Practical Application of Stochastic Qualitative Reasoning to Fault Detection of Building Air Conditioning Systems

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Abstract

Qualitative reasoning is a key technology for the model based fault detection, in which a part in failure is identified by comparing the results of reasoning with the real measured values. However, this approach has a problem of increasing possible patterns of behavior of the model enormously because of ambiguity of the qualitative reasoning.

To solve the problem, we have proposed the stochastic qualitative reasoning. In this method, all states, whose series compose behavior of the system, have existence probability and the state with relatively small existence probability are eliminated.

Through the application of this mechanism to the fault detection of air conditioning systems using field data, we have confirmed the effectiveness of fault detection with the stochastic qualitative reasoning.

Introduction

It is necessary to detect a fault of a building air conditioning system from the viewpoint of the environment(ex. hot, cold) and energy conservation(by equipment and control system) and so on because of confirmation that the system is controlled satisfactorily. However, the cost of the system is limited so strictly that the system can't have enough sensors to obtain crucial data of fault detection. Collecting data specially will be an additional burden for daily operation. And each building air conditioning system has various, vague and changeable structure.

Qualitative reasoning is a powerful technique of analyzing the behavior of a system in such a situation(Kuipers & Berleant 1992)(Lackinger & Nejdl 1993)(Lackinger & Obreja 1991). It has an advantage in that the complicated physical mechanisms of the system are expressed simply with symbolic casual relation. Model based fault detection using the qualitative reasoning, in which a part in failure is identified by comparing the results of reasoning with the real measured values, is expected to cope with the above mentioned problems. However, this approach has a problem of increasing possible patterns of behavior of the model enormously because of ambiguity of the qualitative reasoning.

We have proposed the stochastic qualitative reasoning(Mihara et al. 1994)(Arimoto et al. 1995). In this method, the qualitative model is constructed from the stochastic viewpoint. All the state have existence probability. The probabilistic process is introduced to the state transitions, and the states with relatively small existence are eliminated. As a result, the number of generated states are suppressed under computable order.

This paper describes a practical application of the stochastic qualitative reasoning to the fault detection of building air conditioning systems. In this application, the simulation is performed with a normal or fault qualitative models, which represent systems with a certain fault part. Effectiveness of the fault detection with the stochastic qualitative reasoning is presented using field data at a hospital in Tokyo in winter.

Qualitative Model with Probabilities

A qualitative model is generated based on the hardware diagram and control process. The models can represent probabilistic causal relations between elements of the target with propagation rules. An example of a simple stochastic qualitative model is illustrated in Figure 1.

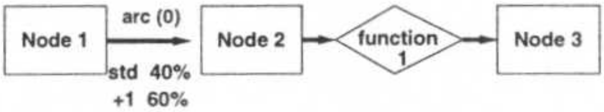

Figure 1: An example of a simple qualitative model.

The qualitative model is constructed from nodes, arcs with propagation rules, and functions.

Nodes

Nodes correspond to the elements of a system. Each node is characterized with some qualitative value as shown in Table 1.

Table 1: Qualitative value of temperature.

Qualitative value	Interpretation	Definition
A	extremely hot	24°C ~
B	hot	23°C ~ 24°C
C	normal	22°C ~ 23°C
D	cold	21°C ~ 22°C
E	extremely cold	~ 21°C

There are some components whose values are measured by the sensors. These elements are expressed with measured nodes, which make the use of decreasing the ambiguity of the qualitative reasoning.

Arcs with the propagation rules

An arc connects two nodes. The direction of an arc implies the direction of the propagation of influence. Propagation rules are attached on an arc. Five types of the propagation rules shown in Table 2 are prepared. More than one propagation rules are often attached to an arc. In this case, each rule has a choosing probability which indicates the probability of the rule being applied.

Table 2: Types of propagation rules.

