Fault Detection and Diagnosis for HVAC Systems Using Stochastic Qualitative Reasoning

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Abstract : HVAC (Heating Ventilating Air Conditioning) system is complex and available sensor information as its fault detection is insufficient. Qualitative reasoning is one of the effective ways for fault detection and diagnosis methods. Especially, the probabilistic process is used for state transition in the stochastic qualitative reasoning. In this paper, the stochastic qualitative reasoning is applied to a modelling method of human qualitative thinking process based on the instrumentation diagram and the control information of building HVAC system. However, several subjects are still to be dealt with for practical use. This paper proposes a real time simulation using the stochastic qualitative reasoning as a way of practical use for fault detection and diagnosis of VAV (Variable Air Volume) system, that is a kind of HVAC system.

Keywords : fault detection, stochastic qualitative reasoning, real time simulation

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1. Introduction

The various abnormalities of building HVAC system are difficult to detect and diagnose automatically because of available sensor information insufficiency. On the other hand, the need to automatically detect and diagnose critical faults is low because they are usually found as soon as they occur. Minor faults can also be found without implying calculation based on a difficult algorithm, as long as their data can be easily taken out as signal from contact switches because it can be converted to an alarm and displayed on a central monitor system (Building Automation System). Measured values can be automatically checked against general high and low limit values. As for a chiller in operation, a simple standardized program is available for checking high and low limits by obtaining the temperature difference between the inlet and the outlet. However, faults attributed to deterioration or inappropriate adjustment exist between the normal state and the completely failed state. If left alone, such faults can have serious adverse effects on energy, environment, and service life. This paper explains a fault detection and diagnosis technique using stochastic qualitative reasoning, which is one of the applications of the qualitative technique[1][2][3]. The behaviour of a VAV system could be expressed using a simple model called qualitative model with probabilities[4] and experiments of fault detection and diagnosis were carried out. This paper reports on the results of experiments.

2. Overview of the Algorithm of Stochastic Qualitative Reasoning

2.1 Expression of Qualitative Model With Probabilities

A qualitative model with probabilities is a model of a qualitative thinking process based on hardware diagram and control processes. Figure 1 shows an example of a model of relationship between the supply air temperature of an air conditioning machine and the room temperature.

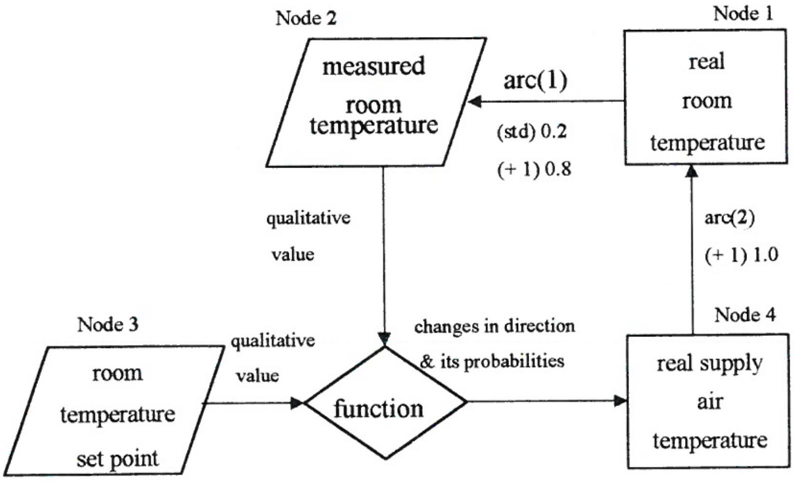

Figure 1. A Stochastic Qualitative Model

The nodes which are elements constituting the model have qualitative values. Successive real numbers are divided by a threshold limit value, and the real number values included in the same threshold limit value are handled as the same qualitative value. In this report, five symbols, A, B, C, D, and E, are used. They have a relationship of A > B > C > D > E. Figure 2 shows examples of threshold limit value used for defining qualitative values of room temperature. Since the measured room temperature node representing a room temperature sensor has real value data, it has one qualitative value at one time unless the threshold limit values of qualitative values are overlaid.

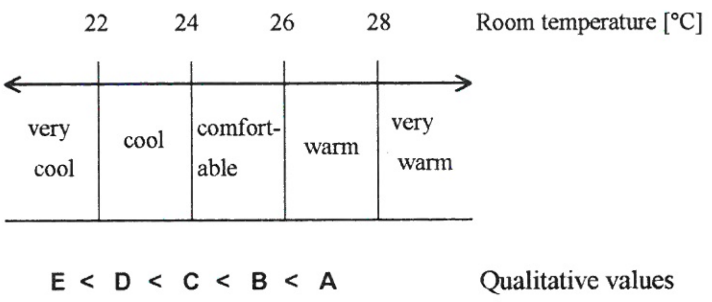

Figure 2. An Example of the Relationship Between Threshold Limit Values and Qualitative Values of Room Temperature

However, the room temperature node representing the state of the room can have multiple qualitative values and probabilities because it has no measured value. This is applicable also to the supply air temperature. A function is a table in which qualitative values are input from one or more nodes and that outputs probabilities of increasing the current qualitative value by one stage (up), keeping it unchanged (constant(const.)), and lowering it by one stage (down) to one node. "Up, const., and down" are called change directions. The probabilities of change directions are called choosing probabilities. The summation of their output probabilities to one node is 1.0. Table 1 is the table corresponding to the functions shown in Figure 1.

Table 1. An Example of Definition of A Function

Qualitative value of measured room temperature	Change in directions	Qualitative value of room temperature set point (High ←→ Low)				
		A	B	C	D	E
A	up	0	0	0	0	0
	const.	1.0	0.4	0	0	0
	down	0	0.6	1.0	1.0	1.0
B	up	0.6	0	0	0	0
	const.	0.4	1.0	0.4	0	0
	down	0	0	0.6	1.0	1.0
C	up	1.0	0.6	0	0	0
	const.	0	0.4	1.0	0.4	0
	down	0	0	0	0.6	1.0
D	up	1.0	1.0	0.6	0	0
	const.	0	0	0.4	1.0	0.4
	down	0	0	0	0	0.6
E	up	1.0	1.0	1.0	0.6	0
	const.	0	0	0	0.4	1.0
	down	0	0	0	0	0

When the room temperature set point is C and the measured room temperature is C, the output to the supply air temperature is up 0, const. 1.0, and down 0. If the measured room temperature goes up to B, the output to the supply air temperature will be up 0, const. 0.4, and down 0.6. The supply air temperature can take two states, 0.4 probability for C and 0.6 probability for D. The arrow that connects node 1 and node 2 in Figure 1 is called arc. Each arc is numbered. Let us take arc (1) as an example. When the room temperature comes to the level of changing the qualitative value from C to B, the probability that the measured room temperature keeps as C is 0.2. This is expressed as (std) 0.2. The probability that it goes as high as to B after one unit time (for example 5 minutes) is 0.8. This is expressed as (+ 1) 0.8. These are called propagation rules.

