Intelligent systems for HAZOP analysis of complex process plants

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Abstract

Process safety, occupational health and environmental issues are ever increasing in importance in response to heightening public concerns and the resultant tightening of regulations. The process industries are addressing these concerns with a systematic and thorough process hazards analysis (PHA) of their new, as well as existing facilities. Given the enormous amounts of time, effort and money involved in performing the PHA reviews, there exists considerable incentive for automating the process hazards analysis of chemical process plants. In this paper, we review the progress in this area over the past few years. We also discuss the progress that has been made in our laboratory on the industrial application of intelligent systems for operating procedure synthesis and HAZOP analysis. Recent advances in this area have promising implications for process hazards analysis, inherently safer design, operator training and real-time fault diagnosis. © 2000 Published by Elsevier Science Ltd. All rights reserved.

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1. Introduction

Complex modern chemical plants pose major challenges for the systematic analysis and assessment of the various process hazards inherent in such plants. This, of course, raises serious environmental, occupational safety and health related concerns. Further, the plants are often operated at extremes of pressure and temperature to achieve optimal performance, making them more vulnerable to equipment failures. Despite advances in computer-based control of chemical plants, the fact that two of the worst ever chemical plant accidents, namely, Union Carbide’s Bhopal, India, accident and Occidental Petroleum’s Piper Alpha accident (Lees, 1996), happened in recent times is a troubling development. Also, industrial statistics show that even though major catastrophes and disasters from chemical plant failures may be infrequent, minor accidents are very common, occurring on a day to day basis, resulting in many occupational injuries, illnesses, and costing the society billions of dollars every year (McGraw-Hill Economics, 1985; Bureau of Labor Statistics, 1998; National Safety Council, 1999).

All these concerns have led the federal agencies in the US to create safety, health and environmental regulations. The Occupational Safety and Health Administration (OSHA) passed its PSM standard Title 29 CFR 1910.119, which requires all major chemical plant sites to perform process hazards analysis (PHA) (OSHA, 1992). In addition, EPA instituted the Risk Management Program (RMP) in 1995 (EPA, 1995). All these require the systematic identification of process hazards, their assessment and mitigation. To analyze process hazards, plant personnel systematically ask questions such as, ‘What can go wrong?’, ‘How likely is it to happen?’, ‘What is the range of consequences?’, ‘How could they be averted or mitigated?’, ‘How safe is safe enough?’ and so on in order to evaluate and improve the safety of the plant. The answers to these and other related questions are sought in what is known as Process Hazards Analysis (PHA) of a chemical plant. Process Hazards Analysis is the systematic identification, evaluation and mitigation of potential process hazards which could endanger the health and safety of humans and cause serious economic losses.

A wide range of methods such as Checklist, What-If Analysis, Failure Modes and Effects Analysis (FMEA), Fault Tree Analysis (FTA) and Hazard and Operability (HAZOP) Analysis are available for performing PHA (CCPS, 1985). Whatever method is chosen, the PHA, typically performed by a team of experts, is a laborious, time-consuming and expensive activity which requires specialized knowledge and expertise. For PHAs to be
thorough and complete, the team can not afford to overlook even routine causes and consequences which will commonly occur in many plants. The importance of performing a comprehensive PHA is illustrated by Kletz (1986, 1988, 1991) with examples of industrial accidents that could have been prevented if only a thorough PHA had been performed earlier on that plant. Of the various available methods, HAZOP is the most widely used PHA methodology and hence it is the approach we have chosen to discuss in this paper.

A typical HAZOP analysis can take 1–8 weeks to complete, costing over $13 000–25 000 per week. By an OSHA estimate, approximately 25 000 plant sites in the United States require a PHA (Freeman, Lee & McNamara, 1992). An estimated $5 billion is spent annually by the chemical process industries (CPI) to perform PHAs and related activities. The estimated cost of process hazards reviews in the CPI is about 1% of sales or about 10% of profits.

Given the enormous amounts of time, effort and money involved in performing PHA reviews, there exists considerable incentive to develop intelligent systems for automating the process hazards analysis of chemical process plants. An intelligent system can reduce the time, effort and expense involved in a PHA review, make the review more thorough, detailed, and consistent, minimize human errors, and free the team to concentrate on the more complex aspects of the analysis which are unique and difficult to automate. Also, an intelligent PHA system can be integrated with CAD systems and used during early stages of design, to identify and decrease the potential for hazardous configurations in later design phases where making changes could be economically prohibitive. It would facilitate automatic documentation of the results of the analysis for regulatory compliance. Also these PHA results can be made available online to assist plant operators during diagnosis of abnormal situations as well as to train novice operators.

