A Knowledge-Based Framework for Automating HAZOP Analysis

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Hazard and operability (HAZOP) analysis is the study of systematically identifying every conceivable abnormal process deviation, its abnormal causes and adverse hazardous consequences in a chemical plant. HAZOP analysis is a difficult, time-consuming, and labor-intensive activity. An automated HAZOP system can reduce the time and effort involved in a HAZOP review, make the review more thorough and detailed, and minimize or eliminate human errors. Towards that goal, a knowledge-based system, called HAZOPExpert, has been proposed in this article. In this approach, HAZOP knowledge is divided into process-specific and process-independent components in a model-based manner. The framework allows for these two components to interact during the analysis to address the process-specific aspects of HAZOP analysis while maintaining the generality of the system. Process-general knowledge is represented as HAZOP models that are developed in a process-independent manner and are applicable to a wide variety of process flowsheets. The important features of HAZOPExpert and its performance on an industrial case study are described.

Introduction

Hazard identification in chemical process plants is an important activity that requires a significant amount of time, effort, and specialized expertise. A wide range of methods such as process system checklists, safety review, what if analysis and hazard and operability (HAZOP) analysis have been developed for the purpose of hazard identification (CCPS, 1985). Of these different methods, HAZOP has been widely recognized and used as a standard approach in the chemical process industries. In addition to identifying the hazards in a process plant, HAZOP analysis also identifies operability problems which may prevent efficient operation of the plant.

HAZOP technique was developed in the early 1970s at ICI in the U.K. The basic principle of HAZOP analysis is that hazards arise in a plant due to deviations from normal behavior. In HAZOP analysis, process Piping and Instrument Diagrams (P&IDs) are examined systematically by a group of experts, and the abnormal causes and adverse consequences for all possible deviations from normal operation that could arise are found for every section of the plant. Thus, the potential problems in the process plant are identified. The HAZOP team is a multidisciplinary team of experts who have extensive knowledge on design, operation, and maintenance of the process plant. The HAZOP team members try to imagine ways in which hazards and operating problems might arise in a process plant. To cover all the possible malfunctions in the plant the imagination of the HAZOP analysis team members is guided in a systematic way using a set of "guide words" for generating the process variable deviations to be considered in the HAZOP analysis.

The set of guide words that are often used are NONE, MORE OF, LESS OF, PART OF and MORE THAN. When these guide words are applied to the process variables in each line or unit of the plant, we get the corresponding process variable deviation to be considered in the HAZOP analysis. The definitions of the guide words are as follows:

NONE = no flow
MORE OF = more of flow, temperature, pressure, and so on that is, higher flow, temperature, pressure, and so on
LESS OF = lower flow, temperature, pressure, and so on

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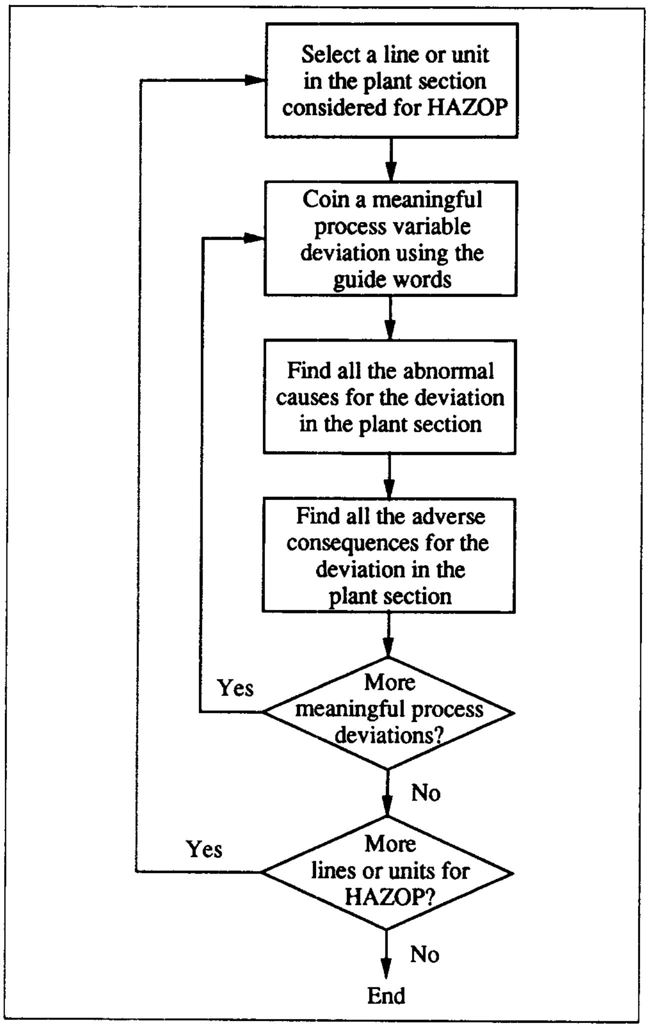

Figure 1. HAZOP analysis procedure.

PART OF = change in composition of the stream
MORE THAN = impurities present, for example, ingress of air, water, and acids: extra phase present, for example, vapor, solids.

The guide words and process variables should be combined in such a way that they lead to meaningful process variable deviations. Hence, all the guide words cannot be applied to all process variables. For example, when the process variable under consideration is temperature, only the guide words MORE OF and LESS OF lead to meaningful process variable deviations. The sequence of a typical HAZOP analysis is shown in Figure 1.

An early description of the HAZOP analysis technique with examples of its application to hazard identification in chemical process plants was given by Lawley (1974, 1976). Various other examples of application of HAZOP analysis have been given by Roach and Lees (1981), Sinnott (1983), Piccinini and Levy (1984), Kletz (1985, 1986), Ozog (1985), Shafaghi and Cook (1988), Mulvihill (1988), Knowlton (1989), and Montague (1990).