2.2 State Transition

A set of qualitative value information of all the nodes of a qualitative model with probabilities is handled as the state of a target diagnosis system. Not all the nodes have measured values. A system can take multiple states at one point of time. When the qualitative values of nodes 1, 2, 3, and 4 in Figure 1 are C, C, C, and C, respectively, the state of this system is expressed as [C C C C]. The probability, that is determined by the output of the function and the propagation rules is given to this state. This probability is called existence probability. If the state at the initial time [time=i-1] is [C C C C], and node 1 changes to B after one unit time [time=i], the resulting state is expressed as [B C C C]. Subsequently, new multiple states are produced by the function and execution of propagation rules after every one unit time. This is called state division. State transitions take place as shown in Figure 3.

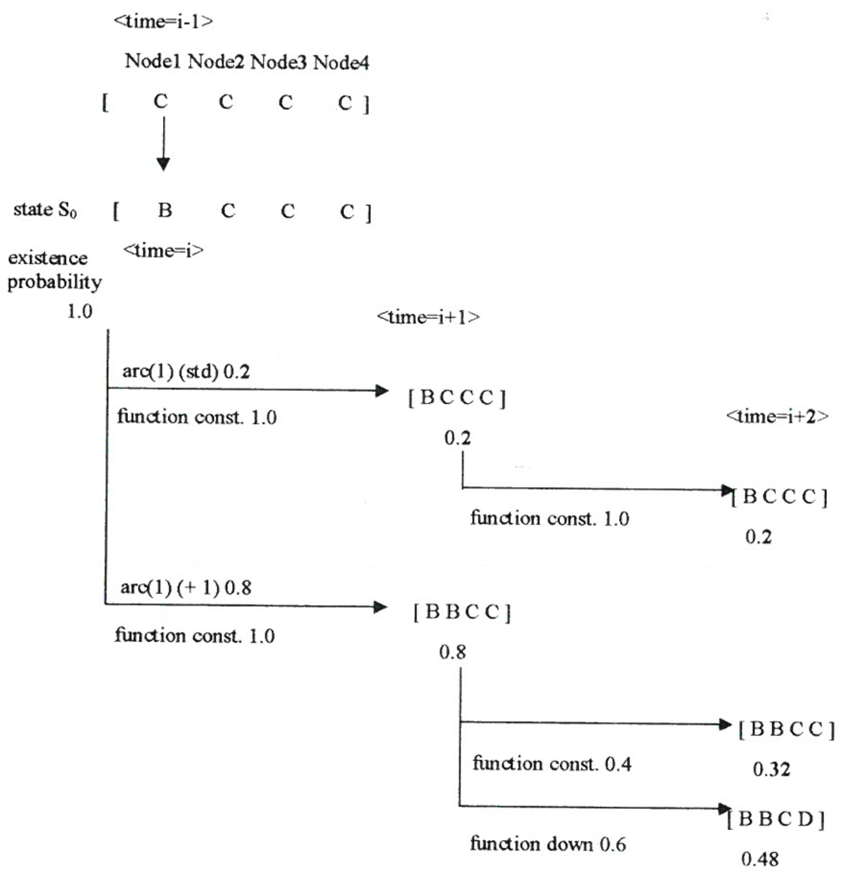

Figure 3. An Example of State Transition

2.3 Procedure of Stochastic Qualitative Reasoning

Let set the initial state and assume its existence probability as 1.0. Then, repeat the procedure shown in Figure 4 after one unit time for the set number of times. If the remaining state becomes 0 before the set number of times, end simulation.

