lines are contented between the purple line and blue line. Figure 10 shows one day's hourly simulation data. Through this figure, we could see that purple line and blue line is also the boundary of all the red line. For the setting of uncertain inner heat gain is from 0 to 25W/m^2, the room's temperature can be controled into room set point which is 22~24 ℃ .

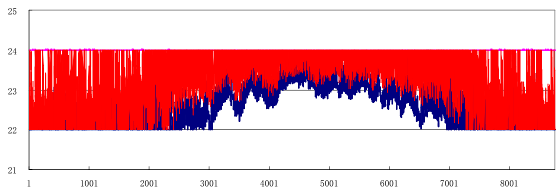

Figure 9 Full year hourly indoor temperatures of Case 1

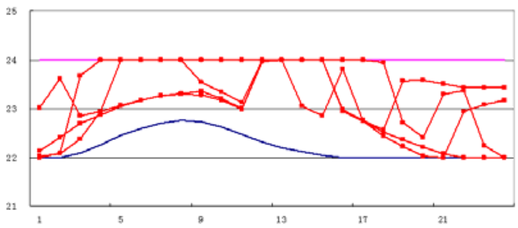

Figure 10 One day's hourly indoor temperatures of Case 1

In Case 2, as figure 11 shows, all the red lines are also contented between the purple line and blue line. Figure 12 shows one day's hourly simulation data. Through this figure, we could see that purple line and blue line is also the boundary of all the red line. For the setting of uncertain inner heat gain is from 0 to 50W/m^2, which is much larger than that in Case1, so it is much hard to controlled the room's temperature into room set point. From figure 12, we could see that in some hours room's temperature is above 24℃ or below 22℃. It is represent that in these hours, the HVAC system has the possibility that could not controlled all the room temperature into set point.

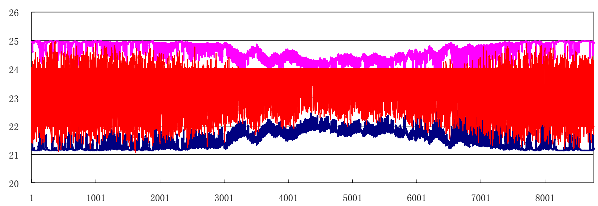

Figure 11 Full year hourly indoor temperatures of Case 2

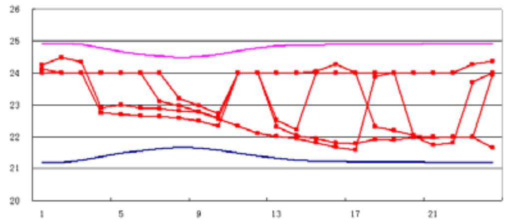

Figure 12 One day's hourly indoor temperatures of Case 2

From these simulation results comparsion, we could draw the consulsion that the room termperature range operation methodology under uncertain inner heat gains in HVAC system simulation is quite consistent to the simulation result of Monte Carlo method.

CASE STUDY

An office building located in Beijing is used for demonstrating the new range simulation methodology in detailed, and show what's kind of new results will be gained by using this range simulation methodology.

Building Details

The building plan is shown in Figure 13. The office building has a total floor area of 480 m^2. The exterior zone is 160 m^2 (denotes Room2 in Figure 3), the interior zone has an area of 256 m^2 (denotes Room1 in Figure 3). The corridor is 64 m^2. The floor to floor height is about 3.6 m. The U-values for external walls and double-glazing external windows are 1.4 W/(m^{2}K) and 3.1 W/(m^{2}K) respectively. The external wall and external window ratio is fixed at 0.5.

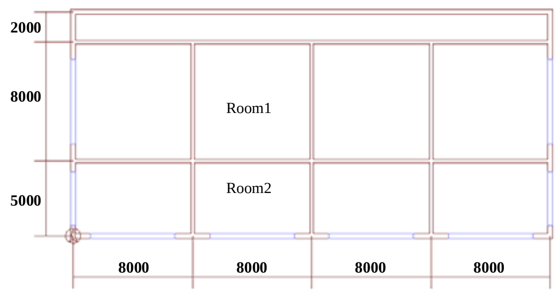

Figure 13 Layout plan of the Case Study Building (Unit: mm)

The office building is located in Beijing, China. The densities of occupancy is taken as 0.1 person/m^2, the inner equipment heat gains including lighting and small power are taken as a range from 10 W/m^2 to 20 W/m^2. The schedules for inner equipment heat gains are shown in Figure 14. The indoor design temperature range is 22 °C – 25 °C and room design humidity range is 40 % - 60 %. The HVAC system is considered to be run continuously throughout the year.

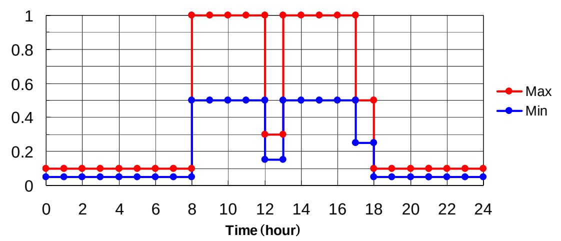

Figure 14 Range setting schedule of Inner heat gains

CAV systems

The preliminary scheme for the building adopted a 4-pipe CAV system and its zoning arrangement is as shown in Figure 15. The supply air flow rates for each room is at 8 ACH. There will be no terminal reheaters and the supply air temperature from the system has a range from 14°C to 32°C.