As mentioned above, HAZOP analysis requires a large amount of time and effort of a team of experts with different specialized expertise. Since HAZOP analysis should be thorough and exhaustive, the team cannot afford to overlook the 'routine' causes and consequences which occur in process units which are common to many plants. Such commonly found units are pumps, tanks, pipes, valves, controllers, heat exchangers, and so on. These kinds of equipments are commonly found in many plants, and they do not vary a great deal from process to process. Hence, the HAZOP analysis of these units applied in one process plant may be applied once again with very little change to similar units in another plant. In that sense, the analysis of such units is 'routine' and may be repeated with relative ease. On the other hand, there are more complex units such as reactors and their support systems which are often unique and differ considerably from process to process. The HAZOP analysis of such units is more difficult to automate as each occurrence might be a unique case and therefore less amenable to a repeatable, generic, approach.

It turns out that considerable amount of time and effort of the HAZOP experts are spent in dealing with the analysis of such 'routine' process units. If we can automate the HAZOP analysis of these process units, it will reduce the workload of the experts by a significant amount, thus, providing more time for the experts to concentrate on the HAZOP analysis of more complex process units which are difficult to automate. Our approach is focused on the HAZOP analysis of such 'routine' units. Since HAZOP analysis is a systematic and logical procedure, it lends itself to the possibility of automation through the use of the knowledge-based systems approach. In this article, we discuss such an approach which separates the process-specific and process-general knowledge to facilitate the development of a widely applicable framework.

Despite the importance of automating HAZOP, there has only been limited work in this area. As one of the first attempts, Parmar and Lees (1987a, b) developed a rule-based system approach utilizing qualitative reasoning and showed its application for the hazard identification of a water separator system. In their method, the causes and consequences generated for a process variable deviation are confined to the line under consideration and the process unit connected to it. Thus, this method finds only the immediate causes and immediate consequences unlike the actual HAZOP analysis in which the process variable deviations are propagated to the end of the process section under consideration to find all the adverse consequences due to every abnormal cause. Another recent attempt in this area was by Karvonen and coworkers (1990) who reported the development of an expert system for HAZOP analysis. In this work, the identification of abnormal causes was more emphasized and less was said about the adverse consequences, though in actual HAZOP analysis the identification of adverse consequences is given priority. In that sense, this work has more of a diagnostic flavor. In addition to the drawbacks mentioned above, both these attempts had not addressed the important problems of the representation of process-specific and generic knowledge, as well as the ambiguities in qualitative reasoning which arise in automating the HAZOP analysis technique.

In this article, we present a knowledge-based framework that addresses these key issues in the automation of HAZOP analysis. The central idea in our framework is the use of generic HAZOP models of various process units that are developed in a context-independent manner such that they are applicable to a wide variety of flowsheets. In addition, we also introduce the notion of separating such generic knowledge from process-specific knowledge and propose an inference mechanism that can combine both these knowledge bases appropriately to perform the HAZOP analysis. We also discuss how some of the problems due to ambiguities inherent in qualitative reasoning may be addressed within the context of HAZOP analysis. A knowledge-based system called *HAZOPExpert* has been implemented in an object-oriented architecture using this framework and its performance on a well-known HAZOP case study is also discussed in this article.

Proposed Knowledge-Based Approach

It is important to recognize that HAZOP analysis requires a combination of many different types of expertise, some of which is specific to the process plant under consideration. Hence, the first task is to identify the HAZOP knowledge that is generic and is applicable to a wide variety of flowsheets (we call this 'process-general' knowledge), and the knowledge that is specific and is valid only for the particular process under consideration (we call this 'process-specific' knowledge). Then, we need to tackle the problem of the separation of these two as well as the appropriate integration. Following the ideas of Venkatasubramanian and Rich (1988), we solve this problem by formally separating the two, in the form of a two-part knowledge base, and allowing for an interaction between the two parts. This way, the generic HAZOP knowledge can be kept in the process-general knowledge base, which can remain fixed irrespective of the process plant under consideration, and the process-specific knowledge can be created separately for each process plant.

Architecture of the knowledge-based framework

The overall architecture of the *HAZOPExpert* knowledge-based system is shown in Figure 2. The process-specific knowledge consists of information about materials used in the given process, their properties, and the P&ID of the plant. The process-specific knowledge varies from plant to plant and has

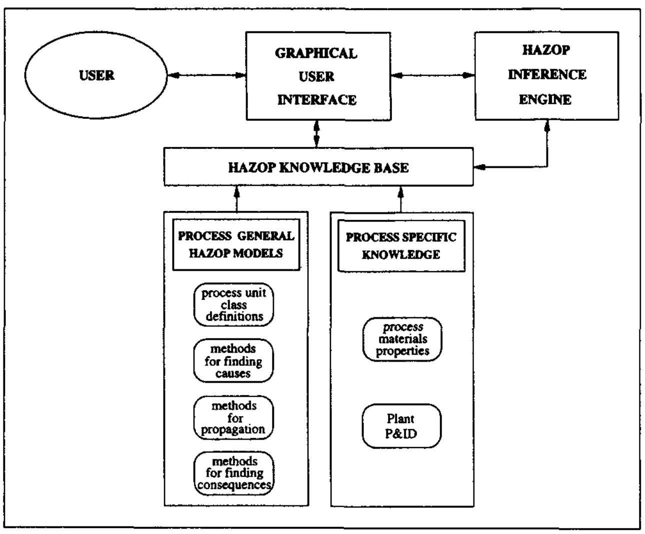

Figure 2. A knowledge-based framework for HAZOP analysis.

to be provided by the user. However, the process-general knowledge, which consists of the generic HAZOP models of process units, remains the same. The HAZOP models of process units consist of the class definition of the process units, the method for finding abnormal causes, the method for propagation of process variable deviation, and the method for finding adverse consequences.

The user requests the knowledge-based system to perform the HAZOP analysis by specifying a process variable deviation in a process unit or pipeline using the graphical user interface. The HAZOP inference engine performs the analysis using the HAZOP knowledge base, and the HAZOP results are displayed to the user through the graphical user interface. *HAZOPExpert* has been implemented in an object-oriented framework in the knowledge engineering environment of G2 (Gensym, 1992). For details on representing causal and fault models in an object-oriented framework, the reader is referred to Venkatasubramanian and Rich (1988).

