Integrated automatic HAZOP analysis and fault diagnosis based on Petri net

Zhao Lindu

(College of Economics and Management, Southeast University, Nanjing 210096, China)

Abstract: Based on systematically analyzing the procedure of hazard and operability (HAZOP) study, the author introduces a method of modeling fault diagnosis with the Petri net with fuzzy colors, in which the fuzzy information can be represented effectively in the process of analysis. The author proposes the architecture of a knowledge base, which integrates HAZOP analysis and fault diagnosis, and provides the conditions for constructing the knowledge-based expert system. The author also presents a method of knowledge representation for on-line HAZOP analysis and on-line fault diagnosis is presented based on the technology of Petri net with fuzzy colors, which establishes a technological fundamental for integrating the automatic HAZOP analysis and fault diagnosis.

Key words: hazard and operability; fault diagnosis; Petri net; expert system; knowledge representation

A hazard has the potential to cause harm, and can take the form of injury to people or damage to property, plant, products or the environment; production losses; business harm and increased liabilities[1]. Hazard analysis is an important step in designing or revamping any processing plant, and an effective measure in reducing hazard and risk. There are several techniques available for such a purpose in practice, e.g. fault tree analysis, event tree analysis, failure modes and effects analysis and hazard and operability (HAZOP), etc[2]. HAZOP analysis is able to analyze batch processes better than other hazard evaluation techniques such as fault tree analysis, failure modes and effects analysis, and cause-consequence analysis[3]. D. H. Kuo, et al. have studied the integrated method of the three widely accepted hazard assessment procedures, i.e. fault tree analysis, event tree analysis and HAZOP, which can be performed automatically[4].

The HAZOP technique was developed in the early 1970s at Imoerial chemical industries (ICI), in the UK[5,6]. The basic principle of HAZOP analysis is that hazards arise in a plant due to deviations from normal behavior[7,8]. HAZOP study is one of the most common tools to qualitatively accomplish hazard assessment, and it is the study of systematically identifying, assessing and eliminating every conceivable deviation. HAZOP analysis is a method of providing a synthetic experience of what can go wrong in the plant operation[9]. Deviation analysis based on an HAZOP analysis is especially useful in building the deep knowledge base of processes in the plant. HAZOP analysis makes it possible to generate the if-then rules for the knowledge base and determine the information to be sent to other levels in the expert system. The starting point of inference and the scope of analysis are distinctive features of hazard analysis methods. Among them, the HAZOP study has proven to be the most systematic and general.

The Petri net is a graphical and also mathematical tool for describing relationships between conditions and events. The technology of Petri net has been widely used in the area of fault diagnosis[10,11], including methods of modeling fault diagnosis and modeling fault propagation with Petri net[12,13]. Several research projects that aimed to automate the procedure of HAZOP based on Petri net have been reported in Refs. [2,14,15].

In the important role of effectively integrating the HAZOP analysis and the fault diagnosis in the framework of a knowledge base, a unified knowledge representation is a key technique. In order to realize the integration of automatic HAZOP analysis and fault diagnosis, the expert system must use a reasonable and unified method of knowledge representation. For this purpose, based on the introduction of the procedure of HAZOP analysis, the modeling method of Petri net with fuzzy colors is introduced, in which an architecture of integrated knowledge base of HAZOP analysis and fault diagnosis is proposed, and a method of unified knowledge representation based on Petri net with fuzzy colors is presented.

Received 2003-05-12.

Biography: Zhao Lindu (1965—), male, doctor, professor, ldzhao@seu.edu.cn.

1 Procedure of HAZOP Analysis

HAZOP analysis considers all the whole equipment as a research object. It systematically analyzes the hazards of deviation in each unit, and generates the best corrective measures. In the process of HAZOP analysis, the economical characteristics of correcting measures must be taken into account, in order to build a relationship between cost and return. The procedure of a typical HAZOP study is shown in Fig. 1[5,16].