+2(−2)	If the source node of the arc changes, the destination node changes in the same (opposite) manner of the source node two unit time later.
+1(−1)	If the source node of the arc changes, the destination node changes in the same (opposite) manner as the source node one unit time later.
std	If the source node of the arc changes, the destination node is still unchanged.

In Figure 1, for example, the arc (0) has two propagation rules, (std) and (+1). Choosing probabilities of them are 0.4 and 0.6 respectively. If the qualitative value of the source node of the arc, namely, "Node 1", changes in this model, the qualitative value of the destination node, "Node 2", is still unchanged in probability of 0.4, otherwise, it changes one unit time later.

Functions

In case that a value of destination node is influenced not by change of the source node but by the qualitative value itself, such a causal relation is expressed with a function. A function receives qualitative values of nodes as inputs, and gives change direction and its probabilities as output. Three types of change direction on the function shown in Table 3 are prepared. Table 4 shows an example of the definition of a function. Each change direction of the source node including its choosing probability is determined according to the table.

Table 3: Types of change direction on the function.

Up	The value of destination node increase.
Down	The value of destination node decrease.
Const	The value of destination node is unchanged

Table 4: An example of a definition of function.

Input	Output		
Set	Prob.(%)		
temp.	Up	Const.	Down
A	0	60	40
B	0	80	20
C	10	80	10
D	20	80	0
E	40	60	0

Stochastic Qualitative Reasoning

The stochastic qualitative reasoning is excused by a series of recursive state transition in the qualitative model. A state of a system on the qualitative model is defined as a set of qualitative values of all node in the model. When the qualitative values of nodes 1,2 and 3 in Figure 1 is respectively B, B, C, the state of this model is expressed as [B, B, C].

An example of a state transition of the model in Figure 1 is shown in Figure 2. Each state has an existence probability. The existence probability of each new state is calculated based on the existence probability of the previous state and choosing probability of

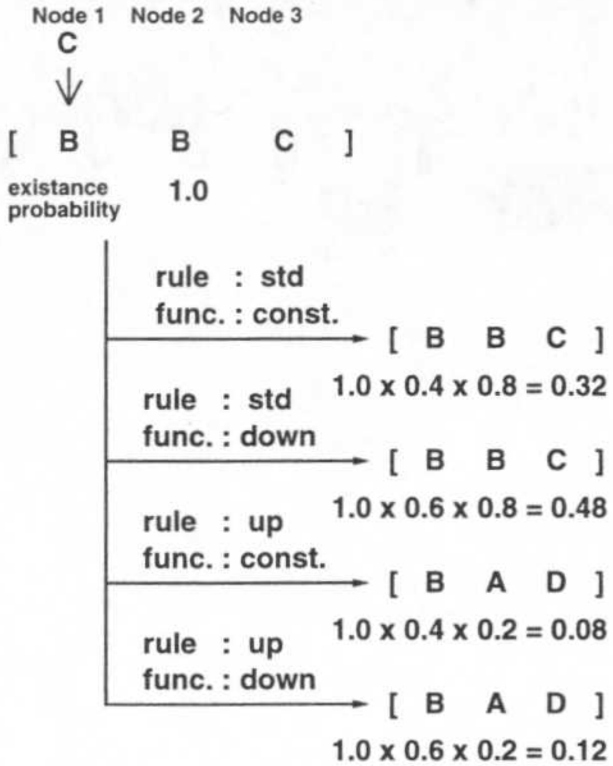

Figure 2: An example of state transition.

the applied rules and functions. The existence probability of the initial state is 1.0.

The basic procedure of the stochastic qualitative reasoning is summarized as follows.

Step 1. Generation of the state

All propagation rules and functions are applied to the current state, and then all possible states are generated and the existence probabilities of them are calculated.

Step 2. Elimination of the states with the small existence probability

The state is sorted in order of the existence probability. Each of the probability is added in order until the sum arrives at the predefined threshold. Then, all of remaining states are eliminated.

Step 3. Discard of the state that cannot agree with the measured value

If the qualitative value of the measured node in a new state is different from the measurement, the state is discarded.