Process-specific knowledge

Process specific knowledge consists of process material models and the P&ID of the plant. Process specific knowledge is supplied by the user for each process plant. Each process material is represented as an object which is an instance of the 'process material class.' The process material class has attributes for specifying the name of the material, the intended role of the material in the plant (for example, reactant, product, impurity), normal physical state of the material, and whether the material is corrosive, flammable, volatile, or toxic.

In addition to these attributes for specifying properties, the process material class also has attributes for explicitly specifying specific consequences that might occur in the presence of a process variable deviation, which cannot be deduced from the given process material properties. For example, the attribute 'high-temperature-consequence' is defined to specify any specific consequence for the deviation 'high temperature,' which may not be obvious from the given properties of the process material. This high-temperature consequence for a particular process material may be 'process material polymerizes to undesired polymer.'

The role of a material in a hazard may be different from its intended role, and this factor is taken into account in *HAZOPExpert*. In *HAZOPExpert*, the role of the materials in a hazard is found from the properties of the materials. For example, a process material which is a reactant may be corrosive, and it might lead to the adverse consequence 'leak in the pipe due to corrosion of the material of pipe.'

Process-general knowledge: the HAZOP models

HAZOP models of process units contain generic, flowsheet-independent, HAZOP knowledge for performing the analysis. An object-oriented representation is used for representing the HAZOP models. The HAZOP model of a process unit consists of the definition of the process unit class and the generic methods for identifying and propagating various abnormal causes and adverse consequences of process variable deviations. Not all of these causes and consequences occur in every plant. The occurrence of these abnormal causes and adverse consequences is conditionally dependent on the process-specific details of the plant. Thus, the process-general knowledge

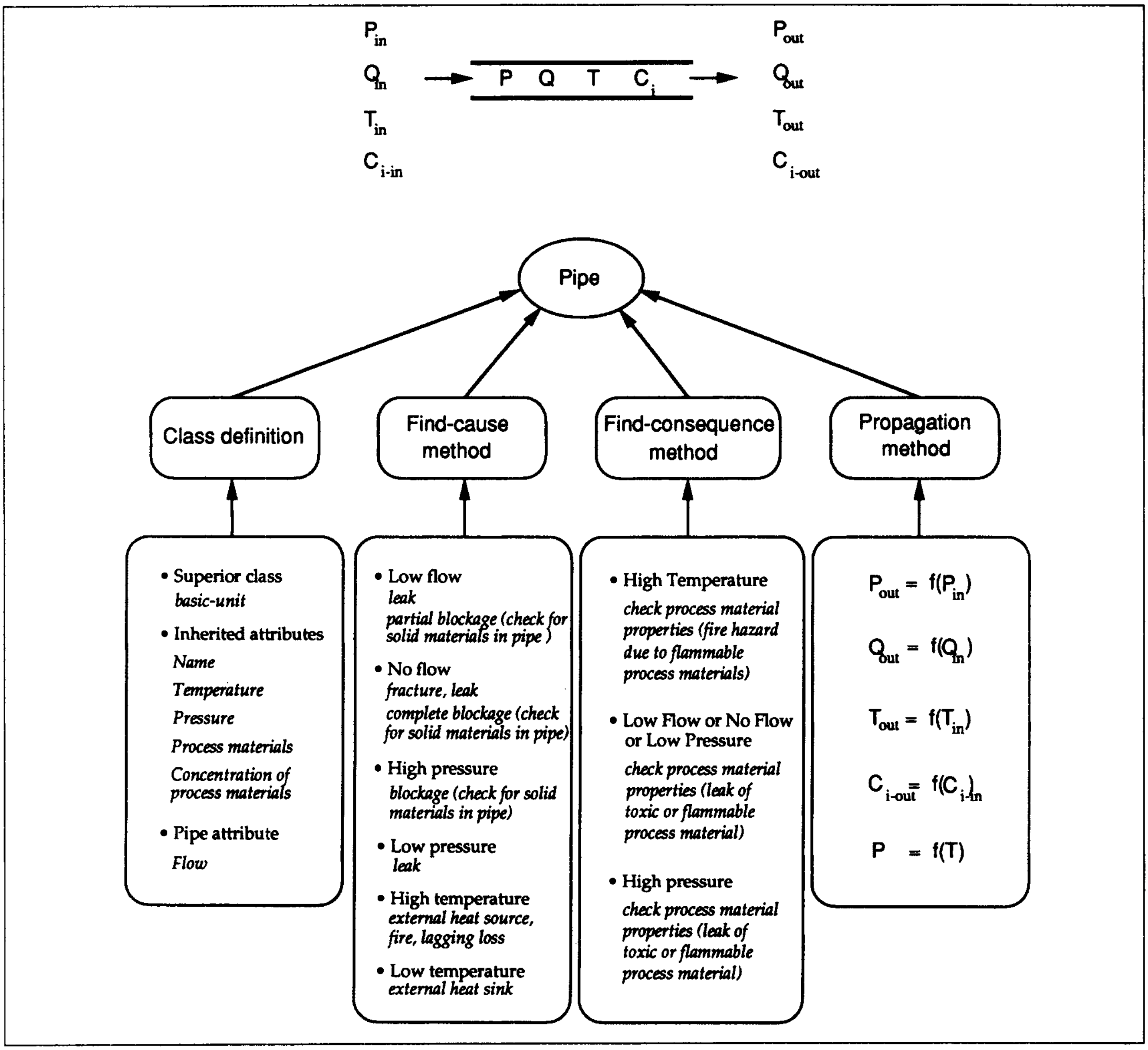

Figure 3. HAZOP model of a pipe.

interacts with the process-specific knowledge to identify the valid abnormal causes and adverse consequences for the given process variable deviations for the particular process under consideration. As examples, the HAZOP model of a pipe and the HAZOP model of a heat exchanger with tube side hot fluid and higher tube side pressure are shown in Figure 3 and Figure 4, respectively. These HAZOP models consist of the class definition, the *find-cause* method, the *find-consequence* method and the *propagation* method of the process units. These HAZOP models are discussed in the following sections.

In the present version, *HAZOPExpert* has process generic HAZOP models for pipe, control valve, nonreturn valve, centrifugal pump, tank, buffer settling tank, heat exchanger, sensor, and controller. We are currently developing similar HAZOP models for other process units.

