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FAULT DIAGNOSTIC ADVISORY SYSTEM USING MOVING-RANGE CHART AND HAZARD OPERABILITY STUDY

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Abstract. In this paper, fault diagnostic advisory system developed by using the combination of Univariate Statistical Process Control (SPC) and Hazard and Operability (HAZOP) study supported by rule-based approach is presented. Firstly, a plant model was simulated by using commercial HYSYS. Plant™ simulator. Moving-Range (*x-MR*) Chart and HAZOP study were used to define the causes and consequences of process deviation based on selected parameter for each study node. Fault is considered to occur if one variable is out of control limit. The advisory system has successfully detected and diagnosed the deviations and displayed the causes and consequences of the faults. Although the scheme was developed based on precut fractionation column, the algorithm of fault detection and diagnosis can be extended to other chemical process by changing the *x-MR chart* and HAZOP study for each selected monitoring variables.

Key Words: Fault Diagnostic Advisory System, Hazard and Operability Study, *x-MR* Chart.

1.0 INTRODUCTION

Poor control or process disruption might lead to plant shutdown and such situations are expected to be solved by human operators with the assistance of an alarm system [1]. If correcting abnormal events is fully reliance on human operators, they might tend to make erroneous decisions and take actions which make matters even worse. Literature has shown that most industrial accidents are caused by human errors and these abnormal events have significant economic, safety and environmental impacts [2]. Hence, fault detection and diagnosis is one of the means for process safety management to aid the operator in improving the process operation.

In the area of plant-wide control at the supervisory level, the process fault detection and diagnosis system plays a key role. Foreseeable, the important of a supervisory system and the potential of computer to provide closer supervision and better information of process safety by monitoring critical parameters and, when circumstances warrant it, initializing and carrying out a safe shutdown.

2.0 THEORY

Fault can be defined as defect or imperfection of character, structure, or appearance. For a plant or instrumentation, faults are deviations from intended operation. Iserman and Balle (1997) defined fault as an unpermitted deviation of at least one characteristic property or

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parameter of the system from the acceptable, usual and standard condition. Meanwhile, Himmelblau (1978) defined fault as a departure from an acceptable range of an observed variable or a calculated parameter associated with a process.

Diagnosis consists of two different but closely related procedures. The first step is to receive response of the system through measuring device. The second step is to make a decision on the state of the system based on the sensory values. Researchers seek a way of using a computer to mimic human reasoning. There are different search techniques that can be applied to perform diagnosis based on the available process knowledge. Venkatasubramanian (2003) and his partner has summarized the basic approach in implementing diagnostic system. Knowledge engineering and advanced software tools such as expert systems can also be used for process supervision purposes.

Variation usually occurs in the manufacturing process. The variation will not only effect the product specifications but also will lead to damage and disaster. Principles of statistics are considered as technique to detect the variation of parameter. Statistical Process Control (SPC) has been established as an important part of quality control in monitoring the values of all process variables and parameters of a product that have an effect on quality and provide the way to monitor chemical and other processes. Process control engineers use SPC to monitor a process's stability, consistency and overall performance.

Lees (1996) classified hazard analysis methodologies into: the starting point of analysis, the direction of inference and the scope of analysis (qualitative or quantitative). Hazard is defined as an inherent potential of a material or activity to harm people, property, or the environment. It does not have a probability component. The specific tool, Hazard Operability (HAZOP) Study, commonly uses a multidisciplinary team to identify, analyze, and control hazards systematically. The main output of the fault detection and diagnosis algorithm focuses on the condition, location, time, causes, and consequences of a process fault.

3.0 EXPERIMENTAL

Fatty acid precut fractionation column has been selected as a case study and the plant model was developed by Ling (2004) using HYSYS.Plant™ simulator as shown in Figure 1. Some modification of the plant model was done to speed up the simulation such as; the pumparound section which consists of an internal direct contact condenser is not available within the HYSYS model library. Therefore, modifications of the standard column template are carried out to produce an equivalent configuration.

The precut fractionation column is commonly used to separate palm kernel oil. Distillate products consist of C8 and C10 and the net bottom product is pumped to the next columns for further separation. The process involves two types of operation: reflux and pump around. In the HYSYS model, two separation columns with mixture and accumulator are required to perform the pump around process. The observation streams and HAZOP analysis is carried out based on fractionation column as shown in Figure 2.

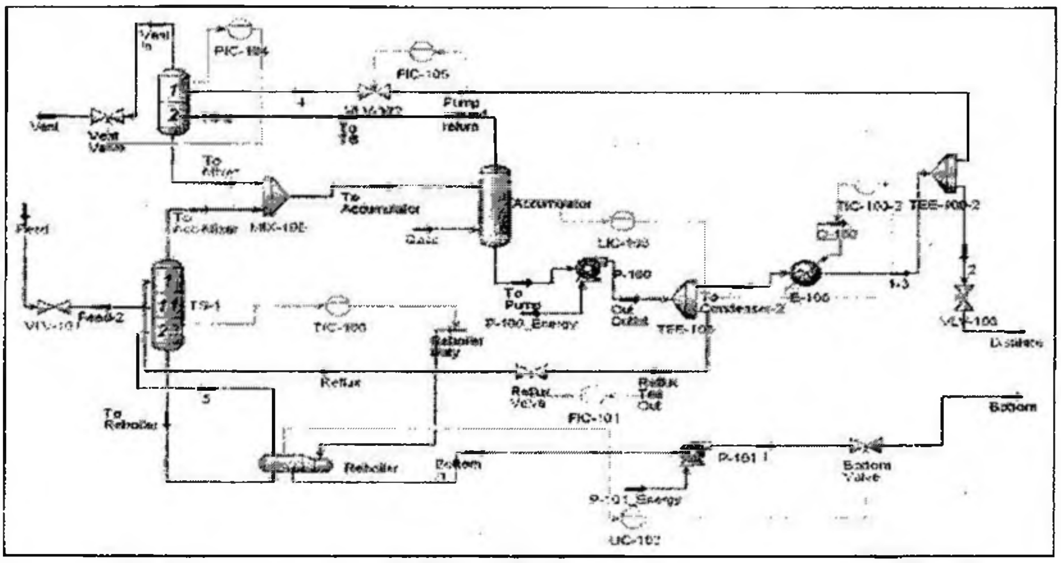


Figure 1 Plant model for precut fractionation process [6]

Fault Diagnostic Advisory (FDA) has developed based on the application of Mean and Moving Range chart and HAZOP study and supported by expert system approaches. Process deviation is detected by comparing the actual process data for each monitoring variables (data set) with *x-MR* chart. The limits are calculated based on a normal processing sampling data. Process deviation is considered to take place if any data us found to be located out of the region.

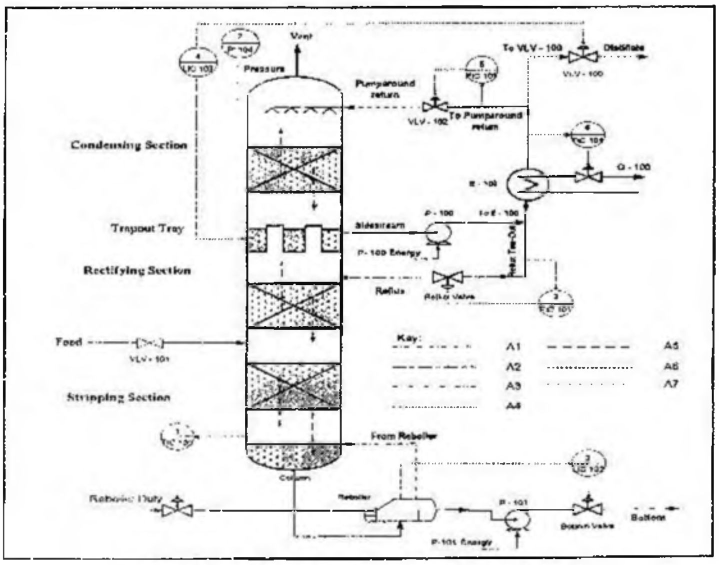


Figure 2 Case study - precut column

The limits for the individual chart are the same as the usual of Shewhart control charts [7]:

$$UCL_x = \bar{x} + E_2 \times \overline{MR} \quad (1)$$

$$LCL_x = \bar{x} - E_2 \times \overline{MR} \quad (2)$$

where, the definition formula for [7,8]:

$$\bar{x} = \frac{\sum x}{n} \quad (3)$$

$$MR = |x_2 - x_1|$$

$$\overline{MR} = \frac{\sum MR}{n-1} \quad (4)$$

The constants $E_2 = 2.659$ and n=2 [7].