Step 4. Normalization of the existence probability

The existence probability of each new state, which has not discarded, is normalized to make the total of the existence probability of the state equal to 1.0. The normalized state is regarded as a new current state of the next stage and the step 1 is performed again until final stage.

In the step 3, 'threshold', which is predefined parameter, expresses the maximum sum of the existence probabilities. The state elimination by the threshold has been introduced in order to avoid consuming enormous execution time and large memory in generating all possible states. The lower 'threshold' is supplied, the more roughly but the more quickly simulation is executed.

For further details of the algorithm, see the reference(Arimoto et al. 1995).

Figure 3 shows a sample of simulation practice. First, ten states are generated based on the initial state S0 in the Step1. The sum of those states' existence probabilities is 1.0. Next, in the Step2, the states are sorted in order of their existence probability. After the sum of probabilities reached 0.7, which is a predefined threshold, remaining states,namely, S1, S4, S7, S9 and S10, are eliminated. S6 and S2, which are disagreed with the real measured values pattern, are discarded in the Step3. Since S3 and S5 are the same states, they are unified into one state S3' and their existence probabilities are added. In the Step4, existence probabilities of survived states S3' and S8 are divided by the sum of them, namely, 0.42. Then those states become the next current states, and simulation is continued.

In the simulation step 3, the states which cannot agree with the measurements are discarded. If most of the new states are discarded, we cannot consider that the state transition reflects the real behavior of the target well. On the other hand, if most of the states are survive, we can conclude that the state transition reflects the real behavior well. We have introduced the evaluation parameter that can estimate the degree of agreement of the simulation result with the measured behavior, named the agreement rate, based on this idea.

The definition of the agreement rate R_a is shown as follows.

$$R_a = \left(\frac{\hat{P}_1}{P_1} \times \frac{\hat{P}_2}{P_2} \cdots \times \frac{\hat{P}_n}{P_n}\right)^{\frac{1}{n}} \simeq \frac{(\hat{P}_1 \times \hat{P}_2 \times \cdots \times \hat{P}_n)^{\frac{1}{n}}}{\theta}$$

In this expression, P_i means the sum of existence probabilities of the states after the elimination of step

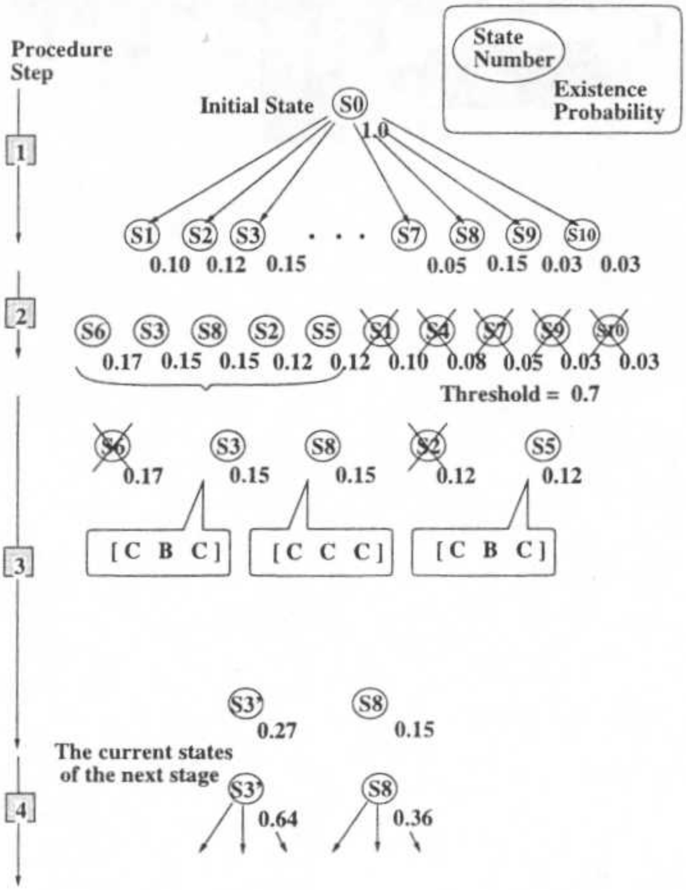

Figure 3: Simulation process.