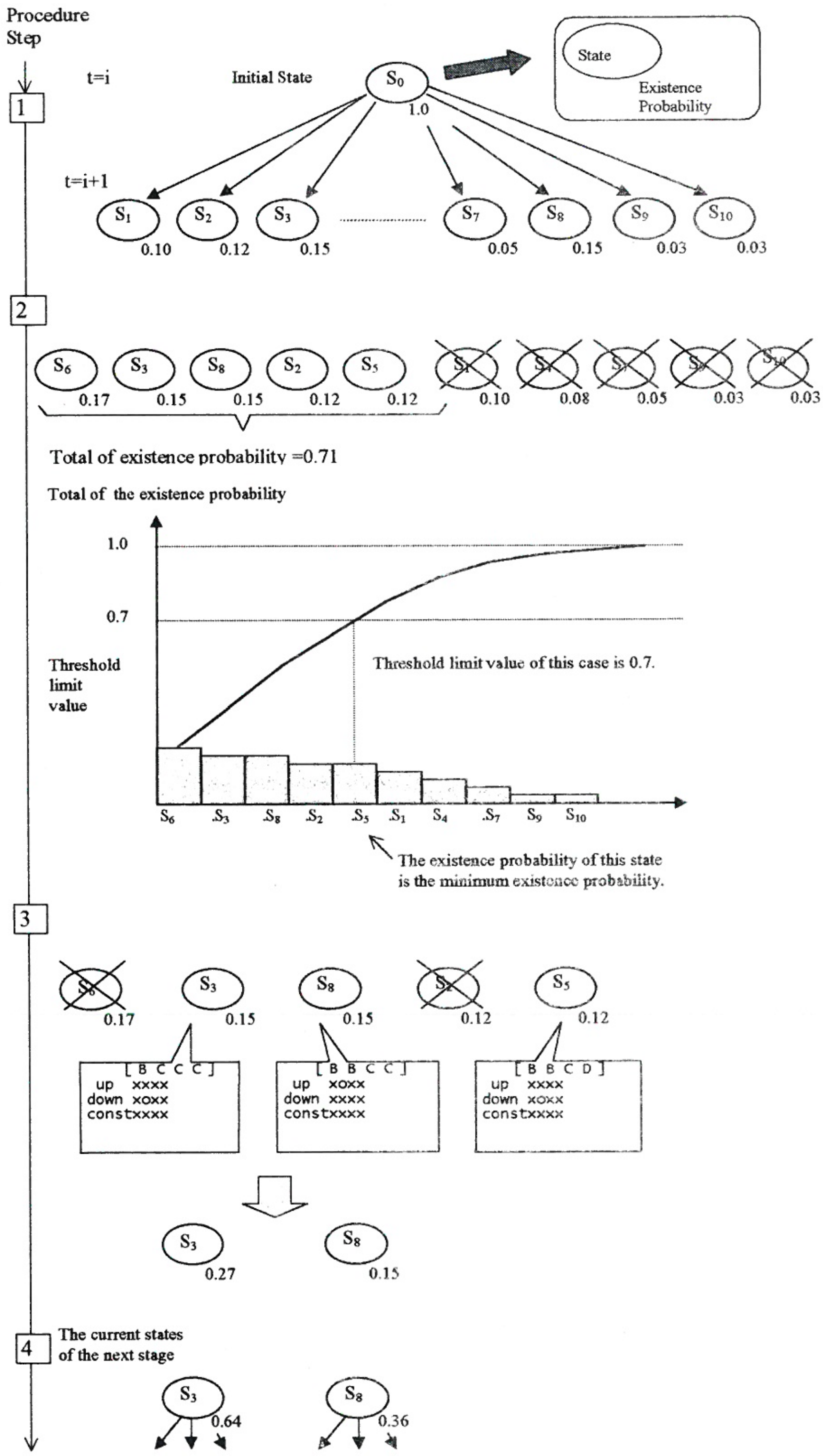

Figure 4. Simulation Process

2.4 Agreement Rate of Measured Values

Obtain the overall ratio of model agreement with the measured data of all the steps by multiplying the sums of the pre-normalization existence probabilities in individual unit steps (1, 2, ..., n). Since the value obtained by probabilities is too small, take n square root, and divide it by the threshold value that eliminates states of low existence probabilities. The result is called agreement rate. If the sum of pre-normalization existence probabilities of individual unit steps is put as Pn and the threshold limit value used for eliminating states of low existence probabilities is put as α, agreement rate Z is expressed by the following formula:

$$Z = \frac{(P_1 \times P_2 \times \ldots \times P_n)^{1/n}}{\alpha}$$

Of multiple abnormality models including a normal model, the model having the highest agreement rate most accurately explains the measured data. This value is used for detecting and diagnosing faults simultaneously.

2.5 Function Generation

Characteristic Parameter Expression of Function

Let take an 1-input function as an example of a characteristic parameter used for determining the choosing probabilities for change directions of the function. It can be defined as shown in Table 2 by giving fs($0.0 \le fs \le 1.0$) as output sensitivity, fc($-5.0 \le fc \le 5.0$) as the center, and fv($-1.0 \le fv \le 1.0$) as output change trends to input changes. In the Table, "x" is the qualitative value input to 1-input function F(x), while A, B, C, D, and E correspond to -2, -1, 0, 1, and 2, respectively. An 2- or more input function is expressed as a linear connection of input to an 1-input function.

Table 2. The Probabilities for Choosing A Function

Conditions	Return values and Choosing probability
$\frac{fs}{\lvert fv \rvert} \le fc+x$	Up* = min(((fc+x)|fv|-fs),0.5) +min(((fc+x)|fv|+fs),0.5) Down* = 0 Const. = 1.0-(Prob. of Up)-(Prob.of Down)
$-\frac{fs}{\lvert fv \rvert} \le fc+x \le \frac{fs}{\lvert fv \rvert}$	Up* = min(((fc+x)|fv|+fs),0.5) Down* = min(-((fc+x)|fv|-fs),0.5) Const. = 1.0-(Prob. of Up)-(Prob.of Down)
$fc+x \le -\frac{fs}{\lvert fv \rvert}$	Up* = 0 Down* = min(-((fc+x)|fv|-fs),0.5) +min(-((fc+x)|fv|+fs),0.5) Const. = 1.0-(Prob. of Up)-(Prob.of Down)

*If fv < 0.0, the Up and Down probabilities are reversed.

```
*** Qualitative function generation program Ver1.2***
How many inputs of function (1~4) ? : 2                          ← fs
Sensitivity (1.Very strong 2.Strong 3.Weak 4.None) ?: 4
Common parameter (not dependent on number of input) was determined
The following parameters are dependent on the number of inputs.
                                         Information about room temp.
***** Input No.1 parameter is determined *****
                                                                  direction of fv1
Center qualitative value (0.A  1.B  2.C  3.D  4.E    5.help) ?: 2  ← fc1
Up of output(1.input increase 2.input decrease 3.isn't dependent on input)?: 2
Sensitivity of output(1.Very strong 2.Strong 3.Weak 4.None) ?: 1    Strength of fv1

                                         Information about room temp. set point
***** Input No.2 parameter is determined *****
Center qualitative value (0.A  1.B 2.C 3.D  4.E 5.help) ?: 2   ← fc2
                                                                  direction of fv2
Up of output (1.input increase 2.input decrease 3.isn't dependent on input)?: 1
Sensitivity of output (1.Very strong 2.Strong 3.Weak 4.None) ?: 1   Strength of fv2
```

(Function Generation Program Execution Result)

Room temp.	Room temp. set point	Up	Const.	Down
0	0	0	100	0
0	1	0	40	60
0	2	0	0	100
0	3	0	0	100
0	4	0	0	100
1	0	60	40	0
1	1	0	100	0
1	2	0	40	60
1	3	0	0	100
1	4	0	0	100
2	0	100	0	0
2	1	60	40	0
2	2	0	100	0
2	3	0	40	60
2	4	0	0	100
3	0	100	0	0
3	1	100	0	0
3	2	60	40	0
3	3	0	100	0
3	4	0	40	60
4	0	100	0	0
4	1	100	0	0
4	2	100	0	0
4	3	60	40	0
4	4	0	100	0

Figure 5. An Example of Function Generation By Qualitative Information

Generating A Function Using Qualitative Information

A method using qualitative information is convenient for determining the values of characteristic parameters from a time-sequential graph of measured values. The following procedure is used for producing the function table shown in Table 1, based on the qualitative information from Figure 5. First, select "none" for "sensitivity" of the whole. As for the room temperature information, select "C" for the center qualitative value. If the room temperature goes down, the supply air temperature gets higher as to make the room temperature closer to the set point. Since this is a proportional relationship with a negative coefficient, select "input decrease" for supply air temperature rise. Select "Very strong" for the supply air temperature change. As for the room temperature set point information, select "C" for the center qualitative value. Select "Input increase" for "Up to output" because the room temperature set point must improve to upgrade the supply air temperature. Select "Very Strong" for output change. A Table showing probabilities of change directions as shown in the lower half of Figure 5, can be obtained.