Meanwhile, the limits for moving-range chart use the regular range chart [7]:

$$UCL_{MR} = D_4 \times \overline{MR} \quad (5)$$

$$LCL_{MR} = D_3 \times \overline{MR} \quad (6)$$

Both $D_3 = 3.267$ and $D_4 = 0$, and where as n=2 [7].

In Figure 3, Phases I and II are steps to gather knowledge (knowledge acquisition) and store them in a database. Meanwhile, Phase III is the step to structure the knowledge base (knowledge representation). In Phase IV, FDA prototype was developed based on expert system approaches and the collected knowledge base. This prototype was developed by using Borland C++ Builder (BCB) 6.0 programming language. Study nodes were defined based on monitoring variables and consequently HAZOP study was carried out on these nodes. The definition of monitoring variables is shown in Table 1. Table 2 states the nodes for HAZOP study.

Table 1 Sensor and monitoring variables

Sensor	Monitoring Variables (Stream)	Measured Variables
S1	TIC 100	Temperature (Celsius)
S2	Reflux	Flow (kg/h)
S3	Bottom	Flow (kg/h)
S4	Distillate	Flow (kg/h)
S5	FIC 105	Flow (kg/h)
S6	TIC 101	Temperature (Celsius)
S7	PI 104	Pressure (kPa)

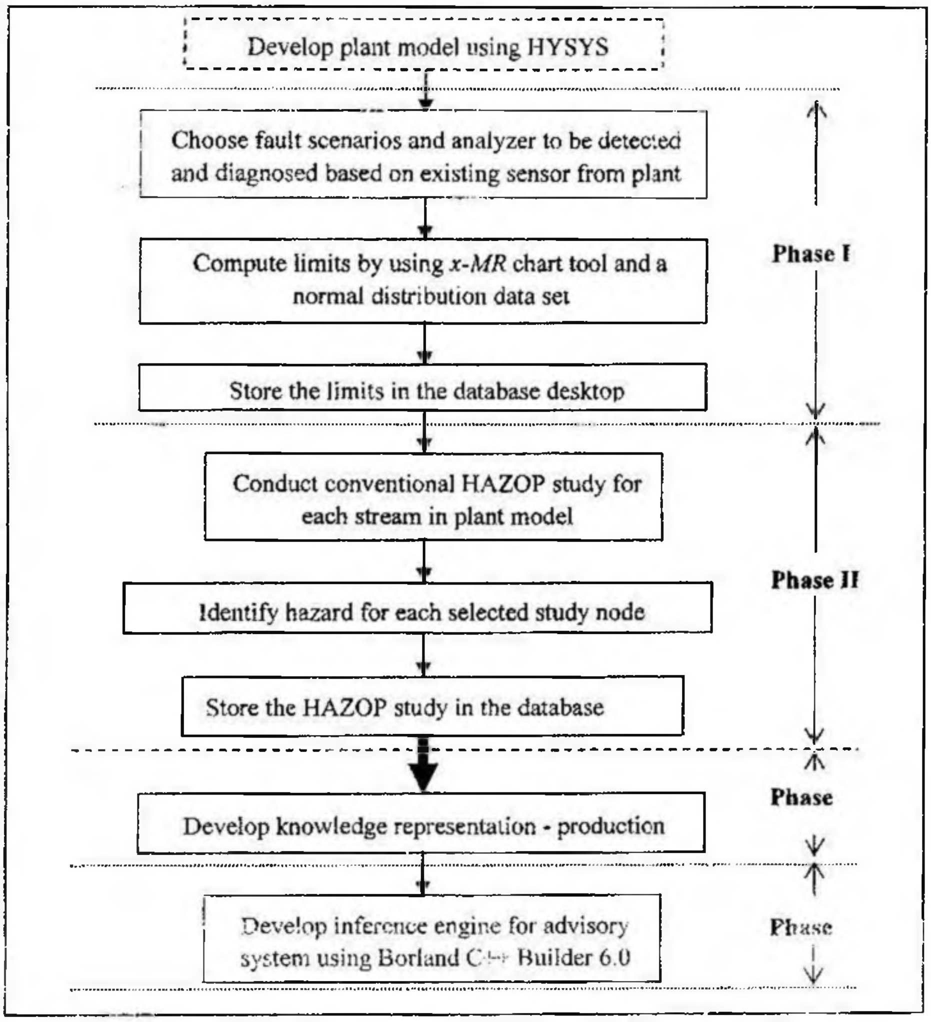


Figure 3 Fault diagnostic advisory system development flowchart

Table 2 Nodes for HAZOP study

Nodes	Deviations
Node 1	Line *From Reboiler* to *Column*
Node 2	Line *Reflux Tee-Out* to *Reflux* stream
Node 3	From *P-101* to *Bottom* stream
Node 4	Line *To-VLV-100* to *Distillate* stream
Node 5	Line *To Pumparound return* stream to *Pumparound return* stream
Node 6	From *E-100* to *Distillate* stream
Node 7	Top Column

4.0 RESULTS AND DISCUSSION

Plant model for the case study was developed by using HYSYS.Plant simulator and was used to compute the *x-MR* acceptable ranges as shown in Table 3. Analyses such as Autocorrelation, Skewness, Kurtosis, and Boxplot were performed to show the data set was random with normal distribution. Fault is defined if one point of data goes beyond the limits where it gives a signal when a signal shifts in the position of the mean or an increase in the standard deviation of the process [9].

Two types of optimization study were carried out in the design of the fault diagnosis algorithm. These include the examination of process variables and the sensitivity analysis. The optimization studies were used to determine the exact causes and consequences of the fault that might occur in the plant process. Sensitivity analysis was carried out for each controller as well as in HAZOP study to specify the possible causes and consequences of a deviation process. HAZOP study for this research encompasses of seven study nodes as stated in Table 2.

Upper and lower limits for *x-MR* chart and a sample of HAZOP study are shown in Tables 3 and 4 respectively. The FDA system consists of a user interface, a knowledge base and an inference engine. Forward chaining strategy was used to search the knowledge base by repeatedly examine existing facts and rules that matched and compare these facts to the information furnished from the process data. For example, a fault was detected by comparing the process variables data with the limits data. Then, the cause and location of the fault and a suitable countermeasure were extracted from the knowledge base.

Table 3 Upper and lower limits

Sensor	UCL_x	LCL_x	UCL_{MR}	LCL_{MR}
S1 = TIC 100 (Celsius)	238.40	236.37	1.24	0
S2 = FIC 101 (kg/h)	3159.04	3064.41	58.14	0
S3 = Bottom (kg/h)	9734.18	9342.48	240.64	0
S4 = Distillate (kg/h)	979.93	421.19	330.96	0
S5 = FIC 105 (kg/h)	8848.69	8165.82	554.61	0
S6 = TIC 101 (Celsius)	79.09	77.51	0.96	0
S7 = PIC 104 (kPa)	7.92	7.27	0.40	0

The computed limits and result of HAZOP study were used in developing the two types of production rule: Rule I and Rule II. Rule I consists of measurement space, feature space and decision space. The relationship of Rule I is - *If* 'Variable' and *If* 'Limits', *Then* "Process deviation of monitoring variable". Meanwhile, Rule II is used to reach the end result of fault diagnostic task and consisted of class space and qualitative information. The followings are the sample coding of Rule I and Rule II. Figure 4 illustrated the architecture and flow of the FDA algorithm.