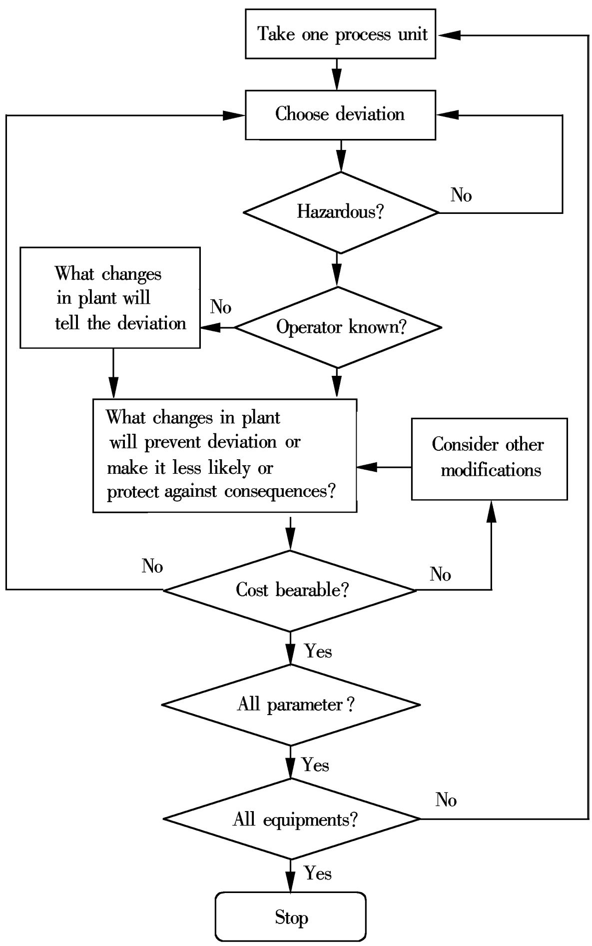

Fig. 1 Procedure of HAZOP study

The HAZOP analysis requires finding the possible consequences of all variable deviations that are examined, identifying the logical-functional models used by the analysts when applying the HAZOP method and searching for the causes and consequences of variable deviations. In order to find the consequences of a variable deviation, specific models are needed in an automatic decision support system[17].

The HAZOP methodology is essentially integrating qualitative and quantitative safety analysis, supporting selection of the most effective measures to reduce risk[18,19]. It is divided into three stages[20]:

1) Assessment of the probability that a deviation occurs at the three levels: operator level, control system level and plant/process level, and the recomposition of these values in the event tree paths;

2) Assessment of the economic impact of the consequences and calculation of the corresponding risk index;

3) Choice of the best corrective measures.

2 Modeling Methods of Petri Net with Fuzzy Colors

Petri net is a kind of digraph with two nodes of place and transition. It can be used to describe the causation of events directly. In the process of deviation analysis, it is difficult to obtain complete or accurate symptom information account of the complexity of the equipment, thus some kind of method needs to be used to present and deal with the fuzzy information.

Definition 1[13] A Petri net system is a six tuple $\Sigma = (P, T, F, K, W, M_0)$, as shown in Fig. 2, where

1) $P = \{P_1, P_2, \cdots, P_m\}$ is a set of places; it represents all the system states that can be estimated.

2) $T = \{t_1, t_2, \cdots, t_q\}$ is a set of finite and non-empty transitions, which represents all possible events, and satisfies $P \cap T = \varnothing$.

3) $F \subseteq \boldsymbol{\alpha}^+ \cup \boldsymbol{\alpha}^-$ is a named arc relation, where $\boldsymbol{\alpha}^-$ represents the input arcs of the transitions, and $\boldsymbol{\alpha}^- \subseteq P \times T$; while $\boldsymbol{\alpha}^+$ represents the output arcs of the transitions, and $\boldsymbol{\alpha}^+ \subseteq T \times P$; and the correlation matrix $\boldsymbol{\alpha} = \boldsymbol{\alpha}^+ - \boldsymbol{\alpha}^-$.

