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Automatic HAZOP analysis method for unsteady operation in chemical based on qualitative simulation and inference

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ABSTRACT

Comparing with continuous production process, unsteady operation process, such as startup and shutdown, tends to abnormal situations due to a large number of operations of operators and dynamic state changes involved. To guarantee a safe operation, process hazard analysis (PHA) is very important to proactively identify the potential safety problems. In the chemical process industry, hazard and operability (HAZOP) analysis is the most widely used method. In this paper, based on proposed qualitative simulation and inference method, an automatic HAZOP analysis method for unsteady operation processes is proposed. Mass transfer and relationships among process variables are expressed by Petri net–directed graph model based fuzzy logic. Operating procedure is expressed according to a formal expression. Possible operation deviations from normal operating procedure are identified by using a group of guidewords. Hazards are identified automatically by qualitative simulation and inference when wrong operation process is performed. The method is validated by a rectification column system.

1. Introduction

In chemical process, besides continuous steady operation mode, there are also unsteady operation modes, such as startup, shutdown and batch operation processes. Comparing with continuous operation, unsteady operation processes tend to abnormal situations due to a large number of operations of operators and dynamic state changes involved [1].

To guarantee a safe operation, process hazard analysis (PHA) is very important to proactively identify the potential safety problems. There are several techniques for performing PHA, such as Checklist, Hazard and Operability (HAZOP) analysis, and Fault Tree Analysis [2]. In the chemical process industry, HAZOP is the most widely used and recognized as the preferred PHA approach and is used to systematically identify every conceivable process deviation, its abnormal causes and adverse consequences [3–5].

HAZOP analysis for continuous steady operation has been very time-consuming when it is performed by experts manually. HAZOP analysis for unsteady operation is not only time-consuming but also more difficult due to the fact that: (1) the system state changes dynamically with sequence operations, and (2) the potential adverse effect of one wrong operation may occur during later operation. Experts need to remember this potential effect during HAZOP analysis. Especially, when two or more wrong operations are considered, they need to judge sequential effects.

In order to eliminate burden of experts, some automatic methods to perform HAZOP analysis have been proposed. For continuous steady operation, methods based on directed graph are classic and mature [6,7]. Directed graph model, however, is constructed mainly based on steady state of production process, and thus it is difficult to describe dynamic state changes during one unsteady operation process, such as startup operation process, by using directed graph model only.

Current automatic methods to perform HAZOP analysis for unsteady operation process will be briefly reviewed. Srinivasan and Venkatasubramanian used Petri net–digraph models for automating HAZOP analysis of batch process [8–10]. Mass transfer and operating procedure were expressed by using Petri net, and causality among variables was expressed by digraph. Because every subtask should be attached to a digraph, the scale of the whole model would be large. On the other hand, the adverse consequence description needed to be added manually. Xu *et al.* used Petri net and dynamic Signed Directed Graph (SDG) to perform HAZOP analysis [11], with which the adverse consequence of maloperation can be identified but it was difficult to deal with maloperation pattern “earlier or later operation”. An improved Petri net structure was used to express operating procedure and local SDG was related to every operating stage [12]. Some checklists, such as operation nodes checklist, were used to check the current state and the local SDG was used to infer adverse consequences for incorrect state. It can identify adverse consequences for maloperation pattern “earlier or later operation”, but

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was limited to single maloperation. Statechart provided an easy way to express state transition of plant equipment and has been used to early hazard identification of chemical plants [13,14]. Conducting statechart model for one product unit may be time-consuming because every state transition of one variable needed to add "Event", "Condition" and "Action", respectively. Palmer and Chung proposed an automatic consequence analysis method for wrong operating procedure [15,16], which used an object-oriented way to model plant items and their connection and simulated the effect of operating procedure. An automated system was developed based on this method and mainly used guidewords "No", "Before" and "After". Zhang *et al.* proposed a consequence analysis strategy for maloperation in batch processes [17]. Qualitative model of environment and every qualitative model describing production process, such as a pump or reactor model, had the faculty of inference, which enabled these models to update their states and infer whether some hazards would occur by themselves when an operation was dealt with. This method can be used to identify adverse consequences led by maloperations occurring sequently. However, this method did not involve control loops. Thus, it cannot qualitatively simulate the effects of controllers on production process. Zhang *et al.* proposed an automatic method for adverse consequence identification for potential maloperation [18]. The qualitative model for production process was expressed by a novel directed graph. Possible operation deviations from normal operating procedure were identified systematically by using a group of guidewords. However, this method also did not involve control loops. Kang *et al.* proposed an automatic safety analysis approach based on multiple models [19], which improved the effectiveness of the reasoning process through cooperation of multiple models.