Process unit classes

Each process unit is represented as an instance of the corresponding 'process unit class.' There is a basic process unit class named 'basic-unit' which is used for building process unit classes of process units. This basic-unit class has the attributes for specifying the values of the name, temperature, pressure, and array of process materials which will be present in the unit during normal operation, and an array of the concentration of the process materials in the unit. The attributes of this basic-unit class will be required for specifying every process unit. So, the basic-unit class is a superior class of all process unit classes. The process unit classes inherit the attributes of the basic-unit class. The process unit classes can also have additional 'attributes specific to class' for their complete specification. For example, the 'settling tank' class inherits the attributes of the basic-unit class. In addition to these inherited attributes, the settling tank also has the attributes 'inlet-flow,' 'outlet-flow-1,' 'outlet-flow-2,' and 'level' defined as the 'attributes specific to settling tank.'

There are two classes of connections defined in *HAZO-*

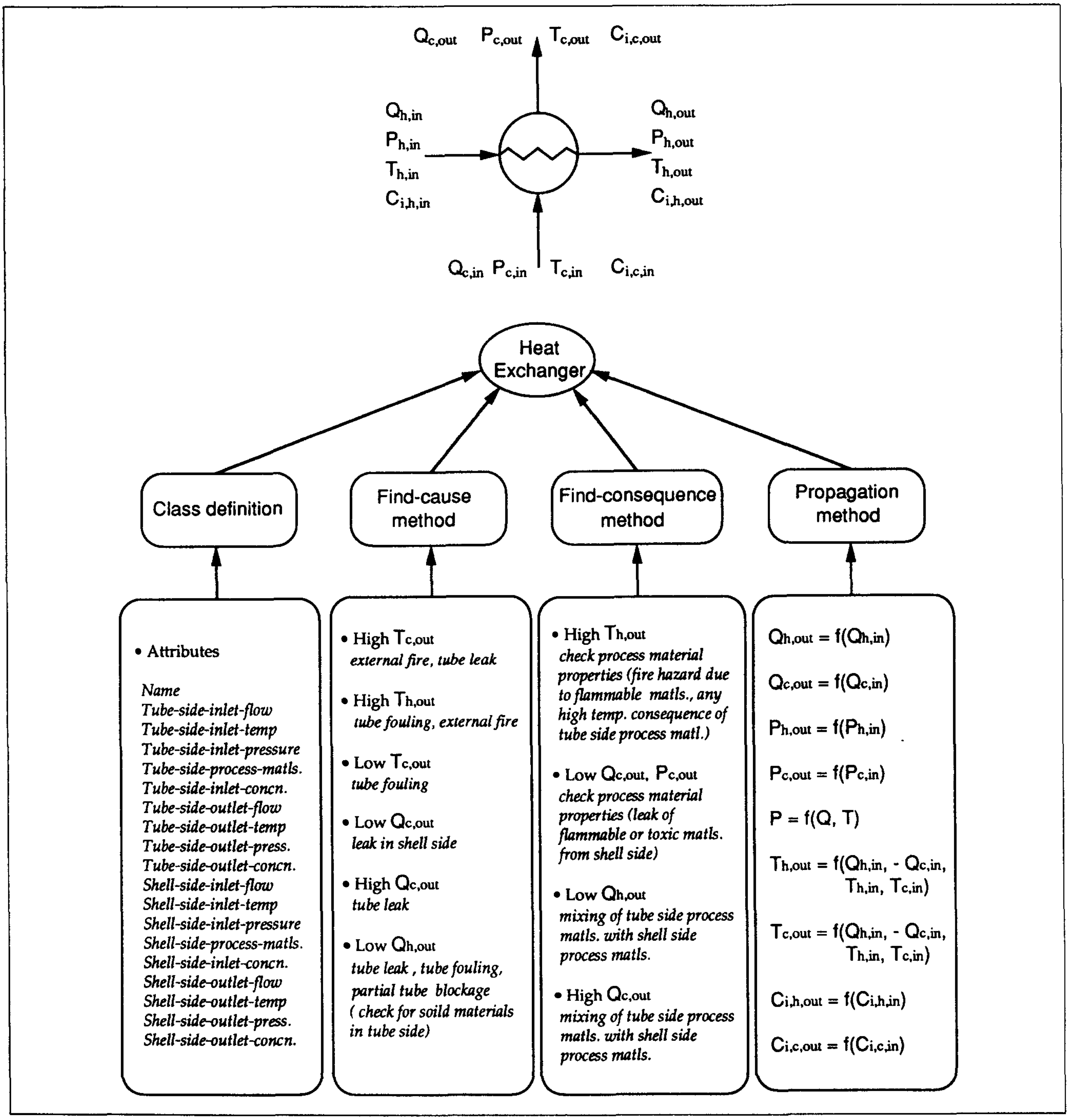

Figure 4. HAZOP model of a heat exchanger.

PExpert. One is the 'pipe,' which is used to connect the process units. The other is the 'instrument-signal' which is used to connect the process units to sensors and controllers. These connections are directed. A 'pipe' connection can be established between two process unit objects by clicking the mouse at the output stub of one process unit object icon and dragging the pipe (which elongates as you move the mouse) to the input stub of the other process unit object icon and clicking the mouse again. Once this connection is established, if we move either of the process unit object icons, the pipe also moves accordingly maintaining the connection. Similarly, the instrument-signal connections can be established. 'HAZOP connection posts' are used to indicate the boundaries of the process flowsheet section considered for HAZOP analysis, that is, the connections to the 'upstream' and 'downstream' sections of the process plant section considered for HAZOP analysis.

The class definitions for pipe and the heat exchanger are shown in Figure 3 and Figure 4, respectively. These class definitions have attributes representing the process variable values of these process units. The values of the process variable attributes are given by the qualitative values 'high,' 'low,' 'zero,' and 'normal.' The process variable values default to 'normal' unless otherwise specified. A process variable deviation is introduced by specifying the value of a process variable attribute to be 'high,' 'low,' or 'zero.'