2, and $\hat{P}_i$ means the sum of existence probabilities of the states that are survived in the step 3 at the i-th cycle of the simulation process, n is the number of cycles of the simulation(the simulation time), and θ means the threshold value.

The value of the agreement rate R_a is an indicator showing how consistent that model was with the series of measured values if any state subsisted until the last step. The higher this value, the higher the possibility of the behavior represented by the simulation model. If there is no survived state at a simulation cycle, the value of the agreement rate R_a is calculated as zero and the simulation is terminated.

Fault Detection of Building Air Condition System

Qualitative Model of Building Air Conditioning System

A building air conditioning system aims at keeping temperature of rooms at a set value by supplying warmed or cooled air. Temperature of supply air is controlled appropriately based on the set value and measured values at sensors in the room, etc. Figure 4 shows an outline of it. Figure 5 illustrates the qualitative model of a building air conditioning system.

In this model, 'measured room temp.' are measured by thermometers.

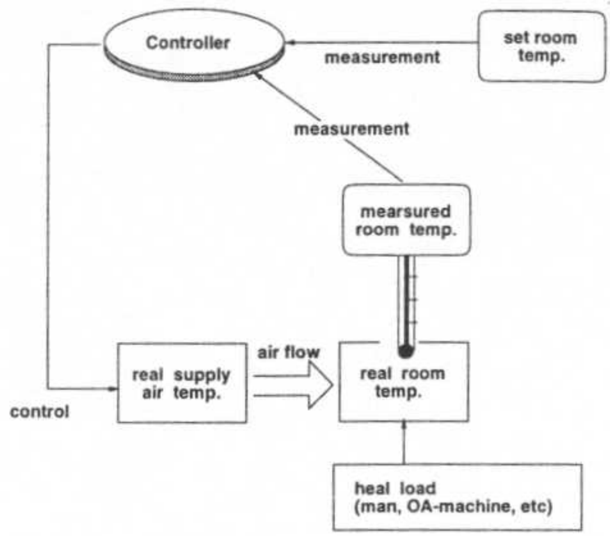

Figure 4: An outline of air conditioning system.

Overview of Fault Detection

Normal qualitative model is generated based on the hardware diagram of an air conditioning system and its control process. If the system has a fault, the fault model is constructed by modifying the normal model according to the fault part. In Figure 4, for example, if 'controller' is the fault part of the system, the function 'h_2' of the normal model is modified.

The simulation on an assumption of a fault is performed with the fault model and measured values. If the agreement rate on the simulation of a fault model becomes the highest in all models, an assumed fault part in this fault model can be considered as a cause of the fault.

Field Data

The data used for this study consists of complaint data, the records on the dates and time, locations, and phenomena of the complaint at a certain hospital in Tokyo in winter from November 11 in 1994 to April 30 in 1995. And the on-line data which show temperatures every ten minutes at 430 points in a hospital, where about 60 air conditioning systems had been in operating, had been also gathered for the same term.

Table 5 shows complaint and hardware failure in the field. An air-conditioner failure occurred only once

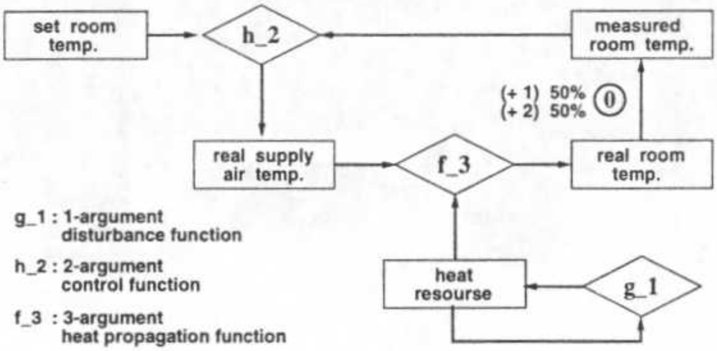

Figure 5: Qualitative '1 room' model of a building air condition system.

