An Expert System for Hazard Identification in Chemical Processes

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ABSTRACT

Hazard identification is one of the most important task in process design and operation. This work has focused on the development of a knowledge-based expert system for HAZOP (Hazard and Operability) studies which are regarded as one of the most systematic and logical qualitative hazard identification methodologies but which require a multidisciplinary team and demand much time-consuming, repetitious work. The developed system enables design engineers to implement existing checklists and past experiences for safe design. It will increase efficiency of hazard identification and be suitable for educational purposes.

This system has a frame-based knowledge structure for equipment failures/process material properties and rule networks for consequence reasoning which uses both forward and backward chaining. To include wide process knowledge, it is open-ended and modular for future expansion. An application to LPG storage and fractionation system shows the efficiency and reliability of the developed system.

1. Introduction

Hazard identification and elimination is one of the main concerns for various chemical processes from the design to the operation stage. There are many hazard identification techniques at each project stage.

Two steps, generally, are required to find out potential hazards in chemical industries. The first step is hazard identification of a process. Qualitative analysis is carried out in this step. Scenarios for the propagation of hazardous events can be found at the step by some qualitative hazard identification methods - Checklists, Safety Review, Dow and Mond Hazard Indices, Failure Modes, Effects and Criticality Analysis (FMECA), and HAZOP studies[5]. Among them, HAZOP studies have been regarded as the most wide-spread and systematic methodology for hazard identification during the last two decades. An important principle of hazard identification is to utilize past experiences. This is one of the motivation for developing the expert system. Using standards and codes helps to identify hazards in this step.

The second step is risk assessment of the scenario produced in the previous step. Quantitative analysis is performed in this step. A risk assessment procedure that determines probabilities is frequently called probabilistic risk assessment - Fault tree analysis and Event tree analysis[3]. The HAZOP study is a good method for providing scenarios to this step.

2. Hazard and Operability (HAZOP) Study and the Modification for the Expert System

The best time to conduct HAZOP studies is when the design is fairly firm. HAZOP studies should be carried out by a multidisciplinary team through brainstorming meetings and the application of this approach includes many a repetitious task. Naturally, it requires considerable manpower and time. But these disadvantages can be overcome by the expert system approach which can represent heuristics efficiently. An advantageous point of this approach is that it provides a more complete identification of the potential hazards, including information on how hazards can develop as a result of operating procedures and operational upsets in the process.

The basic concept of HAZOP studies is to take a full description of the process and to question every part of the process to discover what kind of deviations from the intention of the design can occur and what their causes and consequences may be. This is done systematically by applying suitable guide words[9]. The important features of the study are ;

(1) Intention
(2) Deviation (Using guide words and parameters)
(3) Causes
(4) Consequences (Hazard and operating difficulties)
(5) Recommendations

The procedure for the HAZOP studies is to apply a number of guide words to various parts of the process design intention. These guide words and their meaning are shown in Table 1. But the guide words AS WELL

AS, PART OF, and OTHER THAN have some difficulties for conceptual application[3]. Therefore, we have excluded these guide words from the developed system. But they can be readily added on demand.

Table 1. Guide words and their meanings

Guide Words	Meaning
No	Negation of Intention
Less	Quantitative Decrease
More	Quantitative Increase
Part of	Qualitative Decrease
As Well As	Qualitative Increase
Reverse	Logical Opposition of Intention
Other Than	Complete Substitution

The process parameters which represent the state of the process include flow, temperature, pressure, level, composition, and instrumentaion. The deviations for HAZOP studies are defined by the combination of guide words and process parameters. For example,

Guide Word(No) + Parameter(Flow) = Deviation(No Flow)

For guide words or parameters are not used for the application by themselves, they are not treated separately in the system. We have considered only the specific deviations, and these deviations are given as the input data for the expert system. The causes of equipment failures are classified into the equipment knowledge base by these deviation.

An important aspect of the procedure of HAZOP studies is determining how to divide the process into small process units called study nodes. At each of these study nodes, the deviations in the process parameters are examined using the guide words. We postulate that there are two kinds of nodes. One is a pipeline and the other is a vessel. While we define an equipment such as a storage tank, a distillation column, or a reactor as a *vessel*, and a pipe, a tube as a *pipeline*, others such as a pump, a valve, a control instrument, a heat exchanger are put into either group as an adjunt equipment.