4) $K: P \rightarrow N \cup \{\infty\}$ is a capable function, where $N = \{1,2,3,\cdots\}$.

5) $W: F \rightarrow N$ is a weight function, where $N = \{1,2,3,\cdots\}$.

6) $M_0: P \rightarrow N_0$ is a named initial marking of the Σ, where $N_0 = \{1,2,3,\cdots\}$, represents the initial state of the system.

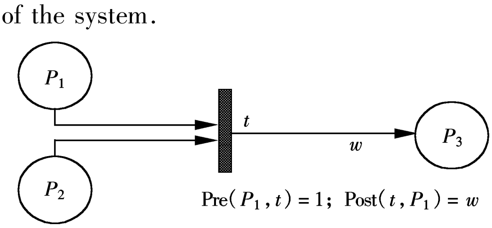

Fig. 2 An architecture of the Petri nets

Petri net with fuzzy colors (PNFC) is generated based on colored Petri nets (CPN)[21]. The colors in the CPN represent assured information, but the colors in the PNFC represent fuzzy information. The fuzzy information can be defined as a vector with two elements, marked $\tilde{\boldsymbol{c}}_i = \langle c_i, \mu(c_i) \rangle$, where c_i represents quantity of information, $\mu(c_i)$ is a membership function that correlated to c_i, which represents the truth degree of c_i. The truth degree of fuzzy colors can be estimated by using the triangle membership function (as shown in Fig.3).

The Petri net with fuzzy colors can be marked as a seven tuple, adding a fuzzy color function $\widetilde{C}: P \cup T \rightarrow \widetilde{\Omega}$ based on definition 1, where $\widetilde{\Omega}$ is a set of finite and non-empty, and $\widetilde{C}(s)$ is a named fuzzy color and fuzzy color set of s. Thus, the marking of PNFC is $\Sigma^{FC} = (P, T, \widetilde{C}, F, K, W, M_0)$.

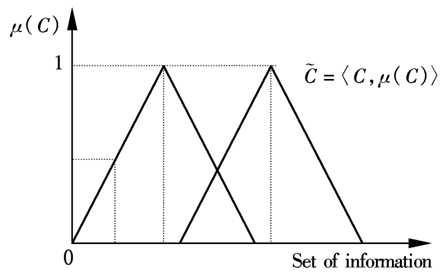

Fig.3 Triangle membership function

The membership function $\mu(c_i)$ that correlates to the fuzzy color $\tilde{\boldsymbol{c}}_i$ can be forecasted with the following methods in PNFC:

1) If $\tilde{\boldsymbol{c}}_i$ can be considered as the firing color of place p_i, then $\mu(c_i)$ is represented by the truth degree of the fuzzy information $\tilde{\boldsymbol{c}}_i$;

2) If $\tilde{\boldsymbol{c}}_i$ can be considered as an enabling color that correlates to the transition t_j, then $\mu(c_i)$ is represented by the truth degree of transition t_j considering the needs of $\tilde{\boldsymbol{c}}_i$.

There are two rules for managing the evolution process of marking in a PNFC.

Enabling Rule A marking M, a transition t_j can be considered $\tilde{\boldsymbol{c}}_k \in \widetilde{C}(t_j)$, if and only if:

$$\forall p_j \in {}^0 t_j, M(p_i) \geqslant a_{ij}^-(\tilde{\boldsymbol{c}}_k) \text{ and } \forall \tilde{\boldsymbol{c}}_i \in M(p_i), \min_{\tilde{\boldsymbol{c}}_h \in \tilde{a}_j^-} [\max_{\substack{\tilde{\boldsymbol{c}}_i \in I_j(\tilde{\boldsymbol{c}}) \\ \tilde{\boldsymbol{c}}_i \in \widetilde{C}(t_j)}} (\mu(c_i))] \geqslant \mu(c_k).$$

Firing Rule $\tilde{\boldsymbol{c}}_k$ can be considered in a firing marking M and a transition t_j, the new marking M' of Petri net can be defined with $\forall p_i \in P$ and $M'(p_i) = M(p_i) - a_{ij}^-(\tilde{\boldsymbol{c}}_k) + a_{ij}^+(\tilde{\boldsymbol{c}}_k)$.

