Risk-based Fault Diagnosis and Safety Management for Process Systems

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Outline

- Objectives
- Motivations
- Background
- Proposed Methodology
- Case Study 1
- Case Study 2
- Characteristics of Proposed Methodology
- Conclusions
- Future Works

Objectives

- To propose an innovative methodology of risk-based SPC fault diagnosis and its integration with Safety Instrumented System to solve the fault diagnosis and safety management problems in process engineering.
- Using G2 development environment, to implement and verify the proposed methodology in a tank filling system developed with G2 software.
- To realize a technique breakthrough, from univariate monitoring to multivariate monitoring, for SPC fault diagnosis, in process fault diagnosis field.
- To simulate a real process system, the steam power plant system, in G2 development environment, to testify the proposed methodology.

Motivations

"To know is to survive and to ignore fundamentals is to court disaster."

—— Fawcett, Howard H.
Wood, William Samuel

- Life and health for people
- Pollution to the environment
- Economic loss to process industry
- Disorder in academia in fault diagnosis and safety management for process engineering

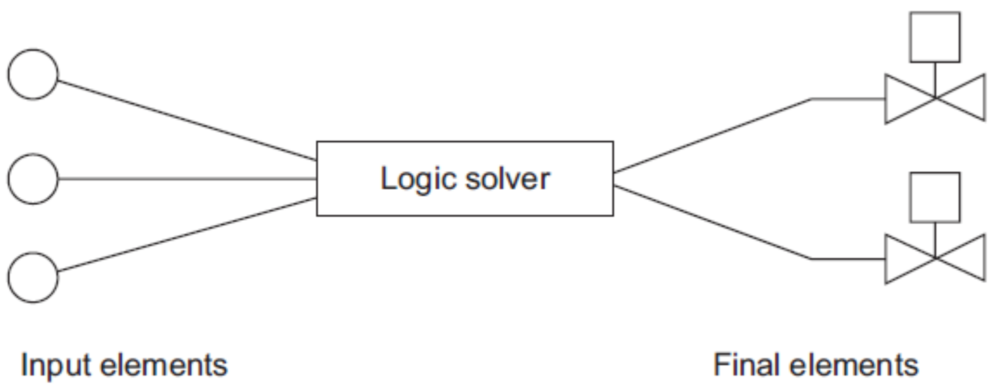
Background

- **The Definition of Fault**

  A departure from an acceptable range of an observed variable associated with a process.

- **What is a SIS?**

  A system composed of sensors, logic solvers and final-control elements for the purpose of taking the process to a safe state, when predetermined conditions are violated.



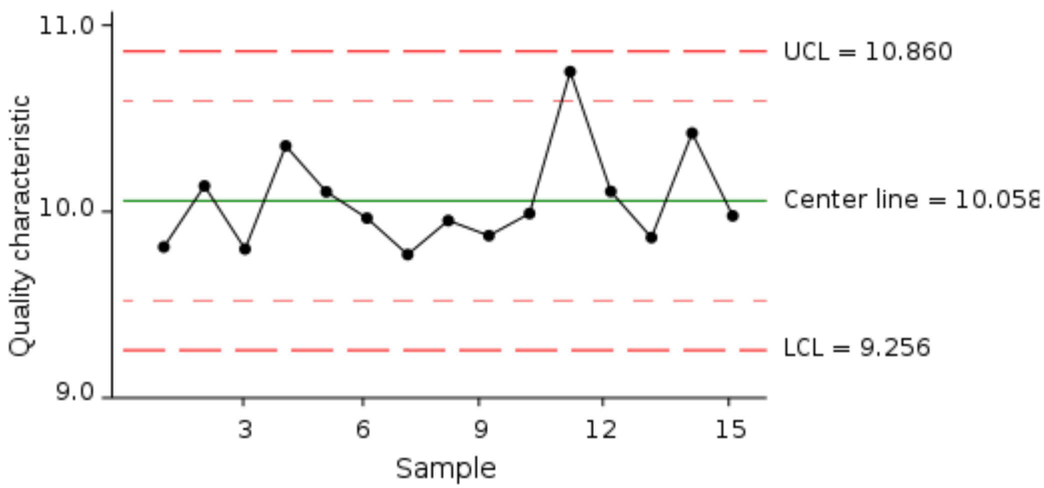
Main Parts of a Safety Instrumented System

Background

- **Definitions of SILs from IEC 61511-1**

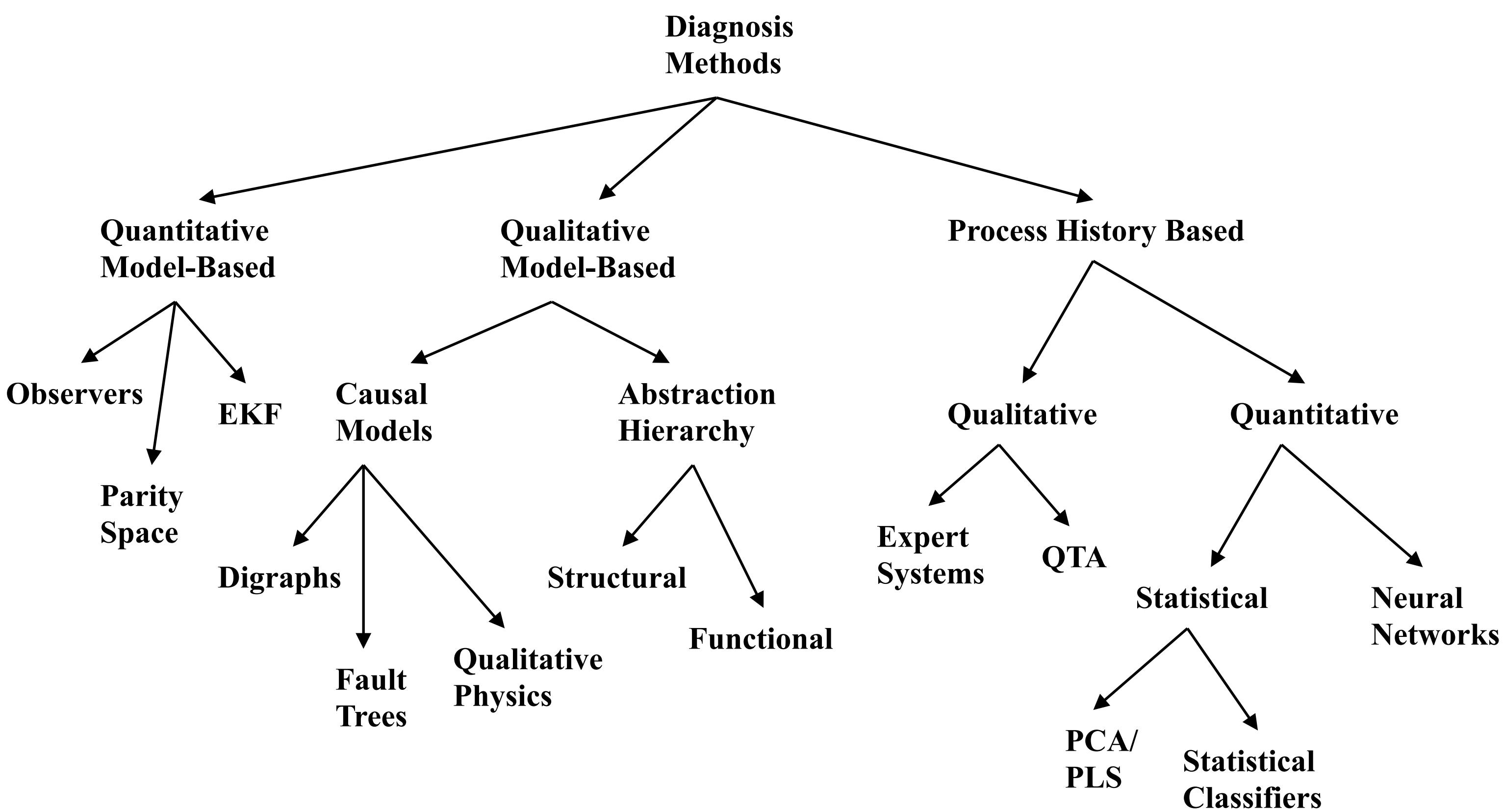
SIL	Range of Averaged PFD	Range of RRF
4	10^{-5} <= PFD < 10^{-4}	100,000 >= RRF > 10,000
3	10^{-4} <= PFD < 10^{-3}	10,000 >= RRF > 1000
2	10^{-3} <= PFD < 10^{-2}	1000 >= RRF > 100
1	10^{-2} <= PFD < 10^{-1}	100 >= RRF > 10

- **Control Chart**



The Proposed Methodology

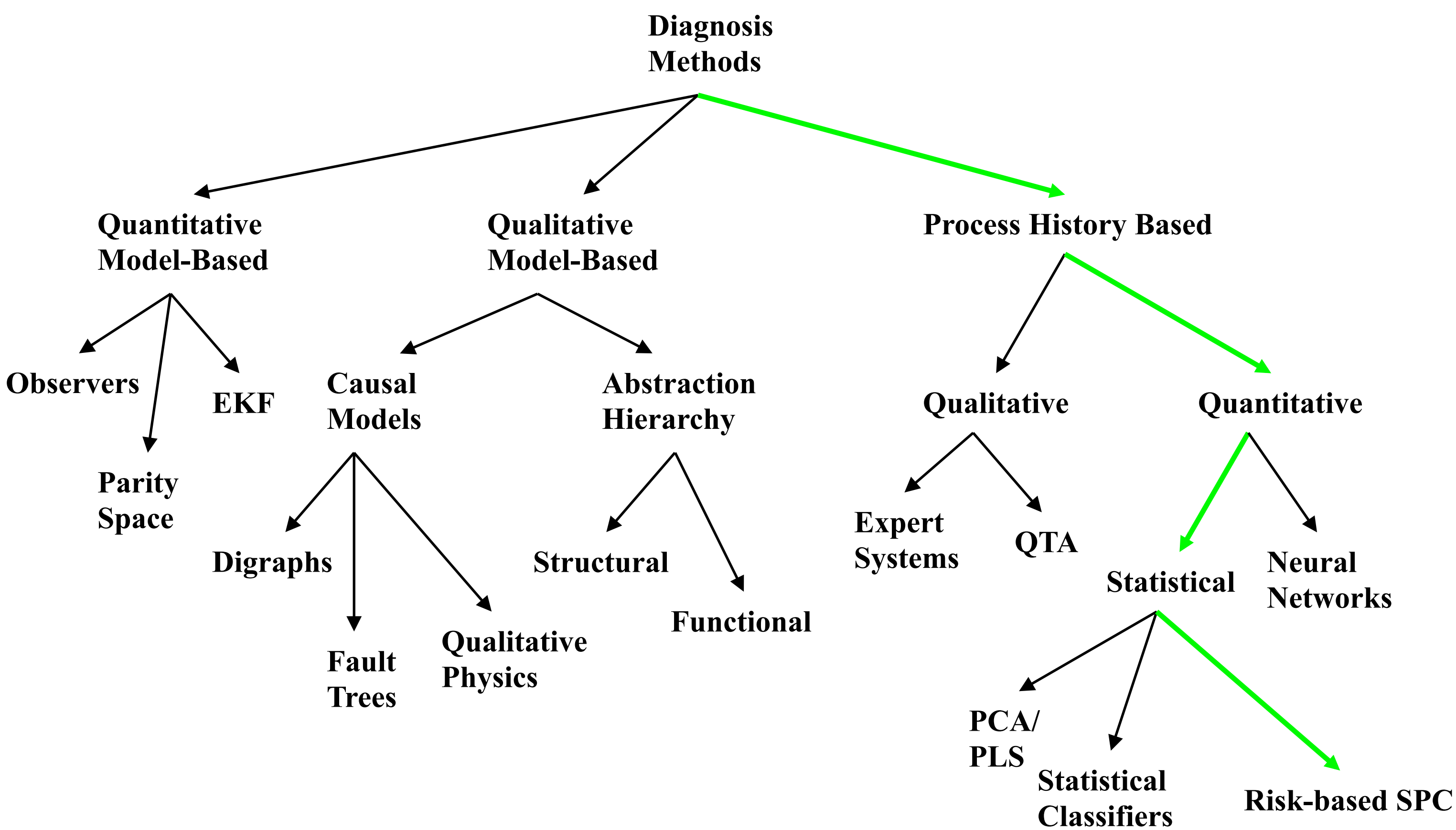
- ## The Existing Fault Diagnosis Methods