Despite the obvious importance of this area, there has only been limited work on developing intelligent systems for automating PHA of process plants. In this paper, we will review the past approaches towards the automation of PHA from the perspective of intelligent systems. This paper is written as a brief survey of the literature in this area with an emphasis on the overview of the results of the Purdue investigations on intelligent systems for PHA over the past 12 years. Of the various methods, HAZOP analysis is the most widely used and recognized as a preferred PHA approach by the chemical process industries. Hence, the main focus of this paper will be on HAZOP analysis which primarily addresses the hazard identification aspect of PHA. This is a practical first step towards automating PHA because the nominal information required for HAZOP, including piping and instrumentation diagrams and operating procedures, is more readily available for every process. The quantitative information required for hazard evaluation and mitigation, such as mean time between failures and failure rates and fundamental mathematical process models, however, are not.

2. Intelligent systems for automating HAZOP analysis

HAZOP analysis was developed in the late 1960s at ICI in the UK. The basic principle of HAZOP analysis is that hazards arise in a plant due to deviations from normal behavior. A group of experts systematically identify every conceivable deviation from design intent in a plant, find all the possible abnormal causes, and the adverse hazardous consequences of that deviation. The experts in the study team are chosen to provide the knowledge and experience in different disciplines for all aspects of the study to be covered comprehensively. The procedure involves examining the process P&ID systematically, line by line or section by section (depending on the level of detail required), by generating deviations of the process variables from their normal state. The possible causes and consequences of each deviation so generated are then considered, and potential problems are identified. In order to cover all possible malfunctions in the plant, the process deviations to be considered are generated systematically by applying a set of guide words, namely, NONE, MORE OF, LESS OF, PART OF, REVERSE, AS WELL AS and OTHER THAN, which correspond to qualitative deviations of process variables.

In addition to identifying the hazards in a process plant, the HAZOP study also identifies operability problems which prevent efficient operation of the plant. Detailed descriptions of the HAZOP analysis procedure with illustrative examples are given in CCPS (1985), Knowlton (1989), Kletz (1986).

Variants on this basic structure of HAZOP analysis have been developed to make the approach more thorough. For example, ICI has adopted a six stage Hazard Study methodology which not only embraces HAZOP within its Hazard Study 3, but also the appropriate elements of the other PHA techniques (Preston & Turner, 1991). Hazard Study 1 is the key SHE (Safety, Health and Environment) study during process conception, including inherent Safety and Environmental Impact. Hazard Study 2 is carried out on the process flow diagrams to identify top events and the need for further quantification, including QRA (frequency/consequence) design modification and hazard elimination/minimization. Hazard Study 3 relates to the engineering phase as the classic line by line critical examination of the Engineering Line Diagram (ELD) or P&ID prompted by guide words. Hazard Studies 4 and 5 relate to construction and commissioning and Hazard Study 6 is a final audit after the plant is in beneficial operation.
Although developed for new plants, the six-stage methodology is equally applicable to modifications and on-going plant safety reviews. Indeed an adaptation of Hazard Study 2 has been specifically targeted to SHE Assurance requirements of existing plants as Process Hazard Review (PHR) (Turney & Ruff, 1995) and has been successfully applied to a range of technologies.

One of the important challenges in automating HAZOP analysis is handling the huge amount of process specific information which is required as the input for performing HAZOP. It is desirable to develop a system that is context-independent so that it can be used for the HAZOP analysis of a wide variety of processes and will also be able to find the process-specific hazards for the various processes. This was a major hurdle that posed difficult conceptual and implementational challenges that thwarted the earlier attempts towards automation.