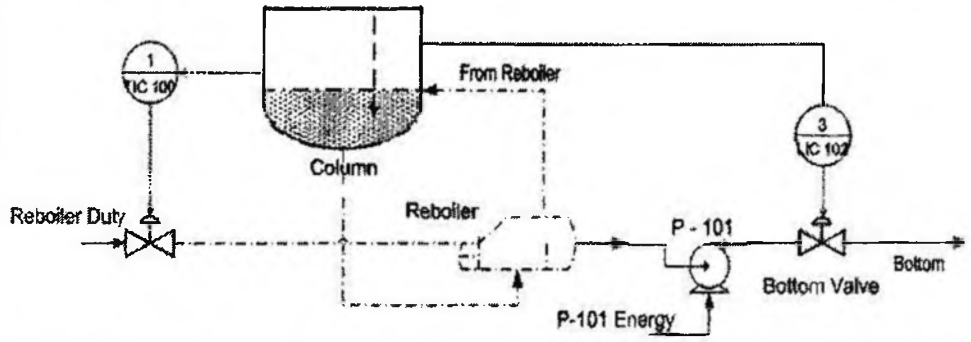
Rule I:

IF: i) **S1** (*measurement space*) and
ii) **Bigger than '243.09'**, (*feature space*)
THEN: **More Temperature** (*decision space*)

(Programming Source Code)
Premise: *if (atof(s1) > (b))*
Action:

```
{   action1 = 'L';
    Label18->Font->Color=clRed;
    Label18->Caption= "MORE";
    firstDet1='H';   }
```

Table 4 Sample of HAZOP worksheet for node 1



Deviations	Causes	Consequences
More Temperature	• Reboiler overheated due to wrong setting of reboiler duty • Reboiler runs nearly dry • Reboiler tube leaks • Less flow from column to reboiler • High flowrate of steam to reboiler	• Column overheated • Pressure high in column • Inefficient stripping process • Off-spec of product
Less Temperature	• Low setting of reboiler duty • Tubes failed in a reboiler heater • Less steam input to reboiler • Fouling of tube reboiler leading to reduced heat transfer • Hardness of the boiler feed water • More flow from column to reboiler	• Low thermal loading • Off-spec of product • Inefficient separation in column
More Pressure	• Reboiler runs nearly dry • TIC 100 failure • Blockage at stream *From Column to Reboiler* caused of fatty acid solidify • Flooding at trayout	• Ineffective separation • Causing explosions • Off-spec of product
Less Pressure	• Reboiler malfunction • Too much steam expands across the nozzle of ejector • TIC 100 failure • Incorrect controller setpoint	• Column Flooding • Ineffective separation • Off-spec of product

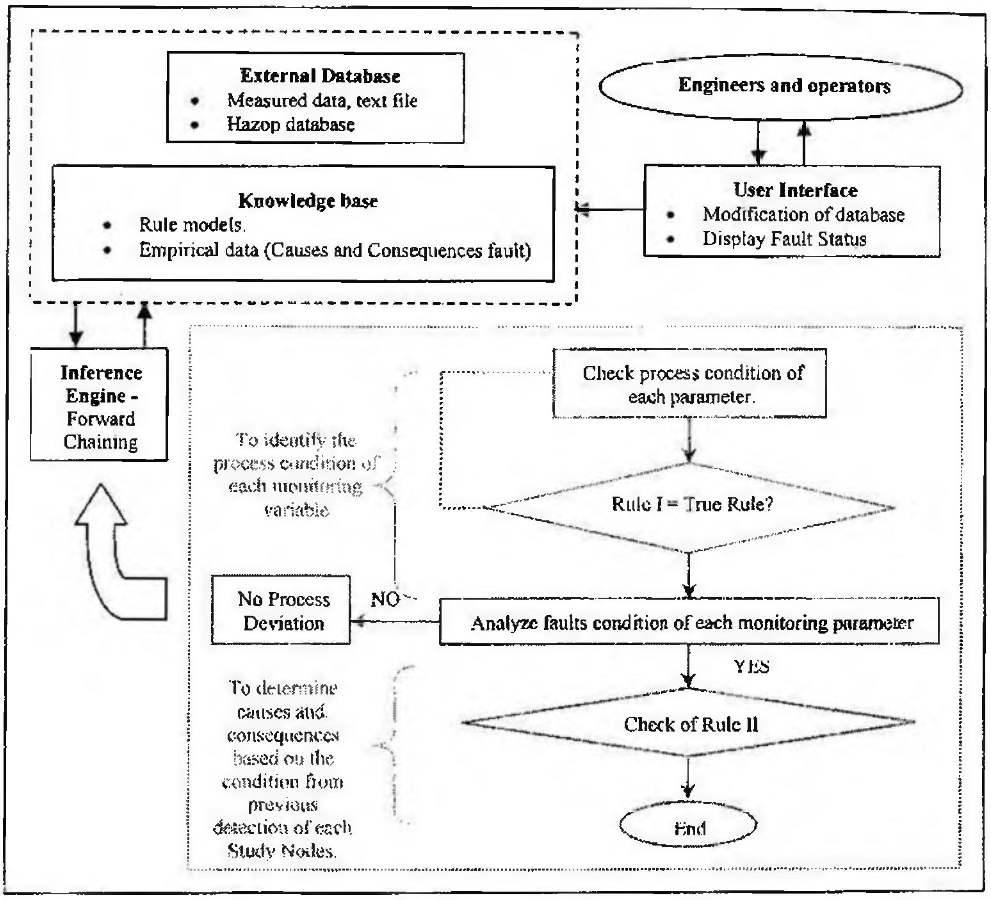


Figure 3 Architecture of the developed algorithm

DoQuery 1 as shown in the source code below is Query component where SQL statements were used to retrieve data from a physical database table (Database Desktop table) via the Borland Database Engine (BDE) table that contain causes and consequences of HAZOP knowledge. The following is the coding written in the properties of Query component:

SELECT CAUSES FROM TEMPERATUREUL and
SELECT CONSEQUENCES FROM TEMPERATUREUL

Rule II:

IF: '**S1** stream is 'High'',(*class space*)
THEN: '**S1** is More Temperature Causes, and Consequences'.
(*qualitative information*)
(Programming Source Code)
Premise: *if (s1 = firstDet1='H')*
Action: *{ DoQuery1(); }*

The following is an example of coding for **S1** where Query is also used to retrieve data from database table containing causes and consequences of HAZOP knowledge. TEMPERATUREUL is a coding of database which contains the knowledge of causes and consequences for **S1** in more flow condition.

SELECT CAUSES FROM TEMPERATUREUL and
SELECT CONSEQUENCES FROM TEMPERATUREUL

SQL statement was also used for detecting the exact time of the deviated data. The following is the sample coding for variable **S1** where 'DATA' is a database of data set to be analyzed and LIMITS is a database of control limit. 'OR' is used to get either the upper or the lower limits.