3. Real Time Processing of Fault Detection and Diagnosis

3.1 Meaning of Real Time Processing

Real time processing means to process measured data immediately and synchronously with an on line system such as a central monitor system (Building Automation System), to judge a fault, namely, to detect and diagnose a fault. Since all operating information of an HVAC system is automatically sent to the central monitor system, operation and monitoring can be facilitated by replacing the thinking process of an operator or a manager who checks time-sequential graphs of real time measured data and finds an abnormal state with stochastic qualitative reasoning.

3.2 Processing Program

The flow shown in Figure 6 takes place to real-time perform stochastic qualitative reasoning in the field. The flow is summarized below.

a. Data collection
Measured data defined under the qualitative model are on line collected from the central monitor system in the fixed cycle.

b. Qualitative value definition
Measured value data of a fixed period are statistically processed to produce a qualitative value table of each measured value. Using these tables, series of measured data are converted to series of qualitative values.

c. Tuning
Characteristic parameters used for periodically generating functions are adjusted synchronously with the qualitative value definition. Basically, that means to adjust the functions of a normal model using normal state data.

d. Fault detection and diagnosis
Fault detection and diagnosis simulation are executed in real time. The agreement rate of measured values is obtained for each model, to detect and diagnose a fault.

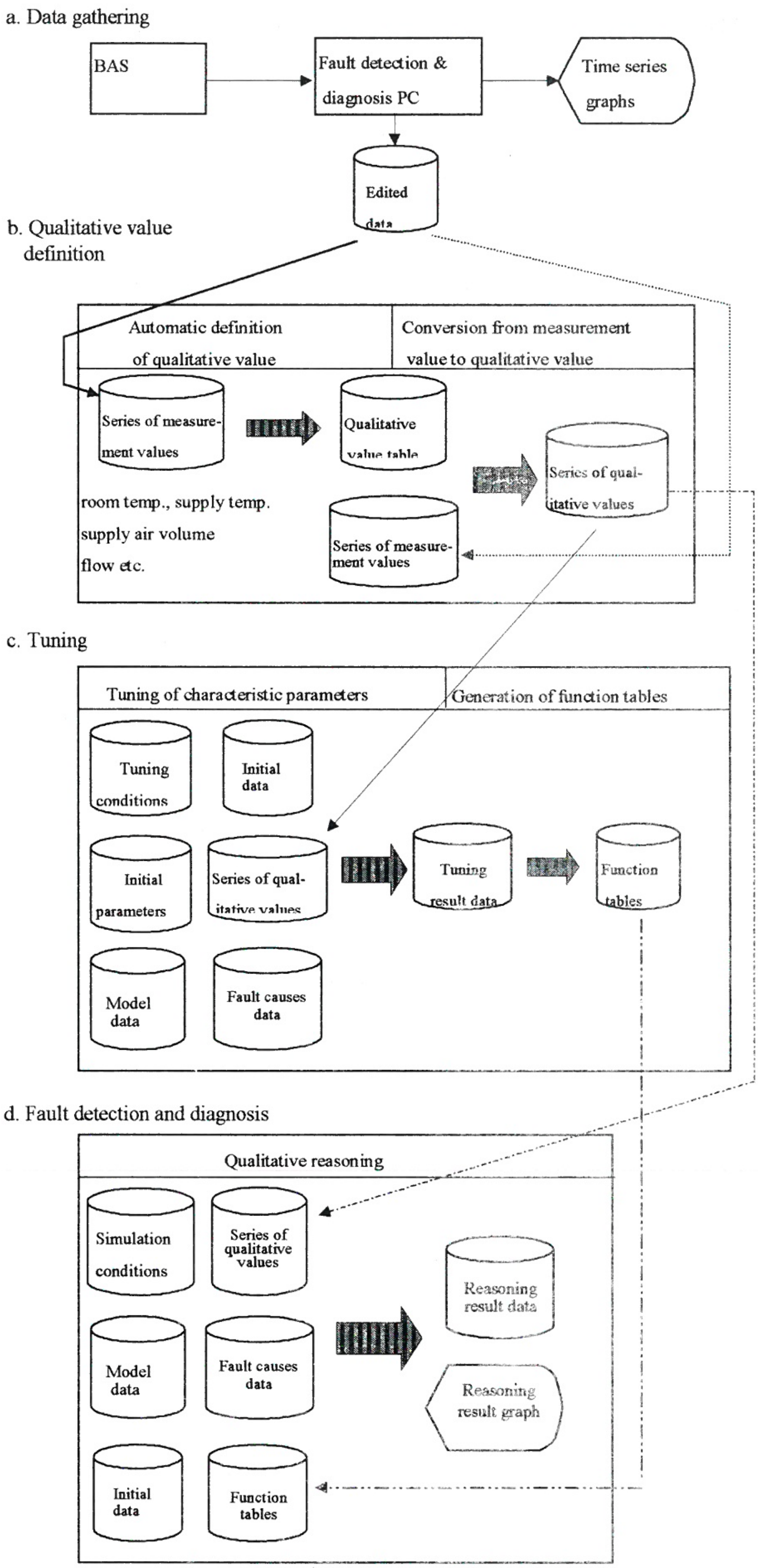

Figure 6. Structure of Real Time Procedure

4. Fault Detection and Diagnosis Experiments of VAV System[5]

4.1 Overview of the VAV System

Figure 7 is a schematic diagram of the VAV system used for experimenting fault detection and diagnosis. It is operated in the cooling mode throughout a year. The automatic control logic of the VAV controller related to the description of the qualitative model with probabilities is explained below.

a. Supply air temperature control
The supply air temperature was kept at 10°C in the summer cooling mode and controlled between 10°C and 18°C in the other modes. Judgments are made in the fixed cycle. If even one of the VAV units has the minimum air volume, the supply air temperature set point is raised by t_1°C. If even one of the VAV units has the maximum flow rate, the supply air temperature set point is lowered by t_1°C. If no VAV has a maximum or a minimum flow rate, the supply air temperature set point is lowered by t_2°C. At the time of the experiment, the judgment cycle took 20 minutes, and t_1 and t_2 were 0.5 and 0.1, respectively.

b. Supply air volume control
If even one of the VAV units is full open, the invertor output raises by i%. Note that the invertor output is unchanged if the room temperature requirement is met. If no one of the VAVs is full open, the invertor output is lowered by i%. The judgment cycle took 1 minute and output control was 1%.

c. Supply air VAV temperature control
VAV air volume is calculated based on the room temperature set point and the measured data in the 1-minute cycle, and the air volume set point is sent to VAV units.