After firing, the truth degree of color $\tilde{\boldsymbol{c}}_k \in a_{ij}^+(\tilde{\boldsymbol{c}}_k)$ can be calculated by a using fuzzy inference function ψ, the function is defined from $[0,1] \times [0,1]$ to $[0,1]$, $\forall t_j \in \Sigma^{FC}$ and $\forall \tilde{\boldsymbol{c}}_k \in \widetilde{C}(t_j)$.

Let t_j be a transition of Σ^{FC}, $\tilde{\boldsymbol{c}}_k$ be an enabling color that correlated to t_j,

$$\forall \tilde{\boldsymbol{c}}_r \in \hat{a}_j^+(\tilde{\boldsymbol{c}}_k)$$

$$\tilde{\omega}(c_i) = \psi\Big[\mu(c_k)\big[\beta_{i\,\substack{\tilde{\boldsymbol{c}}_{\beta_i} \in I_i(\tilde{\boldsymbol{c}}_i) \\ \mu(c_{\beta_i}) \geqslant \mu(c_k)}} (\nu(c_{\beta_i}))\big]^t_{c_r \in \hat{a}_j^+(\tilde{\boldsymbol{c}}_k)}\Big]$$

where β_i is a local decision criterion, its class $\tilde{\boldsymbol{c}}_{\beta_i} \in I_i(\tilde{\boldsymbol{c}}_i)$ and x^t represent the x's transformation.

3 Architecture of Knowledge Base

The HAZOP analysis makes it possible to generate the if-then rules for the knowledge base, and the online hazard models can also be adapted for fault diagnosis applications[7]. According to the results of HAZOP analysis, the generated if-then rules can be used to construct an expert system with the ability of automating inference. The expert system was found to successfully emulate the human experts reasoning and identify the hazards similar to the HAZOP team[22-24]. The architecture of the integrated knowledge base of automatic HAZOP analysis and fault diagnosis is shown in Fig.4[25-27].

The HAZOP analysis allows one to generate the if-then rules for the fuzzy logic system[15] and to determine the information to be sent to other levels in the expert system. The modeling methodology of off-line hazard analysis helps to improve the inference algorithms for on-line fault diagnosis.

The knowledge base includes multiple applications for multiple processes, with architecture of a sharable engineering knowledge repository, including an HAZOP analysis tool, a process monitoring and diagnostic system, as well as a process design decision support system. The if-then rules generated in the process of HAZOP analysis must have a formalism of knowledge representation unified with the process of fault diagnosis, so that the if-then rules generated in the process of HAZOP analysis can be sent to the knowledge base automatically.

4 Method of Knowledge Representation

The Petri net with fuzzy colors can be used to represent the inference algorithms for the knowledge base. Both the process of general HAZOP models and the process of specific knowledge can be used to generate sets of if-then rules, and to construct the diagnostic model of PNFC for the knowledge-based expert system (as shown in Fig.5).