SELECT TIMES, TEMPERATURE FROM DATA
WHERE
TEMPERATURE >= (SELECT TEMPERATUREUL FROM LIMITS) OR
TEMPERATURE <= (SELECT TEMPERATURELL FROM LIMITS

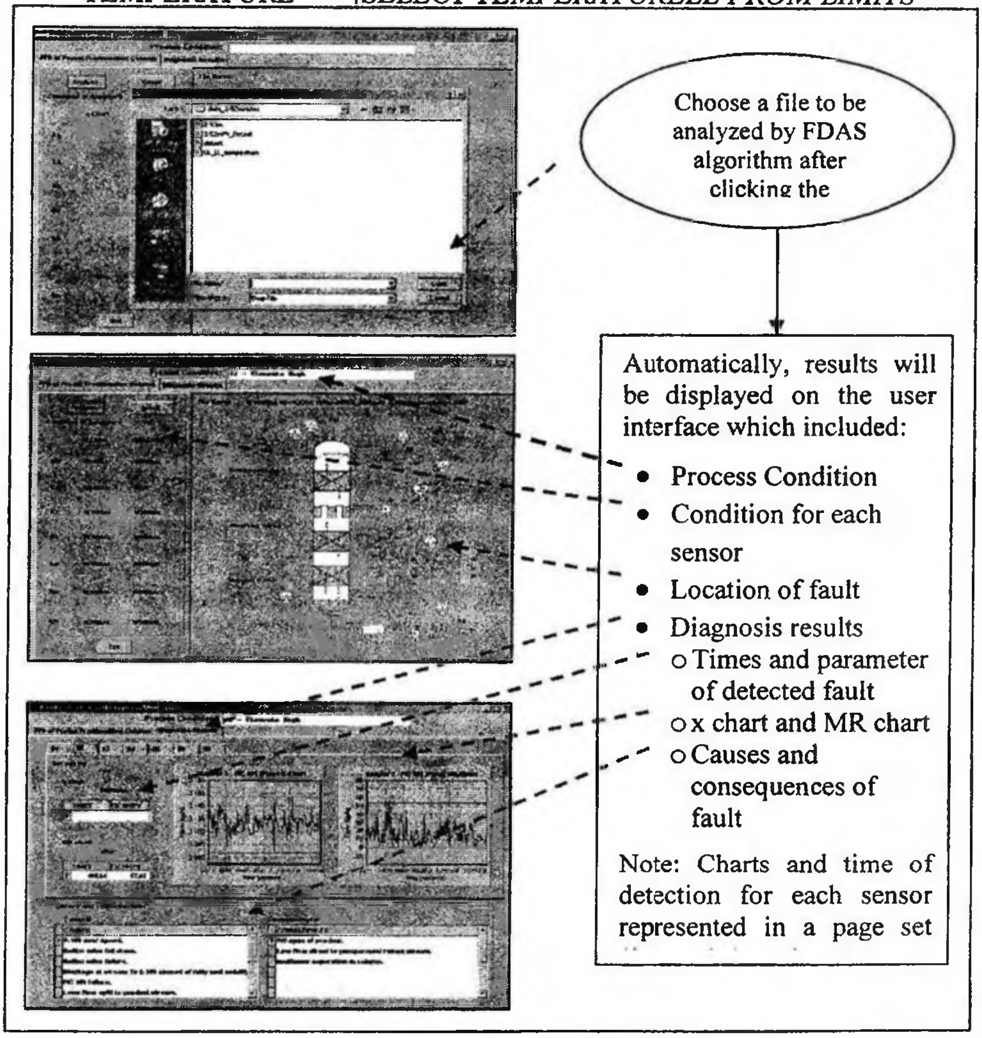


Figure 5 Description of Fault Detection and Diagnosis interface

Description of Fault Detection and Diagnosis interface is shown in Figure 5. The main task of the discriminator in FDA system is to detect the occurrence of any process deviation, out of range data's location and time. As shown in Figure 6, user need to click the 'Analyze' button to open a database with dump file format which consists of data set that will be used for analyses. Fault is detected if one value of the process variables deviates out of the limits. Test has been done on the developed prototype by changing a value of a data set to verify the efficiency of the system. For the case study, *FIC 101* is defined as Sensor 1. The result of the fault detection and diagnosis obtained is shown in Figure 7. The group box 'Condition of Study Nodes' shows 'High Temperature' at S2. Meanwhile, Figure 8 shows the time of the fault, the deviated fault value, and the control chart for each parameter.

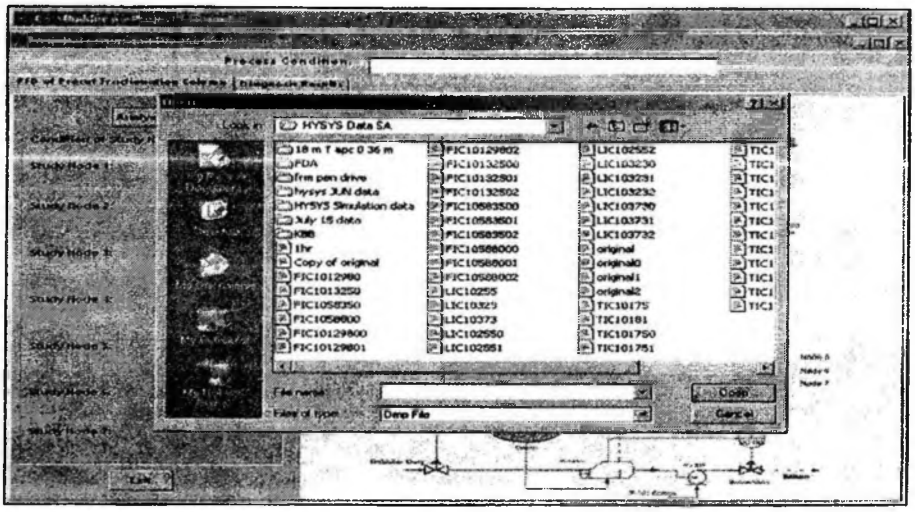


Figure 6 FDD workspace (open file window)

Inference engine examines information from the dump file with the premises of the rules. The upper and lower limits for MR data FIC 101 (S2) monitoring variable are 53.41 and 0 respectively. Assume a data from dump file is 57.23, the inference engine repeatedly finds rules that are matched. From the rule below, searching strategy started with chain forward of premise of the Rule Ia. Rule Ia is triggered looking for the premise of another rule that matches the action part of the Rule Ia while Rule Ib and Rule Ic are discarded. Rule IIa matches the action of Rule Ia and hence, Rule IIa is triggered. Since, there are no more rules to trigger, the end results is reached where fault detected for From Reboiler = 'High' and DoQuery1.

Rule Ia: IF S2 > 53.41
THEN Fault is Detected, S2= 'High'

Rule Ib: IF S2< 0
THEN Fault is Detected, S2 = 'Low'

Rule Ic: IF (S2 <= 53.41 &
S2 >= 01)
THEN Fault is Detected, S2 = 'Normal'