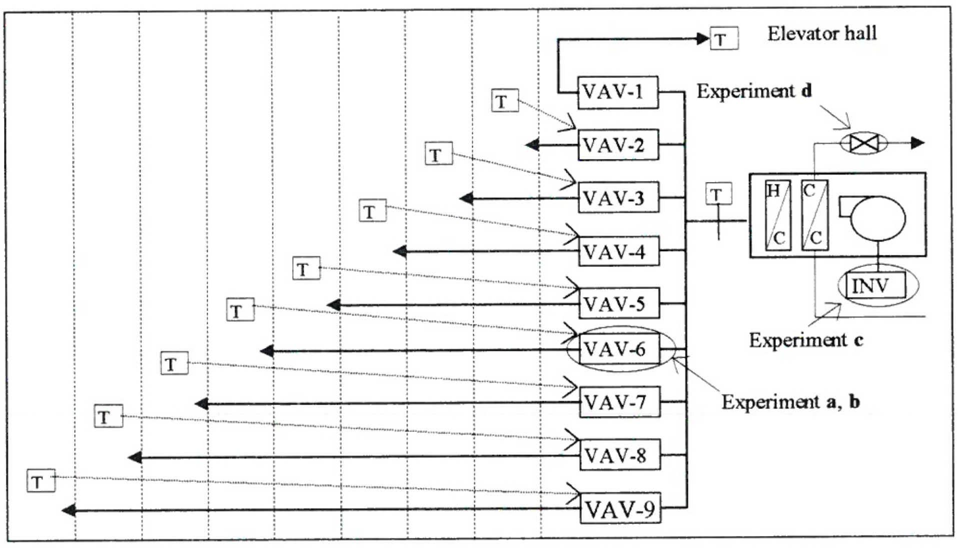

Figure 7. Schematic Drawing of Experimented VAV System

4.2 Collection of Abnormal Data

Experiment

The four types of abnormalities shown in Table 3 were simulated in the system operating in an automatic control mode. The experiment started at about 10 o'clock when the air conditioning state becomes stationary. The system was controlled such that the room temperature was restored to the original level when a deviation of about 1°C could be detected. The data collection cycle took 1 minute and the diagnosis cycle lasted 5 minutes.

a. VAV full opening experiment
The VAV controller output a forceful maximum air flow volume signal to VAV-6 unit and fixed the unit to this state.

b. VAV full closing experiment
The VAV controller output a forceful minimum air flow volume signal to VAV-6 unit and fixed the unit to this state.

c. Supply air volume decreasing experiment
The supply air fan invertor was changed from auto to manual and the output was lowered.

d. Chilled water flow rate decreasing experiment
The opening of the 2-way chilled water valve of the air conditioning unit was decreased by manual setting.

Table 3. Details of Experiments

Experiment \ Abnormality	Abnormality location	Method of causing abnormal state	Related cause of abnormality
a. VAV full open	VAV-6	Fixing the supply air volume setting to the maximum.	VAV motor failure, control problem
b. VAV full closed	VAV-6	Fixing the supply air volume setting to the minimum.	VAV motor failure, duct clogging, control problem
c. Decreasing supply air volume	Air conditioner fan	Fixing the invertor speed.	Fan abnormality, filter clogging, control problem
d. Decreasing chilled water flow rate	Air conditioner 2-way valve	Fixing the position of the chilled water 2-way valve.	2-way valve failure, coil clogging, control problem

Experimental Data in Summer Season and Intermediate Season

a. Summer experiment data

Figure 8 shows the measured data of Summer experiment. In the VAV-6 full opening experiment, the VAV controller output a forceful maximum air volume signal at 10:15, fixed VAV-6 to this state, and released it at 10:40. In the VAV full closing experiment, the air volume set point was fixed to the minimum at 11:25 and released at 12:10. In the air volume decreasing experiment, the supply air fan invertor that had been fixed to 55% was fixed to 40% at 13:40. Since hardly was any change observed, the output was changed to 30% at 14:05 and it was released at 14:40. In the chilled water volume decreasing experiment, the 2-way chilled water valve was fixed to 30% at 15:25 and released at 17:00.

b. Experiment data during intermediate season
The same types of experiments as the summer season experiments were carried out. Figure 9 shows the measured data of the intermediate season.

