Korean J. of Chem. Eng., **10**(1), 36-43 (1993)

SYNTHESIS OF THE KNOWLEDGE MODEL FOR FAULT DIAGNOSIS USING QUALITATIVE SIMULATION

Chang Wook Jeong, Yong Jin Choe, Yeo Hong Yoon and En Sup Yoon

Department of Chemical Engineering, Seoul National University, Seoul 151-742, Korea
(*Received 4 September 1992 • accepted 13 January 1993*)

Abstract—Fault diagnosis requires the knowledge models which describe the behavior of the chemical processes. However it is cumbersome and time consuming work to generate these models. Also the knowledge acquisition required for generation is difficult. The objective of this study is to examine whether the knowledge aquisition for fault diagnosis knowledge models, especially bottom-up models, is possible through qualitative simulation. Qualitative simulation is based on the study of modeling, representation of feedback control and state transition using the QSIM algorithm. Also in this study, qualitative simulation is applied to a buffer tank level control system using the simulation strategy of this paper. The results of the simulation show several behaviors of the processes and the usability for the generation of a knowledge model. However when several different results of simulation are generated, some are spurious solutions which result from insufficient information.

INTRODUCTION

When faults occur in chemical plants, operators treat them by considering the mental model of the plants, heuristic rules, the type of alarms and the values of the related process variables [3]. However, they have difficulties in taking the correct action for unexpected or unexperienced events. Complex integration and tight control of the process in order to manage energy consumption and product quality prevent the operator from perfoming the accurate and the prompt diagnosis. These bring the appearance of expert system for fault diagnosis appealing. Fault diagnosis methods can be classified into two classes; the qualitative and the quantitative approach. In the quantitative approach [5], the numerical estimation of the parameter or the state variables can be used to diagnose the chemical process. However, this approach requires precise modelling of the plant and has difficulties in representing the several types of faults numerically. Qualitative models, which represent the propagation of faults, are used in the qualitative approach. To express fault propagation, many techniques have been used. The fault tree, event tree, HAZOP, FMEA (failure mode and effect analysis) [6] all can be used in the process design phase and SSTM (sub-symptom tree model) [7, 9], STM (symptom tree model) [7, 9], FCD (fault consequence digraph) [8], SDG (signed directed graph) [4], etc., are models used in on-line fault detection and diagnosis.

Identifying the distinguished pattern resulting from faults is very difficult and prevents us from constructing the qualitative model. In SDG, the introduction and the selection of the unmeasured variables are important and tearing the loop is a difficult job. Considering FCD, the construction is not possible until the SDG is constructed. Although FCD can be effective during on-line diagnosis, construction is more tedious work. That is, preparing the SDG and FCD becomes a double burden. Several methods are proposed for fault tree/symptom tree synthesis, but they require tremendous amounts of work. According to the nature of available knowledge, the synthesis method can be classified into two methods. In the first method, the model constructor collects knowledge by experience, then synthesizes the models. In the second method, one uses the steady-state simulation or dynamic simulation. The first method has its drawbacks since it is not simple to acquire the cause-effect relation from the process. In the second method, the need for precise numerical modelling, parameters, and physical properties prevents the builder from synthesizing the models. Moreover, mathematical representation of various faults is not easy. To overcome these problems, research for synthesizing the FCD using qualitative simulation is going on. Qualitative simulation can de-

Table 1. Qualitative constraints

Constraints	Definition
ADD(f, g, h)	f(t)+g(t)=h(t) for every time-point
MULT(f, g, h)	f(t)*g(t)=h(t) for every time-point
MINUS(f, g)	f(t)= −g(t) for every time-point
DERIV(f, g)	f′(t)=g(t) for every time point
M+(f, g)	f(t)=H[g(t)] where H′(X)>0 for all X
M−(f, g)	f(t)=H[g(t)] where H′(X)<0 for all X

scribe the physical phenomena with incomplete information or imperfect relations between variables. The goal of this study is to examine the possibility for constructing the knowledge model, specially the FCD model.