Methods for finding abnormal causes

The methods for finding abnormal causes have knowledge about process-general unit malfunctions which will cause a process variable deviation in a process unit. For example, in the *find-cause* method for pipe shown in Figure 3, 'leak in pipe causes low flow' is a process-general unit malfunction. The *find-cause* method of the pipe checks the values of the attributes flow, temperature and pressure of the pipe, and depending on the value of these attributes it searches the 'abnormal causes' knowledge base of pipe to find the abnormal causes which can cause the process variable deviations. Similarly, in the *find-cause* method for heat exchanger shown in Figure 4, 'tube leak causes low tube side outlet flow' and 'tube fouling causes high tube side outlet temperature' are process general abnormal causes.

The methods for finding abnormal causes also a search for any properties of the process materials present in the process unit which might cause the process variable deviation. For example, in the *find-cause* method for pipe shown in Figure 3, for the process variable deviation 'low flow,' the presence of any solid process material in the pipe is checked and the cause, 'partial blockage of pipe' is found. Thus, there is interaction between the process-general knowledge (methods for finding abnormal causes) and the process-specific knowledge (process material properties). Similarly, in the *find-cause* method for heat exchanger shown in Figure 4, the abnormal cause for the process variable deviation, 'low tube side outlet flow' is found.

The abnormal causes for the process variable deviations which will be found by the *find-cause* methods of the pipe and the heat exchanger are given in Figure 3 and Figure 4, respectively.

Methods for finding adverse consequences

The methods for finding adverse consequences have knowledge about process-general adverse consequences of process variable deviations which can occur in a process unit. For example, 'no flow in centrifugal pump causes overheating of pump,' is a process-general consequence in a centrifugal pump. The methods for finding adverse consequences also search for the properties of any process materials present in the process unit which in the presence of the process variable deviation will cause adverse consequences. For example, in the *find-consequence* method for pipe shown in Figure 3, for the process variable deviation 'high temperature,' the properties of process materials in the pipe are checked to see if there is any flammable process material and the consequence 'fire hazard due to flammable process material' is found. Similarly, in the *find-consequence* method for the heat exchanger shown in Figure 4, the consequences for the process variable deviation 'high tube side outlet temperature' are found.

The methods for finding adverse consequences also search for any combination of the process material properties with the 'process unit malfunction causing the process variable deviation' which will lead to adverse consequences. For example, in the *find-consequence* method for pipe shown in Figure 3, for the process variable deviation 'low flow,' 'no flow,' or 'low pressure,' the properties of process materials are checked to see if there is any flammable or toxic process material present in the pipe and the consequence, 'leak of flammable or toxic process material' is found. In this case, the 'leak in pipe' is the malfunction of the pipe which causes the process variable deviation low flow, no flow, or low pressure in the pipe. Thus, there is interaction between the process-general knowledge and process-specific knowledge. Similarly, in the *find-consequence* method for the heat exchanger shown in Figure 4, the consequences for the process variable deviation 'low shell side outlet flow' which might be caused by the malfunction 'leak in shell side of the heat exchanger,' as well as the consequences for the process variable deviations 'low tube side outlet flow' or 'high shell side outlet flow' which might be caused by the malfunction 'leak from the tubes of heat exchanger' are found.

The adverse consequences for the process variable deviations which will be found by the *find-consequence* methods of the pipe and the heat exchanger are given in Figure 3 and Figure 4, respectively.

Methods for propagation

The methods for propagation are used for propagating the deviation of a process variable in a process unit in the following manner:

- to find the local causes for process variable deviations in the process unit and in the pipes connected at the inlet ports of the process unit; and
- to find the local consequences of process variable deviations in the process unit and in the pipes connected at the outlet ports of the process unit.

The methods for propagation use the causal models of process units, which consist of the causal relations between process variables. The causal models of process units are derived from the material and energy balances and confluence equations (qualitative differential equations) which represent the influence of one process variable on another process variable. The derivation of causal models from confluences and the propagation of process variable deviations using a quasi-steady-state approach is described in detail by De Kleer and Brown (1984). Additional literature on qualitative modeling of propagation of process variable deviations in chemical plants can be found in Umeda et al. (1980), Andow et al. (1980), Lees (1984), Oyeleye and Kramer (1988), and Grantham and Ungar (1990).

The causal relations between the process variables of a pipe in the form of qualitative functional relations that are used by the *propagation method* for pipe are shown in Figure 3. The causal relation $Q_{out} = f(Q_{in})$ means, as Q_{in} (inlet flow) increases Q_{out} (outlet flow) increases and vice versa. Similar causal relations exist for temperature, pressure, and composition of process materials in the pipe. These causal relations are derived from the steady-state material and energy balances and confluence equations of the pipe. The causal model that is used by the *propagation method* of the heat exchanger is shown in Figure 4. The causal relation $T_{h,out} = f(Q_{h,in}, -Q_{c,in}, T_{h,in}, T_{c,in})$ means $T_{h,out}$ (tube side hot fluid outlet temperature) increases as $Q_{h,in}$ (tube side hot fluid inlet flow) increases, or $Q_{c,in}$ (shell side cold fluid inlet flow) decreases, or $T_{h,in}$ (tube side hot fluid inlet temperature) increases, or $T_{c,in}$ (shell side cold fluid inlet

