DEVELOPMENT OF AN EXPERT SYSTEM TO CONDUCT AUTOMATED HAZOP STUDIES

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BY

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Abstract

Process hazard analysis is an important step to identify risk in a process facility. Automation of hazard identification requires efficient search techniques with the aid of a knowledge base. It also requires an easy menu driven interface so that an ordinary user can interact with the system with minimal intervention from an expert. One of the models to implement automation of hazard analysis is HAZOP (hazard and operability) study. Fault propagation, an aspect of HAZOP analysis, defines the propagation of deviation among equipment in a process facility. To identify all the possible hazards and their faster access, it is necessary to develop an efficient fault propagation algorithm with a knowledge-base. The existing tools performing automated HAZOP analysis does not provide any means to identify the propagation of deviation to all downstream equipment. Also some of the developed tools are slower in data extraction, require an expert to interpret the analyzed result, focuses more on causes of deviation in a process facility than the consequences, and is specific to process facility structure.

This thesis focuses on development of an expert system to perform automated HAZOP analysis with a unique fault propagation algorithm that will identify propagation of deviation to all downstream equipment in a process facility. Furthermore, the expert system has a knowledge base that identifies all general causes and consequences of equipment failure in a process facility and enables effective and efficient decision making tool for the user of the system.

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CHAPTER 1

INTRODUCTION

1.1 RISK ANALYSIS IN A PROCESS FACILITY

Risk is defined as the probability of the occurrence of an event which is seen as undesirable (Holton, 2004). Process hazard analysis (PHA) is an important step to identify risks involved in a process facility. A process facility has to take into consideration human lives, expensive equipment, and the surrounding environment during its operation. A slight error in operation due to equipment failure or human error may cause serious havoc (fire, explosion, chemical release, etc.) in the facility. In Bhopal, India, a poisonous vapor discharged from a pesticide plant killed more than 2000 civilians and injured 20,000 more on December 3rd, 1984 (Crowl & Louvar, 2001). A vapor cloud explosion in Flixborough, England caused the death of 28 people while injuring many in June, 1974. A massive explosion in Pasadena, Texas resulted in 23 fatalities and 314 injuries in October, 1989. A series of explosion at British Petroleum Texas City Refinery, caused the death of 15 and injuring 170 on March 23, 2005. Although the above accidents are major, minor accidents occurs frequently costing billions of dollars every year. This resulted in the development of many safety regulatory standards such as the Occupational Safety and Health Administration's (OSHA) Process Safety Management (PSM) standard, and Environmental Protection Agency's (EPA) Risk Management Program(RMP).

As a result of the safety regulatory standards, part of the risk analysis involves the automation of process hazard analysis. Automation of process hazard analysis requires the simulation of a hypothetical risk in a process facility (McCoy, 1999). It is an important step to reduce accidents and acts as an aid or guideline for preventive measures in process facilities. A successful automated system should be able to identify all kinds of possible causes and consequences of hazards, failures, and disturbances in a process facility and also be able to recommend possible solutions to prevent hazards. There are several models for automating risk analysis. The major ones are discussed below.

1.2 MODELS FOR AUTOMATION OF RISK

Process hazard analysis models include Checklist Analysis, "What–if" Analysis, Fault Tree Analysis, Event Tree Analysis, and HAZOP (hazard and operability) analysis. A brief description of each model is given below followed by a detailed description of HAZOP analysis.

1.2.1 CHECK-LIST ANALYSIS MODEL

A checklist (AICHE, 2000) is a systematic approach built on historical knowledge recorded in checklist questions. The questions are related to process material properties, process design, and operation procedures. It is applicable to any activity or system including equipment issues and human factor issues. Checklist analysis is generally performed by an individual trained to understand the checklist questions. It is applicable to a process facility throughout its lifetime and can be used as a guideline for maintaining regulatory safety compliance. The answer to check-list questions determines the acceptability of a particular item in a process facility. The quality of evaluation is determined primarily by the experience of the people creating the checklist and is useful to the plant only if continuously updated.

1.2.2 WHAT-IF ANALYSIS MODEL

What-if analysis (AICHE, 2000) is a brainstorming approach that puts forth questions related to an anomaly in process facility behavior that may result in accidents or system performance problems. This analysis also ensures appropriate safeguards against those problems. These questions are typically formulated by one or more teams with diverse backgrounds and experience that participate in group review meetings of documentation and field inspection. What-if analysis is applicable to any part of the process facility and can be used as a high level or detailed risk assessment technique. Just as checklists, What-if analysis requires experienced analysts and frequent updates. However, there is always a chance to miss a potential problem which would result in an incomplete analysis.

1.2.3 EVENT TREE ANALYSIS MODEL

An event tree analysis (AICHE, 2000) is an inductive reasoning process that starts with an initiating event (node) followed by the binary success or failure of subsequent safeguards, human responses, and other safety measures to determine possible outcomes. It is especially suitable to find possible outcomes of particular initial events and their respective probabilities using the data for initial events and subsequent protections and procedures. Event tree analysis is generally applicable for almost any kind of risk assessment application but most effective where multiple safeguards are in place as protective measures. An event tree considers every node as an independent event and considers the outcome of the subsequent nodes to be conditional only on the preceding outcome. The downside of this approach is that every new node in the tree doubles the number of outcomes in the formation of the tree which in turn increases the complexity of analysis.