Classification of Diagnostic Algorithms (Venkatasubramanian et al., 2003)

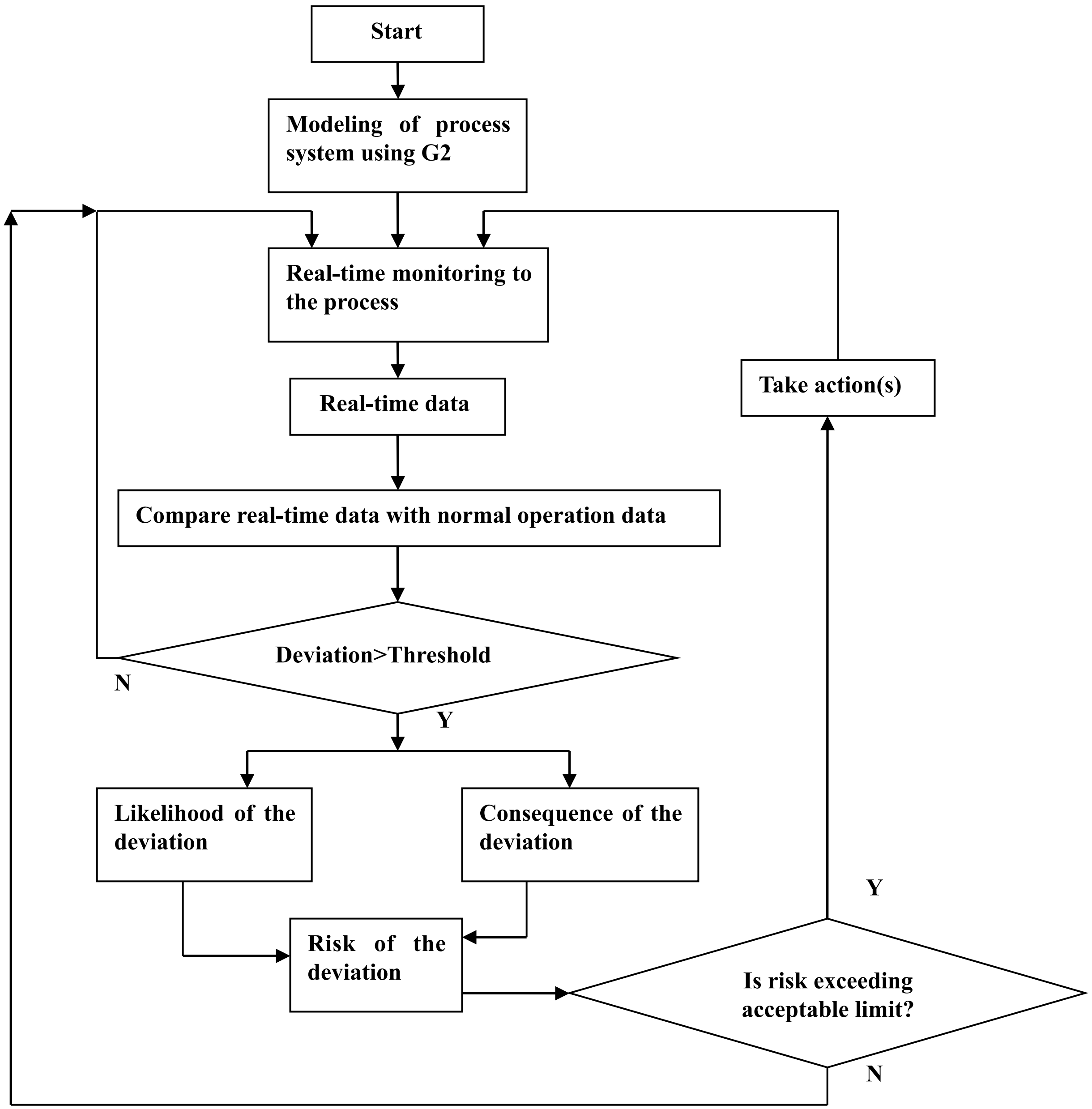
The Proposed Methodology

- **The Pathway of Proposed Methodology**



Pathway of Proposed Methodology in the Classification of Diagnostic Algorithms

- **The Flow Chart of the Proposed Methodology**



The Proposed Methodology

- **Theoretical Verification of Proposed Methodology**

Historical data from Thermodynamics and Fluids Lab in Faculty of Engineering and Applied Science building at Memorial University of Newfoundland obtained during 12:49 p.m. through 12:58 p.m. on July 13, 2006 :

Steam Pressure Data for the Steam Power Plant :

Normal Situation

Time	12:49-12:53	12:54-12:58
	678	673
	656	679
	638	658
	633	639
	645	643

Abnormal Situation

Time	12:49-12:53	12:54-12:58
	678	673
	656	700
	638	730
	633	639
	645	643

The Proposed Methodology

- **Theoretical Verification of Proposed Methodology**

Moving Average Steam Pressure Data for the Steam Power Plant :

Normal Situation

Time	12:49-12:51	12:50-12:52	12:51-12:53	12:52-12:54	12:53-12:55	12:54-12:56	12:55-12:57	12:56-12:58
	678	656	638	633	645	673	679	658
	656	638	633	645	673	679	658	639
	638	633	645	673	679	658	639	643
Xbar	657.3	642.3	638.7	650.3	665.7	670	658.7	646.7

Note:

The normal steam pressure is 640 kPa, and the maximum steam pressure is 690 kPa.

Abnormal Situation

Time	12:49-12:51	12:50-12:52	12:51-12:53	12:52-12:54	12:53-12:55	12:54-12:56	12:55-12:57	12:56-12:58
	678	656	638	633	645	673	700	730
	656	638	633	645	673	700	730	639
	638	633	645	673	700	730	639	643
Xbar	657.3	642.3	638.7	650.3	672.7	701	689.7	670.7

The Proposed Methodology

- **Theoretical Verification of Proposed Methodology**

1. Fault Diagnosis Principle —— Three-sigma Rule:

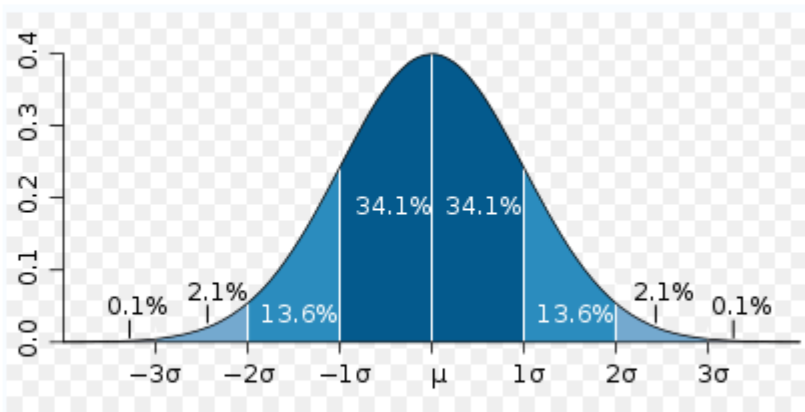


Fig. 16 Standard Deviation Diagram

In statistics, for a normal distribution, nearly all (99.7%) of the values lie within 3 standard deviations of the mean. Statisticians use the following notation to represent this: $\mu \pm 3\sigma$.

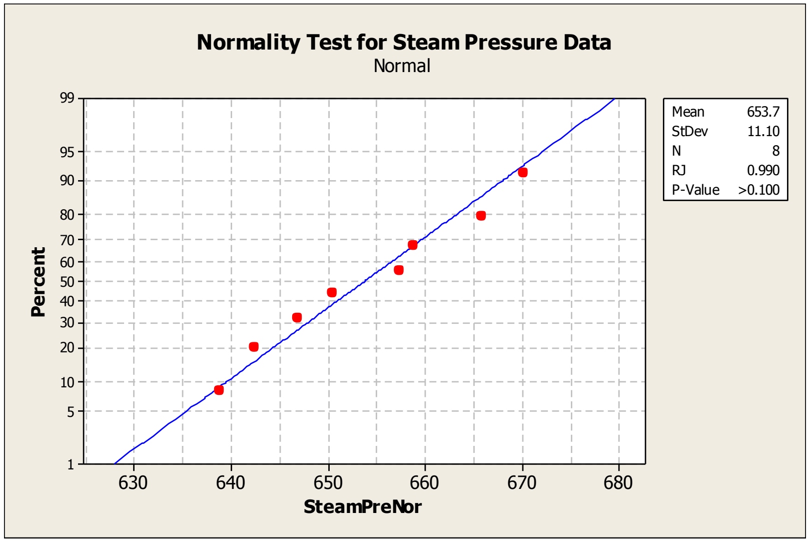
The Proposed Methodology

- **Theoretical Verification of Proposed Methodology**

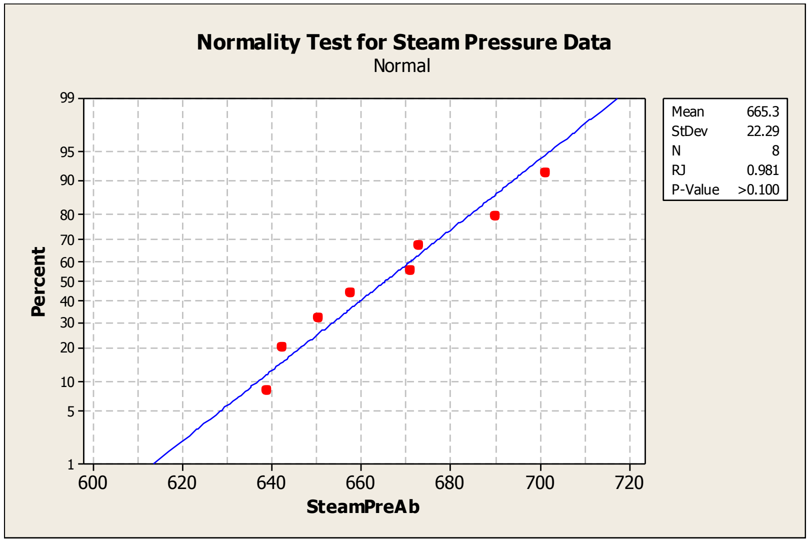
2. SPC Fault Diagnosis :

Normality Test to the Moving Average Steam Pressure Data in Minitab15 :

Normal Situation



Abnormal Situation



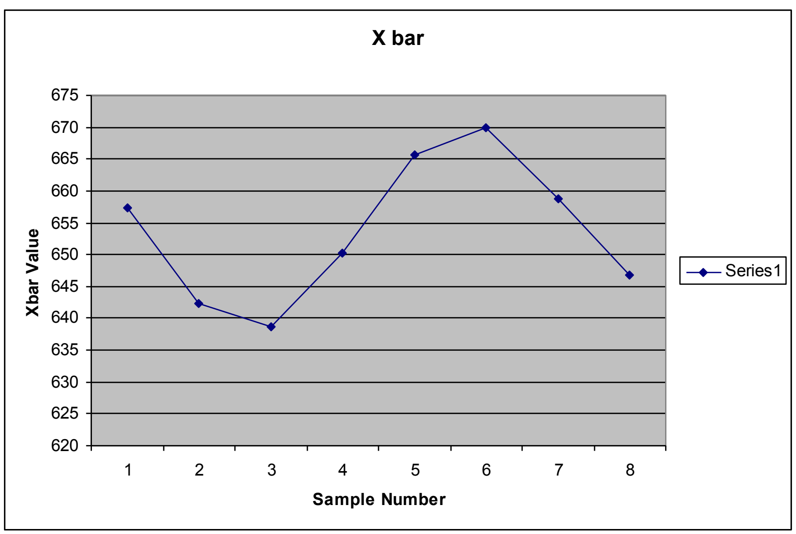
The Proposed Methodology

- **Theoretical Verification of Proposed Methodology**

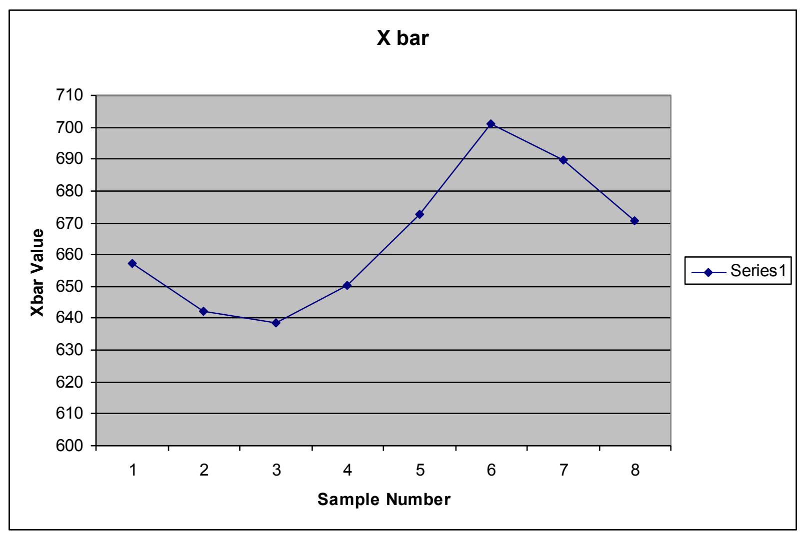
SPC Fault Diagnosis Results :