As one of the early attempts, Parmar and Lees (1987a,b) developed a rule-based approach to automate HAZOP analysis and showed its application for the hazard identification of a water separator system. They represent the knowledge required for propagating faults in each process unit using qualitative propagation equations and event statements for initiation and termination of faults. The P&ID of the plant was divided into lines consisting of pipes and other units such as pumps and valves through which a process stream passes, and vessels. And the control loop which consists of sensor, controller and control valve and its bypass was represented as a single process unit. The starting point of HAZOP analysis is a process variable deviation in a line. The causes are generated by searching for the initial events and the consequences by searching the terminal events. But the causes and consequences generated for a process variable deviation are confined to the line under consideration and the vessel connected to it. Thus this method finds only the immediate causes and consequences, unlike the actual HAZOP analysis in which the causes and consequences are propagated to the end of the process section under consideration to find all the adverse consequences due to every abnormal cause. This automated hazard identification system was implemented using Fortran 77 and Prolog. While it was a commendable early attempt, the system was limited to the process under consideration as the knowledge-based was hardwired for the given process thus making it difficult to use for other processes. It was also limited to small process configurations and was not suitable for large-scale plants. These problems plagued other early attempts such as the ones discussed below as well.

Waters and Ponton (1989) attempted to automate HAZOP analysis using a quasi steady state qualitative simulation approach. They found the approach to be highly combinatorial, thus restricting its practical usefulness. Their qualitative simulation program was developed in Prolog and implemented on a Sun 3/50 workstation. They reported that the time taken to perform qualitative simulation even for simple systems substantially exceeded that required for a numerical simulation involving considerable detail.

A rule-based expert system prototype called HAZOPEX was developed using the KEE shell by Karvonen, Heino and Suokas (1990). The HAZOPEX system’s knowledge base consisted of the structure of the process system and rules for searching causes and consequences. The rules for the search of potential causes are of the type, ‘If deviation type AND process structure/conditions THEN potential cause’. One important drawback of these rules is that the condition part of the rules depended on the process structure. This increases the number of rules required as the number of process units increases, thereby limiting the generality of the system. In HAZOPEX, the identification of abnormal causes was more emphasized and less was said about the adverse consequences, though in HAZOP analysis the identification of adverse consequences is given priority. In that sense, this work had more of a diagnosis flavor. HAZOPEX’s performance was evaluated on a small part of an ammonia system case study for which HAZOPEX was found to include useful knowledge about the potential causes of deviations which can be used as a check-list for the user.

Nagel (1991) developed an inductive and deductive reasoning based approach to automatically identify potential hazards in chemical plants caused by hazardous reactions, the requisite conditions that enable the occurrence of these reactions, and the design or operational faults. This is a reaction-based hazard identification approach limited to only such hazards, and thus is not as general or as useful as conventional PHA approaches. The potential top level reaction hazards are identified by considering all the possible reactions using an inductive reasoning approach. A language for Chemical Reactivity is used to describe chemicals, properties and reactions. The modeling language developed by Stephanopoulos, Henning and Leone (1990a,b) is used to describe processing systems, unit operations, operating conditions and behavior. Topological fault trees are constructed based on the generated results.

Catino and Ungar (1995) developed a prototype HAZOP identification system, called Qualitative Hazard Identification (QHI). QHI works by exhaustively positing possible faults, automatically building qualitative process models, simulating them, and checking for hazards. QHI matches a library of general faults such as leaks, broken filters, blocked pipes and controller failures against the physical description of the plant to determine all specific instances of faults that can occur in the plant. For some of these faults, simulation and hazard identification were completed in seconds while
for many others it took days. Moreover, for some faults the memory on a Sun SparcStation was exhausted and the QHI could not identify the hazards. This disadvantage prevented QHI from practical industrial applications.

Suh, Lee and Yon (1997) developed a knowledge-based prototype expert system for automated HAZOP analysis. This system comprises of three knowledge bases: unit knowledge base, organizational knowledge base and material knowledge base, and three hazard analysis algorithms: deviation, malfunction and accident analysis algorithm. This system has been developed using object-oriented language — C++ based on PC. However, only models of CSTR, pipe, valve, heat exchanger, tank, mixer, control valve and pump had been developed. Models for other process units were under programming. This approach and the one discussed next are similar in their conceptual framework to the earlier model-based object-oriented methodology demonstrated by Venkatasubramanian and Vaidhyanathan (1994, 1996) and Vaidhyanathan and Venkatasubramanian (1995, 1996) which is described later in the paper.