Table 5: Complaint and hardware failure in the field.

	Over Cool	Over Warm	Draft	Low Humi.	Anemometer Noise	Room temp. Alarm	Hardware Trouble	Total
Nov., 1994	6	4	1			1	1	13
Dec., 1994	6		2	1	1			10
Jan., 1995	6	3						9
Feb., 1995	4	2	2					8
Mar., 1995	5	1						6
Apr., 1995	4	4						8
Total	31	14	5	1	1	1	1	54

when the inverter circuit fuse blew out. Since the system was switched to air-conditioner by-pass operation immediately, the problem was not reflected to the measured data. A complaint is made once every 3.5 days. Complaints concerning temperature account for more than 80 % of the total.

Through the stochastic qualitative simulation with these field data, we show some examples of the fault detection of the systems.

Fault Detection for Complaint of "Hot" or "Cold"

In this study, the stochastic qualitative model shown in Figure 5 is applied to fault detection of a certain building air conditioning system.

Case 1: Deviation between a set value and room temperature is large

Complaint "cold" occurred in a west sickroom on the sixth floor of the hospital at 14:30 on November 3 in 1994, when set and measured temperatures have changed as Figure 6. Fault detection by the stochastic qualitative reasoning was performed with the data from 12:40 till 14:20. The qualitative values of the temperatures are defined as Table 6. Table 7 shows the agreement rate, which was obtained as the result of the qualitative reasoning for every fault model.

The agreement rate of the thermometer fault model remained because no change in the room temperature was observed. This can be interpreted that the fine coil is turned off or its capacity is insufficient or the temperature setting of the air conditioner is low.

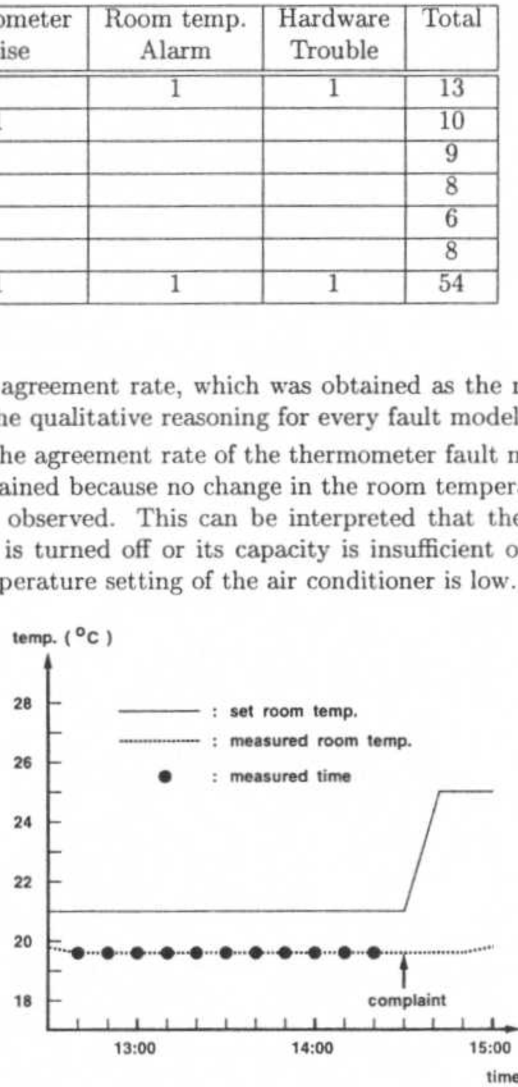

Figure 6: Set and measured temperature transition at the sickroom on Nov. 3.

Table 6: Qualitative value of Case 1,2.