The Moving Average Steam Pressure Data in Excel 2003 :

Normal Situation



Abnormal Situation



The Proposed Methodology

- **Theoretical Verification of Proposed Methodology**

3. Risk-based SPC Fault Diagnosis :

$$RI = Risk = P(F) * S$$

$$P(F) = \phi[\frac{x-(\mu+3\sigma)}{\sigma}]$$

$$S = 100^{P(F)}$$

The two types of Euler integrals in mathematics are:

(1). the Beta function

$$B(x,y) = \int_0^1 t^{x-1}(1-t)^{y-1}dt = \frac{\Gamma(x)\Gamma(y)}{\Gamma(x+y)}$$

(2). the Gamma function

$$\Gamma(z) = \int_0^\infty t^{z-1}e^{-t}dt$$

While,

$$P(F) = \phi[\frac{x-(\mu+3\sigma)}{\sigma}] = \int_{-\infty}^{x} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(t-\mu')^2}{2\sigma^2}} dt$$

Where

$$\mu' = \mu + 3\sigma$$

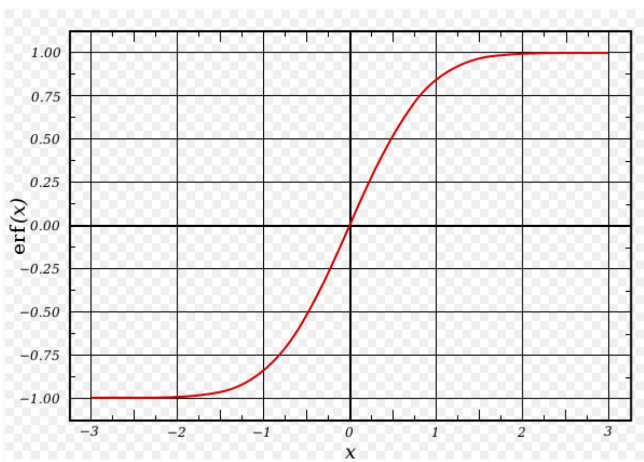
The Proposed Methodology

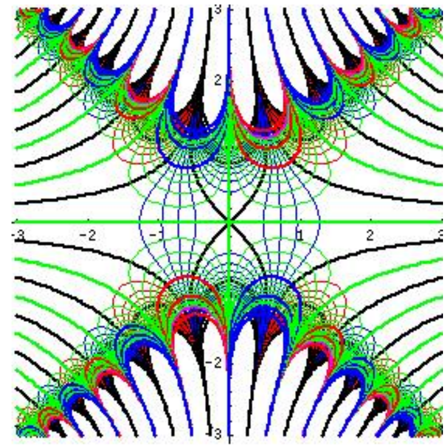
- **Theoretical Verification of Proposed Methodology**

3. Risk-based SPC Fault Diagnosis :

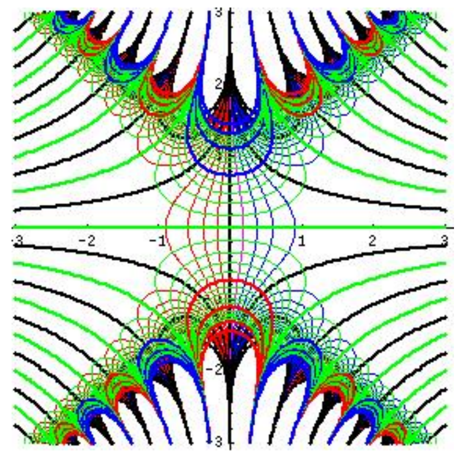
Error Function:

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt$$





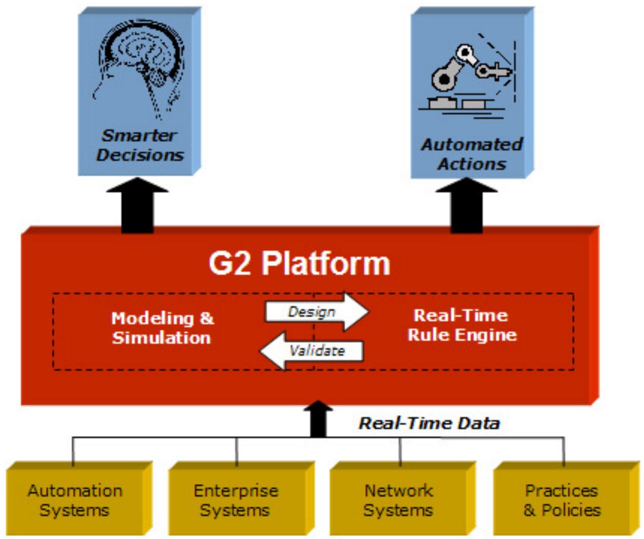
Integrand $f = \exp(-z^2)$



erf (z)

$$P(F) = \phi(x') = \frac{1}{2}[1 + erf(\frac{x'}{\sqrt{2}})] \quad \text{Where } x' = \frac{X - \mu'}{\sigma}$$

G2 Development Environment



G2 Platform from Gensym Corporation

Application Situations :

- Monitoring, diagnosis, and alarm handling.
- Supervisory and advanced control.
- Process design, simulation, and re-engineering.
- Intelligent network management.
- Decision support for enterprise-wide operations.

Integrated Development Environment :

- G2
- GDA
- GUIDE

Case Study 1 — Tank Filling System

- **Requirements to the Tank Filling System**

A tank filling system, i.e., a tank level monitor, is to be developed in G2 development environment. In this system, tank is filled with inflow liquid through a manual valve. The controlled variable is tank level.

The system to be designed comprises:

1. BPCS
2. SIS1
3. SIS2

Functions to be realized in the tank filling system are:

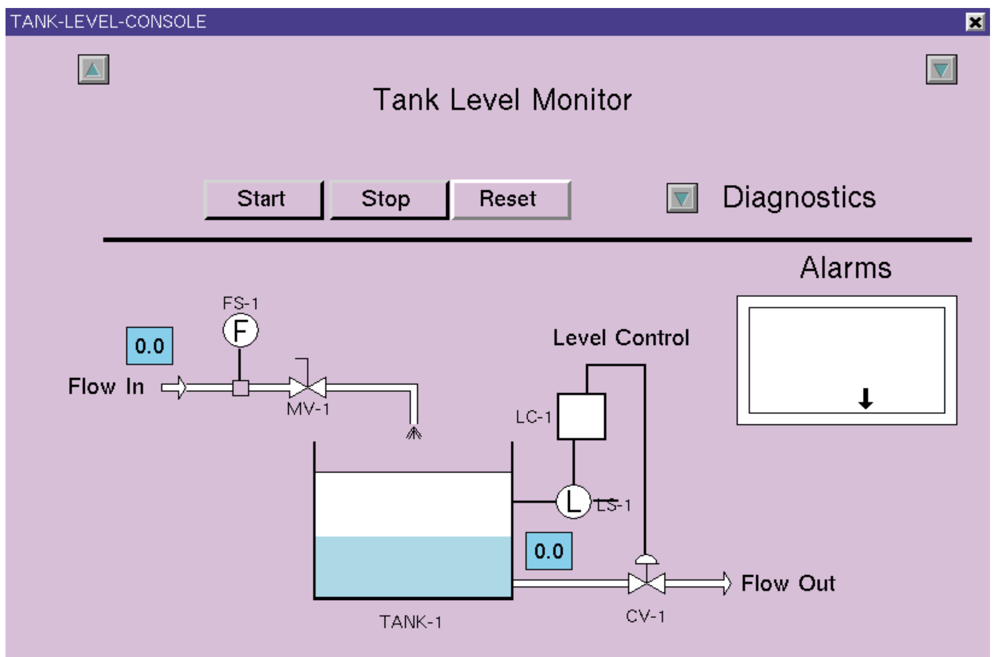
1. Popping up warning message when tank level reaches some limit.
2. Raising alarm when tank level exceeds upper control limit.
3. Raising alarm when there is a fault and then shut down the system.
4. Raising alarm and shut down the system immediately when there is an excessive deviation in inflow.