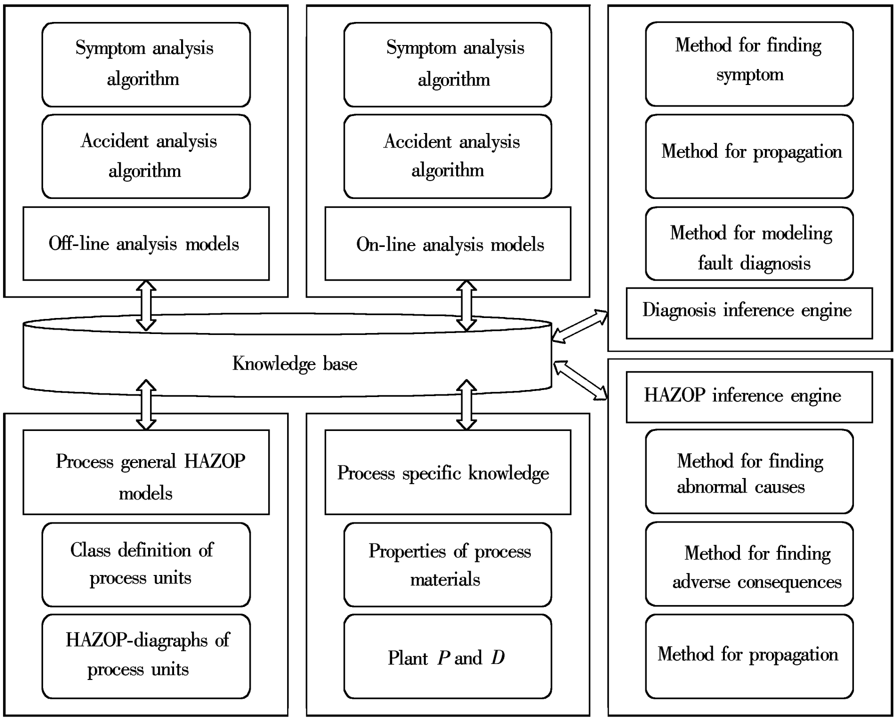

Fig.4 The architecture of the integrated knowledge base

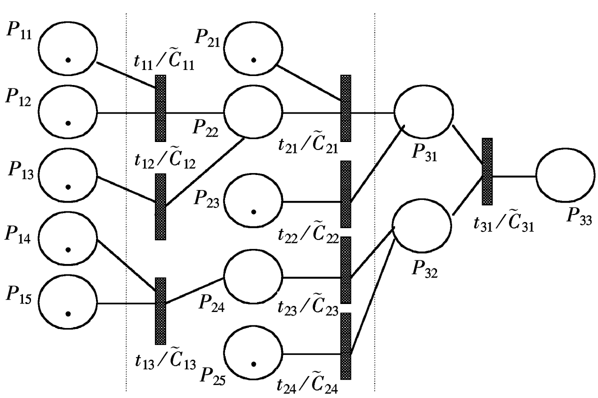

Fig.5 HAZOP study model or diagnostic model of PNFC

Places P_{ij} denote the step of HAZOP analysis or diagnosis. Transitions $t_{ij}/\tilde{C}_{ij}$ characterize changes from one step to another. If all enabling conditions associated with a transition are satisfied then the transition can be fired. In the process of applying HAZOP inference engine, the enabling rule and firing rule can be used to manage the evaluation of fuzzy colors, and the fuzzy inference function can be used to calculate the truth degree of colors. So that, the Petri net modeling technique and the HAZOP analysis technique are integrated in the area of automatic HAZOP and fault diagnosis. As shown in Fig.5, the diagnostic model represents a set of inference rules that is generated in the process of HAZOP analysis. The diagnostic model of PNFC is correlated to the model of consequences and deviations of the equipment. The unified knowledge representation can be used in the area of HAZOP analysis and fault diagnosis.

5 Conclusion

The focus of the paper concerns the integration of automatic HAZOP analysis and fault diagnosis. An architecture of the integrated knowledge base has been developed to construct the knowledge-based expert system. The application of Petri net with fuzzy colors has enhanced the ability of modeling fault diagnosis with Petri net. Affected with the knowledge base, the architecture of HAZOP analysis can implement on-line diagnosis, and generate new if-then rules for the knowledge base. The automatic HAZOP analysis technique is a powerful tool for designing the safety process, which can provide effective preventative measures and reduce the hazard level.