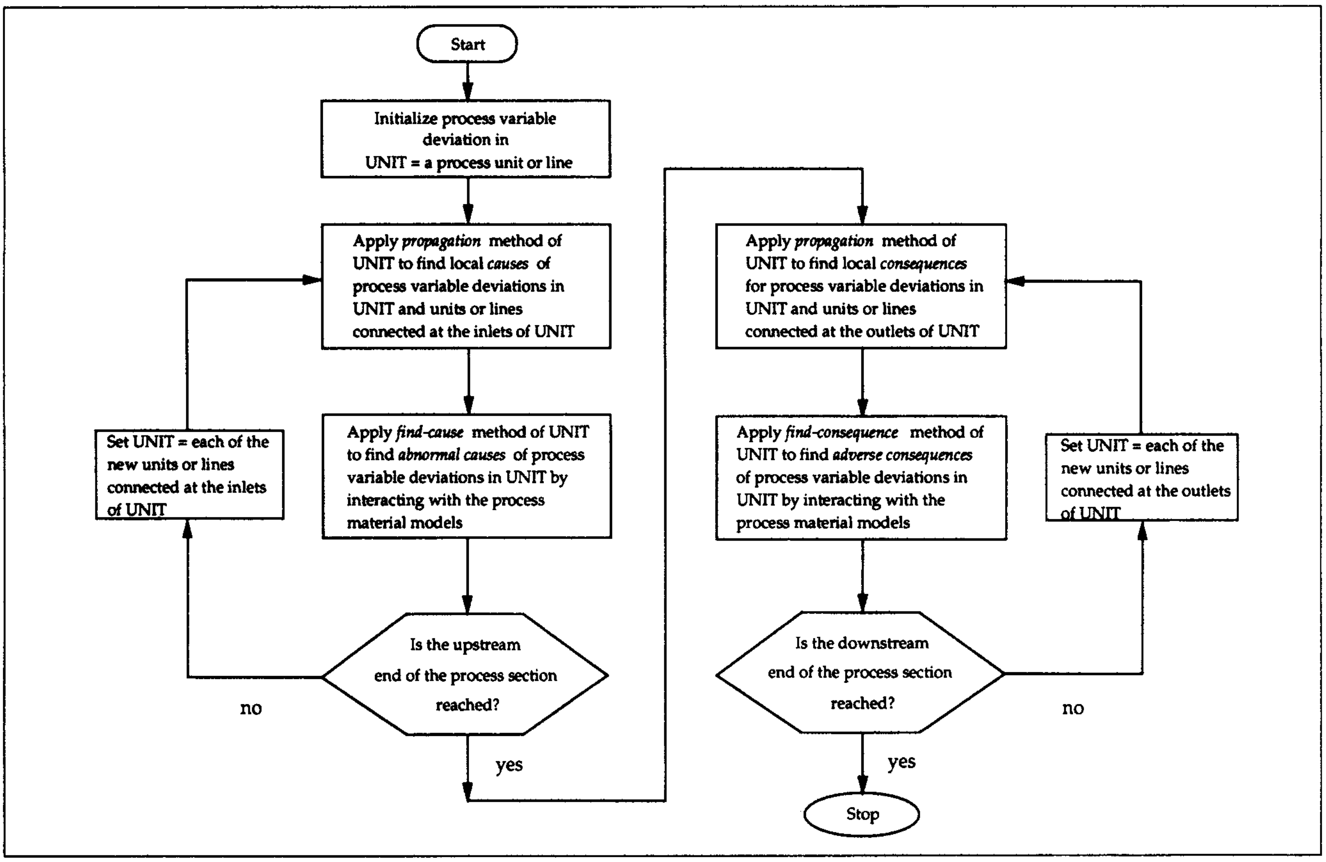

Figure 5. Flow of control of HAZOP in the HAZOP inference engine.

temperature) increases, and vice versa. The causal relations between the process variables of the heat exchanger are derived from the steady-state material and energy balances and confluence equations of the heat exchanger.

The propagation methods propagate the effects of process variable deviations from one variable to another, eventually satisfying the steady-state process unit constraints. The propagation of process variable deviations enables the determination of all the abnormal causes and adverse consequences which could occur in the plant due to a process variable deviation in a process unit.

Ambiguities in propagation.

Using the qualitative values, 'high' and 'low,' for process variable deviations can lead to ambiguous values for some of the process variables. For example, consider the case of a tank with two inlets and one outlet. If one of the inlet flows has the qualitative value high and the other inlet flow has the qualitative value low, then it is not clear what the resulting liquid level would be. The level can increase, decrease, or remain constant. This is due to the fact that the result of adding qualitative high and qualitative low can be high, low or normal.

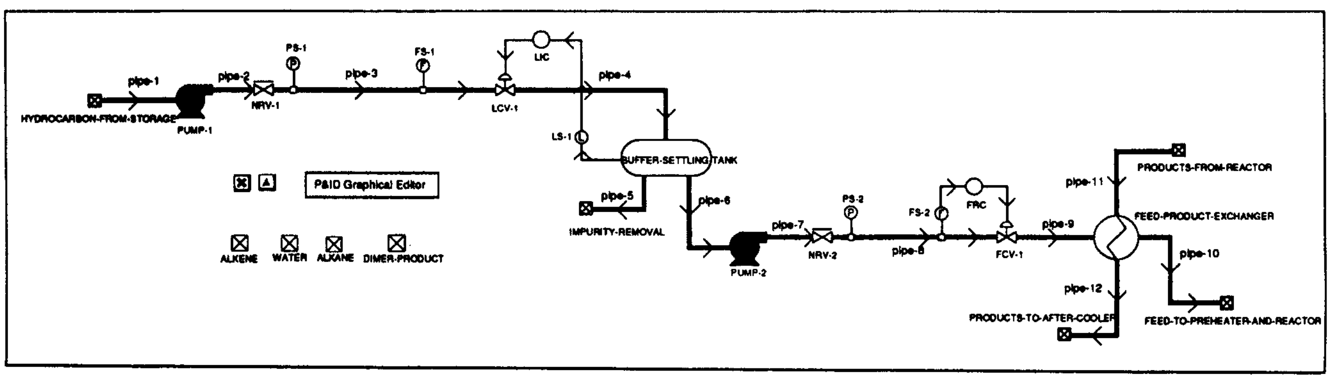

Figure 6. Feed section of olefin dimerization plant.

Thus, the level of the tank can have the values high, low or normal as a result of this propagation. This kind of ambiguity that is inherent in qualitative reasoning can lead to such undecidable behaviors as well as spurious ones.

Several strategies for tackling this situation have been provided in the literature. De Kleer (1979) uses the quantitative and 'design-purpose' information, Raiman (1986) uses order of magnitude information, and Oyeleye and Kramer (1988) use redundant process constraints for reducing the spurious behaviors.