Case Study 1 — Tank Filling System

- **Deterministic Development Stage**

1. The Console Construction of the Tank Filling System

Console of the Tank Level Monitor with BPCS

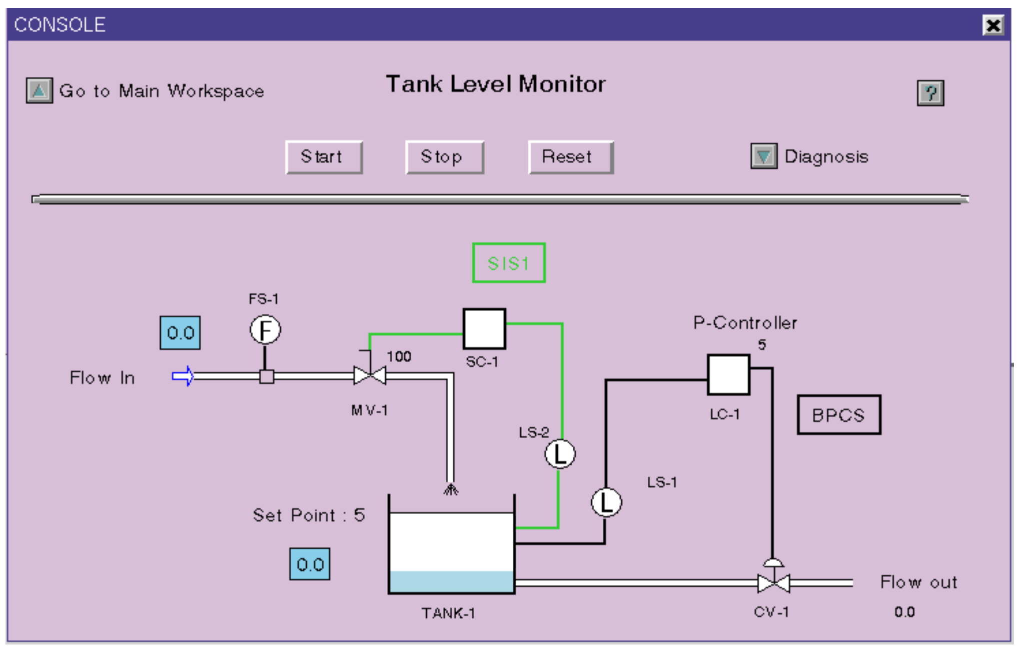


Case Study 1 — Tank Filling System

- **Deterministic Development Stage**

1. The Console Construction of the Tank Filling System

Console of the Tank Level Monitor with BPCS & SIS1

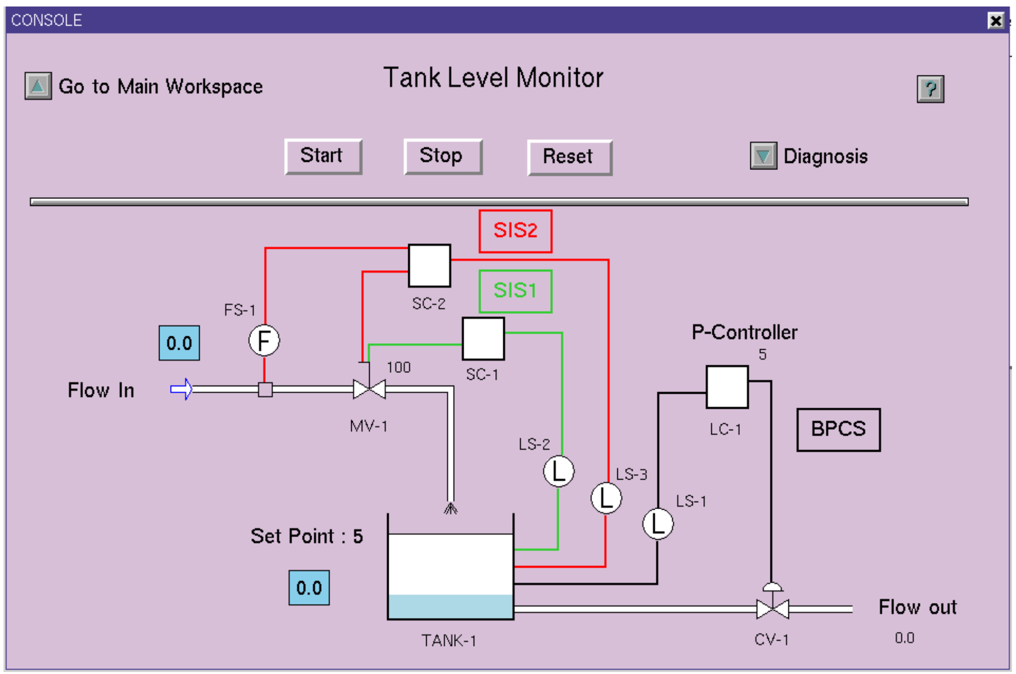


Case Study 1 — Tank Filling System

- **Deterministic Development Stage**

1. The Console Construction of the Tank Filling System

Console of the Tank Level Monitor with BPCS & SIS1 & SIS2



Case Study 1 — Tank Filling System

- **Deterministic Development Stage**

2. Safety Integrity Level (SIL) Evaluation

Safety Integrity Level (SIL) Evaluation to the Tank Filling System

System Composition	PFDavg	Risk Reduction	SIL
BPCS	10^{-1} to 10^{-2}	10 to 100	SIL1
BPCS+SIS1	10^{-2} to 10^{-3}	100 to 1000	SIL2
BPCS+SIS1+SIS2	10^{-3} to 10^{-4}	1000 to 10,000	SIL3

Case Study 1 — Tank Filling System

- **Deterministic Development Stage**

3. Functions Realized in Deterministic Stage

a) Popping up warning message when tank level exceeds set point 5 m.

b) Raising alarm when tank level exceeds upper limit 6 m.

c) Raising alarm when tank level is out of control and then shut down the system in specified time period (in SIS1).

d) Popping up dangerous warning message, raising alarm and shutting down the system immediately when there is an excessive deviation in the inflow (in SIS2).

Case Study 1 — Tank Filling System

- **SPC Development Stage**

1. The Definition of Fault in SPC Stage

If three successive data points of tank level exceed the upper limit 6 m, then this is defined as a fault event.

2. The Tasks in SPC Stage

a) Eliminate noise disturbances.

b) Visually monitor the entire process.

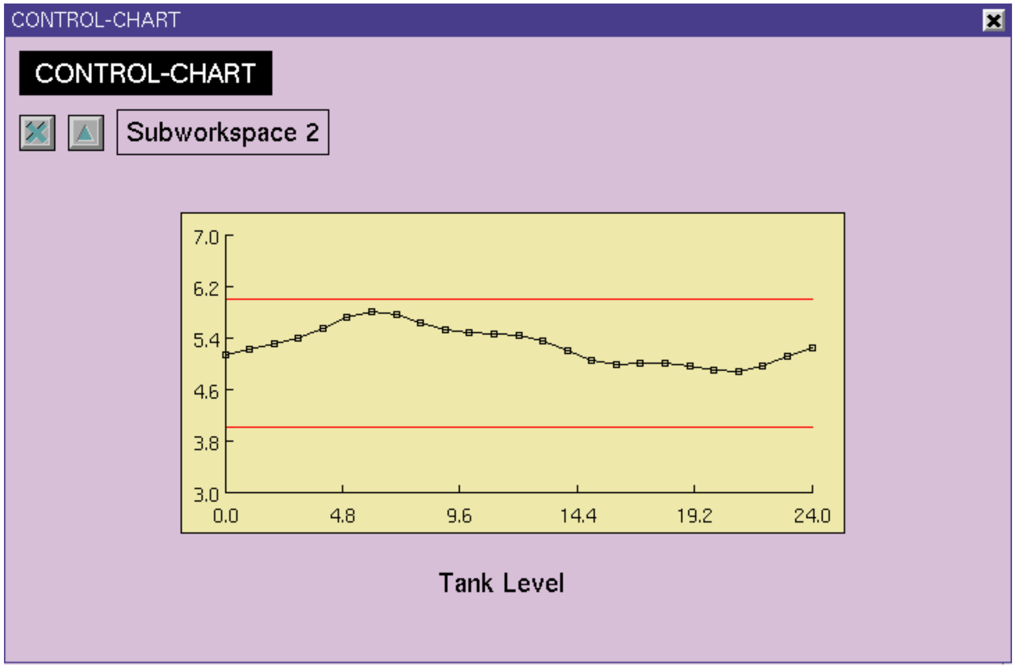
c) Distinguish abnormal situation from normal situation.

Case Study 1 — Tank Filling System

- **SPC Development Stage**

3. The Developed Control Chart

Control Chart for the Tank Filling System



UCL: 6 m   Mean: 5 m   LCL: 4 m

Case Study 1 — Tank Filling System

- **SPC Development Stage**

4. Functions Realized in SPC Stage

a) Popping up warning message when tank level exceeds set point 5 m.

b) Raising alarm with severity 1 when tank level exceeds upper limit 6 m.

c) Raising alarm with severity 2 when three successive data points of tank level exceed upper limit 6 m.

d) Raising alarm with severity 3 when tank level is in range [6.1, 6.2], then shut down the system in specified time period (in SIS1).

e) Popping up dangerous warning message, raising alarm with severity 4 and shut down the system immediately when there is an excessive deviation in the inflow (in SIS2).

Case Study 1 — Tank Filling System

- **Risk-based SPC Development Stage**

1. The Definition of Fault in Risk-based SPC Stage

Fault is defined as three successive data points exceed some limit(s). In these three data points, two successive data points are the real values of the moving average of controlled variable, and the third successive data point is the predicted value of the moving average of controlled variable.

2. The Tasks in Risk-based SPC Stage

a) Develop forecast capability to one controlled variable.

b) Develop visually real time monitoring to the system.

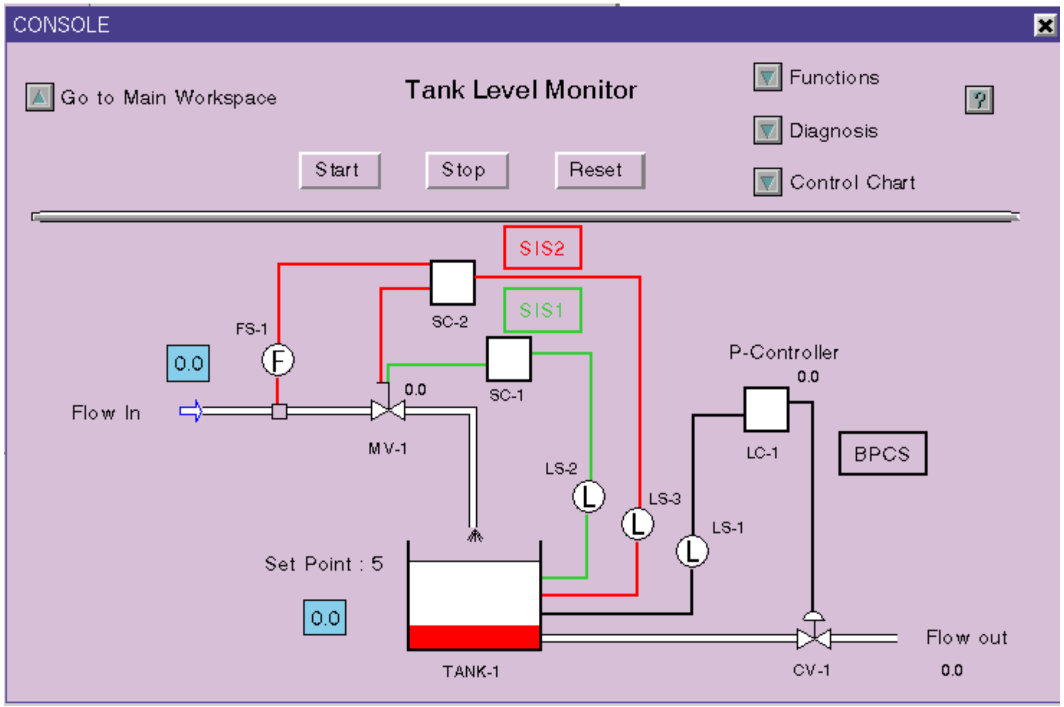
c) Minimize the number of false alarms.