Besides the HAZOP analysis, the methods of inherent safety analysis and layer of protection analysis (LOPA) can also be used to generate if-then rules. In these two methods, the method of inherent safety is a proactive approach for hazard/risk management during process plant design and operation[29], and the layer of protection analysis method for determining the needed safety integrity level of a safety instrumented system is a tool that can be used subsequent to the HAZOP, but prior to the using of fault tree analysis or quantitative risk analysis[30]. Thus, the set of methods for obtaining the information of fault diagnostic symptoms is an important way to provide added value for the knowledge base.

References

[1] Mushtaq F, Chung P W H. A systematic HAZOP procedure for batch processes, and its application to pipeless plants [J]. *Journal of Loss Prevention in the Process Industries*, 2000, **13** (1):41-48.

[2] Wang Yifeng, Wu Jeryu, Chang Chueitin. Automatic hazard analysis of batch operations with Petri nets [J]. *Reliability Engineering and System Safety*, 2002, **76**(1):91-104.

[3] Leone H. A knowledge-based system for HAZOP studies: The knowledge representation structure [J]. *Computers and Chemical Engineering*, 1996, **20**(Supp):S369-S374.

[4] Kuo D H, Hsu D S, Chang C T. A prototype for integrating automatic fault tree/event tree/HAZOP analysis [J]. *Computers and Chemical Engineering*, 1997, **21**(Supp):S923-S928.

[5] Khan, Faisal I, Abbasi S A. Mathematical model for HAZOP study time estimation [J]. *Journal of Loss Prevention in the Process Industries*, 1997, **10**(4):249-257.

[6] Swann C D, Preston M L. Twenty-five years of HAZOPs [J]. *Journal of Loss Prevention in the Process Industries*, 1995, **8** (6):349-353.

[7] Venkatasubramanian V, Zhao Jinsong, Viswanathan S. Intelligent systems for HAZOP analysis of complex process plants [J]. *Computers and Chemical Engineering*, 2000, **24**(9): 2291-2302.

[8] Graf H, Schmidt-Traub H. Early hazard identification of chemical plants with statechart modeling techniques [J]. *Safety Science*, 2000, **36**(1):49-67.

[9] Srinivasan R, Venkatasubramanian V. Petri net-digraph models for automating HAZOP analysis of batch process plants [J]. *Computers and Chemical Engineering*, 1996, **20**(Supp):S719-S725.

[10] Zhao Zhigang, Lu Huixian, Qian Jixin. The study of novel algorithm of fault diagnosis with Petri net [J]. *Computer Engineering and Applications*, 2003, **39**(1):86-88. (in Chinese)

[11] Zhao Lindu. *Fault diagnostic technology of large-scale mechanical and electronic system* [M]. Beijing: China Sinopec Publishing Company, 2001. (in Chinese)

[12] Chen Yubao, Xia Jiqiang, Wu Xueli. Study on the application of Petri nets to fault diagnosis [J]. *China Mechanical Engineering*, 2000, **11**(12):1386-1389. (in Chinese)

[13] Ding Caihong, Jiang Xingwei, Huang Wenhu. Behaviour Petri model based diagnostic inference [J]. *Journal of Harbin Institute of Technology*, 2001, **33**(2):158-161. (in Chinese)

[14] Srinivasan R, Venkatasubramanian V. Automating HAZOP analysis of batch chemical plants I: the knowledge representation framework [J]. *Computers and Chemical Engineering*, 1998, **22**(9):1345-1355.

[15] Srinivasan R, Venkatasubramanian V. Automating HAZOP analysis of batch chemical plants II: algorithms and application [J]. *Computers and Chemical Engineering*, 1998, **22** (9):1357-1370.

[16] Schubach S. A modified computer hazard and operability study procedure [J]. *Journal of Loss Prevention in the Process Industries*, 1997, **10** (5,6): 303-307.