It is important to note here that this problem of ambiguity is also encountered during conventional HAZOP analysis performed by human HAZOP experts, as the experts also use qualitative guide words. However, this problem is circumvented in conventional HAZOP by recognizing that one is only interested in *worst case* situations in HAZOP analysis. Thus, we need to consider only the abnormal states (for example, tank level 'high' leading to an overflow or 'low' leading to the tank running dry), and we can neglect the other intermediate states during propagation of process variable deviations. We utilize the same philosophy in our knowledge-based framework.

Inference mechanism and the flow of control

The top level goal of the knowledge-based system is to perform HAZOP analysis for a process variable deviation in a process unit or line. The flow of control in the HAZOP inference engine of the knowledge-based system *HAZOPExpert* is outlined in Figure 5. All the abnormal causes in the process plant for a process variable deviation in a process unit are found by executing the propagation and the find-cause methods of that process unit and all the upstream process units. Similarly, all the adverse consequences in the process plant for a process variable deviation in a process unit are found by executing the propagation and the find-consequence methods of that process unit and all the downstream process units. The find-cause and the find-consequence methods of the process units interact with the process material models of the process materials which are present in the process unit to find the process-specific abnormal causes and adverse consequences. The HAZOP results from the knowledge-based system is in the form of a listing of all the abnormal causes and adverse consequences in the plant for the process variable deviation in a process unit or line.

P&ID graphical editor

The user specifies the P&ID of a process plant using the P&ID graphical editor in *HAZOPExpert*. The user first creates instances of the process unit classes defined in the process unit class library. This causes the graphical icon of the process unit class to appear in the process unit class library window, and it is transferred to the P&ID graphical editor window. Once the graphical icons of various process units are transferred to the P&ID graphical editor, the inlet ports and outlet ports of these process units are connected by pipe connections using the mouse. Similarly, graphical icons of sensors and controllers are created and transferred to the P&ID graphical editor and connected by instrument-signals connections. Once the flowsheet is drawn on the screen, the corresponding HAZOP models get connected automatically internally in the appropriate manner. This greatly simplifies knowledge acquisition for a given process.

The graphical icons of the process units and the pipes have 'attribute tables' which display the values of the process variable attributes. These attribute tables can be accessed by the user by clicking on the process unit icon or on the pipe. The process variable attributes (flow, temperature, pressure and the concentration of process materials) have the default value normal. The user has to specify the 'name' and 'the array of the process materials present' for each of the process unit and pipe in the P&ID.

Table 1. Comparison of Conventional HAZOP Study and *HAZOPExpert*'s Results

Process Variable Deviation: (i) No Flow in pipe-4
Conventional HAZOP Study Causes: No hydrocarbon available at intermediate storage Pump-1 fails Line blockage or LCV fails shut Line fracture
HAZOPExpert's Causes: No flow into the 'hydrocarbon-from-storage' HAZOP connection post from upstream units Cavitation or failure of pump-1 Pipe blockage, LCV-1 or NRV-1 fails closed Pipe fracture
Conventional HAZOP Study Consequences: Loss of feed to reaction section and reduced output Polymer formed in heat exchanger under no flow conditions Pump-1 overheats Hydrocarbon discharged out Pump-2 overheats
HAZOPExpert's Consequences: No flow to the downstream units from the 'feed-to-preheater-and-reactor' HAZOP connection post High temperature in the tube side of the heat exchanger The 'dimer-product' polymerizes to undesired polymer Pump-1 overheats Pipeline subjected to surge pressure Fire hazard due to the release of flammable process materials alkane and alkene Pump-2 overheats High pressure in the tube side of 'feed-product-heat-exchanger' and in pipe-12 due to higher temperature, since volatile process materials alkane, alkene and dimer-product are present Fire hazard in the tube side of heat exchanger and pipe-12 due to high temperature and the presence of the flammable process materials alkane, alkene and dimer-product
Process Variable Deviation: (ii) High Temperature in pipe-4
Conventional HAZOP Study Causes: High intermediate storage temperature
HAZOPExpert's Causes: High temperature flow from upstream units into 'hydrocarbon-from-storage' HAZOP connection post
Conventional HAZOP Study Consequences: Higher pressure in transfer line and settling tank Line fracture, major spillage, lost output, possibility of major plant fire
HAZOPExpert's Consequences: Higher pressure in pipelines and settling tank due to volatile olefins alkane and alkene Leak of flammable olefins alkane and alkene leads to fire hazard High temperature and pressure in the tube and shell sides of the heat exchanger Fire hazard due to the flammable olefins, alkane, alkene and the dimer-product