Faisal and Abbasi (1997) proposed a knowledge-based software tool, called TOPHAZOP, for conducting HAZOP. The knowledge base consists of two main branches: process-specific and general. The process-specific knowledge base has been classified in two main groups: objects (process units) and its attributes, causes, and consequences. The objects are developed in frame structure with attributes while causes and consequence are developed in rule networks attached to the frame. The general knowledge is classified in generic causes and generic consequences. However, the interactions between parameters and deviation propagation to the downstream process units were not indicated, which might lead to incomplete HAZOP analysis.

A quantitative model-based approach for process safety verification of hybrid system was proposed by Dimitradis, Shah and Pantelides (1997). In their approach, a state transition network was used to represent hybrid behavior. Using the state transition representation, a mathematical model of the system in the discrete time domain was constructed which expressed the system behavior in terms of equality and inequality constraints. The inputs to the system may indeed correspond to typical process inputs, but may additionally be used to represent possible disturbances entering the process or possible failure models of the equipment. The safety verification problem requires the system to identify disturbance profiles which could lead to hazards. The mathematical formation results in a mixed integer optimization problem. For industrial scale problems, therefore, the resulting optimization problems may be difficult to solve, particularly if significant non-linearities are present in the system model. In addition, even when the solution of the mathematical program indicates that the system is safe for the time horizon considered, in the presence of local optima, there is no guarantee that none of the hazards considered in the analysis can occur.

To overcome shortcomings of purely quantitative and qualitative HAZOP analysis methods, Srinivasan and Dimitradis (Srinivasan, Dimitradis, Shah & Venkatasubramanian, 1998) proposed a hybrid knowledge-based mathematical programming framework where the overall features of a particular hazardous scenario are extracted by inexpensive qualitative analyses. If necessary, a detailed quantitative analysis is then performed to verify the hazards with ambiguity captured by the qualitative analysis. The results of this framework are compared to those of purely qualitative reasoning using an industrial case study.

Turk (1999) presented a procedure for the synthesis of a non-timed discrete model which captures the relevant continuous dynamic and sequential phenomena of the chemical process for the given specifications. The proposed procedure focuses the construction of discrete models with the aid of the given specifications. The specifications identify the relevant causal paths in the chemical process. The procedure searches backward along these causal paths in building the transition relations for the state variables from the physical system, control systems, operating procedures, and operator behavior. Therefore, the proposed procedure builds a discrete model for verifying the safety and operability of the chemical process.

Most of the above approaches to automated hazards analysis were demonstrated on small-scale processes or academic prototypes. They were, in general, limited to the process that was under consideration and were difficult to modify and apply to a wide-variety of industrial-scale process plants. In the following, we will review the two major efforts in developing intelligent systems for the HAZOP analysis of continuous processes and batch processes, namely, the HAZOPExpert and Batch HAZOPExpert (BHE) projects at Purdue University, which have been applied successfully to numerous real-life industrial process plants.

2.1. HAZOPExpert: a model-based intelligent system for HAZOP of continuous processes

HAZOPExpert is a model-based, object-oriented, intelligent system for automating HAZOP analysis developed by Venkatasubramanian and Vaidhyanathan during 1990–1994 for continuous processes. In their approach, they recognized that while the results of a HAZOP study may vary from plant to plant, the approach itself is systematic and logical, with many aspects of the analysis being the same and routine for different process flowsheets. It turns out that about
70% of time and effort is spent on analyzing these routine process deviations, their causes, and consequences. Hence, they focused on these routine cause-and-effect analyses by developing generic models which can be used in a wide variety of flowsheets, thus making the expert system process-independent. They also recognized that the process-specific components of knowledge, such as the process material properties and process P&IDs, have to be flexibly integrated with the generic models in an appropriate manner. To address this integration, they developed a two-tier knowledge-based framework by decomposing the knowledge base into process specific and process general knowledge, represented in an object-oriented architecture.

Process-specific knowledge consists of information about the materials used in the process, their properties (such as corrosiveness, flammability, volatility, toxicity, etc.) and the P&ID of the plant. The process-specific knowledge is likely to change from plant to plant and is provided by the user. Process-general knowledge comprises of the process unit HAZOP models that are developed in a context-independent manner, which remains the same irrespective of the process plant under consideration. The HAZOP model of a process unit consists of its class definition and generic qualitative causal model-based methods for identifying and propagating abnormal causes and adverse consequences of process variable deviations. Based on this framework, an expert system called HAZOPExpert has been implemented using Gensym’s G2 real-time expert system shell. HAZOPExpert’s inference engine allows for the interaction of the process-general knowledge with the process-specific knowledge to identify the valid abnormal causes and adverse consequences for the given process variable deviations for the particular HAZOP study section of the plant under consideration.