Qualitative value	Room temp. Supply air temp.	Heat resource
A	24°C ~	extremely hot
B	23°C ~ 24°C	hot
C	22°C ~ 23°C	normal
D	21°C ~ 22°C	cold
E	~ 21°C	extremely cold

Table 7: Agreement rate with measured values on Nov. 3.

Fault model	Threshold		
	0.7	0.6	0.5
Normal	0.000	-	-
Control system Failure	0.000	-	-
Control valve adhere	0.000		
Room Thermometer Failure	0.507	0.507	0.515
Supply Air System Failure	0.896	0.915	0.980
Strong Bias against Load	0.000	-	-

Case 2: Deviation between a set value and room temperature is small

In the same system as 'Case 1', complaint "hot" occurred in the sickroom at 19:00 on November 13 in 1994, when set and measured temperatures have changed as Figure 7. Fault detection by the stochastic qualitative simulation was performed with the data from 17:10 till 18:50. The qualitative values of the temperatures are defined as Table 6. Table 8 shows the agreement rate.

The reminded models are the normal, the control failure, control valve adhere, and room thermometer failure model. Since no change in the room temperature is observed like 'Case 1', the thermometer failure cannot be erased in Table 8. In this simulation, the deviation between a set value and the room temperature is too small to classify the normal, the control failure, and control valve adhere.

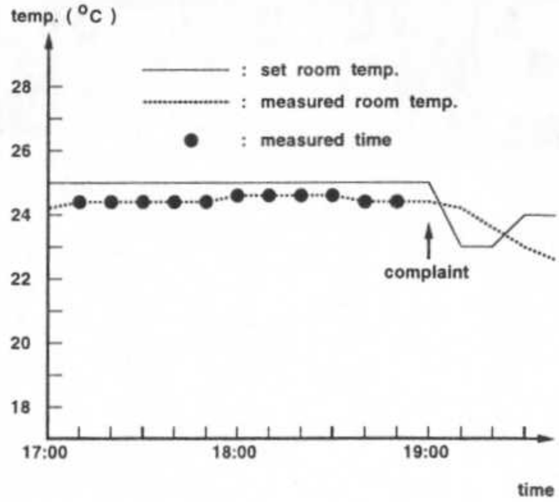

Figure 7: Set and measured temperature transition at the sickroom on Nov. 13.

Table 8: Agreement rate with measured values on Nov. 13.

Fault model	Threshold		
	0.7	0.6	0.5
Normal	0.638	0.631	0.668
Control system Failure	0.638	0.631	0.668
Control valve adhere	0.638	0.631	0.668
Room Thermometer Failure	0.521	0.509	0.527
Supply Air System Failure	0.000	-	-
Strong Bias against Load	0.000	-	-

Case 3: Air-Conditioner is Started in Out-patient Department

Ordinarily, the air-conditioner for the out-patient department is started 30 minutes before the service for out-paints begins. It does not reach the set temperature when a complaint "cold" occurred in the room at 9:50 on Dec. 21 in 1994. Set and measured temperature changed as Figure 8. Figure 9 shows a typical state when no complaint occurred during the same time. The general trend is that no complaint occurs when the room temperature becomes 23 °C or higher by around 10 o'clock. On the other hand, a complaint of "hot" was occurred at the room temperature of 25 °C at 14:30 on January 26.

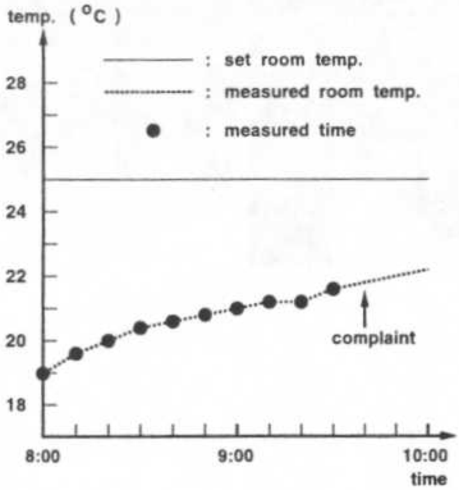

Figure 8: Set and measured temperature transition at the room for out-paint on Dec. 21.