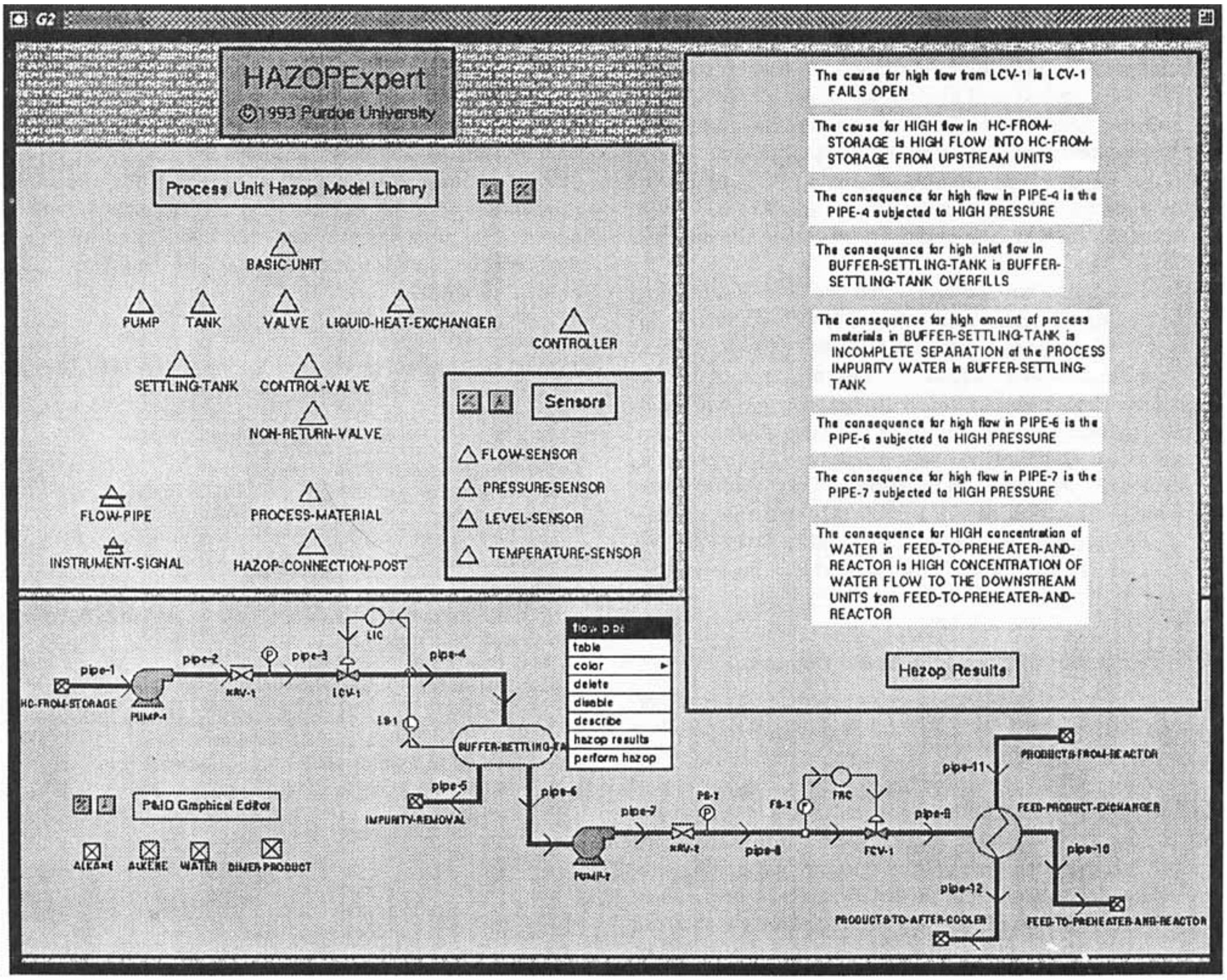

Figure 7. Graphical user interface of the *HAZOPExpert*.

HAZOP Analysis Case Study

We have tested our knowledge-based framework by performing a HAZOP analysis on a well-known industrial case study from the literature involving the feed section of an olefin dimerization plant (Lawley, 1974). The P&ID of this case study is shown in Figure 6. The original HAZOP analysis of the line section from the "hydrocarbon storage" to the "settling tank" for this plant was performed by a team of HAZOP experts. This section describes a summary of the evaluation of the HAZOP results obtained by *HAZOPExpert* in comparison with the original results.

The Graphical User Interface (GUI) of *HAZOPExpert* in the G2 environment is shown in Figure 7. This figure displays the essential features of the user interface, namely, the process unit models library, the P&ID graphical editor, and the HAZOP results window. The P&ID of the process, the process materials, and their properties are the process-specific information that has to be supplied by the user. For this case study, the process material objects alkane, alkene, water, and dimer-product are created as instances of the process material class, and their properties are specified. The process materials alkane and alkene are reactant hydrocarbons which are flammable and volatile. The dimer-product is a flammable product and water is a process impurity. This information is also supplied to the process-specific part of the knowledge base through the GUI.

A process variable deviation is initiated in a process unit or pipe by changing the value of the 'process variable attribute' in the attribute table of the process unit or pipe. For example, the 'flow' attribute of the pipe 'pipe-4,' may be given a value 'high.' To invoke HAZOP analysis, the user clicks on pipe-4 in the P&ID and a menu-choice of 'Perform HAZOP' appears in a small menu window (see Figure 7). If this choice is selected, the knowledge-based system performs HAZOP analysis for this process variable deviation and outputs the results in the form of abnormal causes and adverse consequences in all the process units in the plant in the 'HAZOP results window' (see Figure 7). Similarly, the HAZOP analysis for the deviation of any other process variable, flow, pressure, level, concentration of process materials, and so on, in any of the process unit or pipe can be performed.

For all the cases considered by Lawley (1974), we evaluated *HAZOPExpert*'s performance. Since the HAZOP results from all the cases considered is too large to be listed in this article, we have presented only two sample cases, namely, the deviations 'no flow' and 'high temperature' in pipe-4, in Table 1. As can be seen from Table 1, *HAZOPExpert* was able to successfully identify all the causes and consequences that were reported in Lawley's article. Similarly, in all the other cases considered for HAZOP analysis by Lawley, the *HAZOPExpert* identified all the causes and consequences that were reported by Lawley.

Conclusions

A knowledge-based framework for automating HAZOP analysis has been developed and successfully tested on a well-known HAZOP case study in the literature. In our framework, we utilize several key techniques to make this automation feasible and useful. One is the identification and the separation of HAZOP knowledge into process-specific and process-general components and then allowing for these two components to interact with each other. The process-specific knowledge has information about process materials and the P&ID of the plant, which tends to change from plant to plant. The process-general knowledge is represented as HAZOP models of the process units, and it remains the same for different process configurations. These HAZOP models consist of class definitions of the process units, methods for finding causes, consequences, and for propagating process variable deviations. These models are developed in a process-independent manner and are applicable for a wide variety of process flowsheets. The interaction between the process-specific and process-general knowledge enables the knowledge-based system to cover the process-specific aspects of HAZOP analysis while maintaining the generality of the system as much as possible. Ambiguities due to qualitative reasoning is tackled by considering only the extreme behaviors as only those are important in HAZOP analysis.

A knowledge-based system, called *HAZOPExpert*, has been implemented using this framework in an object-oriented architecture using Gensym's G2 expert system shell. Upon testing the proposed approach on Lawley's industrial case study, *HAZOPExpert* was found to generate all of the results of the conventional HAZOP analysis. While the results are very encouraging, *HAZOPExpert*'s capabilities are currently limited to simple process units for which HAZOP models have been developed. We are presently developing HAZOP models for more complex process units to augment the process-general part of the knowledge base. Further research is also needed to handle reverse flows, recycle loops, and semi-quantitative information to accommodate design specifications of process units.

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