Case Study 1 — Tank Filling System

- **Risk-based SPC Development Stage**

3. The Developed Console for the Risk-based Tank Filling System

Console of the Risk-based Tank Filling System

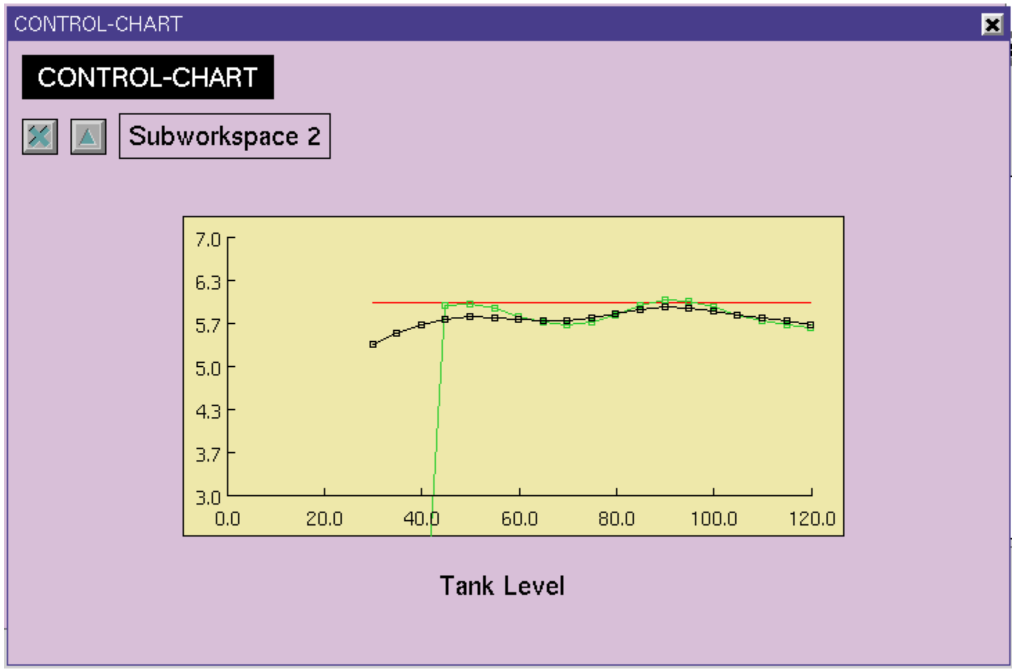


Case Study 1 — Tank Filling System

- **Risk-based SPC Development Stage**

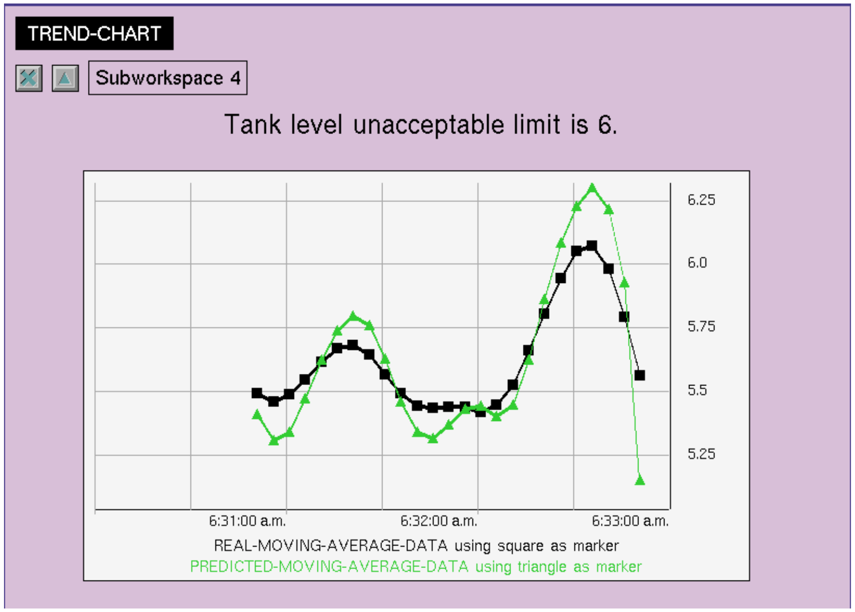
4. The Developed Forecast Function

Data Points in Time Order

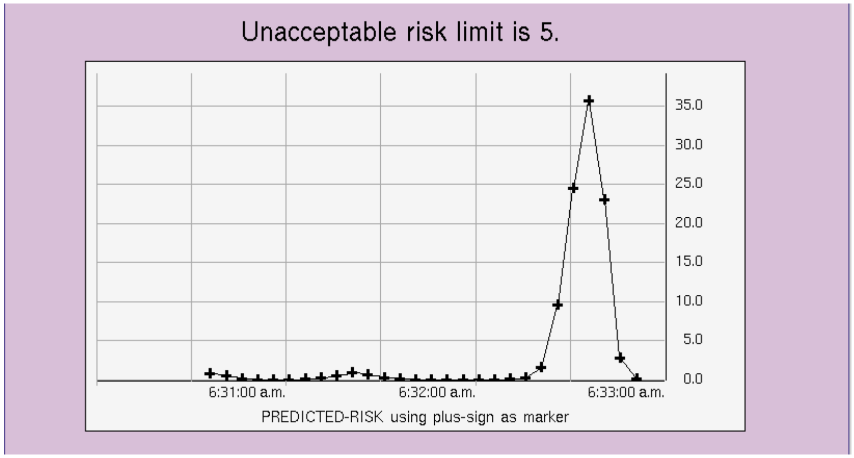


5. Fault Diagnosis Results in SIS1

Risk-based Tank Level Trend Chart – SIS1



Predicted Risk Chart – SIS1



Case Study 1 — Tank Filling System

- **Risk-based SPC Development Stage**

6. Functions Realized in SIS1

a) Popping up warning message when risk value for the predicted tank level is in range 1-5.

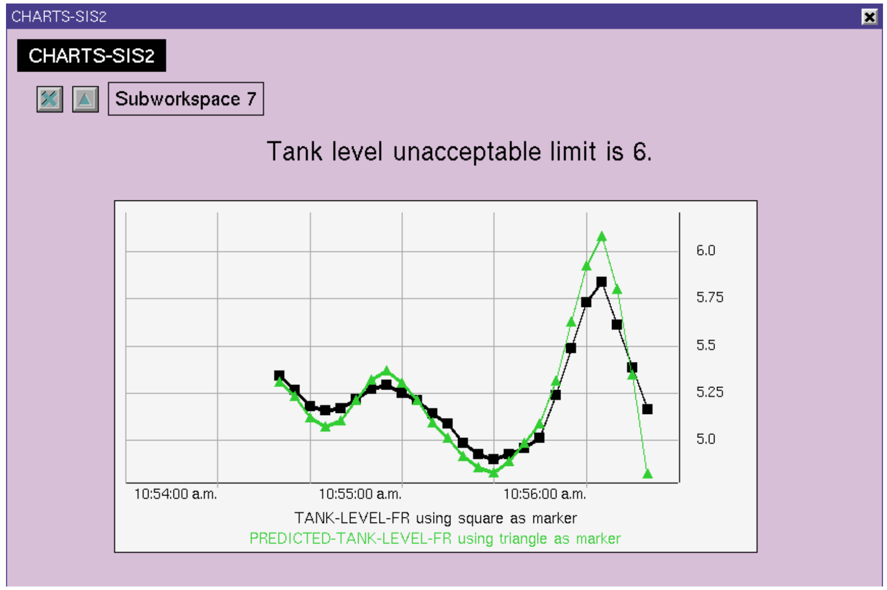
b) Raising alarm with severity 2 when risk value exceeds 5, i.e., the predicted tank level exceeds upper control limit 6 m.

c) Raising alarm with severity 3 when the real tank level exceeds upper control limit 6 m.

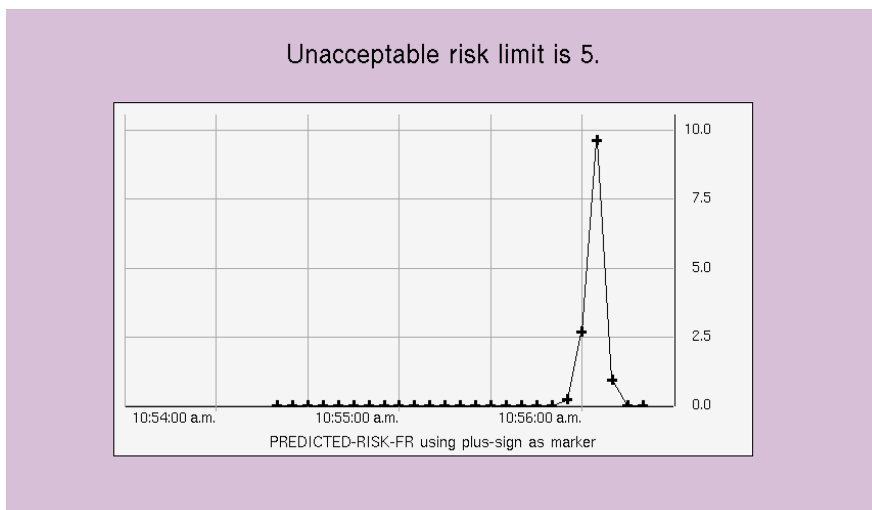
d) Raising alarm with severity 4 when a fault happens, shutting down the system and highlighting the valve MV-1 in green.

7. Fault Diagnosis Results in SIS2

Risk-based Tank Level Trend Chart – SIS2



Predicted Risk Chart – SIS2



Case Study 1 — Tank Filling System

- **Risk-based SPC Development Stage**

8. Function Realized in SIS2

a) Raising alarm with severity 4 when there is an excessive deviation in inflow, shutting down the system and highlighting the valve MV-1 in red.

9. Comparison with Cen Nan's Work

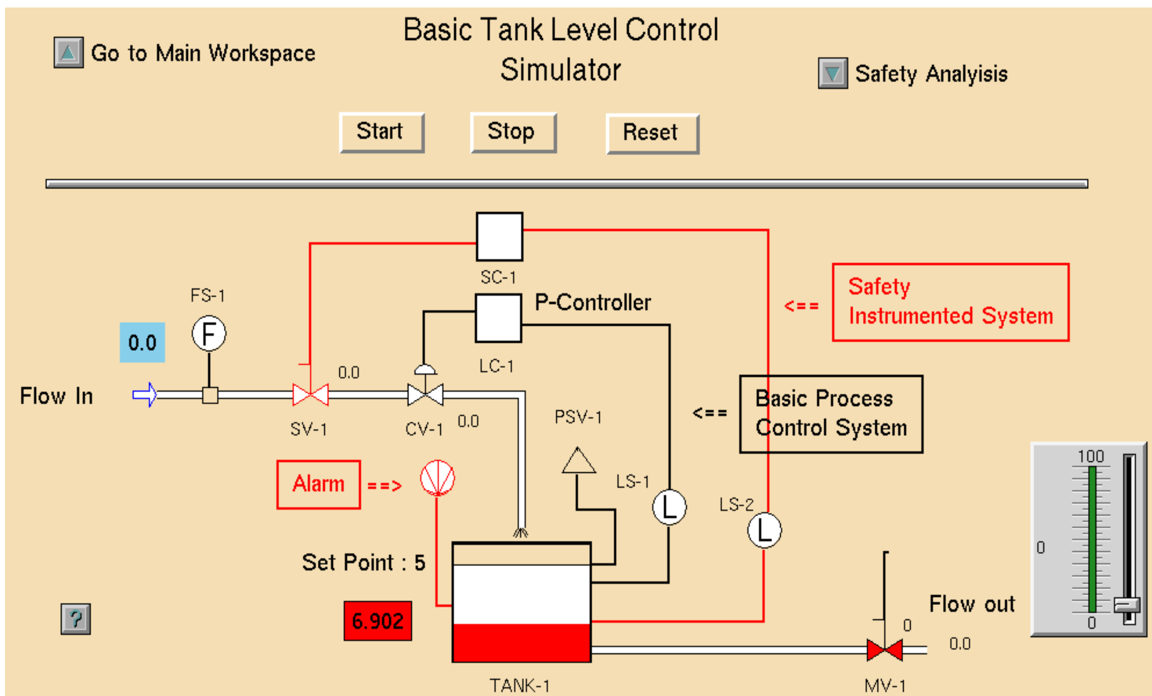
Cen Nan, the previous developer for the tank filling system and the steam power plant system in case study 2.

Case Study 1 — Tank Filling System

- **Risk-based SPC Development Stage**

9. Comparison with Cen Nan's Work

Console of the Tank Filling System in Cen Nan's Work



Case Study 1 — Tank Filling System

Comparison to Cen Nan's Work for the Tank Filling System

Characteristics	Cen Nan's System	Huizhi Bao's System
BPCS	Yes	Yes
SIS1	Yes	Yes
SIS2	No	Yes
Real Time Monitoring	Yes	Yes
Trend Chart	No	Yes
Forecast Capability	No	Yes
Deterministic Development	Yes	Yes
SPC Development	No	Yes
Risk-based Development	No	Yes
Noise Filtering	Yes	Yes
Additional Hardware for Noise Filtering	Yes	No
SIL	2	3

Case Study 2 — Steam Power Plant System

- **Requirements to the Steam Power Plant System**

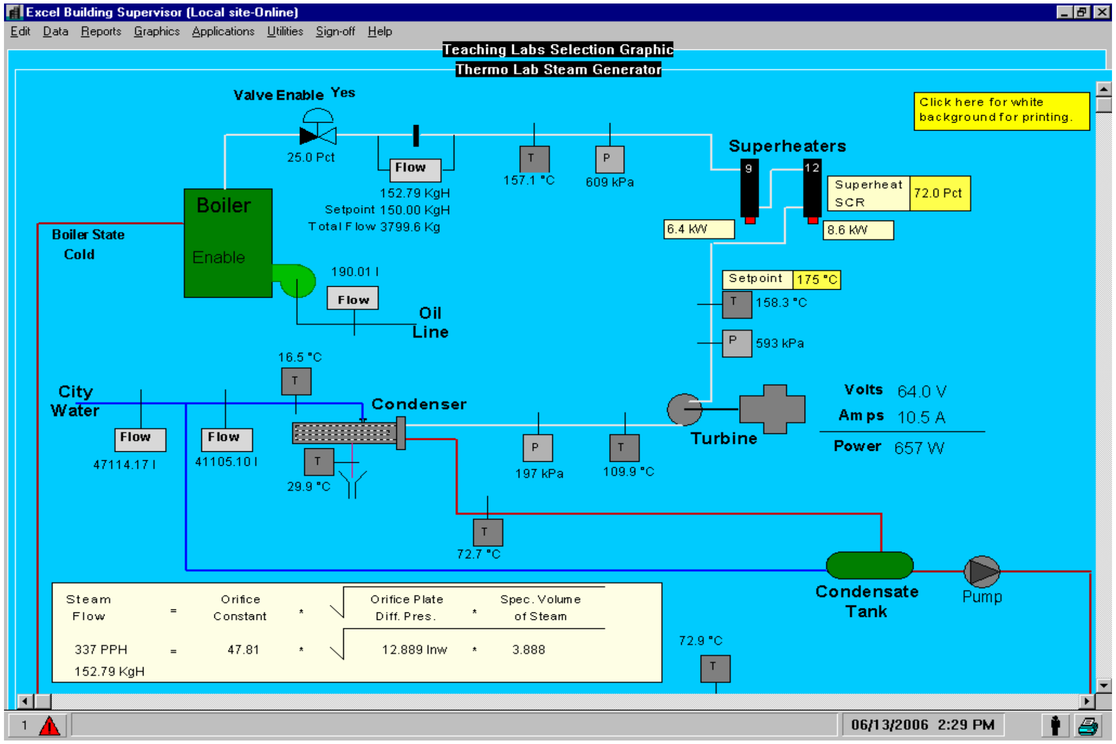
The steam power plant is located in Thermodynamics and Fluids Lab in Faculty of Engineering and Applied Science building at Memorial University of Newfoundland.