3. Process Knowledge Classification

The classification of knowledge determines the structure of knowledge base of a expert system. The process knowledge for HAZOP study is classified according to deviation, causes and consequences. The causes are represented in the form of frame structure and the consequences are in the form of rule networks.

3.1 Elements of Accidents

The purpose of safety analysis is to identify possible accidents and estimate their frequency and consequences. For this purpose, an accident is defined as a specific unplanned sequence of events that has an undesirable consequence. This first event of the sequence is the initiating event. Generally, the initiating event is not the only event for the consequence; usually there are one or more events between the initiating event and the consequence. These intermediate events are the responses of the system and its operators to the initiating event. Different respones to the same initiating event will often lead to different accident consequences. Even when the consequences are of the same type, they will usually differ in magnitude. As well as initiating events, intermediate events (system and operator responses) and consequences are the components of accidents. Initiating events are represented as the causes of a accidents, and accidents are as the final consequences of a scenarios. But intermediate events are represented as causes or consequences and are linked to intial and final consequences of a accidents through rule networks.

3.2 Causes

Typical causes can be classified as equipment failure, improper design, misoperation, and external events. The external events such as flood, airplane clash and earthquakes are excluded in this study. Most of typical causes belong to equipment failure and misoperation that is human errors. Improper design is critical, but this kind of approach (HAZOP study) for hazard identification provides design engineers with the chances to find out their faults. The part of causes that is implemented in this expert system are as follow:

Heat Exchanger :
Cold/hot side blocking, Cooling/heating medium loss, Fouling, Insulation Loss, Releif valve opening, etc.

Control Valve :
Mechanical failure, Power failure, Sensor failure, etc.

Valve :
Actuator Failure, LeaKage, Mechanical failure, Power failure, Seal failure, etc.

Pump :
Discharge valve closing, High viscosity of liquid, Large impeller than the capacity, LeaKage, Lubrication loss, NPSH(net positive suction head) loss, Overspeed, Power failure, Seal failure, Shaft break, Stop failure, Suction line plugging, Suction valve closing, Underspeed, etc.

Pipe :
Corrosion, Downstream rupture, High pressure difference, High pressure at down stream, LeaKage, Plugging, Rupture, No supply from upstream,

Tank :
Agitator failure, Circulation failure, Improper rupture disk, Cooling/Heating system failure, Inerting system failure, Overfilling, Relief valve failure, Seal failure, etc.

Column :
Cooling/heating loss, Discharge valve wide open, Dicharge valve blocking, No feed from upstream, PacKing loss, Reflux loss, Relief valve failure, Try blocking, etc.

3.3 Consequences

The major hazards with which the chemical industry is concerned are fire, explosion and toxic release. Of these three, fire is the most common, but explosion is particularly significant in terms of fatalities and loss. Toxic release has perhaps the greatest potential to kill a large number of people, but large-scale toxic gas fatalities hardly occur. The problem of avoiding major hazards is essentially that of avoiding loss of containment. This includes not only preventing an escape of materials from leaks, etc., but also avoidance of an explosion inside the plant vessels and pipework.

Common consequences examined are :
- Personnel injury (woker, public) : Toxic material, Hot surface, Exposure to high pressure
- Property damage (onsite, offsite) : Equipment damage
- Environmental impacts
- Toxic gas/liqud/solid release
- Gas/liquid/solid fire
- Explosion : Unconfined vapor cloud explosion(UVCE), Confined vapor explosion, Dust explosion, Boiling Liquid Expanding Vapor Explosion (BLEVE)
- Hydrogen generation

Consequences classification for implementations are as follow :

Heat Exchanger :
Stream contamination, Side Reaction,
Pressure buildup, Cold/Hot Side Failure
Control Valve :
Pipe blocking, Valve wide open,
Controller malfunction, Pressure buildup
Pump :
Equipment damage, Equipment trip, Overheat,
High pressure, Material release, Backpressure,
Excessive flow, Vaccum, Evaporation, Cavitation,
Motor damage
Pipe :
No transfer, Excessive flow, Pipe rupture,
Pipe blocking, Material loss
Tank :
High pressure, Leakage
Column :
No transfer, Cold side failure, Discharge valve
wide open,Discharge valve blocking, Leakage,
Pressure buildup

3.4 Recommendations

A HAZOP study often results in the generation of two basic types of recommendations. Inforamtion needs and action items.