Rule IIa: IF Fault is Detected, S2 = 'High'
THEN DoQuery1

Rule IIb: IF Fault is Detected, S2 = 'Low'
THEN DoQuery2

Rule IIc: IF S2 = 'Normal'
THEN S2 in normal operation

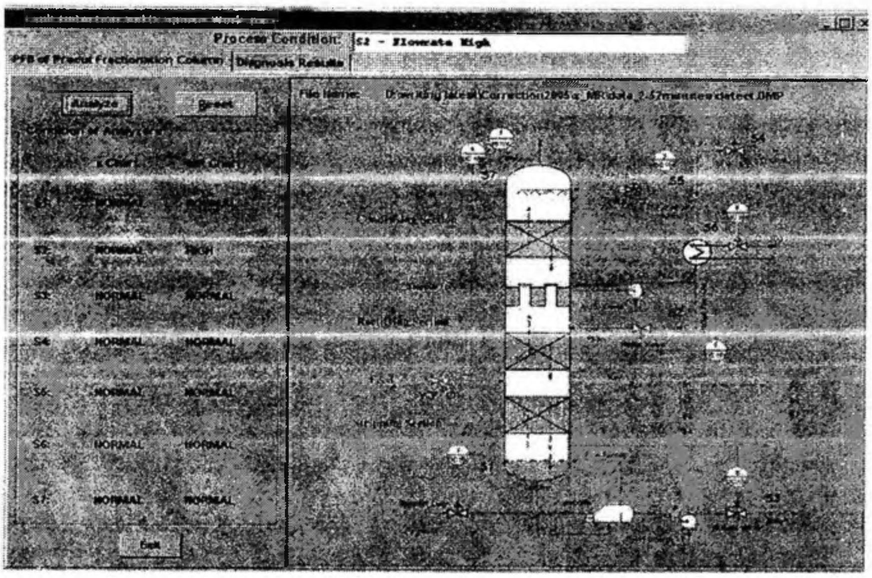


Figure 7 End results of fault diagnostic algorithm

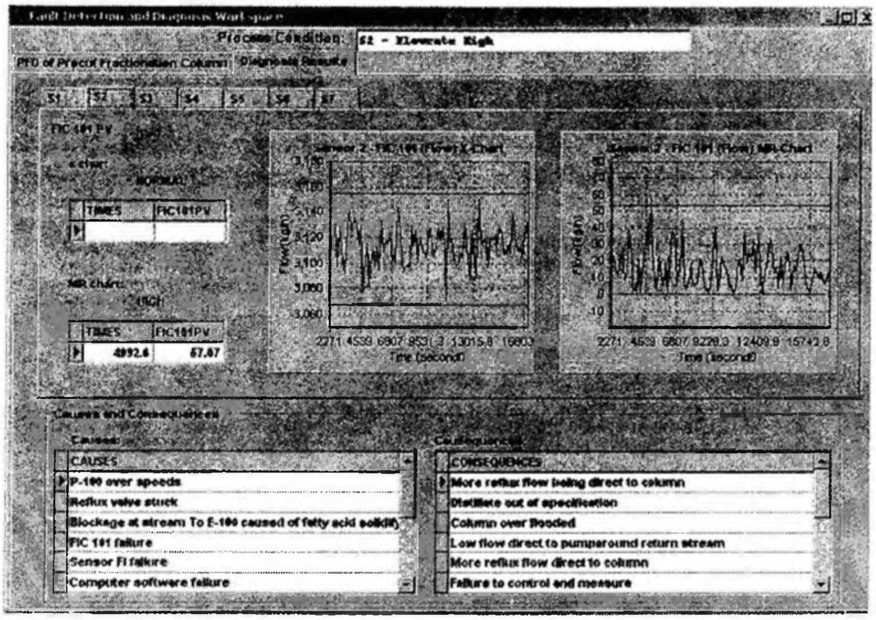


Figure 8 Time, causes and consequences results

(a) (b) (c) (d) (e) (f)

Figure 9: Results of *x-MR* chart for other sensors

Once the discriminator has detected, the causes and consequences from the database are then displayed on the diagnostic windows as shown in Figure 8. Figure 9 shows the results and *x-MR* chart for other sensors. Figure 10 show the forward chaining for FDA system in firing rules. From Figure 10b, Rule Id was fired and added to Working Memory. Based on the first fire rule, Rule IIa was fired. The execution shown high flow was detected at S2 and HAZOP study for S2 was obtained.