QUALITATIVE SIMULATION

Structured methods for qualitative simulation have been developed in the artificial intelligence domain since 1984. Forbus [2], de Kleer [1] and Kuiper's [10-12] schemes have been applied to chemical plants. Qualitative simulation is another way to abstract the actual behavior in the real world through comparison with the quantitative simulation. The QSIM algorithm proposed by Kuiper is used in this study. The following section explains this scheme.

1. Qualitative State

The qualitative state of some variable f at time t is a pair $\langle qval, qdir \rangle$ and it is represented in the following form.

$$qval \begin{cases} l_i & \text{if } f(t)=l_i \\ (l_i\ l_{i-1}) & \text{if } f(t)\in(l_i,\ l_{i+1}) \end{cases}$$

$$qdir \begin{cases} inc & \text{if } f'(t)>0 \\ std & \text{if } f'(t)=0 \\ dec & \text{if } f'(t)<0 \end{cases}$$

One value from the set called landmark values is assigned to qval, or the value between the landmark values is assigned to qval. These landmark values are ordered as

$$l_1<l_2<l_3\cdots<l_k$$

The value qdir is the tendancy of variables, and is based on the time derivative. If the derivative of a variable is positive, qdir has a value 'inc'. Time is composed of two parts in qualitative simulation. They are the successive time-point and time-interval. If a variable has landmark values at some time-point, this time-point is called the distinguished time-point. So system F can be represented by

Table 2. Qualitative state transition

(a) P-transition

ID	$QS(f, t_i)$	$QS(f, t_i, t_{i+1})$
P1	$\langle l_i,\ std\rangle$	$\langle l_i,\ std\rangle$
P2	$\langle l_i,\ std\rangle$	$\langle (l_i, l_{i-1}),\ inc\rangle$
P3	$\langle l_i,\ std\rangle$	$\langle (l_{i-1}, l_i),\ dec\rangle$
P4	$\langle l_i,\ inc\rangle$	$\langle (l_i, l_{i+1}),\ inc\rangle$
P5	$\langle (l_i, l_{i+1}),\ inc\rangle$	$\langle (l_i, l_{i+1}),\ inc\rangle$
P6	$\langle l_i,\ dec\rangle$	$\langle (l_{i-1}, l_i),\ dec\rangle$
P7	$\langle (l_i, l_{i+1}),\ dec\rangle$	$\langle (l_i, l_{i+1}),\ dec\rangle$

(b) I-transition

ID	$QS(f, t_i, t_{i-1})$	$QS(f, t_{i-1})$
I1	$\langle l_i,\ std\rangle$	$\langle l_i,\ std\rangle$
I2	$\langle (l_i, l_{i+1}),\ inc\rangle$	$\langle l_{i+1},\ std\rangle$
I3	$\langle (l_i, l_{i-1}),\ inc\rangle$	$\langle l_{i+1},\ inc\rangle$
I4	$\langle (l_i, L_{i+1}),\ inc\rangle$	$\langle (l_i, l_{i+1}),\ inc\rangle$
I5	$\langle (l_i, l_{i+1}),\ dec\rangle$	$\langle l_i,\ std\rangle$
I6	$\langle (l_i, l_{i+1}),\ dec\rangle$	$\langle l_i,\ dec\rangle$
I7	$\langle (l_i, l_{i+1}),\ dec\rangle$	$\langle (l_i, l_{i+1}),\ dec\rangle$
I8	$\langle l_i, l_{i-1}),\ inc\rangle$	$\langle l^*,\ std\rangle$
I9	$\langle (l_i, l_{i+1}),\ dec\rangle$	$\langle 1^*,\ std\rangle$

(l* means new landmark value)

$$QS(F, t_i)=[QS(f1, t_i),\ QS(f2, t_i),\cdots,QS(fn, t_i)]$$

$$QS(F, t_i, t_{i+1})=[QS(f1, t_i, t_{i+1}),\quad QS(f2, t_i, t_{i+1}),\cdots,QS(fn, t_i, t_{i+1})]$$

and the behavior of the system F is

$$behavior=[QS(F, t_0),\ QS(F, t_0, t_1),\ QS(F, t_1),\cdots,QS(F, t_k)]$$

and fi is the variable in system F.