Action items are the results of the hazard identificaion to be reflected in redesign and/or modification of operation procedures. Action items is used when a need for improvement should be considered, for example:

- Consider additional safeguards (safety system, alarms, emergency control)
- Provide missing safeguards
- Consider need for addtional/alternative controls, alarms, instrumentation, etc.
- Modify design, equipment, or procedures
- Improve reliability of equipment or utilities
- Increase capacity of services/utilities

Information needs is used when additional inforamtion is needed to determine if a potential hazard exists, for example:

- Verify design intent
- Confirm actual installation of equipment
- Obtain missing inforamtion
- Evaluate need for equipment, procedural step, instrumentation, etc.

4. Process Knowledge Representation

The process knowledge domain for HAZOP studies is wide and most of the knowledge exist in the form of checklists for equipment. To implement the knowledge with modularity, we adopted a frame-based structure as well as rule networks. The frames represent the knowledge to be referred to by the rules. Hierarchical relationships between classes and objects can give rule networks greater flexibility. The input required and the output produced are described in Figure 1 and the internal architecture of the system is shown in Figure 2.

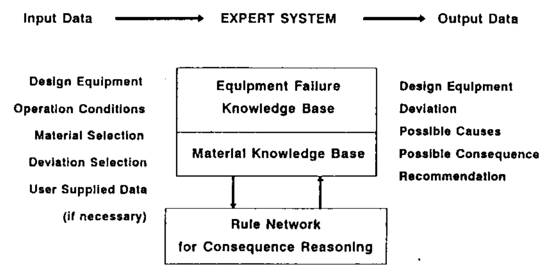


Figure 1. The input and output data of the expert system

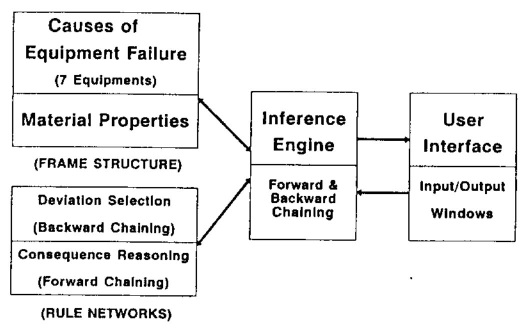
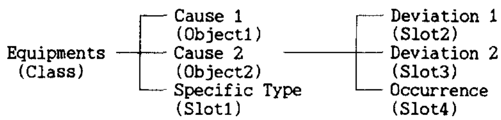


Figure 2. Internal system architecture

The system has two kinds of frames. One is the frame representing knowledge about the process equipment and the other, process materials. The seven types of equipments which are currently available on the expert system are the heat exchanger, the control valve, the pipe, the pump, the valve, the tank, and the column. The equipment frame has the knowledge about the causes of equipment failures. The frame is composed of classes, objects, and slots. Each equipment is represented as a class. The causes of an equipment failure are represented as objects which belong to classes and the objects have deviations as slots which belong to the objects. The frame structure for process equipment is as follows :



As shown in the frame structure above, every piece of equipment has its own slot which represents the type of equipment or its own attributes. For example, the pump class has the slot which describes the pump type - cetrifugal or reciprocating. And each object has the slot representing the occurrence of the event, which means that the rules relevant to the causes are to be triggered. The partial form of the implemented structure for process equipment is represented in Figure 3.

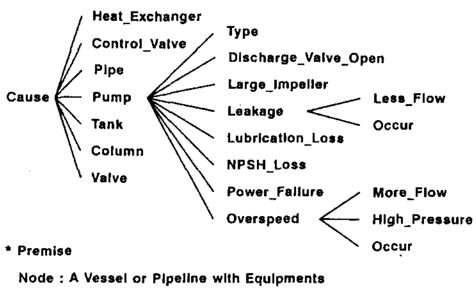


Figure 3. Frame structure for process equipments

The frame for process material has the indices of the material properties which represent health (Nh), flammability (Nf) and reactivity (Nr) hazard rating according to NFPA 325M code. Each index has five degrees ranging from 0 to 4. These material data are used in rules to reason the expected effect from the causes. Every material class has slots for the indices. The frame structure for process material is shown in Figure 4.