Steam Power Plant in Thermodynamics and Fluids Lab

Case Study 2 — Steam Power Plant System

- **Requirements to the Steam Power Plant System**

Schematic Diagram of the Steam Power Plant



Case Study 2 — Steam Power Plant System

- **Requirements to the Steam Power Plant System**

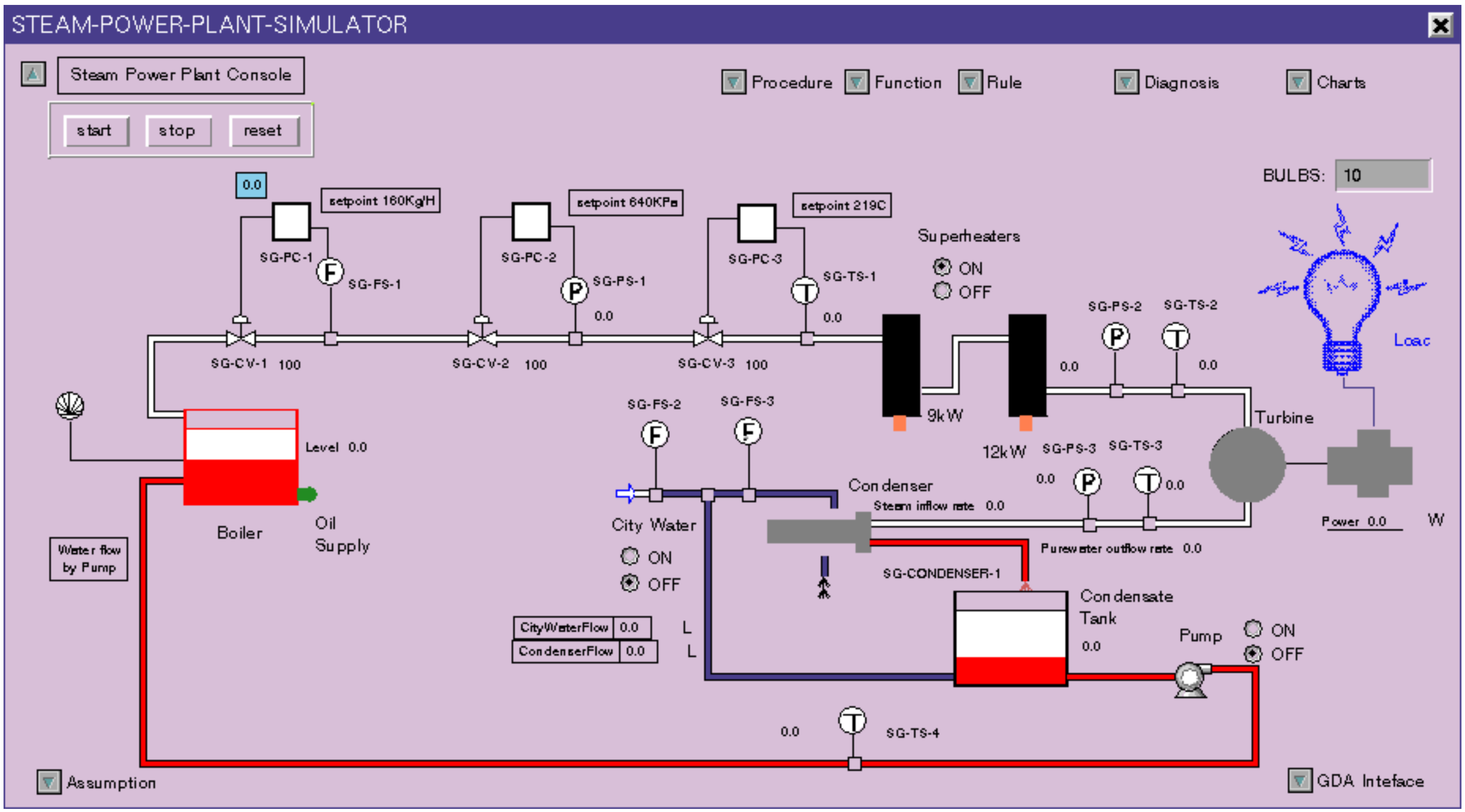
Development Works:

1. Construct the console of the steam power plant in G2 development platform.
2. Model and simulate the entire process for the steam power plant in G2 environment.
3. Design BPCS, SIS1 and SIS2 to the controlled variables. In this development system, the controlled variables are three parameters of the boiler, that is, the steam flow rate, the steam pressure and steam temperature.
4. Realize a technique breakthrough, from univariate monitoring to multivariate monitoring for SPC fault diagnosis, in process fault diagnosis field.
5. Apply the proposed methodology of risk-based SPC fault diagnosis and its integration with SIS into the developed steam power plant system.

Case Study 2 — Steam Power Plant System

- **Console Construction in G2 Environment**

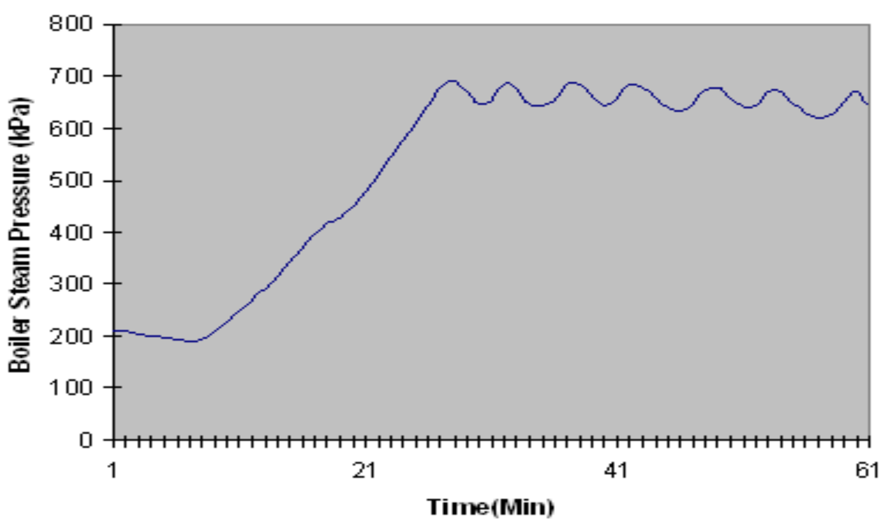
Console of the Steam Power Plant System



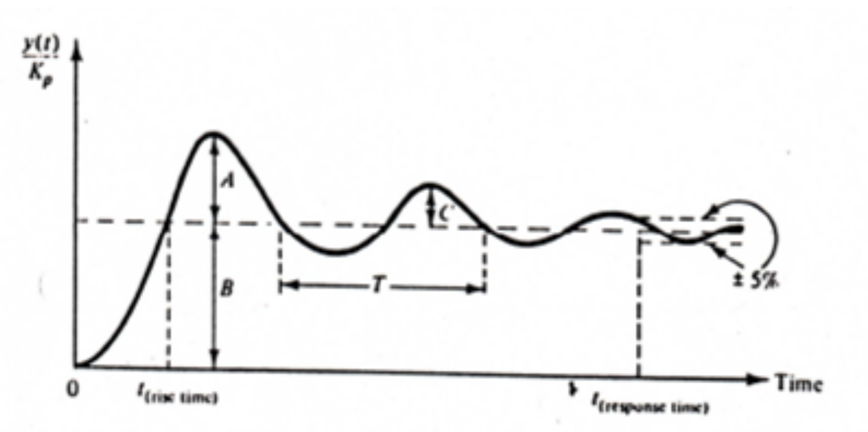
Case Study 2 — Steam Power Plant System

- **System Modeling**

Historical Data Chart for the Boiler Steam Pressure



Response of an Underdamped Second-Order Process



Steam Pressure of the Boiler: Underdamped Second-Order System

Steam Temperature of the Boiler: Second Order Polynomial

Steam Flow Rate of the Boiler and Other Parameters or Components: First-Order System

Case Study 2 — Steam Power Plant System

- **SPC Development Stage**

1. The Definition of Fault in SPC Stage

If three successive data points of controlled variable exceed the upper control limit, then this is defined as a fault event.

2. The Tasks in SPC Stage

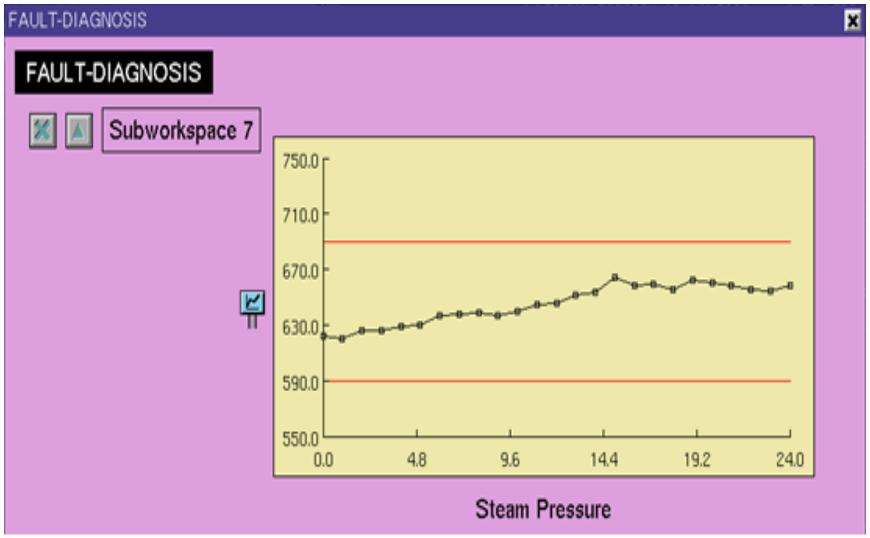
a) Eliminate noise disturbances.
b) Visually monitor the entire process.
c) Distinguish abnormal situation from normal situation.