HAZOPExpert is not meant to replace the HAZOP team. Its objective is to automate the routine aspects of the analysis as much as possible, thereby freeing the team to focus on more complex aspects of the analysis that can not be automated. It can be used in an interactive mode or fully automated batch mode.

2.1.1. HAZOP-Digraph (HDG) models

The initial version of HAZOPExpert was modified into a HAZOP-Digraph (HDG) model-based framework to facilitate model development and refinement by the users as well as to tackle more complex process configurations (Vaidhyanathan & Venkatasubramanian, 1995). The overall architecture of the HDG model-based HAZOPExpert system is shown in Fig. 1. The HDG models are modified signed directed graphs (SDG) developed for the purpose of hazard identification. A framework for automated development of SDG models of chemical process units has been proposed by Mylaraswamy, Kavuri and Venkatasubramanian (1994).

Hazard-Digraphs provide the infrastructure for graphically representing the causal models of chemical process systems in a transparent manner to the user. The knowledge about finding the abnormal causes and the adverse consequences are incorporated into these digraphs. The HDG models of the process units are used for propagating the process variable deviations and for finding abnormal causes and adverse consequences by interacting with the process specific knowledge. The HDG models are developed in a context-independent manner so that they are applicable to a wide variety of flowsheets. The user can build a new HDG model or add more knowledge to the existing HDG model using the graphical HDG model developer. A graphical HAZOP-Digraph model building tool is provided for this purpose.

The graphical user interface (GUI) of HAZOPExpert is shown in Fig. 2. This figure displays the essential features of the GUI, namely, the process unit HAZOP model library, the P&ID graphical editor and the HAZOP results windows. HAZOPExpert's model library currently has generic models for process units such as pump, tank, surge drum, heat exchanger, condenser, accumulator, reboiler, stripper, controller, valve, pipe, etc. The P&IDs of the process and the process materials properties are the process-specific information that is to be supplied by the user. If the P&IDs of the process are available in CAD format, they can be automatically imported into HAZOPExpert. Otherwise, the user can easily draw the P&IDs of the process using the P&ID graphical editor in HAZOPExpert. Similarly, if the process material property data are available in any database format they can be imported automatically into HAZOPExpert. Once the P&IDs and the process materials property data are input into the system, the corresponding HAZOP models of the process units in the P&IDs get connected automatically internally in the appropriate manner. This greatly simplifies knowledge acquisition.

![Fig. 1. Structure of HAZOPExpert](http://www.paper.edu.cn)
The user can initiate any process variable deviation in any pipeline or process unit. HAZOPExpert will systematically perform HAZOP analysis for the process variable deviation both upstream and downstream until the end points of the P&ID are reached. The HAZOP results are also stored in user-defined files which can be automatically imported into spreadsheeting software such as Microsoft Excel, or relational databases such as Oracle, or word-processing software such as Microsoft Word to generate the standard HAZOP review tables. These can be further manipulated and formatted in a user-defined manner for meeting regulatory compliance and other requirements.

2.1.2. Performance of HAZOPExpert on industrial case studies

HAZOPExpert is the first intelligent system in the published literature that was found to be successful on real-life, industrial-scale, HAZOP case studies by HAZOP professionals. It has been tested on a number of actual process systems of varying degrees of complexity by HAZOP consultants at the Arthur D. Little Company, Cambridge, MA, USA. In this section, we will present results from one such case study, namely, the sour water stripper plant case study that has been reported by Vaidhyanathan and Venkatasubramanian (1995). The consultants from Little had performed a HAZOP review for this process earlier and their results were used to compare with the expert system’s performance. In this process, there are 26 pipes, five flow control valves, five non-return valves, five pumps, one surge drum, one storage tank, one stripper, one condenser, one stripper overhead accumulator and six controllers. This process contains a refinery sour water stream that is separated in a surge drum to remove slop oil from the sour water. The sour water is pumped into a storage tank where any carried over slop oil can be skimmed off. From the storage tank the sour water is pumped through a heat exchanger to a steam stripper where ammonia and hydrogen sulfide are stripped from the water. Hydrocarbon oil is a flammability hazard and hydrogen sulfide and ammonia are toxic hazards. The release of these materials is a safety concern for the plant. Also, if there is poor separation of hydrocarbon oil from the sour water, the oil will escape into the stripper. This can gum-up the stripper packing which will cause operational problems.