2. Constraints

Use of the various types of qualitative constraints helps in modelling for interpretation of the object system. Table 1 enumerates several constraints. The M+ and M− constraints represent the square root, log, exponential, n-th order function or a complex combination of these functions. These constraints give a simple, easy way to construct the model, but are apt to drive a spurious solution, thereby decreasing the resolution of the simulation results.

3. State Transition

State transition is when variables have a new qualitative state from a time-point to a time-interval as time goes on, *vice versa*. There are two possible transition methods as tabulated in Table 2.

4. Filtering

Fig. 1 is the flowchart of the QSIM algorithm. QSIM is composed of two parts. The first part generates

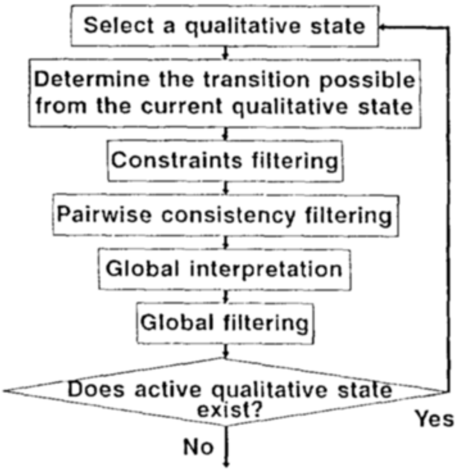

Fig. 1. Flow chart of QSIM algorithm.

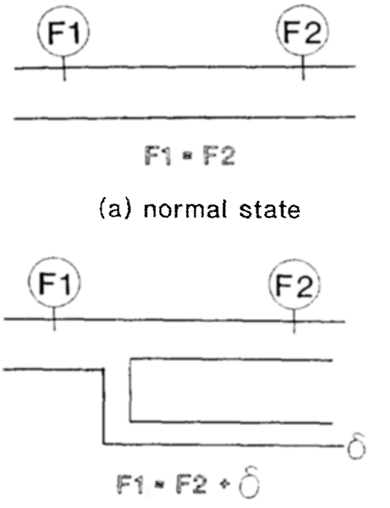

Fig. 2. Fault parameter.

possible candidates of variables with consistency with state transition rules.

The second part filters, eliminating the candidates which don't satisfy the following rules.

- constraints consistency filtering rule:
  rule for satisfying the properties of constraints
- pairwise consistency filtering rule:
  rule for controlling the state transition of variable contained in at least two constraints simultaneously.
- corresponding values filtering rule:
  rule using corresponding values which each variable of one constraints should have simultaneously at a special time.
- global filtering rule:
  rule for eliminating the cyclic behavior, divergence or asymptotic approach of system.

SYNTHESIS STRATEGY

The simulation of the abnormal situation is different from that of the normal system, since the models for the abnormal behavior must be added. The occurred faults also shift the state of the system into the abnormal region. Also, other conditions and aspects should be considered. In this section, we will briefly explore these.

1. Fault Parameter

When the process model for the simulation is constructed, fault parameters are used to represent the various faults. These are not needed for normal operation of the process but are inserted into constraints in order to perform the fault simulation effectively. Usually fault parameters represent the loss of materials or energy when the balance of the equipment is considered. Consider pipe leakage as in Fig. 2. The leakage of the pipe can be thought of like Fig. 2(b). If F1 and F2 are the measured flows, the material balance equation is

$$F1 = F2$$

for normal conditions. But with the leakage, the material balance equation is

$$F1 = F2 + \delta$$

δ is called fault parameter and should be set according to the type of fault.

2. Heuristic Knowledge

There are two methods for constructing the qualitative model. The first method is using differential equations or algebraic equations which are already known. These quantitative equations are easily decomposed and changed into qualitative constraints. This method is simple and easy. We can construct the model using the experience for the system. The collection of experiential knowledge and observation is widely useful for fault diagnosis, since they give heuristic rules which can be used for rapid diagnosis. Qualitative simulation reflects the heuristic information in the modelling step. Therefore the simulation results naturally include heuristic information. The symbolic values in constraints contain the fuzziness in themselves and help to model heuristic knowledge.