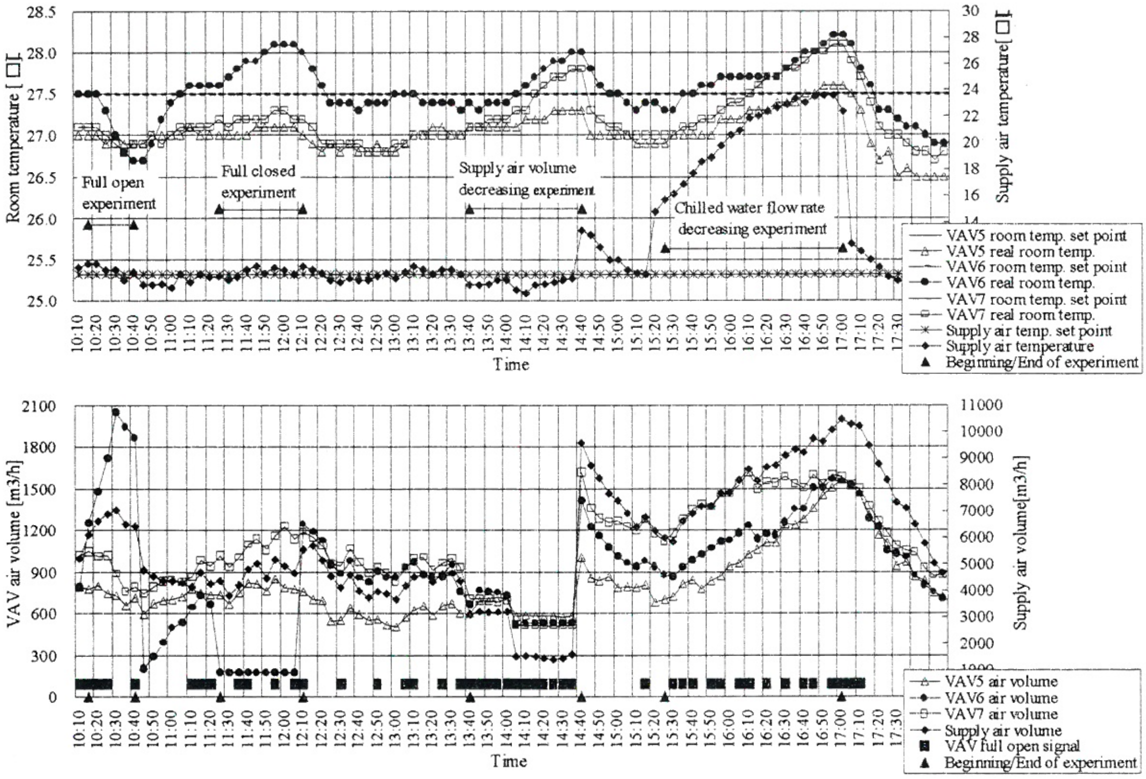

Figure 8. Measured Data of Summer Season Experiments

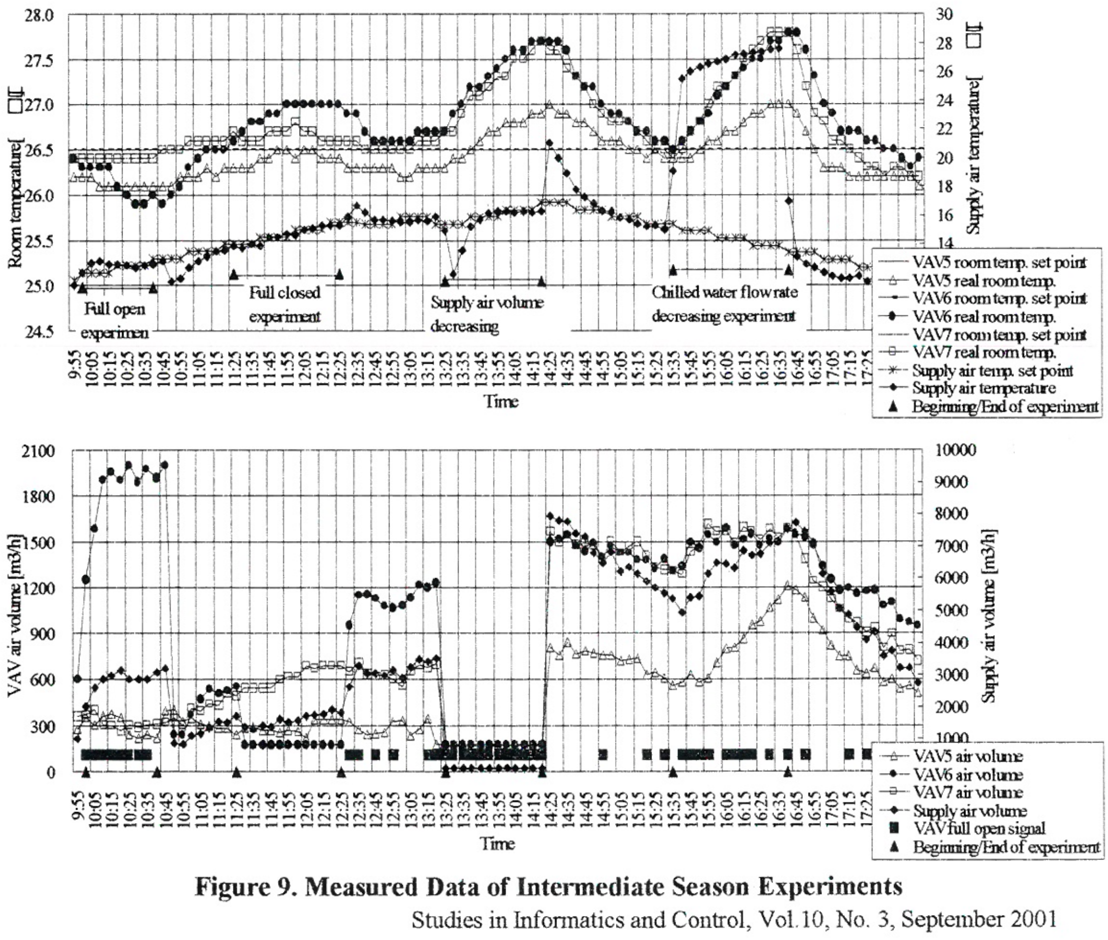

Figure 9. Measured Data of Intermediate Season Experiments

4.3 Development of A Qualitative Model With Probabilities

The basic model is shown in Figure 10. In consideration of actual processing time, a model consisting of three VAV units was used. The VAV-6 unit which caused the full-open/closed state was positioned in the middle. The supply air volume and the supply air temperature of the air conditioning unit were included.