HAZOP analysis was performed using HAZOPExpert for all conceivable process variable deviations in all the units and pipes in the sour water stripper plant. In any process unit, there are three deviations for flow (high, low, zero), two deviations for temperature (high, low), two deviations for pressure (high, low), three deviations for level (high, low, zero), and three deviations for each process material concentration (high, low, zero). Thus, HAZOP analysis was performed for a
total of 734 deviations in all the process units in the sour water stripper plant. It identified 100 abnormal causes and 90 adverse consequences for these deviations. HAZOPEXpert has propagated the deviation all the way downstream to the stripper and has found the ultimate consequence, ‘gumming up of the stripper due to high amounts of hydrocarbon oil entering the stripper’. For a human team, it is often difficult for the team members to propagate the consequences through all the downstream units as far as HAZOPEXpert does.

When a team of personnel perform the conventional HAZOP analysis it is not possible for them to consider the process variable deviations in each of the pipes, valves and pumps separately, a total of 734 deviations. So, they would group a number of connected pipes, valves, and pumps and other units into study nodes and perform HAZOP for these study nodes. This way, the total number of deviations considered by the HAZOP team will be far less. In the sour water stripper case study performed by the HAZOP team, 135 total process variable deviations were considered for HAZOP analysis, and 32 abnormal causes and 32 adverse consequences were reported. All these causes and consequences were identified by HAZOPEXpert. In addition, it had identified a number of other causes and consequences. Many of these were judged to be as less important by the human team. The generation of excessive number of causes and consequences is due to the qualitative nature of the HAZOP analysis procedure implemented in HAZOPEXpert. In conventional HAZOP analysis, experts filter their initial HAZOP results using additional quantitative information in the form of the design specifications and normal operating conditions of the process units, and the quantitative properties of the process materials.

To incorporate these aspects of expert’s reasoning, Vaidhyanathan and Venkatasubramanian (1996) proposed a semi-quantitative reasoning methodology for filtering and ranking HAZOP results in HAZOPEXpert. This methodology used quantitative threshold values for comparing the design and operating values of the process variables and the process material property values in order to decide whether a particular adverse consequence would occur in a process unit in the given process plant. The HAZOPEXpert with semi-quantitative filtering identified fewer consequences than with purely qualitative analysis. The filtered results however, included all the causes and consequences that were identified by the team.

The performance on other case studies were similar, except in some cases the system missed certain causes and consequences as they had not been modeled as a part of the HDG models library.

2.2. Batch HAZOPEXpert: a model-based intelligent system for HAZOP of batch processes

Batch HAZOPEXpert (BHE) is a model-based intelligent system for automating HAZOP analysis for batch processes based on HAZOPEXpert. It was first developed by Srinivasan and Venkatasubramanian (1998a,b), and improved later by Zhao, Viswanathan, Venkatasubramanian, Vinson and Basu (1998) by considering batch control, dynamic propagation of materials concentration and quantitative process information. For a batch process, HAZOP analysis is more complex because of the discrete-event character, which raises issues about its temporal nature. The status of the plant is constantly changing in some established discrete sequence. Since the P&ID does not sufficiently define the system, a set of operating instructions and some form of sequence chart are also needed. In batch plants, these sequence and instructions are called product recipe. Product recipe consists of a series of tasks occurring at discrete instants of time. In each task, many subtasks are executed to achieve the task. Differential equation based mathematical model, therefore, is not enough to describe batch chemical processes. Tools for describing discrete systems such as Petri nets (Peterson, 1981) are often used to represent batch processes (Srinivasan & Venkatasubramanian, 1998a).

In BHE, the product recipe is represented with two-layered Petri Nets-Recipe Petri Net (RPN) and Task Petri Net (TPN). RPN indicates the sequence of the tasks while TPN demonstrates the sequence of the subtasks in each task. Associated with each subtask, there is a digraph model which qualitatively captures the general cause-effect relationships between the variables of the subtask. Currently, about 40 subtask digraph models have been established in the model library to cover most of batch operations such as heat, cool, and filtration and so on. Fig. 3 shows a Petri net-based knowledge representation of a simple product recipe containing three tasks-reaction, filtration and drying.