3. Representation of Feedback Control

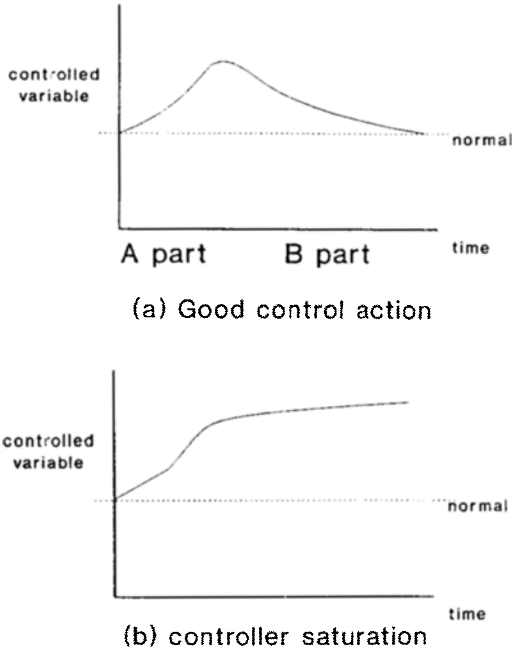

Fig. 3. Two types of behavior for control action.

Feedback control has raised a question in knowledge modelling and pattern matching. When the feed back controller is not saturated, it is difficult to describe the behavior of the controlled variable. It is impossible to use the behavior of controlled variable as a distinguished symptom. The important point in describing the feedback control is not a perfect description for the control action but a description of the effects of the control. If the controller is saturated, the symptom cannot be eliminated, the deviation of the variable propagates to another section. For fault diagnosis, the simulation of feedback control contains the following two assumptions.

- The feedback controller is tuned well. The behavior resulting from tuning is not our focus.
- The behavior by controller is described in only two ways shown in Fig. 3.: good control action/failure of the controller by saturation.

Fig. 3 shows two types of behavior due to the controller. For successful simulation, the concept of the simulation control variable is adopted. This variable is a guide to instruct the direction of the change.

4. Interregion State Transition

Besides the normal operation of each component, extreme condition (ex: saturation of controller, dry-up of the tank) should be considered sufficiently. When some fault propagates the symptom, the state of the system is often shifted into the abnormal region as shown in Fig. 4. If the cross-sectional area is constant, the material balance equation is

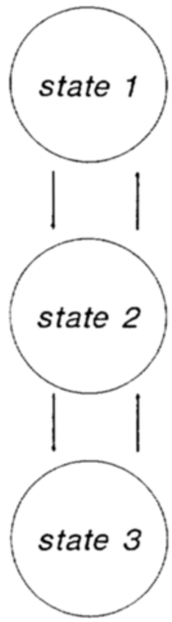

Fig. 4. State diagram.

Table 3. Tendency of $d^n f1/dt^n$, $d^{n-1}f1/dt^{n-1}$ for interregion state transition

$\frac{d^{n-1}f_1}{dt^{n-1}}$ tendency	inc→std
$\frac{d^n f_1}{dt^n}$ tendency	inc→std→dec→std dec→std
$\frac{d^{n-1}f_1}{dt^{n-1}}$ tendency	dec→std
$\frac{d^n f_1}{dt^n}$ tendency	dec→std→inc→std inc→std

$$A\frac{dL}{dt} = Fi - Fo$$

$$(Lmin < L < Lmax)$$

where Lmax and Lmin are upper and lower boundaries. If the level of tank goes beyond these boundaries due to the some reason, the governing equation is

$$Fi = Fo$$

Therefore the operating region of tank has three regions as in Fig. 4. The interregion state transition is the state change of the system between each region. This interregion state transition is controlled according to Table 2 & Table 3, where $d^n f/dt^n$ represents the n-th order derivative of variable f.

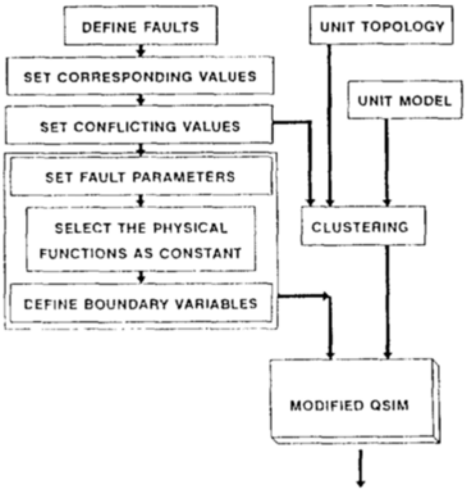

Fig. 5. Qualitative simulation strategy.