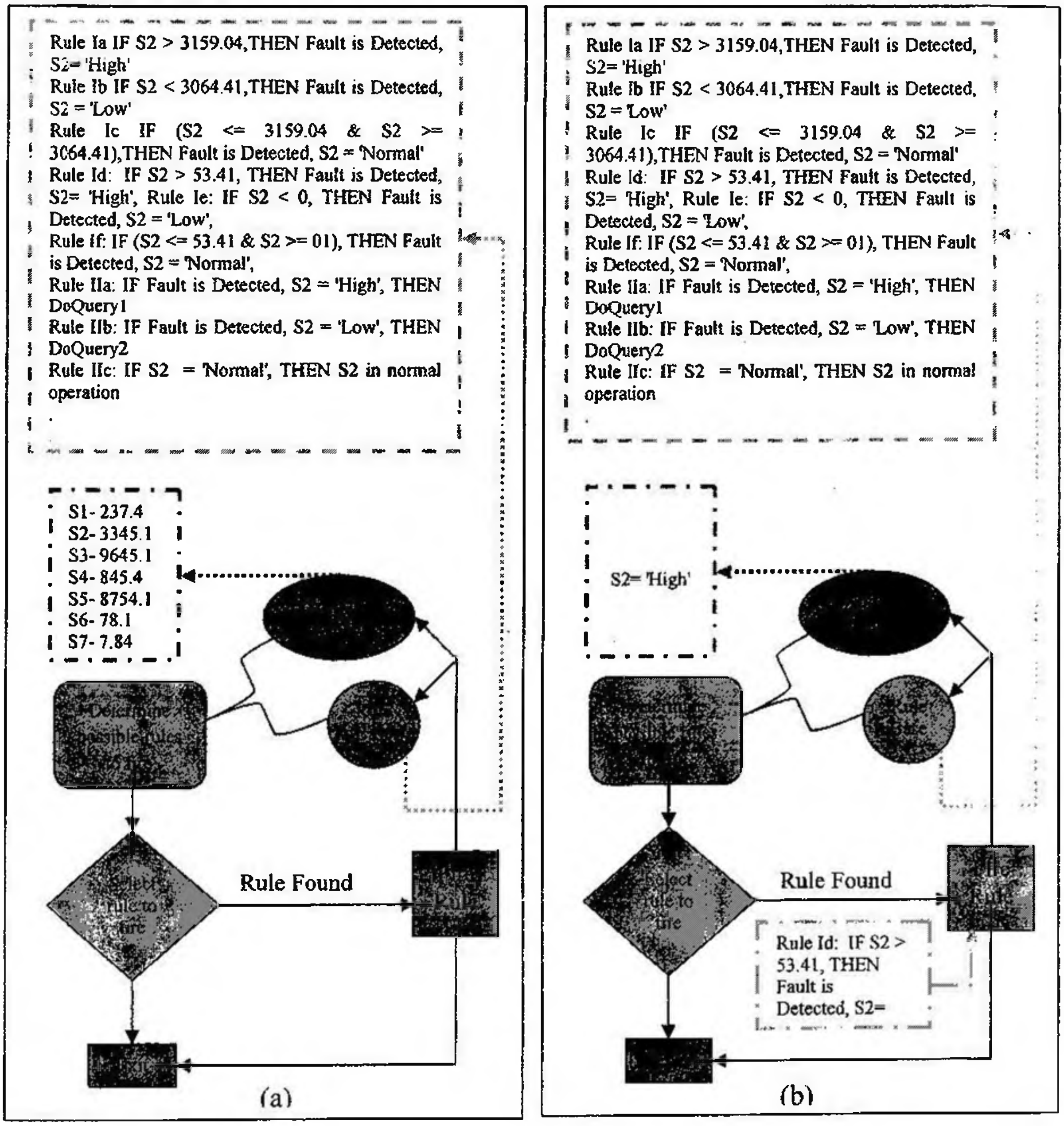


Figure 10a: Forward chaining procedure for FDA system

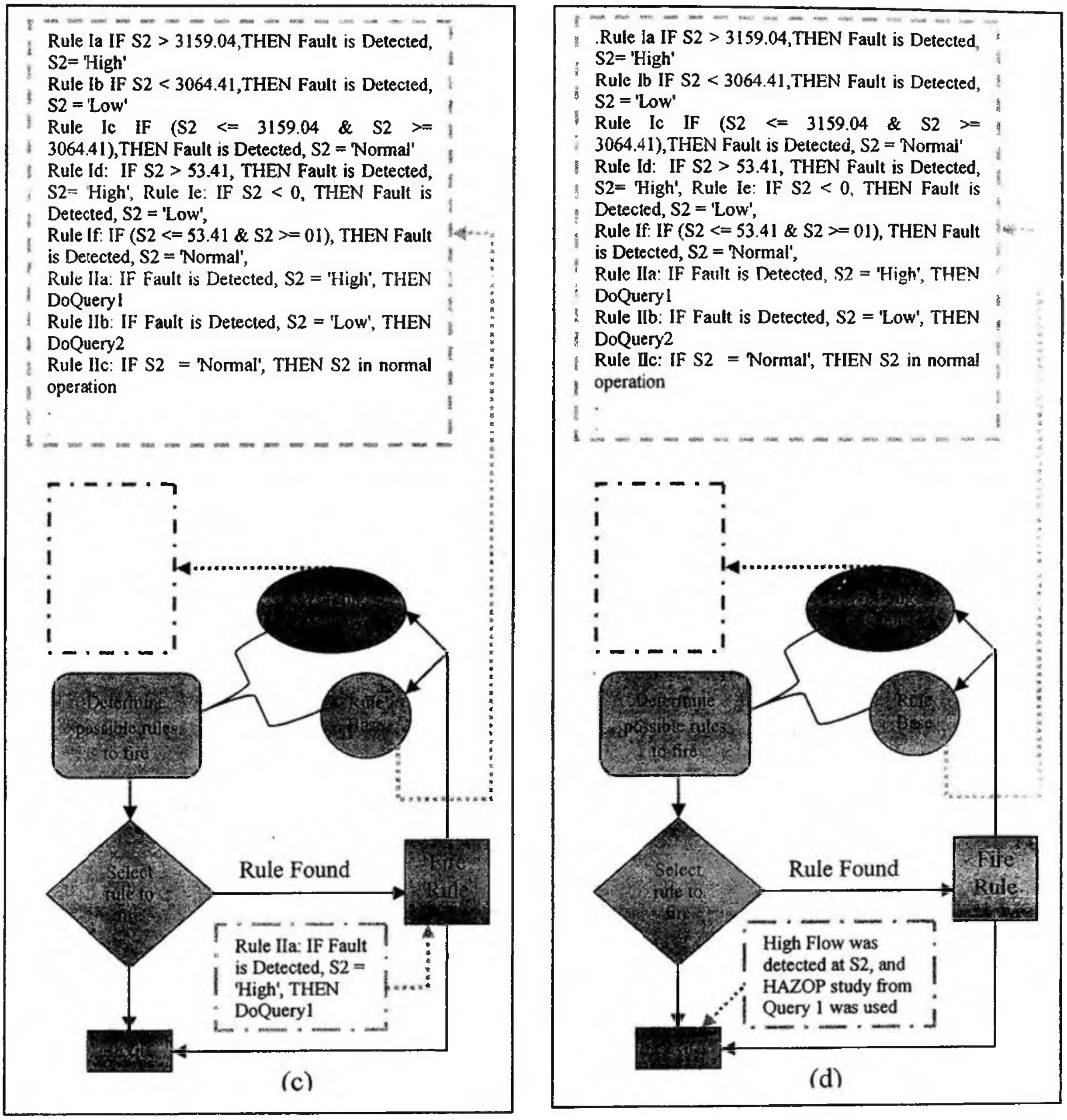


Figure 10b Forward chaining procedure for FDA system

4.1 Results and Discussion for Offline FDA System

Two samples of experiments were performed offline and discussed in the following. This included failure sensor for FIC 101 and TIC 101. The detected and diagnosed faults by FDA system were also discussed and explained with the illustration of user interface. The main point of performing these experiments was to evaluate the detection and diagnose results in term of efficiency. It is important to verify that the FDA algorithm is able to detect and diagnose fault.

In order to create a drift data, ±5% to ±10% bias was added to each sensor during the simulation of the process. The FDA system was developed only to detect the single fault. Process deviation was detected by *x-MR* chart. Some control charts showed the data nearly touched the limits, but it was still considered as normal condition. Summary of the output results of fault detection and diagnose experiment were tabulated in Table 5.

Table 5 Summary of an experiment for FDA system

Output of FDA System	**Diagnose Results**			
	Case 1		**Case 2**	
	x	MR	x	MR
S1 = TIC 100	N	N	N	N
S2 = FIC 101	[redacted]	[redacted]	N	N
S3 = Bottom	N	N	[redacted]	[redacted]
S4 = Distillate	N	N	[redacted]	N
S5 = FIC 105	[redacted]	N	N	N
S6 = TIC 101	N	N	N	N
S7 = PI 104	N	N	N	N
Process Condition	High flow at sensor 2		Low flow at Sensor 3	
Causes and consequences	HAZOP study for More Flow at sensor 2		HAZOP study for Less Flow at sensor 3	

Fault Case 1: Faulty Condition at Sensor for FIC 101

In this experiment, two deviating conditions were detected by FDA system. At 13318.8 seconds (222 minutes), the flowrate at sensor 2 started to deviate outside the upper limits which as shows in Figure 11a. Sensor 5 also started to deviate after 30 minutes as shown in Figure 11b. Although there was deviation occurred at sensor 5, the system has successfully detected the earlier fault point as shows in Figure 11a. This concluded that high flowrate has happened at sensor for FIC 101 Figure 11c illustrates the user interface of the other sensors under normal condition.