To improve the reliability of HAZOP analysis results, various techniques are used in the inference engine. Batch control and conditional interactions among process variables are modeled in deviation propagation, which results in filtering out consequences with low possibility. Batch control prevents propagating deviations of the control variables further to downstream. Conditional interactions reflect the sensitivity degree of interactions among variables. For example, for a heat subtask in the normal operating state, high agitation can not cause high temperature, but low agitation can lead to low temperature. The semi-quantitative reasoning methodology used in HAZOPEXpert is also used here to mimic the HAZOP analysis of human HAZOP experts.
The HAZOP team normally ranks the adverse consequences found in a study based on the frequency and severity of the hazards they cause in the plant. Consequences with high frequency of occurrence and high severity will have a high priority of mitigation. Ranking hazards can help the user focus on those severe hazards with higher ranks. A methodology for ranking process hazards according to the severity level of the consequences was proposed by Vaidhyanathan and Venkatasubramanian (1996). A similar method is used here to rank the hazards in batch processes. In addition, safeguards are also recommended for most adverse consequences.

Information including operating parameters and quantitative hazard-critical properties of materials and equipment is used during semi-quantitative reasoning to reduce the number of impossible consequences. Material and equipment databases are therefore connected with this system to get necessary quantitative information.

However, the input of the Petri nets with dozens or hundreds of subtasks is a time-consuming process if it is manually done by users. To reduce the effort of users in using BHE and apply BHE at the design stage, an intelligent tool for operating procedure synthesis (iTOPS) is integrated with BHE by Viswanathan, Zhao and Venkatasubramanian (1999).

Operating procedure synthesis (OPS) is to generate the detailed sequence of instructions an operator needs to manage a batch process. iTOPS uses grafchart-based concepts to model the process at the four levels—procedure, unit procedure, operation and phases as identified in S88 (ISA, 1995). It uses a hierarchical planning technique to synthesize the operating procedures. iTOPS starts with information about the process materials, equipment, and chemistry to synthesize the procedures, unit procedures, operations, and phases for the process. The operating procedures are then generated based on the phases. The framework of OPS in iTOPS is shown in Fig. 4. The knowledge base of iTOPS includes the procedural knowledge, declarative knowledge and inferred knowledge. Procedural knowledge is represented using Grafchart procedures. The basic components of Grafchart are steps and transitions. Declarative knowledge contains information on process materials, equipment, chemistry and block process sequence diagram (PSD). Block PSD is a high level description of a batch process. It represents the sequence of main tasks. The declarative information is the input from users. Inferred knowledge stores the information of the generated PSD and master operation record (MOR). The inference engine used in iTOPS includes the algorithms for path search, equipment assignment, preliminary sequencing operations and the logic for OPS. iTOPS was the first intelligent system that was put to use in an industrial facility. It has been in routine use since January, 1998 at the Monsanto Pharma facility (G.D. Searle) in Skokie, IL.

![Recipe Petri Net](image1)

![Subtask Digraph Model](image2)

**Fig. 3.** Hierarchical petri-net-based knowledge representation of a simple product recipe.
Fig. 4. Framework of iTOPS.

Fig. 5. Integration framework of HAZOP and OPS.

and was used to develop more than 60 pharmaceutical batch processes. Its usage resulted in about 50% savings in time and effort. Details of iTOPS can be found elsewhere (Viswanathan, Johnsson, Srinivasan, Venkatasubramanian & Erik, 1998a,b).

Fig. 5 shows the framework of the integration system. In the framework, the information on material interaction, hazard critical material properties and equipment design parameters is directly obtained from database. The process chemistry, including the information on reactions and separations, still needs to be input by users. To specify a reaction, the user has to determine the reactants, products and solvent and so on. To specify a separation, the user has to determine the materials in the input flow and the output flows. When these specifications are finished, OPS is performed. Then the Grafchart-based Block PSD and PSD generated by iTOPS are converted through the OPS-PHA interfaces to Petri net-based RPN and TPNs required by BHE. When the conversion is completed, BHE can perform HAZOP analysis in batch mode. The PHA results then are used to make MOR safer by modifying the instructions.