Every reviewed automatic HAZOP analysis method for unsteady operation process has following one or more aspects that can be improved: (1) Modeling process is time-consuming; (2) adverse consequence description in model need be added manually; (3) only one maloperation can be dealt with; (4) few guidewords can be used; (5) effects of control loops on production process are seldom involved, which are necessary during startup and shutdown operation process; and (6) lack of considering effect of dynamic change process of one variable on another, which is a characteristic of unsteady operation process.

In order to address these aspects, an automatic HAZOP analysis method for unsteady operation processes is proposed based on qualitative simulation and inference. Mass transfer and relationships among process variables are expressed by Petri net–directed model based fuzzy logic. Operating procedure is expressed according to a formal expression. Possible operation deviations from normal operating procedure are identified by using a group of guidewords. Hazards are identified automatically according to proposed qualitative simulation and inference methods when wrong operation process is performed.

2. Proposed Method

2.1. Method structure

The structure of proposed method is shown in Fig. 1. When one unsteady operation process is simulated qualitatively, basic operation in operating procedure makes material move from one place to another in Petri net. A fuzzy directed graph attaching to a place expresses causality among variables in this place and determines variables' values of place. When process variables in places are too high or too low, qualitative hazard inference will be started. Firstly, use "Hazard Patterns" to identify hazards. When one or more materials leak from equipment, or when air is drawn into equipment with high temperature, "Material Hazard Digraph" is used to automatically identify hazard related materials. During this hazard identification process, a table recording properties of materials is used to provide physical and chemical properties related to production safety.

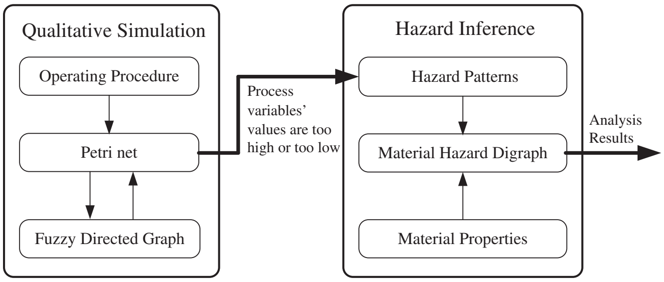

Fig. 1. Structure of proposed method.

2.2. Qualitative simulation

2.2.1. Colored Petri net model

A classical Petri net is composed of three parts: a set of place, a set of transitions and a set of directed arcs. Each place contains $m (m \geq 0)$ tokens. The execution of a Petri net is controlled by the number and distribution of tokens. The graphic elements of Petri net are listed in Table 1.

Table 1
Graphic elements of Petri net

Name	Graphic sign
Place	○
Token	●
Transition	▭
Directed *Arc*	→

In classical Petri net, each place can be occupied by m token. Hence, the state of a system can be described only by integer. Colored Petri net (CPN) can express more information in chemical process [9], for example state changes of materials in a chemical unit with subtasks being performed. In CPN conventional token is replaced by colored token and a colored token is an object to which attributes can be attached. In this paper, CPN is used to express mass transfer and state changes of chemical materials. In order to well cooperate with proposed operating model expression, new model structure and different physical meanings of graphic elements of Petri net are proposed.

Place represents not only equipment that can contain materials, such as reactor or rectification column, but also path. A path is defined as a whole that connects equipment with valves, pumps and pipes. Therefore, place is divided into two types: Container Place and Path Place. Each place can have one or more process variables, such as flow, level, temperature, which express state of production process. The place belonging to Path Place has a parameter *pass* so as to indicate whether path can transfer material. The value of parameter *pass* can be 1 or 0, representing path can or cannot transfer material.

Token represents a material with attributes Name, Amount, Temperature and State of Matter.

Transition expresses not only basic operation such as charging, discharging, heating or cooling, but also mass transfer led by basic operation. A basic operation represents a series of actions, such as open valve and start pump. When a transition is used to express mass transfer, a Liquid or Gas parameter can be assigned to particularly control which state of material will be transferred.

Arc represents normal direction of material transfer.

2.2.2. Fuzzy directed graph model

One place can associate a fuzzy directed graph (FDG). Fuzzy directed graph expresses causalities among variables in equipment or path.