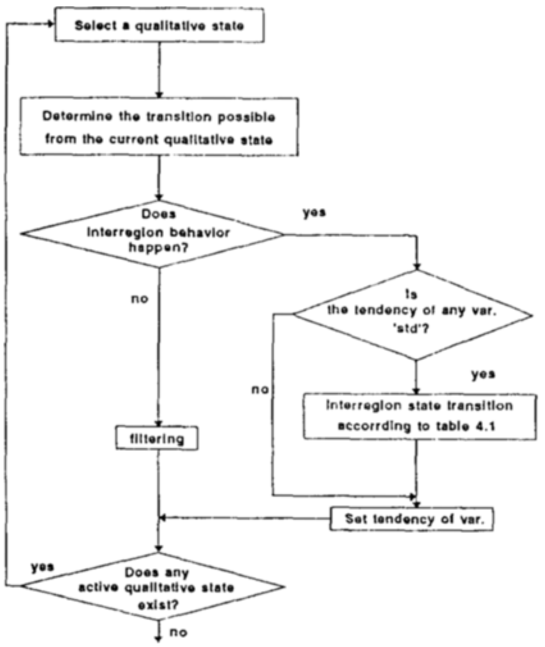

Fig. 6. Modified QSIM algorithm.

5. Conflicting Values

The use of conflicting values means that variables contained within the same constraints should not have special value set at the same time. For constraint (f1, f2, f3), if the relation

$$\{f1, f2, f3\} \notin \{(a, b, c)\}$$

is satisfied at special time, (a, b, c) are called conflicting values, and they can be used in a filtering step.

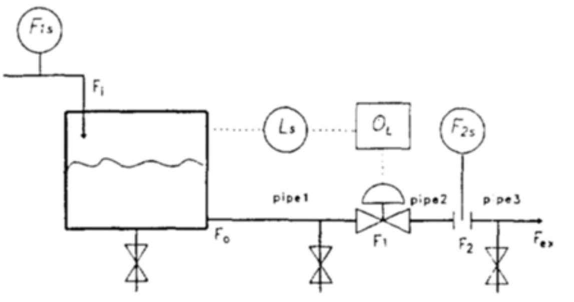

Fig. 7. Buffer tank system.

The reason for their use is that it is impossible to recover the system without the changes of some variables. That is, after the occurrence of fault, the previous state cannot be achieved without any state change of system.

6. Simulation Strategy

The flowchart of fault simulation in shown in Fig. 5. It consists of three parts: the information for the fault, the information for the process, and the modified QSIM. The flowchart of the modified QSIM algorithm is shown in Fig. 6.

EXAMPLE STUDY

Fig. 7 depicts a buffer tank system. This system is a good example for showing the usefulness of qualitative simulation. This system was also used by Oh [7] to explain the FCD model. In this system, three sensors are located for measuring inlet flow, outlet flow, and the tank level. The values of the five process variables (the values of three sensors, the output of the controller, and the value of the valve position) can be acquired. Assume that the pressure of tank is higher than that of the down stream. The model constraints of the six components of this system and landmark values are arranged in Table 4 and Table 5. Pipe blockage information is shown in Table 6. The initial qualitative state of the outlet flow at time to is

$$QS(Fo, to) = \langle (Fmin, Fn), inc \rangle$$

If the initial qualitative value of Fo is given, the initial values of other variables can be determined by qualitative constraints. The first row of Table 7 represents the initial values. Because time goes from t_0 to (t_0, t_1), P transition can be applied. Only P4 transition of the Table 2 is possible except variable dL/dt, P7. After the P transition, I transition is applied according to Table 2. For each variable, following transitions are