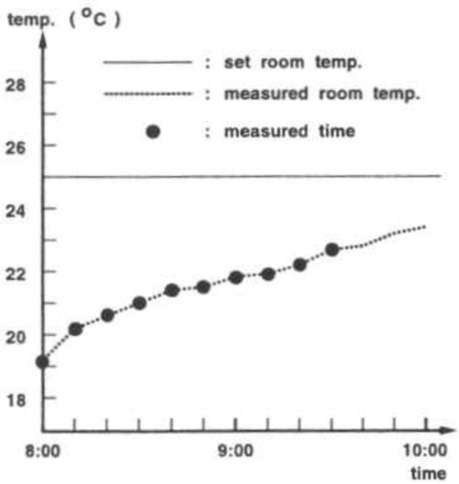

Figure 9: Set and measured temperature transition at the room for out-paint on Jan 9.

Table 9: Qualitative value of Case 3.

Qualitative value	Room temp. Supply air temp.	Heat resource
A	27°C ~	extremely hot
B	25°C ~ 27°C	hot
C	23°C ~ 25°C	normal
D	21°C ~ 23°C	cold
E	~ 21°C	extremely cold

Table 10: Agreement rate with Measured values on Dec. 21.

Fault model	Threshold		
	0.7	0.6	0.5
Normal	0.000	-	-
Control system Failure	0.302	0.000	-
Control valve Failure	0.000	-	-
Room Thermometer Failure	0.000	-	-
Supply Air System Failure	0.530	0.000	-
Heat Propagation delay	0.490	0.286	0.000
Strong Bias against Load	0.000	-	-

Table 11: Agreement rate with Measured values on Jan. 9.

Fault model	Threshold		
	0.7	0.6	0.5
Normal	0.374	0.385	0.299
Control system Failure	0.380	0.000	-
Control valve Failure	0.000	-	-
Room Thermometer Failure	0.000	-	-
Supply Air System Failure	0.000	-	-
Heat Propagation delay	0.000	-	-
Strong Bias against Load	0.513	0.493	0.526

The qualitative models are illustrated by Figure 5. Two new fault models were added. One is a heat propagation delay model which was developed in consideration of the delay due to the heat capacity of the building at the time of starting up. The other is an overload model. Table 9 shows the definition of the qualitative values.

Table 10 and 11 show the agreement rate as the simulation results. In Table 10, "Heat Propagation delay" takes the highest agreement rate of all. As a result, we can infer that the system had no failure but was not able to warm so quickly.

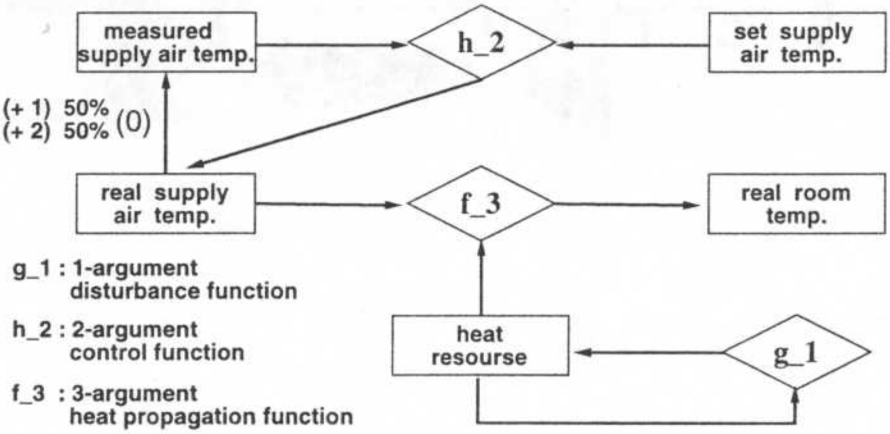

Figure 10: Qualitative model of Air conditioner.