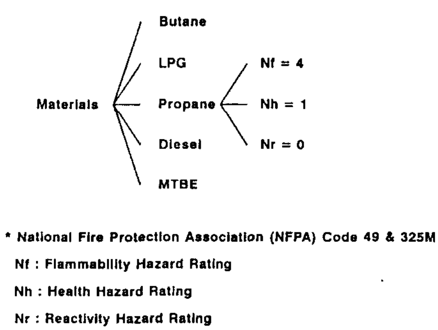


Figure 4. Frame structure for process materials

The rules describe heuristics for inferences while the frames have equipment knowledge. The rules are used for reasoning consequences with causes of failures and user-supplied data for this system. The rules are the knowledge structure which is referred to by backward or forward chaining along the reasoning mechanism. The format of a rule is as follows :

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IF   All Conditions are met  (AND Gate among Conditions)
THEN HYPOTHESIS becomes true (OR Gate among HYPOTHESES)
DO   Actions are executed.
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The rules implemented in the system are classified into two types. One of them is to activate the inference engine from the given deviation by backward chaining. The other is to verify the related consequences using the data from equipment and material frames by forward chaining. By forward chaining mechanism, the rules can trigger the activation or the evaluation of other rules. The inference mechanism is represented in Figure 5.

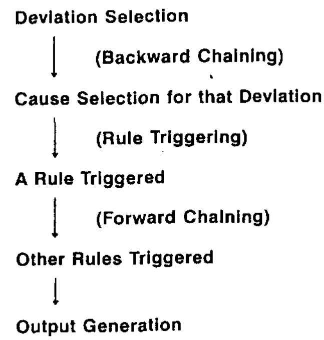
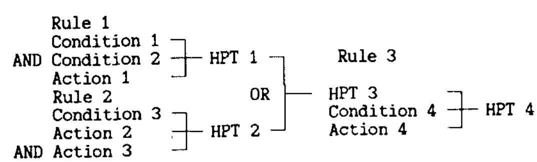


Figure 5. Inference mechanism

The hierarchical rule structure for consequence reasoning is as follows :



* HPT : Hypothesis

With the hierarchical rule structure, this system can provide partial scenarios for hazardous events propagation, which are required at the stage of risk assessment. The partial form of the rule structure is shown in the following figure.

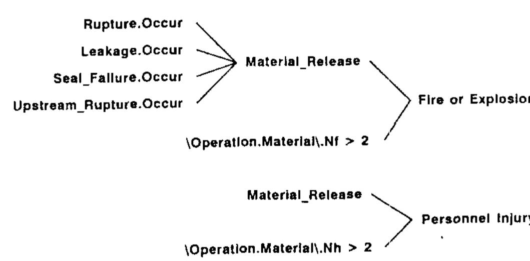


Figure 6. Rule strucutre

The inference starts with the user's deviation selection. And then this system proceeds with questions about basic information for design intention such as design equipment and some operation conditions. Then rules are used for consequence reasoning of the cause of the design equipment as shown in Figure 5. These rules are an important part of this system with frame-based structure. The frame and rule network make this system expand to a more practical one with flexiblity and modularity. This system has been developed on SUN4 SPARCstation with an expert system development shell, NEXPERT OBJECT. The developed system is operated in interactive mode.

5. Examples

For a case study, we applied the expert system to the LPG storage and fractionation process. The diagram for the process is shown in Figure 3. We divided the process into three study nodes - the storage tank, the column, and the transport lines between them. A transport line from LPG storage to fractionation column was studied as an example. This transport line was selected as a study node for the example. This study node has some components - the valve, the pump, the control valve, and the heat exchanger. For the full study of this node with this expert system, it is necessary to apply repeatedly all the deviations to these components. That example shows the case in which we have applied this expert system to the pump with a deviation of "Less Flow" for that study node.