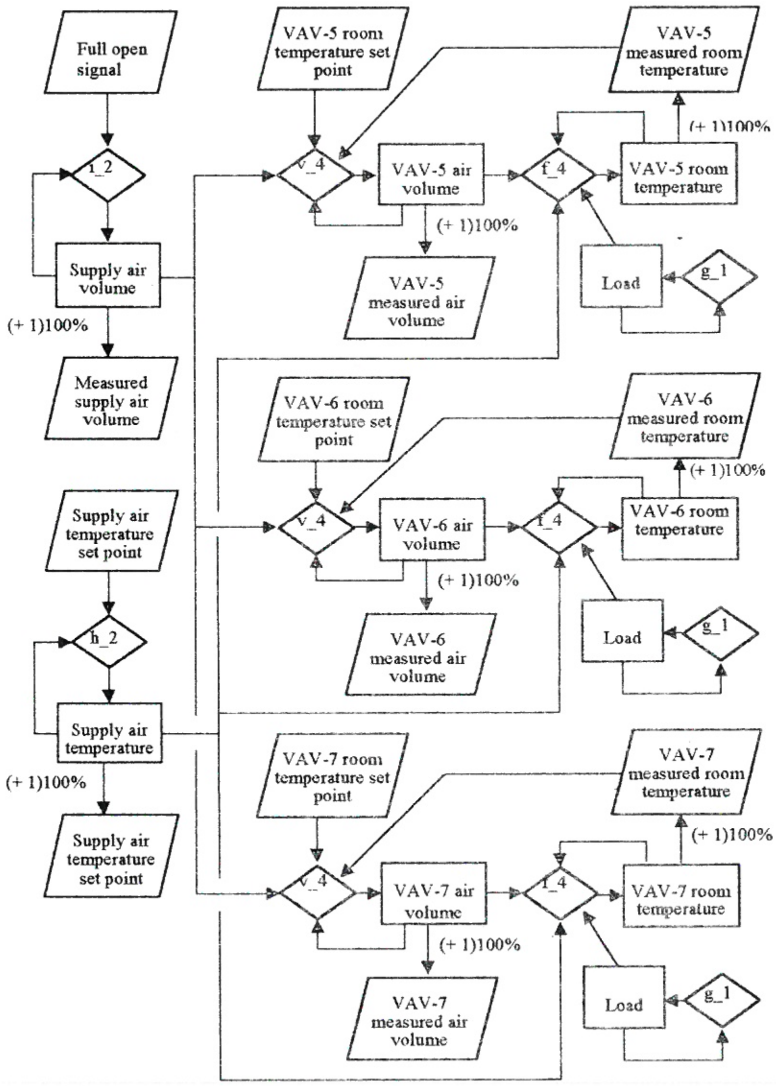

Figure 10. Qualitative Model of the VAV System

Qualitative Value Definition

Basic statistic quantities of individual measured value nodes were obtained from 15-cycle data during air conditioning hours (9:00~19:00) on an ordinary operating day in August for the Summer season and in November for the intermediate season. Table 4 shows the real number range of qualitative values of the Summer season determined from the standard deviations, average values of measured data and set values. Also, the intermediate season is shown in Table 5. For the Summer experiment, the spectrum of qualitative values was 4σ because both supply air temperature and room temperature were stable. Each set point value was the centre of quality value C.

Table 4. Automatic Definition of Qualitative Values (Summer Season)

Sensor / Qualitative value	Supply air temperature set point (°C)	VAV5 room temperature set point (°C)	VAV6 room temperature set point (°C)	VAV7 room temperature set point (°C)	Supply air volume (m^3/h)	VAV5 air volume (m^3/h)	VAV6 air volume (m^3/h)	VAV7 air volume (m^3/h)	Full open signal
A	16.8~	27.6~	28.6~	28.0~	9027~	1226~	1289~	1487~	1
B	12.3~16.7	27.2~27.5	27.9~28.5	27.3~27.9	6306~9026	908~1225	920~1288	1123~1486	0
C	7.7~12.2	26.8~27.1	27.1~27.8	26.7~27.2	3584~6305	590~ 907	551~919	759~1122	
D	3.2~ 7.6	26.4~26.7	26.4~27.0	26.0~26.6	863~3583	273~ 589	182~ 550	395~758	
E	~ 3.1	~26.3	~26.3	~25.9	~ 862	~ 272	~ 181	~ 394	
Standard deviation	1.13	0.11	0.18	0.16	1,361	159	185	182	
Average value	10.1	27.0	27.5	27.0	4,945	750	735	940	
Room temperature set point		27.0	27.5	27.0					

Table 5. Automatic Definition of Qualitative Values (Intermediate Season)

Sensor / Qualitative value	Supply air temperature set point (°C)	VAV5 room temperature set point (°C)	VAV6 room temperature set point (°C)	VAV7 room temperature set point (°C)	Supply air volume (m^3/h)	VAV5 air volume (m^3/h)	VAV6 air volume (m^3/h)	VAV7 air volume (m^3/h)	Full open signal
A	21.8~	28.5~	27.7~	27.7~	6917~	570~	1795~	1451~	1
B	16.9~21.7	27.2~28.4	26.9~27.6	26.9~27.6	4213~6916	402~ 569	1231~1794	953~1450	0
C	12.1~16.8	25.8~27.1	26.1~26.8	26.1~26.8	1509~4212	234~ 401	667~1230	455~ 952	
D	7.3~12.0	24.5~25.7	25.3~26.0	25.3~26.0	1195~1508	65~ 233	103~ 666	-43~ 454	
E	~ 7.2	~24.4	~25.2	~25.2	~-1196	~ 64	~ 102	~ -44	
Standard deviation	2.42	0.11	0.20	0.20	1,352	84	282	249	
Average value	14.5	27.0	26.5	26.5	2,861	317	949	704	
Room temperature set point		27.0	26.5	26.5					

Since the supply air volume and the air volume of each VAV fluctuate considerably, 2σ was set as the range of qualitative values and the average value was set as the center of C. As for the intermediate season, since the supply air temperature setting fluctuates within the range of 10 °– 18°C, 2σ of supply air temperature setting was set as the range of qualitative values and the average value was set as the centre of C.

Generating the Functions of A Fault Model

The functions expressing a fault model were generated based on the qualitative information given in Table 6.

a. VAV full open model
It was assumed that the room temperature set point and the measured room temperature, which are input variables to the v_4 function of VAV-6, had nothing to do with the VAV-6 air volume.

b. VAV full closed model
Like the VAV full open model, the room temperature set point and the measured room temperature were separated from the VAV-6 air volume.

c. Supply air volume decreasing model
It was assumed that the supply air volume does not rise by full open information.

d. Chilled water flow rate decreasing model
As the supply air temperature increases as the chilled water volume decreases, the centre qualitative value at which the supply air temperature becomes stable was assumed as A.

Table 6. Function Change Information

Model		Characteristic parameter qualitative information		Normal function	Abnormal function
VAV full open	Modify V-4 function	Sensitivity		1.Very strong	2.Strong
		Room temperature set point	Center qualitative value	2.C	→"
			Output up	2.Input decrease	3.Non-dependent on input
			Output sensitivity	2.Strong	4.None
		Supply air volume	Center qualitative value	2.C	3.D
			Output up	1.Input increase	→"
			Output sensitivity	2.Strong	→"
		Measured room temperature	Center qualitative value	2.C	→"
			Output up	1.Input increase	3. Non-dependent on input
			Output sensitivity	3.Weak	4. None
		VAV air volume	Center qualitative value	3.D	0.A
			Output up	2. Input decrease	→"
			Output sensitivity	2.Strong	→"
VAV full closed	Modify V-4 function	Sensitivity		1.Very strong	2. Strong
		Room temperature set point	Center qualitative value	2.C	→"
			Output up	2. Input decrease	3. Non-dependent on input
			Output sensitivity	2.Strong	4. None
		Supply air volume	Center qualitative value	2.C	1.B
			Output up	1. Input increase	→"
			Output sensitivity	2.Strong	→"
		Measured room temperature	Center qualitative value	2.C	→"
			Output up	1. Input increase	3. Non-dependent on input
			Output sensitivity	3.Weak	4. None
		VAV air volume	Center qualitative value	3.D	→"
			Output up	2. Input decrease	→"
			Output sensitivity	2.Strong	→"
Supply air volume decreasing	Modify I-2 function	Sensitivity		2. Strong	→"
		Full open signal	Center qualitative value	1.B	→"
			Output up	1. Input increase	3. Non-dependent on input
			Output sensitivity	2. Strong	4. None
		Supply air volume	Center qualitative value	2.C	→"
			Output up	2. Input decrease	→"
			Output sensitivity	3.Weak	2. Strong
Chilled water flow rate decreasing	Modify h-2 function	Sensitivity		2. Strong	→"
		Supply air temperature set point	Center qualitative value	2.C	→"
			Output up	1. Input increase	→"
		Supply air volume	Output sensitivity	1. Very strong	→"
			Center qualitative value	2.C	0.A
			Output up	2. Input decrease	→"
			Output sensitivity	1. Very strong	→"