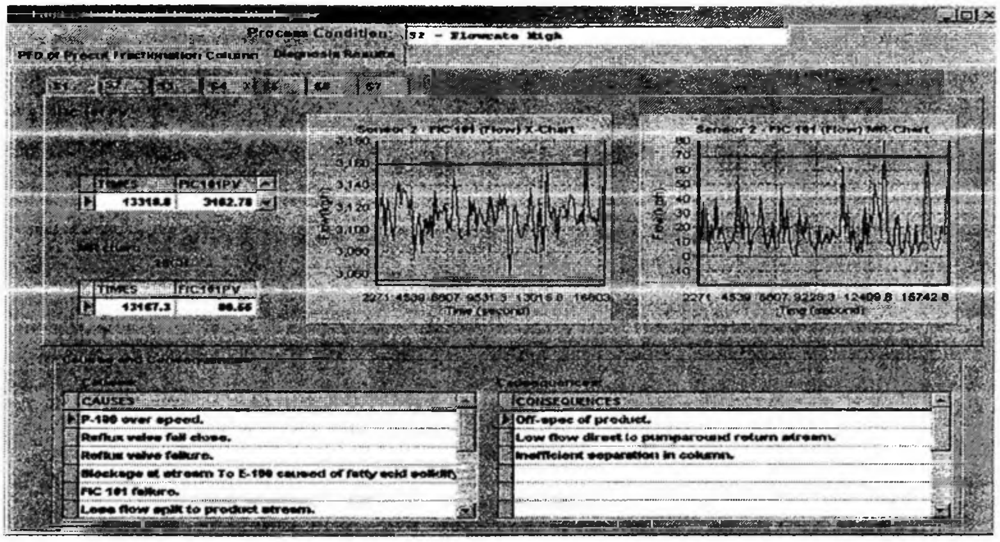


Figure 11a Fault detected and diagnosed results for sensor FIC 101 – sensor 2

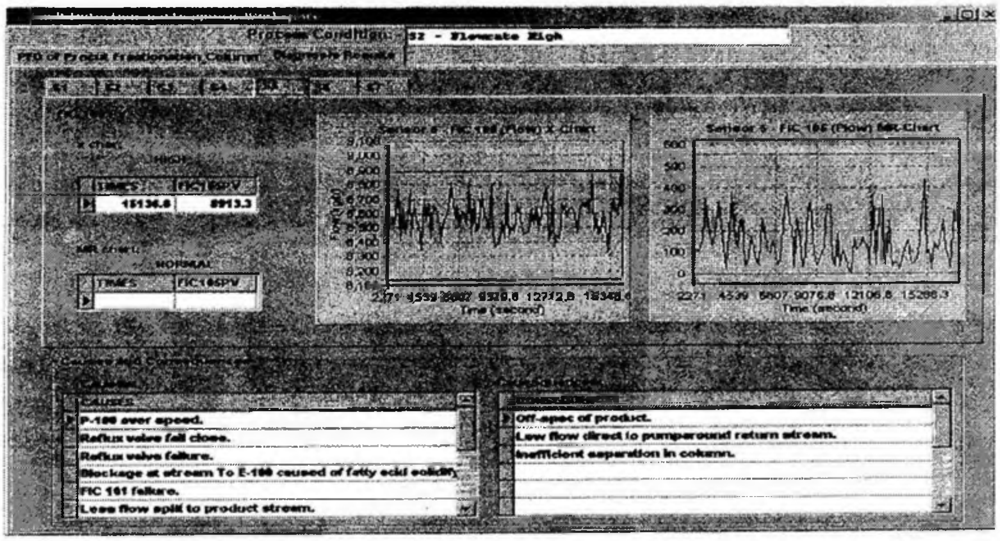


Figure 11b Fault detected and diagnosed results for sensor FIC 101 – sensor 5

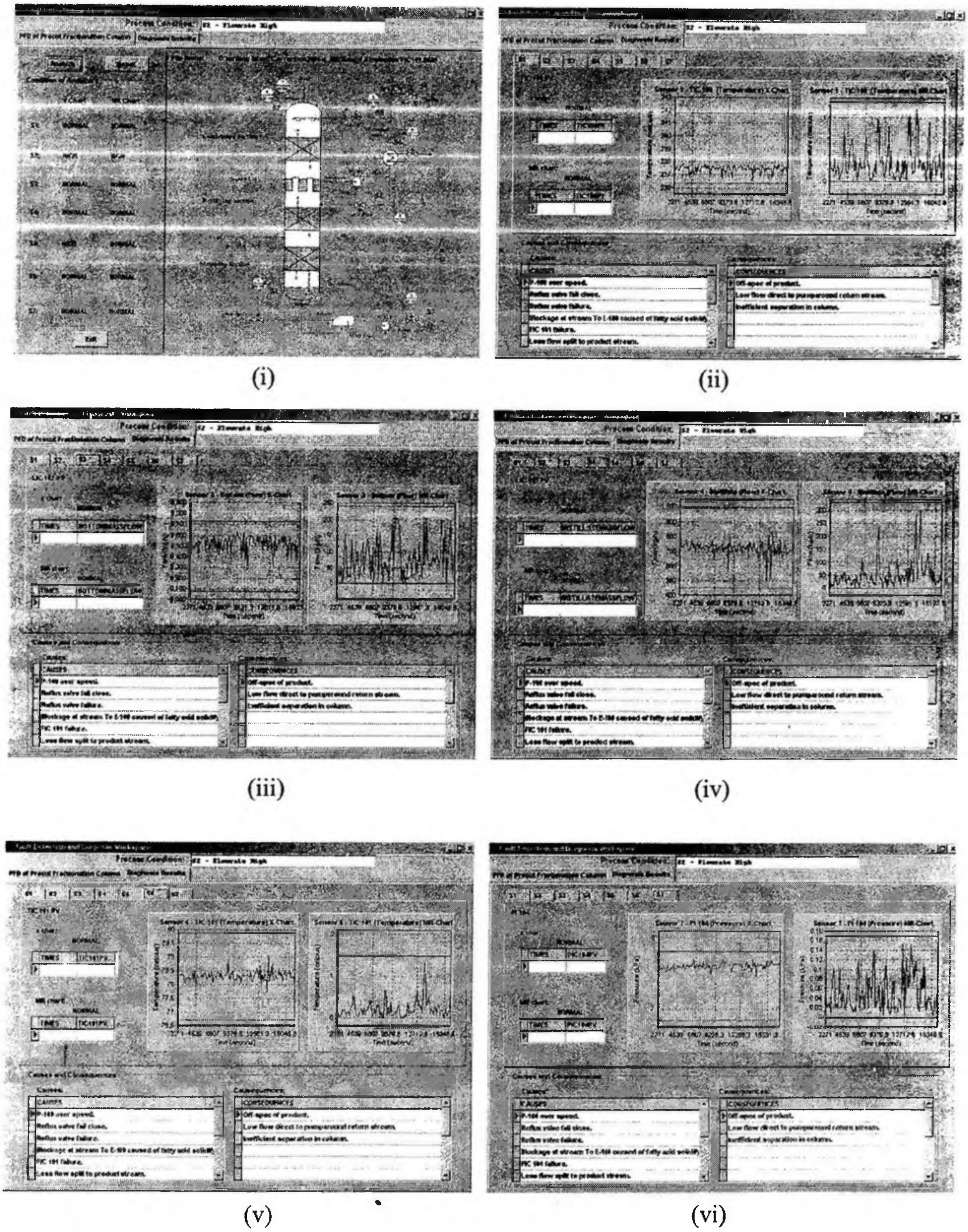


Figure 11c Normal condition for other sensors

Fault Case 2: Faulty Condition at Sensor for TIC 101

The last experiment was based on the fault data at sensor for TIC 101. FDA system has analyzed low flowrate occurred at sensor 3 as shown in Figure 12a, x chart shows the bottom stream flow started to decrease at 12712.8 seconds (211.9 minutes). Suppose the fault for this case was caused by sensor for TIC 101 as shown in Figure 12c. Since the temperature at sensor 6 still remains in the range of control limits, conclusion can be made that the FDA system has successfully diagnosed the exact location of fault occurred and the consequences were caused by the failure of sensor for TIC 101. Figure 12d illustrates the user interface of process under normal operating condition.