Table 4. Component model

Component	Constraints
Tank	0≤L<pinf
	DERIV(dL/dt, L)
	ADD(Fi, Fo, dL/dt)
	L<0
	EQUAL(Fi, Fo)
	L≥pinf
	EQUAL(Fi, Fo)
Pipe 1	Fo, Fi>0
	ADD(F1, δ1, Fo)
	Fi=Fo=0
	Value(Fo, 0)
Pipe 2	F2, F1>0
	ADD(F2, δ2, F1)
	Fi=Fo=0
	Value(F1, 0)
Pipe 3	Fex, F2>0
	ADD(Fex, δ3, F2)
	Fi=Fo=0
	Value(F2, 0)
Controller	Omsat≤O_L≤Opsat
	M-(O_L, dL/dt)
	ADD(E, Ls, Lset)
	Minus(dE/dt, dL/dt)
Valve	Amin≤A≤Amax & L>0
	M+(A, O_L)
	M+(F2, A)
	A<Amin
	VALUE(F2, 0)
Sensor	EQUAL(F1s, Fi)
	EQUAL(F2s, F2)
	EQUAL(Ls, L)

Table 5. Landmark values of variables

Var	Landmark values
L	0, Ln, pinf
dL/dt	minf, 0, pinf
Fi	0, Fn, pinf
Fo	0, Fn, pinf
F1	0, Fn, pinf
F2	0, Fn, pinf
Fex	0, Fn, pinf
E	minf, 0, pinf
dE/dt	mint, 0, pinf
O_L	Omsat, On, Opsat
A	Amin, An, Amax

L : level of tank
dL/dt : derivative of L
Fi, Fo, F1, F2, Fex : flow rate at each position
E : error (E=Lset−L)
dE/dt : derivative of E
O_L : Controller output
A : Valve position

Table 6. Information for pipe blockage

var. excepted from S.T.	Fi, Lset
fault parameter	$\delta_1=\delta_2=\delta_3=0$
related boundary variables	Fo=F1=F2=Fex
corresponding values	(dL/dt, Fi, Fo)∈{(0, Fn, Fn)}
	(O_L, A)∈{(Omsat, Amin), (On, An), (Opsat, Amax)}
	(E, Lset, Ls)∈{(0, Lset, Ln)}
conflicting values	(A, Fo)∉{(An, Fn)}

(S.T. means state transition)

Table 7. Pipe blockage failure

(a) Controller saturation

time	dL/dt	L	Fo	O_L	A
t0	(0, pinf), dec	Ln, inc	(Fmin, Fn), inc	On, inc	An, inc
(t0, t1)	(0, pinf), dec	(Ln, pinf), inc	(Fmin, Fn), inc	(On, Opsat), inc	(An, Amax), inc
t1	(0, pinf), dec	(Ln, pinf), inc	(Fmin, Fn), inc	Opsat, inc	Amax, inc
t2	DL_new, std	(Ln, pinf), inc	F_new, std	Opsat, std	Amax, std

(b) Good control action 1

time	dL/dt	L	Fo	O_L	A
t0	(0, pinf), dec	Ln, inc	(Fmin, Fn), inc	On, inc	An, inc
(t0, t1)	(0, pinf), dec	(Ln, pinf), inc	(Fmin, Fn), inc	(On, Opsat), inc	(An, Amax), inc
t1	0, dec	L_new, std	Fn, inc	(On, Opsat), inc	(An, Amax), inc
(t1, t2)	(minf, 0), dec	(Ln, L_new), dec	(Fn, pinf), inc	(On, Opsat), inc	(An, Amax), inc
t2	DL_new, std	(Ln, L_new), dec	F_new, std	O_new, std	A_new, std
(t2, t3)	(DL_new, 0), inc	(Ln, L_new), dec	(Fn, F_new), dec	(On, O_new), dec	(An, A_new), dec
t3	0, std	Ln, std	Fn, std	O_new2, std	A_new2, std

Table 7. Continued

(c) Good control action 2

time	dL/dt	L	Fo	O_L	A
t0	(0, pinf), dec	Ln, inc	(Fmin, Fn), inc	On, inc	An, inc
(t0, t1)	(0, pinf), dec	(Ln, pinf), inc	(Fmin, Fn), inc	(On, Opsat), inc	(An, Amax), inc
t1	0, dec	L_new, std	Fn, inc	(On, Opsat), inc	(An, Amax), inc
(t1, t2)	(minf, 0), dec	(Ln, L_1_new), dec	(Fn, pinf), inc	(On, Opsat), inc	(An, Amax), inc
t2	DL_new, std	(Ln, L_new), dec	F_new, std	Opsat, std	Amax, std
(t2, t3)	(DL_new, 0), inc	(Ln, L_new), dec	(Fn, F_new), dec	(On, Opsat), dec	(An, Amax), dec
t3	0, std	Ln, std	Fn, std	O_new, std	A_new, std