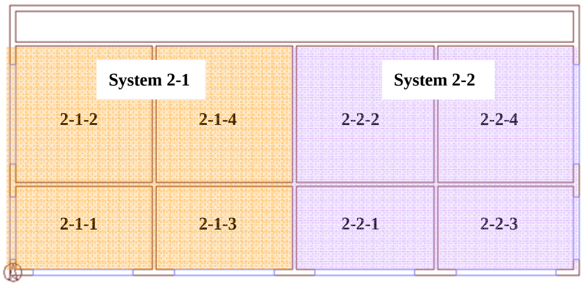

Figure 15 System zoning diagram

From the range simulation methodology presented in the above-mentioned, the hours of possible dissatisfied, which is the room temperature calculated has the possibility does not fall within the specified design temperature range, could be obtained for analysis as shown in Table 2 below.

Table 2 Possible dissatisfied hours of CAV system

System No.	2-1	2-2
Hour of possible dissatisfied	2870	3081

Figure 16 shows the room temperatures on 15 pm 16 Oct. of system 2-1.

In Figure 16, the room temperature design range is at maximum of 25°C and at minimum of 22°C. The room 2-1-1's maximum value of temperature range at 15 pm on 16 Oct. is 26.2°C, and found to be exceeding the maximum design room temperature of 25°C. Thus means, if the uncertain inner heat gains is go to the maximum value, then the room's temperature will have the risk to be exceeding the upper level of room temperature set point. And in the worst condition, the room's temperature will be 26.2°C, whereas, it will not exceed it.

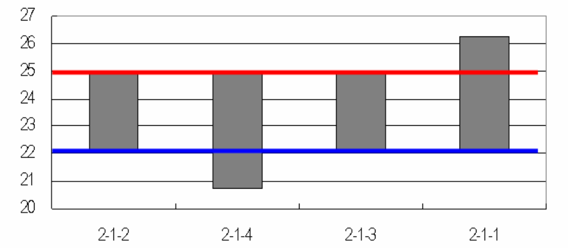

Figure 16 Room temperatures on 15 pm 16 Oct. of system 2-1

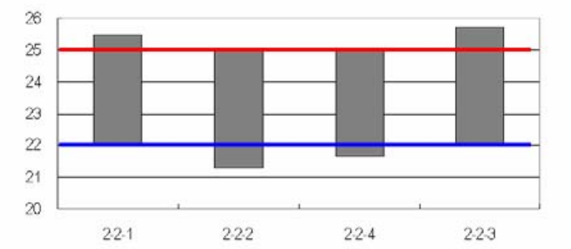

Figure 17 Room temperatures on 15 pm 16 Oct. of system 2-2

Figure 17 shows the room temperatures range of room 2-1-4. The room 2-1-4's minimum value of temperature range at 15 pm on 16 Oct. is 20.9°C, it is below the lower design room temperature of 22°C. It reflect that if the uncertain inner heat gains is go to the minimum value, then the room's temperature will have the risk to be below the lower level of room temperature set point. And in the worst condition, the room's temperature will be 20.9°C, whereas, it will not under it.

Room 2-1-1 is located in the exterior zone and facing south-west. It is the warmest room in the afternoon. In another hand, room 2-1-4 is in the interior zone, it is relative cool than that in room2-1-1. Clearly, in this hour, system 2-1 could not couple with the simultaneous cooling and heating demands for both room 2-1-1 and room 2-1-4.

VAV systems

The first scheme proposed above has a large number of hour of dissatisfied. It is therefore not possible to meet the design conditions for all rooms for the whole year. A change of system type is proposed to improve this situation. A VAV system is used instead and the range of supply air flow rates is set at 2~8 ACH while all other design parameters remain unchanged.

The simulation results are shown in Table 3. It is obvious that the VAV systems has a lower hour of dissatisifed, thus the situation has been improved.

Table 3 Possible dissatisfied hours of VAV system

System No.	2-1	2-2
Hour of dissatisfied	2006	2125

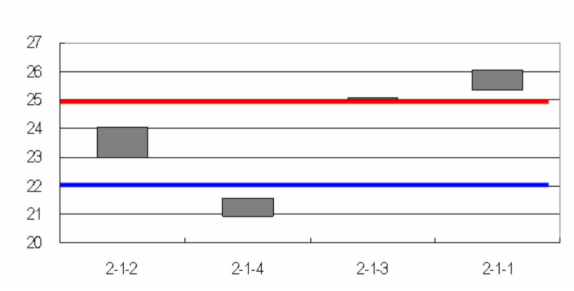

Figure 18 Room temperatures on 15 pm 16 Oct. of system 2-1

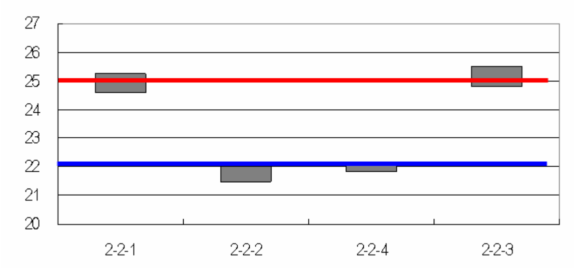

Figure 19 Room temperatures on 15 pm 16 Oct. of system 2-1

In Figure 18 and 19, by changing the HVAC system from CAV to VAV, the room temperature range became much small than that of CAV system. And the temperature range is also closer to the set point than the CAV's. However, at this time, the room temperature still has the possibility be overheating or overcooling.

CONCLUSION

The inner heat gains acts in an uncertain way in time serial and space. Presently, fixed schedule is generally used to describe the inner heat gains in the state of arts HVAC system simulation which couldn't reflect the uncertain characteristic of inner heat gains. This new mathematic methodology could be used to calculate the results under the interaction between uncertain factors and controlling means. By testify the validity of this method with Monte Carlo method, the results show the accurcy of this range opertion simulation method. With the applications of the HVAC system simulation method under uncertain heat gains, it represent a new way to perform HVAC system simulation which dealing with uncertain inner heat gains.

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