[17] Bartolozzi V, Castiglione L, Picciotto A, et al. Qualitative models of equipment units and their use in automatic HAZOP analysis [J]. *Reliability Engineering and System Safety*, 2000, **70**(1):49-57.

[18] Srinivasam R, Dimitriadis V D, Shah N, Venkatasubramanian V. Integrating knowledge-based and mathematical programming approaches for process safety verification [J]. *Computers and Chemical Engineering*, 1997, **21**(Supp):S905-S910.

[19] Holger Graf, Henner Schmidt-Traub. An integrated approach to early process hazard identification of continuous and batch plants with statechart modeling and simulation [J]. *Computers and Chemical Engineering*, 2001, **25**(1): 61-72.

[20] Cagno E, Caron F, Mancini M. Risk analysis in plant commissioning: the multilevel HAZOP [J]. *Reliability Engineering and System Safety*, 2002, **77**(3):.309-323.

[21] Ouali M S, Ait-Kadi D, Rezg N. Fault diagnosis model based on Petri net with fuzzy colors [J]. *Computers and Industrial Engineering*, 1999, **37**(1,2):173-176.

[22] Khan F I, Abbasi S A. Towards automation of HAZOP with a new tool expertop [J]. *Environmental Modelling and Software*, 2000, **15**(1): 67-77.

[23] Cocchiara M, Bartolozzi V, Picciotto A, et al. Integration of interlock system analysis with automated HAZOP analysis [J]. *Reliability Engineering and System Safety*, 2001, **74** (1):99-105.

[24] Zhao Jinsong, Viswanathan S, Zhao Chunhua, et al. Computer-integrated tools for batch process development [J]. *Computers and Chemical Engineering*, 2000, **24** (2-7): 1529-1533.

[25] Vaidhyanathan R, Venkatasubramanian V. Experience with an expert system for automated HAZOP analysis [J]. *Computers and Chemical Engineering*, 1996, **20**(Supp):S1589-S1594.

[26] Miller D C, Josephson J R, Elsass M J, et al. Sharable engineering knowledge databases for intelligent system applications [J]. *Computers and Chemical Engineering*, 1997, **21** (Supp):S77-S82.

[27] Ruiz D, Canton J, Nougues J M, et al. On-line fault diagnosis system support for reactive scheduling in multipurpose batch chemical plants [J]. *Computers and Chemical Engineering*, 2001, **25** (4-6):829-837.

[28] Ruiz D, Nougues J M, Zuly Calderon, et al. Neural network

based framework for fault diagnosis in batch chemical plants [J]. *Computers and Chemical Engineering*, 2000, **24**(2-7): 777-784.

[29] Khan F I, Amyotte P R. Inherent safety in offshore oil and gas activities: a review of the present status and future directions [J]. *Journal of Loss Prevention in the Process Industries*, 2002, **15**(4): 279-289.

[30] Arthur M Dowell III. Layer of protection analysis for determining safety integrity level [J]. *ISA Transactions*, 1998, **37**(3): 55-165.

基于 Petri 网的自动 HAZOP 分析和故障诊断集成

赵林度

（东南大学经济管理学院，南京 210096）

摘　要　在系统分析 HAZOP (hazard and operability)研究流程的基础上,介绍了具有模糊色的 Petri 网故障诊断建模方法,该方法可以有效地表示模糊信息.为构建基于知识库的专家系统,提出了一种有效集成 HAZOP 分析与故障诊断的知识库结构;基于具有模糊色的 Petri 网建模方法,提出了一种面向在线 HAZOP 分析和在线故障诊断的知识表示方式,该方式奠定了自动 HAZOP 分析和故障诊断集成的技术基础.

关键词　危险和操作性能；故障诊断；Petri 网；专家系统；知识表示

中图分类号　TH165⁺.3；TP18