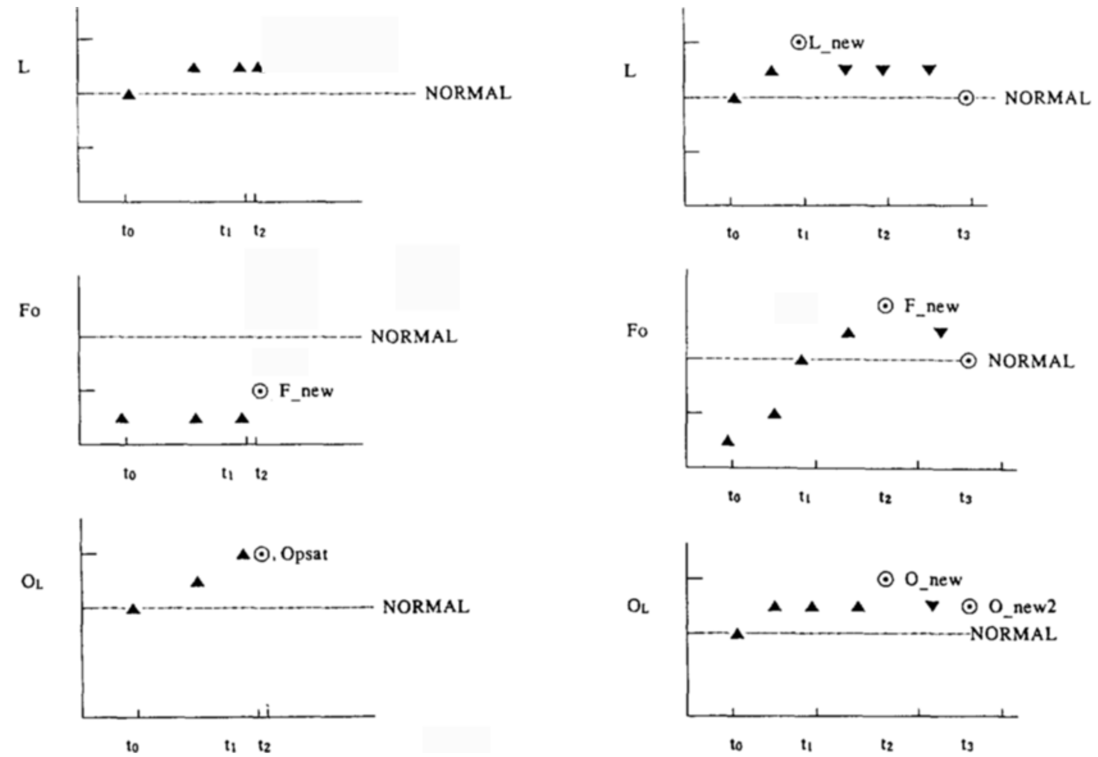

Fig. 8. Qualitative plot for pipe blockage.

possible.

dL/dt : I5 I6 I7 I9
L : I2 I3 I4 I8
Fo : I2 I3 I4 I8
O_L : I2 I3 I4 I8
A : I2 I3 I4 I8

In this case 4^5 transitions sets can be combinated without any filtering. But by the constraints of the model and the filtering rule, only two transition sets are possible.

dL/dt	:	I7	I6
L	:	I4	I8
Fo	:	I4	I3
O_L	:	I3	I4
A	:	I3	I4

Table 7 shows three behaviors for pipe blockage. Fig. 8 shows the qualitative plots for this system. The simulation for pipe blockage produces three behaviors. The first behavior shows that the controller can not hide the symptoms, since the degree of the blockage