4.4 Simulation Results

Figure 11 shows the real time Summer season simulation results. The detection rate of the vertical axis is a nearly normalized value obtained through dividing the value by an appropriate number determined based on the maximum value of the agreement rate. The standard threshold limit value that eliminates the state of low existence probabilities was 0.5. Steps of the simulation are 6. Also, the result of intermediate season experiment is shown in Figure 12. Also, Table 7 shows the fault detection results. The denominator indicates the number of steps from the beginning to the end of each experiment.

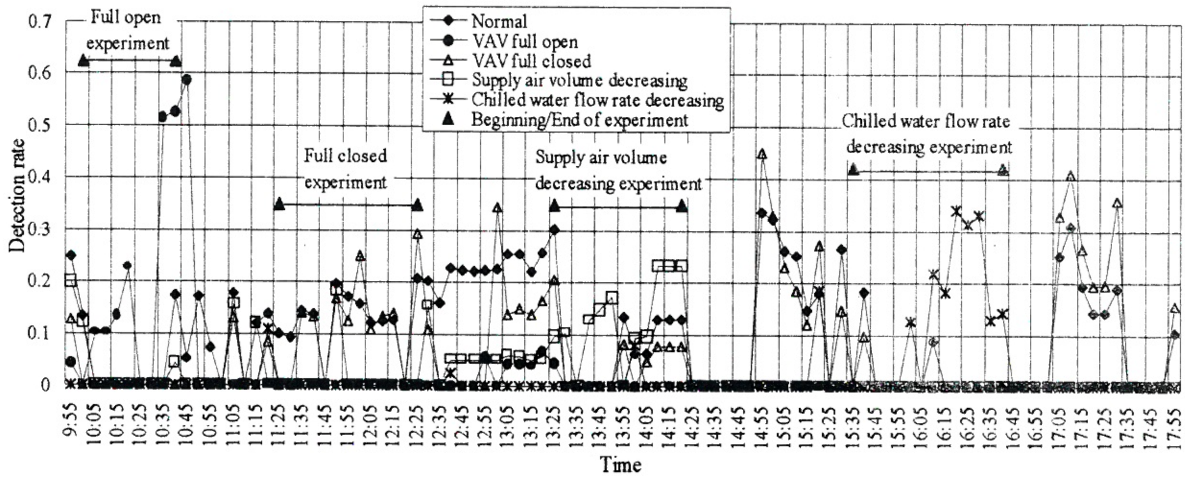

Figure 11. Simulation Results of Summer Season Experiments

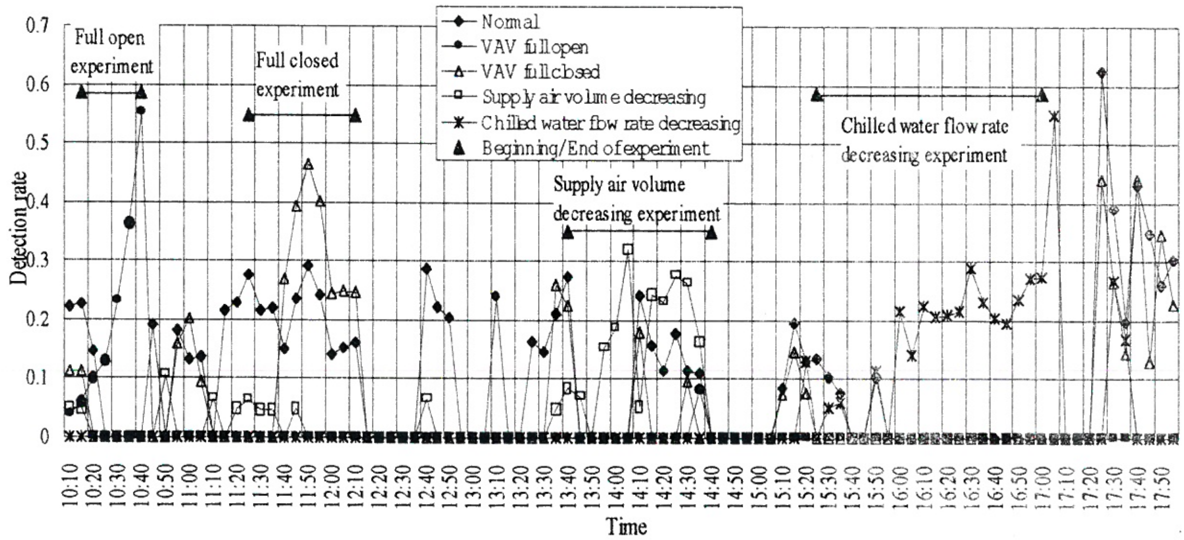

Figure 12. Simulation Results of Intermediate Season Experiments

As for the Summer season, a fault could be detected and diagnosed 4 times out of 6 in the full open experiment, 7 times out of 10 in the full closed experiment, 9 times out of 13 in the air volume decreasing experiment, and 14 times out of 20 in the chilled water rate decreasing experiment, namely, about 70%.

Table 7. List of Detection Results

Experiment \ Season	Summer season experiment	Intermediate season experiment
①VAV-6 full open experiment	4/ 6	6/ 9
②VAV-6 full closed experiment	7/10	4/13
③Supply air volume decreasing experiment	9/13	9/12
④Chilled water flow rate decreasing experiment	14/20	8/14

As for the intermediate season, a fault could be detected and diagnosed 6 times out of 9 in the full open experiment, only 4 times out of 13 in the full closed experiment, but 9 times out of 12 in the air volume decreasing experiment, and 8 times out of 14 in the chilled water rate decreasing experiment, namely. The percentage of fault detection and diagnosis was generally high.

5. Conclusions

This paper described the procedure of stochastic qualitative reasoning as an example of applying the qualitative technique and reported the results of applying it to fault detection and diagnosis of an VAV system.

We plan to conduct case studies of various HVAC systems. We must continue the research because it is a pending issue whether a model that is larger than the qualitative model of this report can be processed within practical time or not.

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