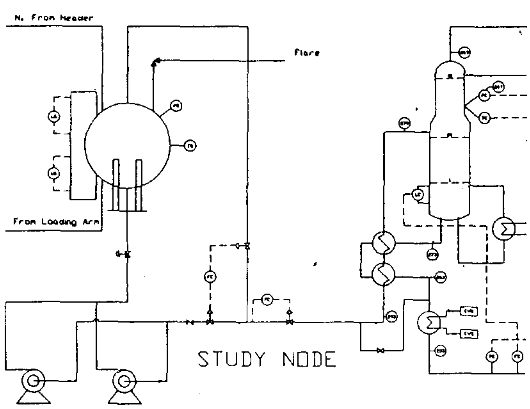


Figure 7. Process diagram for the example

One step of the system operation for the example is illustrated in Figure 4. The input and output windows are shown in the topside of the figure, the frame-based structure in the middle and the rule networks in the bottom. For run-time mode, only an input (left above) and an output (right above) window are needed. The result for this example is summarized in Figure 9. Figure 8 is the third step of the example as described in Figure 9. In Figure 9, the "->" mark is used to represent the

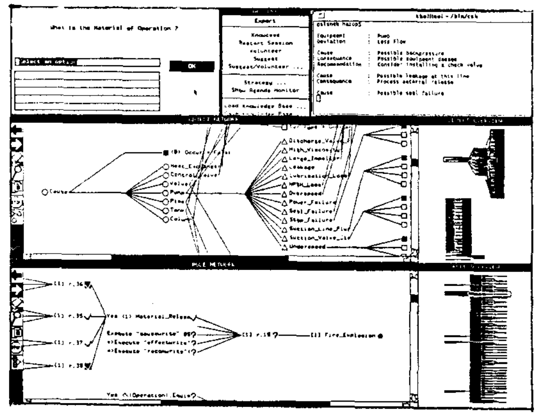


Figure 8. System development environment

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-> Select Deviation      : Less Flow
-> Select Equipment      : Pump

C  : Possible excessive backpressure
E  : Possible equipment damage
R  : Consider installing a check valve

C  : Possible seal failure
E  : Process material release

C  : Possible leakage
E  : Process material release

-> What is the Material of Operation ? : LPG

C  : Flammable material release
E  : Possible fire with ignition source
R  : Consider installing a release detector

-> What is the Pressure of Operation ? : 10 atm

C  : Material leakage with high pressure
E  : Possible personnel injury
R  : Check the pressure relief equipment

-> What is the Type of Pump? : Centrifugal

  C  : Underspeed of this equipment
  E  : Less transfer of this equipment
  R  : Check safeguard at this equipment

  C  : Lubrication loss
  E  : Possible equipment damage
  R  : Check safeguard at this equipment

  C  : Possible suction line plugging
  E  : Possible caviation
  R  : Check the suction pressure

  C  : Loss of net positive suction head
  E  : Possible cavitation
  R  : Consider installing a vertical type

* C:Cause     E:Consequence     R:Recommendation
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Figure 9. System output for the example

question in the input window and other messages are the results shown in the output window.

The recommendations made in this system including this example can be classified into hardware and software solution. The hardware solution is to install some equipment or to modify the design. The software solution is, for example, to ensure training operator, or to modify the maintenance program.

No recommendation is shown at the second and third results in Figure 9, because the reasoning has not finished for that consequence. While reasoning the rule relevant to leakage or seal failure, this system requires the answer for which process material would be treated. Then it asks the operation pressure and the type of pump for further reasoning. The rule checks the flammability index (Nf) after the third question. The consequences are the results obtained by reasoning the rule networks with knowledge base and user-supplied information.

6. Conclusions and Further Studies

The developed system shows that the approach of a knowledge-based expert system is quite efficient and time-saving for HAZOP studies for chemical processes. The system can be used not only for industrial purposes but also for educational ones.

The system represents the knowledge by frames and rules. The frame-based structure was adopted for process equipment/process material and the rule networks for reasoning consequence. The rule uses forward chaining for consequence reasoning and backward chaining for inference start. The frame and rule network have the hierarchical structure.

The expert system substantiates the efficiency and reliability for HAZOP study. To be more specific, the system is flexible and modular enough to expand its knowledge base by including checklists and design experience. More than 50% of the requested manpower for HAZOP studies could be reduced with the developed system when the application results were reviewed. And the results of the system provide safety engineers with scenarios for hazardous events to perform risk assessment. Further studies are needed to include capability to accept the wide topology of complex chemical plant and to include layout and startup/shutdown procedure.

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