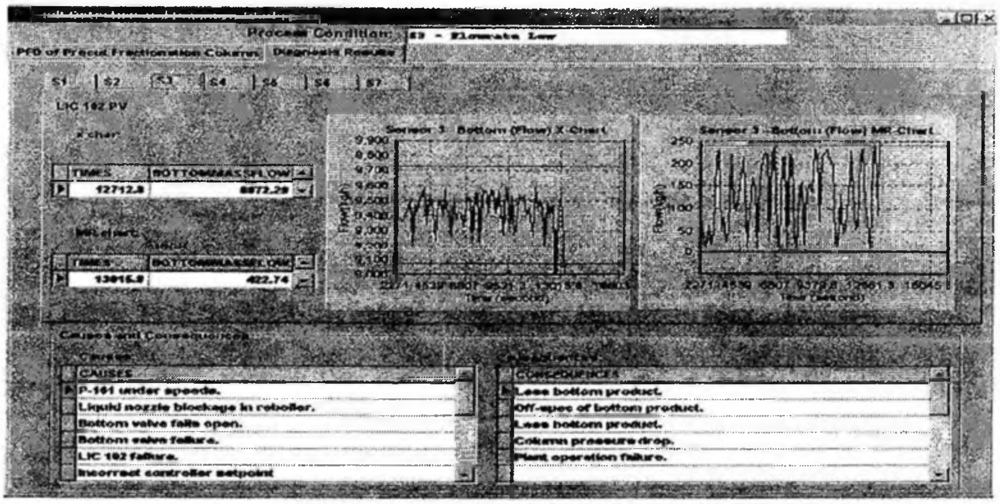


Figure 12a Fault detected and diagnosed results for sensor TIC 101- sensor 3

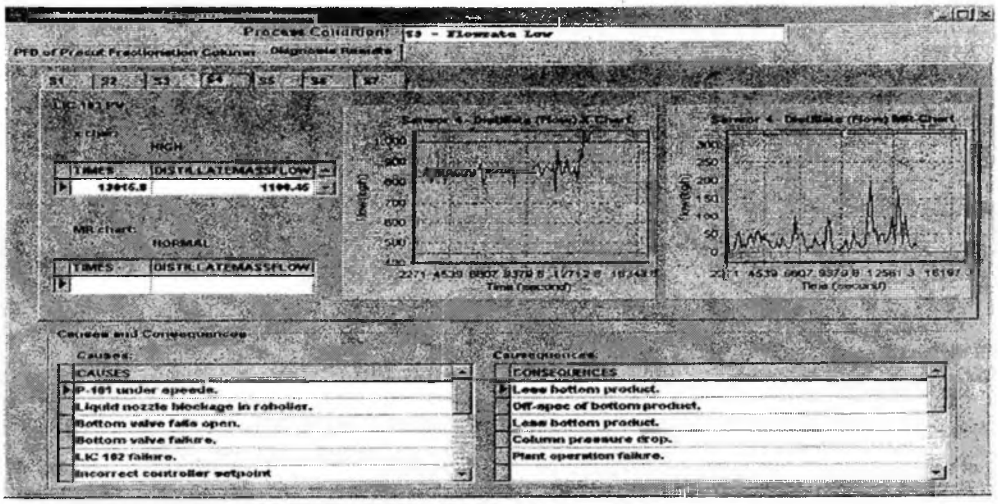


Figure 12b Fault detected and diagnosed results for sensor TIC 101 – sensor 4

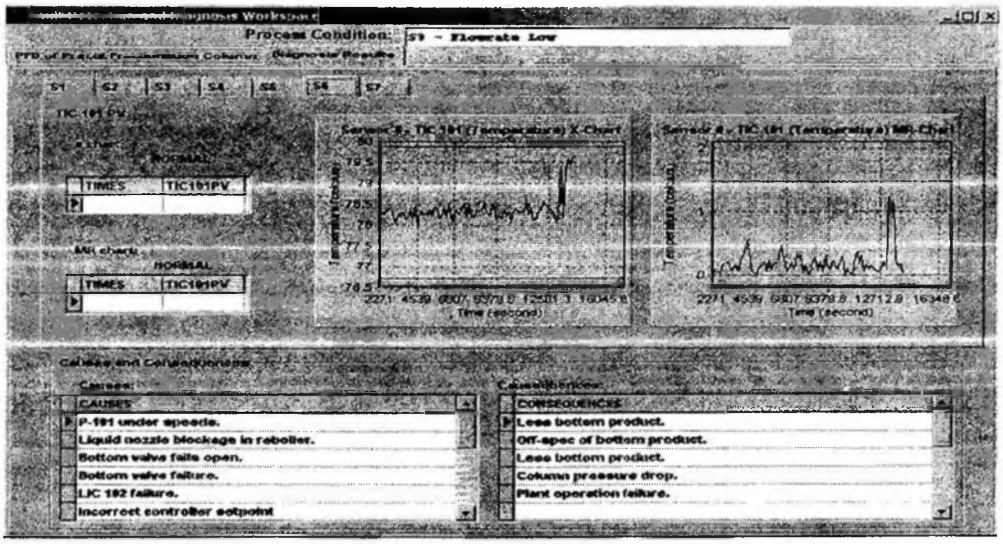
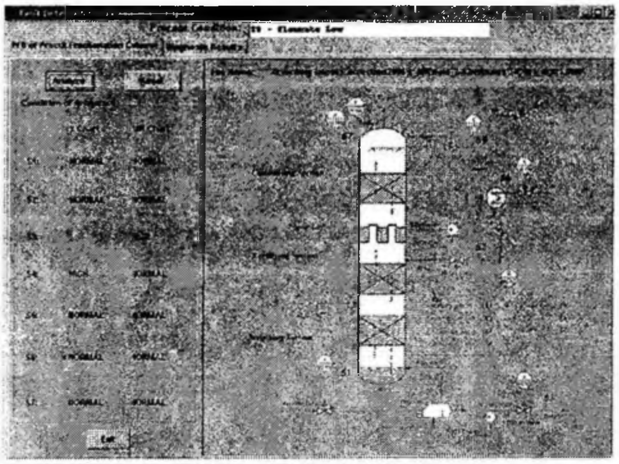
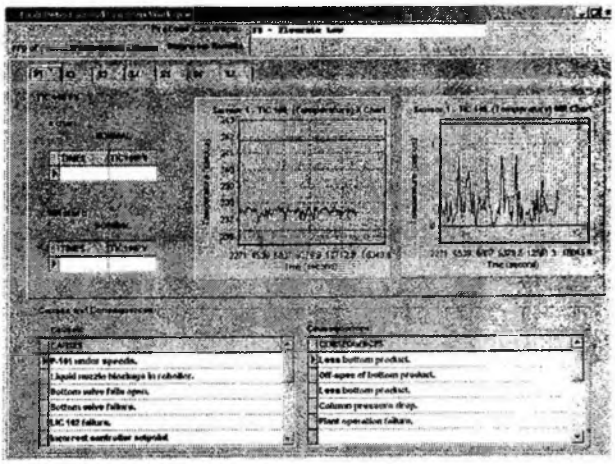


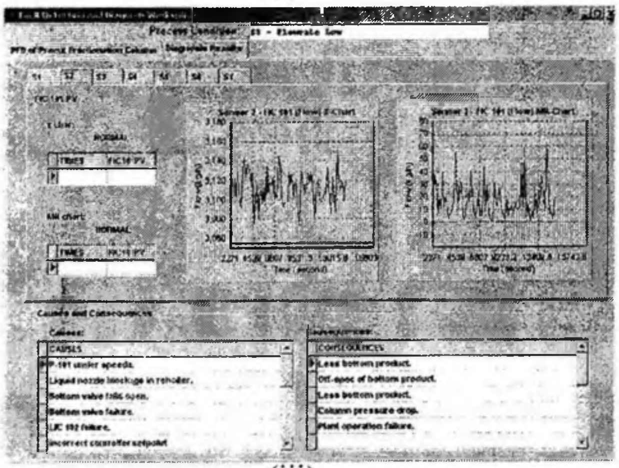
Figure 12c Fault detected and diagnosed results for sensor of TIC 101 – sensor 6



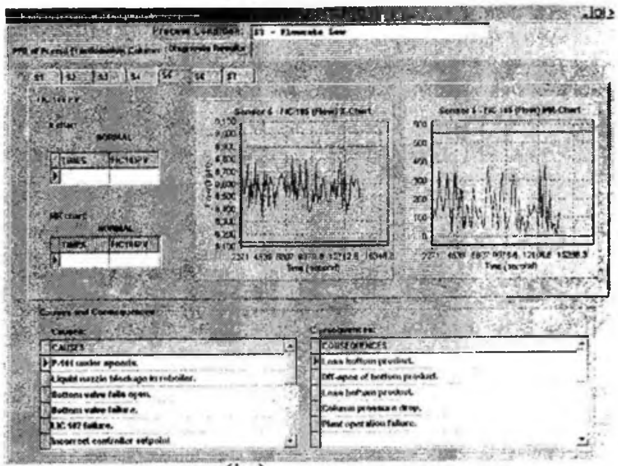
(i)



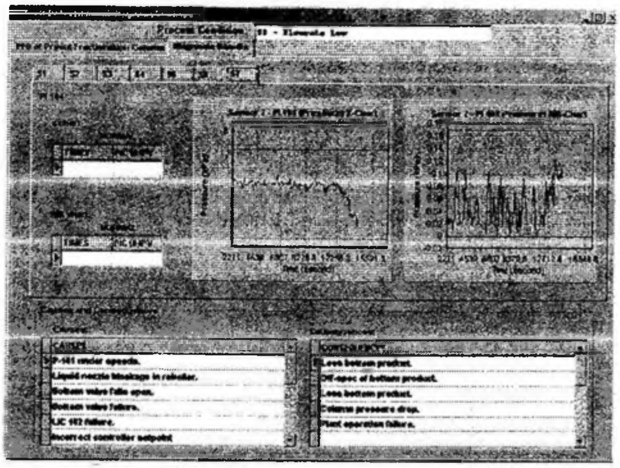
(ii)



(iii)



(iv)



(v)

Figure 12d Normal condition for other sensors

5.0 CONCLUSIONS

An algorithm was developed for fault detection and diagnosis with the combination of *x-M* chart and HAZOP study supported by rule-based expert system. Plant model was simulated by using commercial HYSYS.Plant™ simulator. The x-*M* chart was used to analyze the condition of process and to detect any process deviation that might have taken place. The main causes and consequences of the analyzer were specified based on the HAZOP study carried out specifically for precut fractionation column. The HAZOP study carried out was based on the process parameter for each existing sensor. The developed fault diagnostic system is aimed to enhance the safety of process operation, to reduce the alarm false and aid to operators to cope with fault.

The following are the general conclusions and contributions of the developed Fault Diagnostic System:

i. The study combined the application of *x-M* chart and HAZOP study in developing a framework of Fault Diagnostic System especially for a fractionation column.

ii. The developed FDA system was able to detect the exact time and place of process deviation for precut column and then diagnose it. Information about the root cause and consequences were presented.

iii. The developed Fault Diagnostic System could be applied to any precut fractionation column. This is due to the available section for user to change or add additional data in the database and hence, the limits and HAZOP study.

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