2.2.1. Performance of batch HAZOPExpert on industrial case studies

Batch HAZOPExpert is the only intelligent system that has been successfully applied to batch chemical plants. It has been tested on 18 industrial batch processes with our industrial partners. In this section, we will present results from one such case study, namely, the Step-2 process at Monsanto’s Searle Pharma facility in Skokie, IL, that has been reported by Zhao, Viswanathan and Venkatasubramanian (2000a). Due to the proprietary nature of the process, specific details of the product recipe and process conditions are not presented here. However, the exact values of the process conditions are not crucial to illustrate the effectiveness of BHE. Values for temperature, pressure, amount of reactants, and other variables which would be considered reasonable for similar process chemistry are therefore used.

The P&ID of this step are shown, respectively in Fig. 6. In this step, the following reaction is performed in reactor R1:

\[ A + B + C \rightarrow D + E + F + G + H \]

The gas product F is purged to scrubbers S1 and S2. After this reaction is finished, the other materials are transferred to containers R2 and R3 where the product E get crystallized. The crystal product E is separated in...
Besides the above two consequences, BHE captured two more consequences as follows:

- Possible runaway reaction.
- Flammability hazard due to flammable material F and L above flash point.

In addition, three causes for this deviation, hazard severity and safeguard are provided by BHE.

More results on industrial applications of BHE can be found in the literature (Zhao et al., 2000a; Zhao, Viswanathan, Zhao, Mu & Venkatasubramanian, 2000b).

After generating the HAZOP results, efficiently managing the results and quickly getting the required information to help make decisions is important. The following kind of questions are often asked after obtaining the HAZOP analysis results:

- What are the upsets that result in a fire hazard?
- What are the hazards in Node two?
- What hazards are due to Chemical F?
- How many hazards have a severity greater than one?

To promptly answer the above questions, a dialog and spreadsheet based result database management system was built in BHE. Its interface is shown in Fig. 7. The four columns in the upper section of Fig. 7 are tables by which the user can perform some queries. The spreadsheet in the lower section on the dialog lists the query results. By clicking the button Save, the query results can be saved in a comma separated text file that can be further managed by MS office software such as MS Word or Excel. For example, the user can get all runaway reaction hazards in Task-1 by selecting Op-1: R1 in the Nodes table, and runaway reaction in the Classes table. With the improved result structure, users can easily communicate with the HAZOP analysis results, and therefore quickly get the information they want.

3. Conclusions and future directions

Process safety, occupational health and environmental issues are among the top priorities of all chemical, pharmaceutical and specialty chemicals companies. They collectively spend billions of dollars every year in the US on process hazards analysis to address these concerns. The current tedious manual approaches to PHA can benefit significantly from the appropriate use of intelligent systems.

This paper has reviewed how manual hazards analysis techniques and methodologies can be leveraged by an intelligent systems approach to reduce the time, effort and cost involved, and to improve the consistency and thoroughness of the analysis. Such systems are not meant to replace the human team but to assist them in improving the overall efficiency and productivity of the team. Of the various PHA methodologies, the
HAZOP analysis is the prime one for automation using intelligent systems due to its wide spread usage in the process industry and its systematic and comprehensive nature. The iTOPS, HAZOPexpert and Batch HAZOP-expert intelligent systems developed at Purdue University are now well beyond proof of concept and are ready for industrial applications and commercial exploitation.

In addition to routine PHA, such systems can facilitate HAZOP reviews at an early stage of process development and design. This means that problems can be identified and rectified during detailed design or while formulating operating procedures. Making changes once a plant is built are very expensive compared with changes at the design stage (Skelton, 1997). Early identification of hazards will also lead to effective avoidance or control of such hazards. HAZOP at this stage will also help to develop confidence that the desired process is safe. Along these lines, the longer-term aim may well be to move towards process conception and synthesis to create inherently safer designs and operating plants that tend towards zero defects. A more immediate development could be the use of online hazard reviews for the training of operators for abnormal situation management. The online hazard models can also be adapted for fault diagnosis applications. The application of the intelligent systems framework for complex problems such as process hazards analysis, which were formerly solved only by human teams, has come a long way since its modest beginning in the 1980s. Intelligent systems are now well poised to make significant contributions to PHA in real-life industrial settings thus improving the quality of the analyses while reducing the time and effort involved.

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