Detection of Control System Failure

Hunting of supply air temperature has been observed though this did not lead to any complaint during the period covered for the present study. A certain system shows hunting almost everyday.

The air conditioner for the general treatment department shows hunting of 2 – 4°C at a cycle of 20 – 30 minutes, while air conditioner for the animal house shows hunting of 4°C at a cycle of 2 hours. A complaint of "cold" was occurred in a certain out-patient department at 9:50 on Dec. 21, 1994. We tried to detect hunting using the data of the air conditioner for the general department at this time. Figure 10 shows the qualitative model, and Table 12 shows the definition of the qualitative values. Table 13 shows the agreement rate as simulation results. And Table 14 shows the measured values and their qualitative values. Qualitative reasoning seems to be especially useful for catching such a hunting phenomenon.

Table 12: Qualitative value to detection of control system.

Qualitative value	Room temp. Supply air temp.	Heat resource
A	22°C ∼	extremely hot
B	21°C ∼ 22°C	hot
C	20°C ∼ 21°C	normal
D	19°C ∼ 20°C	cold
E	∼ 19°C	extremely cold

Table 13: Agreement rate with Measured values under various model.

Fault model	Threshold		
	0.7	0.6	0.5
Normal	0.250	0.000	-
Control system Failure	0.259	0.239	0.000
Control valve Failure	0.000	-	-
Room Thermometer Failure	0.000	-	-
Supply Air System Failure	0.000	-	-

Table 14: A sequence of Measured value and Qualitative value.

Time Step	Measured Value of Supply temp.		Set Value of Supply temp.	
	measurement	qualitative value	measurement	qualitative value
0	21.7	B	20.0	C
1	21.2	B	20.0	C
2	22.6	A	20.0	C
3	21.3	B	20.0	C
4	22.8	A	20.0	C
5	21.3	B	20.0	C
6	21.8	B	20.0	C
7	20.9	C	20.0	C
8	20.1	C	20.0	C
9	20.4	C	20.0	C
10	20.8	C	20.0	C

Conclusion

This paper reported that the fault detection of air conditioning systems was well achieved by the stochastic qualitative reasoning using the practical field data. We plan to conduct researches on the sensitivity analysis and the automatic model construction to develop practical qualitative reasoning programs(Yumoto et al. 1996). We will continue to perform the fault detection of the other target such as heat source.

A fault detection program based on qualitative reasoning will be useful for testing and adjusting the air-conditioning system of a building when it is completed.

References

Kuipers, B., and Berleant, D. 1992. Qualitative-numeric simulation with Q3. *Recent Advances in Qualitative Physics, The MIT Press.*: 3–16

Lackinger, F., and Nejdl, W. 1993. Diamon: A model-based troubleshooter based on qualitative reasoning. *IEEE Expert, vol.8, no.1*:33–40

Lackinger, F., Obreja, I. 1991. Model-based troubleshooting of complex technical systems using integrated qualitative techniques. In Proc. of AI, Simulation and Planning in High Autonomy System:122–129

Mihara, K., Aono, Y., Ohkawa, T., Komoda, N., Miyasaka, F. 1994 Stochastic qualitative reasoning and its application to diagnosis of air conditioning system. In Proc. of the IEEE Industrial Conference on Industrial Electronics, Control and Instrumentation '94: 1401–1406

Arimoto, S., Mihara, K., Ohkawa, T., Komoda, N., Miyasaka, F. 1995. Real-time stochastic qualitative simulation of large scale air conditioning system. In Proc. of IEEE International Symposium on Industrial Electronics '95: 902–907

Yumoto, M., Ohkawa, T., Komoda, N., Miyasaka, F. 1996 to appear. An Approach to Automatic Model Generation for Stochastic Qualitative Simulation of Building Air Conditioning Systems. In Proc. of of IEEE International Symposium on Industrial Electronics '96