Case Study 2 — Steam Power Plant System

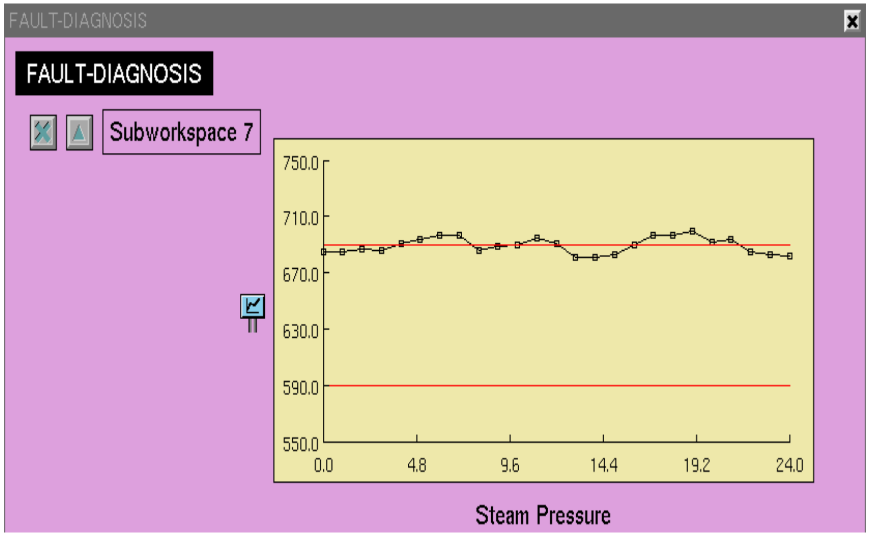
- **SPC Development Stage**

3. The Developed Control Charts

Control Chart of the Steam Pressure (Normal Situation)



Control Chart of the Steam Pressure (Abnormal Situation)



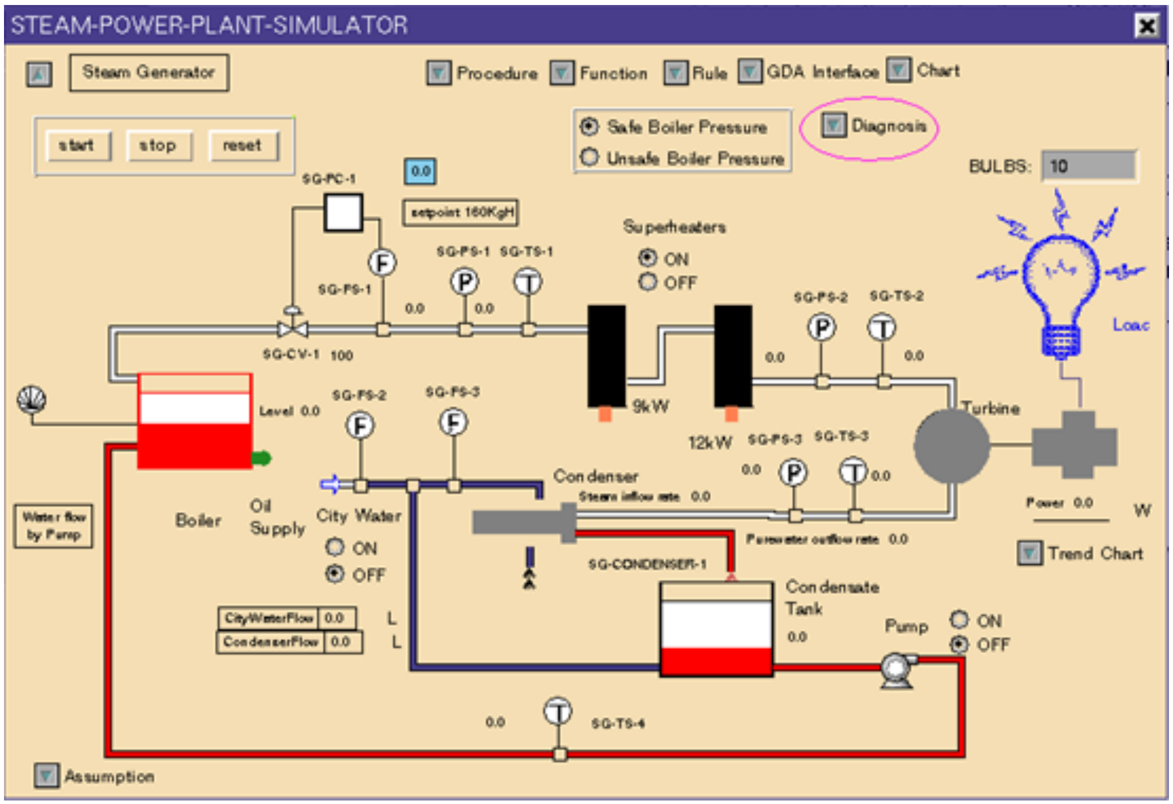
UCL: 690 kPa Mean: 640 kPa LCL: 590kPa

Case Study 2 — Steam Power Plant System

- **SPC Development Stage**

4. An Experiment for Effectiveness Demonstration

Cen Nan's Steam Power Plant System + Huizhi Bao's Diagnosis Module



Case Study 2 — Steam Power Plant System

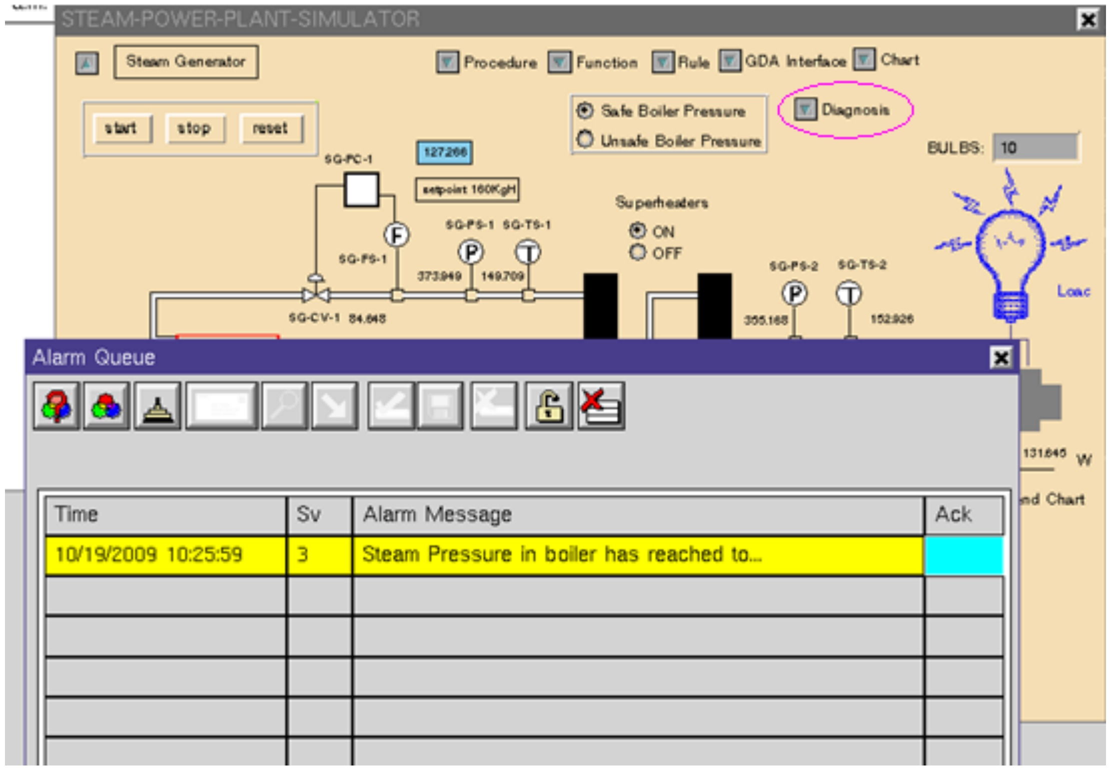
- **SPC Development Stage**

4. An Experiment for Effectiveness Demonstration

Problems Detected That Exist in Cen Nan's System:

Case Study 2 — Steam Power Plant System

(1). Raising false alarms when the steam pressure data are still safe.



(2). Raising false alarms when the steam pressure is still in safe range, i.e. [590 kPa, 690 kPa].

Case Study 2 — Steam Power Plant System

- **SPC Development Stage**

4. An Experiment for Effectiveness Demonstration

From Viewpoint of KB File Capacity:

Cen Nan’s KBRT System: 957 KB

Huizhi Bao’s SPC System: 431 KB

Case Study 2 — Steam Power Plant System

- **Risk-based SPC Development Stage**

1. The Definition of Fault in Risk-based SPC Stage

Fault is defined as three successive data points exceed some limit(s). In these three data points, two successive data points are the real values of the moving average of controlled variable, and the third successive data point is the predicted value of the moving average of controlled variable.

2. The Tasks in Risk-based SPC Stage

a) Develop forecast capability to three controlled variables.

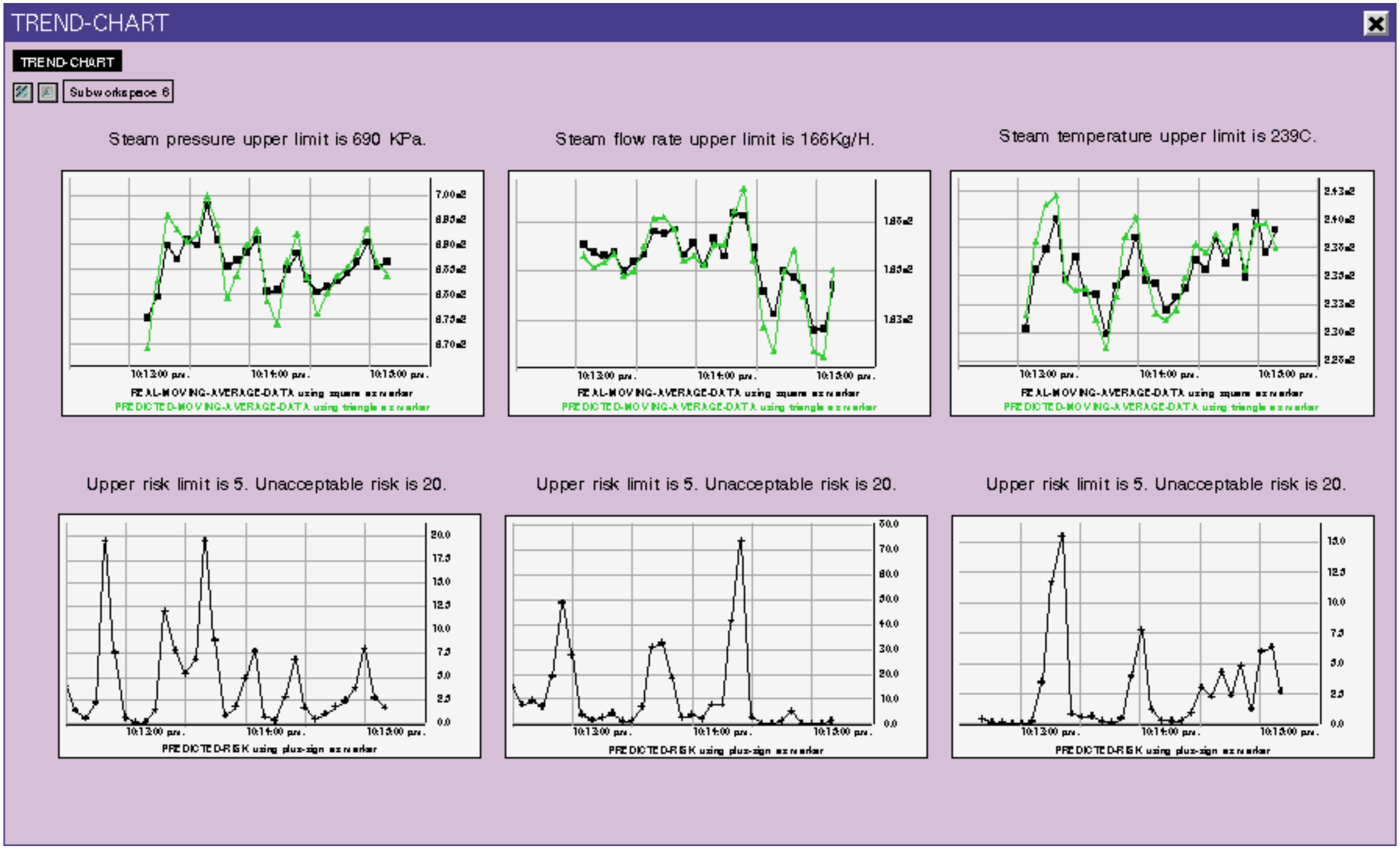
b) Develop visually real time multivariate monitoring to the system.

c) Minimize the number of false alarms.