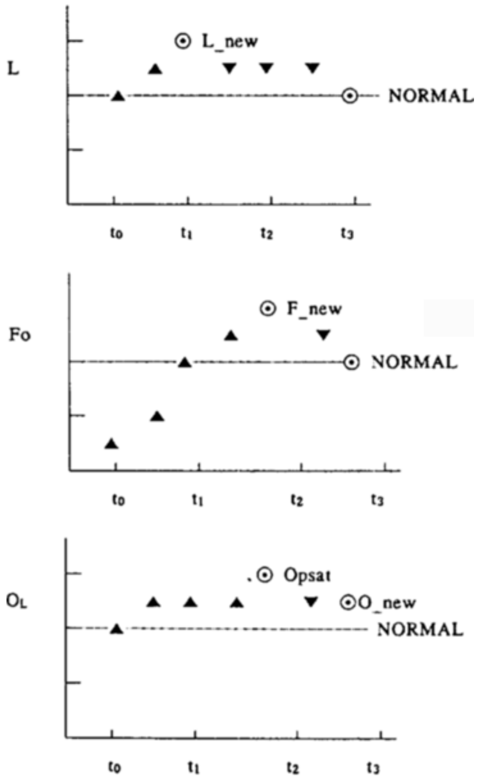

Fig. 8. Continued.

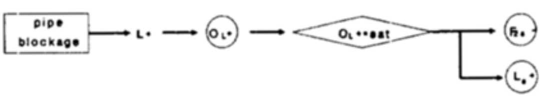

Fig. 9. FCD for pipe blockage.

is severe. The second and the third behavior show that the blockage is not controlled until the controller is saturated. The production of these three behaviors resulted from incomplete knowledge about the system and faults. Using this information, the FCD with a condition gate can be generated as in Fig. 9. The different sections of these three results, according to the time, can be represented by the conditional gate of the FCD. This different section depicts the state of the system dependent on the process conditions.

RESULTS AND DISCUSSION

In this study, the semi-automatic synthesis of the FCD through qualitative simulation for a tank system is shown. This study uses QSIM algorithm but the strategy for fault simulation is suggested. For this, the representation of the feedback control in the qualitative manner, fault parameter for modelling, state transition, filtering by conflicting values are introduced. It is shown after simulation that the FCD can be derived using the qualitative simulation. However, the qualitative simulation generates spurious solutions because of its use of insufficient and incomplete knowledge. The generation of three solutions has adequate reasons in its own way. The drawbacks of qualitative simulation are the spurious solutions which are derived in addition to the useful information. It is very short to handle one event of the example except the time that a user consumes. The calculation time depends on the computing environment and the size of the system. If the size of the system is changed from n variables to n+1, the expanded searching pace is 4^{n+1}-4^{n} without any filtering. So several filtering rules have to be applied and the direct control of a user is needed for the real big system. In order to solve these problems, research for constraints, addition of rebundant constraints, and an effective filtering method should be considered.

ACKNOWLEDGEMENT

The Authors are grateful to the Automation Research Center, POSTECH/ERC for financial support.

REFERENCES

1. de Kleer, J. D. and Brown, J. S.: *Artific. Intell.*, **24**, 7 (1984).
2. Forbus, K. D.: *Artific. Intell.*, **24**, 85 (1984).
3. Kramer, M. A. and Palowitch, Jr, B. L.: *AIChE J.*, **33**, 1067 (1987).
4. O'Shima, E. and Iri, M.: *Comput. Chem. Eng.*, **9**, 285 (1985).
5. Isermann, R.: *Automatica*, **20**, 387 (1984).
6. Crowl, D. A. and Louvar, J. F.: "Chemical Process Safety : Fundamentals with Application", Prentice-Hall, Inc. (1990).
7. Oh, J. K., Yoon, E. S. and Choi, B. N.: KACC, 805 (1989).
8. Yoon, B. S., Oh, J. K. and Yoon, E. S.: *HWAHAK KONGHAK*, **29**, 19 (1991).
9. Yoon, Y. H., Nam, D. S., Jeong, C. W. and Yoon, E. S.: KACC, 1705 (1991).
10. Kuiper, B.: *Artific. Intell.*, **29**, 289 (1986).
11. Kuiper, B.: *IEEE SMC*, **17**, 432 (1987).
12. Kuiper, B.: *Automatica*, **25**, 571 (1989).