3. The Results of the Fault Diagnosis

Case Study 2 — Steam Power Plant System

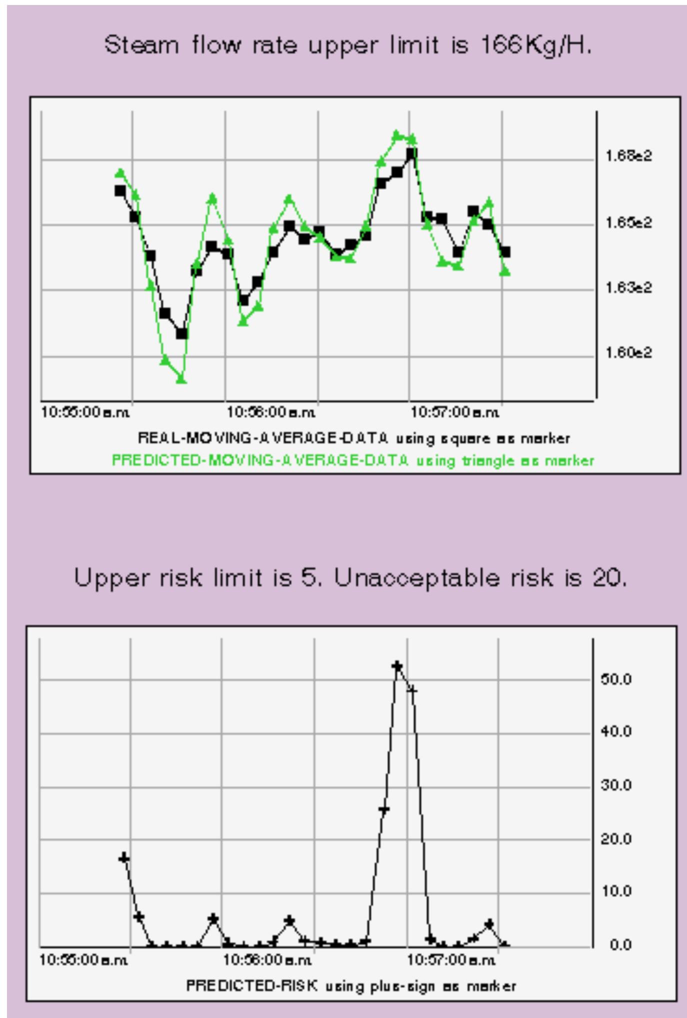
Trend Charts for Steam Pressure, Steam Flow Rate and Steam Temperature & Risk Charts for Steam Pressure, Steam Flow Rate and Steam Temperature



Case Study 2 — Steam Power Plant System

Some fault snapshots:

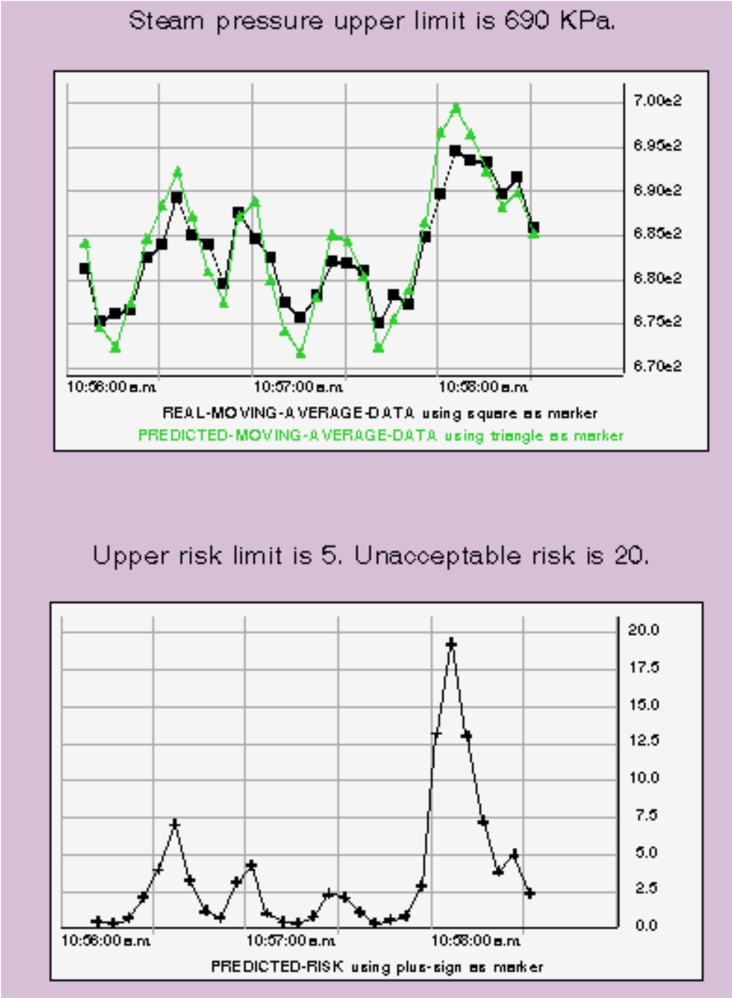
Steam Flow Rate Trend Chart and Risk Chart



Case Study 2 — Steam Power Plant System

Some fault snapshots:

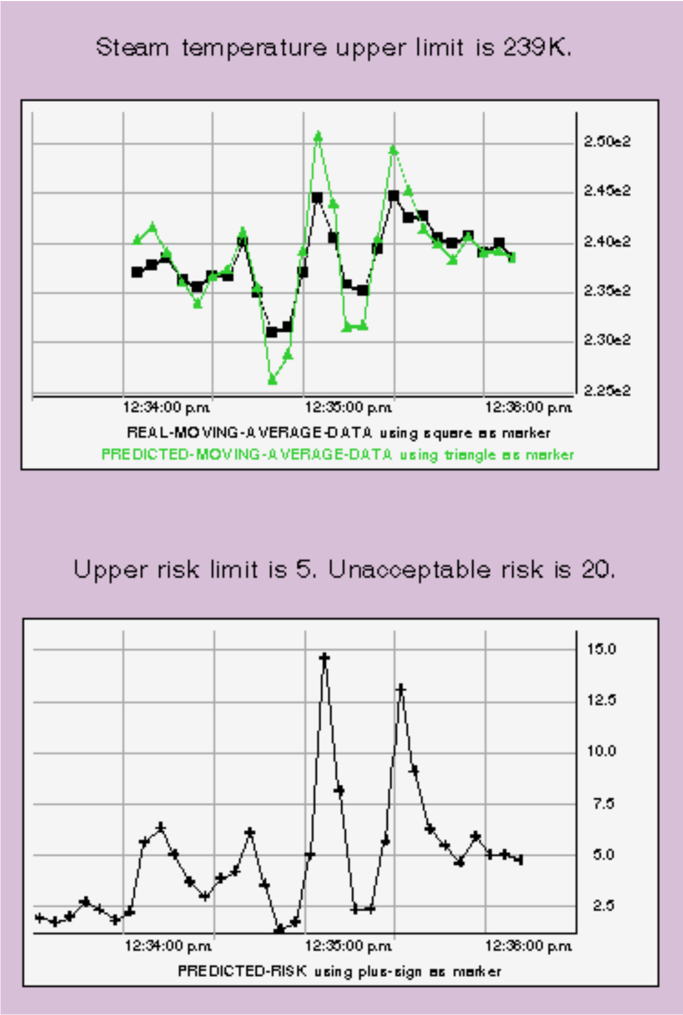
Steam Pressure Trend Chart and Risk Chart



Case Study 2 — Steam Power Plant System

Some fault snapshots:

Steam Temperature Trend Chart and Risk Chart



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- **Risk-based SPC Development Stage**

4. Functions Realized in SIS1

a) When there is a fault in any individual variable, the system pops up a warning message.

b) When any of the risk of steam pressure, steam flow rate, or steam temperature is greater than 20, the system raises the alarm of shutting down the system with severity of 4.

5. Functions Realized in SIS2

a) When the overall risk is in range 5-10, the system pops up warning message.

b) When the overall risk is in range 10-20, the system pops up severe warning message.

c) When the overall risk is greater than 20, the system raises the alarm of shutting down the system with severity of 4.

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- **Risk-based SPC Development Stage**

6. Other Functions Added in the Developed System

a) When the predicted value for any variable reaches the extreme value, the system raises an alarm with severity of 2.

b) When the real value for any variable reaches the extreme value, the system raises an alarm with severity of 3.

7. Comparison with Traditional Approach (Expert System)

Major Distinctions:

a) Univariate Monitoring ←→ Multivariate Monitoring

b) Risk-based SPC Fault Diagnosis

c) Unsafe State

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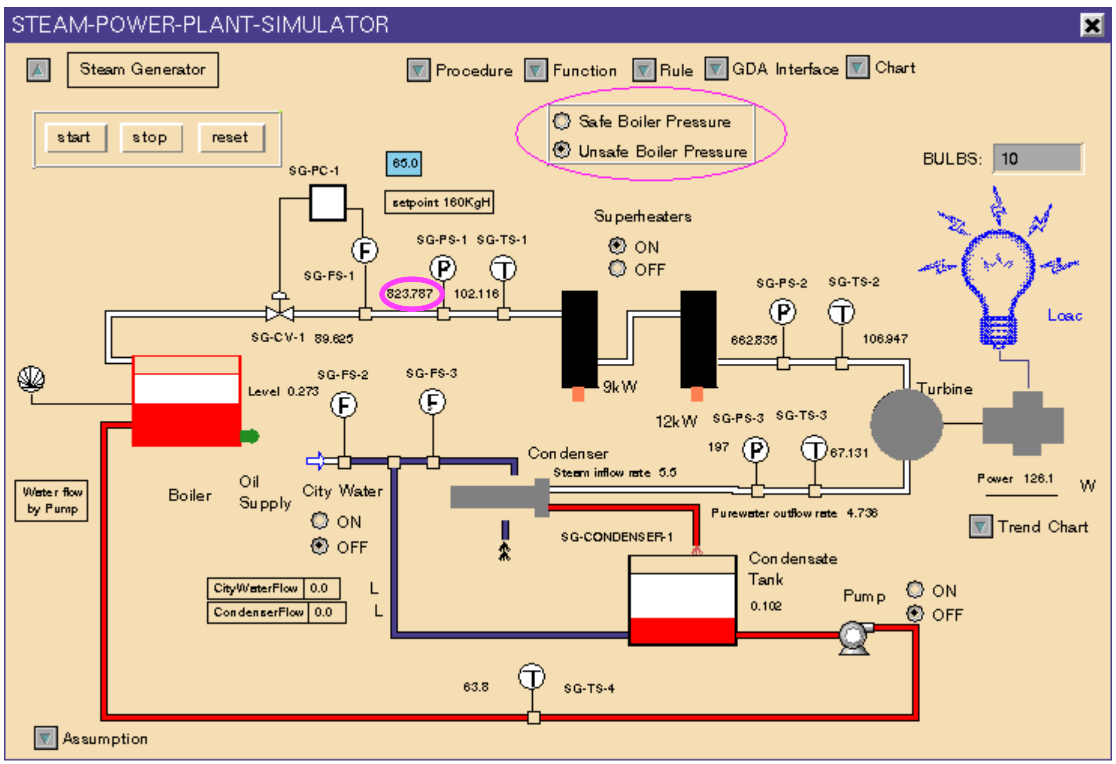
- **Risk-based SPC Development Stage**

7. Comparison with Traditional Approach (Expert System)

Unsafe Boiler Pressure Button in Cen Nan's KBRT system



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Comparison between the KBRT Approach and the Risk-based SPC Approach

Characteristics	KBRT approach	Risk-based SPC approach
Controlled Variable	Univariate	Multivariate
BPCS	Yes	Yes
SIS1	No	Yes
SIS2	No	Yes
Real Time Monitoring	Yes	Yes
Forecast Capability	No	Yes
Risk-based Development	No	Yes
Noise Filtering	Yes	Yes
Additional Hardware for Noise Filtering	Yes	No
SIL	2	3
Independency	No	Yes
Redundancy	Yes	No
Adaptability	Not Good	Excellent
Sensitivity to Fault	Not Good	Excellent
Extensibility	Not Good	Excellent

Characteristics of the Proposed Methodology

10 Outstanding Characteristics of the Proposed Methodology:

- Adaptability
- Real-time Monitoring Capability
- Forecast Capability
- Effectiveness and Strong Safety Management Capability
- Independency
- Robustness
- Transplantable Capability
- Reasonability in System Design
- Extensibility
- Multiple Fault Identifiability

Conclusions

6 Conclusions for the Proposed Methodology:

- An innovative methodology of risk-based SPC fault diagnosis and its integration with Safety Instrumented System (SIS) for process systems has been proposed.
- The proposed innovative methodology has been verified through two process systems that it neither depends on any model as model-based approaches, nor depends on large amount of historical data as conventional process history based methods.
- A technique breakthrough, from univariate monitoring to multivariate monitoring, has been achieved in this research.
- The advantages of the proposed methodology over Cen Nan's work for Tank Filling System are listed on Page 35.
- The advantages of the proposed methodology over traditional expert system for Steam Power Plant System are listed on Page 55.
- 10 outstanding characteristics of the proposed methodology are summarized on Page 56.

Future Works

- Further develop the multivariate monitoring for the proposed methodology of risk-based SPC fault diagnosis and its integration with safety instrumented system (SIS).
- Try to realize another breakthrough for the other limitation of the SPC fault diagnosis in the data acquisition technology.
- Apply the proposed methodology which has broken through the two limitations into real process systems.

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Thanks

Questions/Discussion?