1.2.4 FAULT TREE ANALYSIS MODEL

Fault tree analysis (AICHE, 2000) is a technique that visually models how logical relationships among equipment failures, human errors and external events can combine to cause specific accidents. It is used most often as a system level risk assessment technique. It is also used to address fundamental causes of specific accidents dominated by a relatively complex combination of events. The tree itself is formed using symbols representing events and logic gates. Usually the formation of the tree depends on the selection of the TOP event which is the accident being analyzed. Fault tree analysis focuses on a single specific accident of interest and requires significant expertise to derive a valid conclusion. The main weakness is that much effort is spent in developing the tree and any omission of potential failure path may result in incomplete risk analysis.

1.2.5 HAZOP ANALYSIS MODEL

1.2.5.1 DEFINITION

HAZOP is defined as the application of a formal, systematic, critical, rigorous examination to the process facility and engineering intentions of new and existing facilities to access the hazard potential of mal-operation or mal-function of individual items or equipment and the consequential effects of the facility as a whole. The objective of HAZOP is to stimulate the imagination of a review team, including designers and operators, in a systematic way so that they can identify potential hazards in a facility. HAZOP is usually applied when detailed process Piping and Instrumentation Diagrams (P&ID) are ready but not yet frozen (design stage of a process facility). The application of HAZOP in a project means that if the problems are identified, they can be corrected before the actual detailed design of the process facility. This results in substantial saving. The strength of HAZOP is that it examines the process facility as a whole thus making it possible to study the effect of a deviation at one point of P&ID in another.

1.2.5.2 HISTORY

HAZOP originated from personnel management in the early 1970 at Imperial Chemical Industries (ICI) based in the UK. Here the concepts of information flow and communication among the workers is extended to hazard identification. There has been subsequent refinement in the HAZOP procedure, but it has remained similar to its original form and content. This technique was gradually developed into a formal methodology named HAZOP and become the first major risk assessment tool after check-list (Khan & Abbasi, 1998; Kletz, 1985; Knowloton, 1997; Lawley, 1974; Mckelvey, 1998; Sweeny, 1993). Eventually HAZOP would become the single most widely used risk assessment tool (Khan & Abbasi, 1998; Kletz, 1985; Knowloton, 1997; Lawley, 1974; Mckelvey, 1998; Sweeny, 1993).

1.2.5.3 PROCEDURE

In a typical HAZOP, a detailed study of the entire process line from start to finish is done with the help of piping and instrumentation diagrams (P&IDs) covering each and every vessel, conduit, valve, and other control equipment employed in the process line. These P&IDs are studied in relation to the operation of the process, the causes that may lead to variations in the plant operation due to human, process, or material failures, and the likely consequences of such failures. HAZOP thus takes into consideration the conditions such as temperature, pressure, leak, creep, fatigue, etc. under which the physical parts (piping and instruments) are used, the aspects of human interaction with the piping and instruments, and the possible aberrations that may occur due to human errors, loss of process control, or material failures.

The group of experts conducting HAZOP is helped along by guide words, which enable them to cover all possible malfunctions in the plant in a systematic way. The guide words often used are NONE, MORE OF, LESS OF, PART OF and MORE THAN. When these guide words are applied to the process variables (temperature, pressure etc.) in any unit of a plant ("study nodes"), one gets the corresponding process variable deviations (MORE PRESSURE, MORE TEMPERATURE etc.) to be considered for HAZOP analysis.

To conduct HAZOP successfully by the existing methods, it is essential to put together a fairly large team of experts (six or more) (Khan & Abbasi, 1997) who have to systematically and critically examine the piping and instrumentation diagrams (P&IDs) in relation to the process conditions and human factors. The team has to determine the various permutations and combinations of possible deviations that can occur during the operation of the plant and the adverse consequence of all such deviations. The end objective is to identify the potential problems or the soft spots. A flow diagram of a typical HAZOP analysis is shown in Figure 1.1 (Ozog, 1985; Pully, 1983; Quershi, 1988; Shafaghi and Cook, 1988; Sweeny, 1993).

1.3 BENEFITS OF AUTOMATED RISK ANALYSIS

In many process facilities, a HAZOP study is conducted manually. Due to lack of sophisticated tools and expertise, the results of such studies remain in paperwork. The data collected in the study is often lost over a period of time. Furthermore, the team members performing the study become unnecessarily occupied with the system complexities and may lose their focus of study. Automated HAZOP analysis overcomes these limitations and has several advantages over manual HAZOP analysis. The advantages are listed below:

- Significant saving of human effort and manpower cost by reviewing most commonly occurring fault conditions.
- The HAZOP study process becomes standardized by automatically recalling process parameters and reviewing the results.

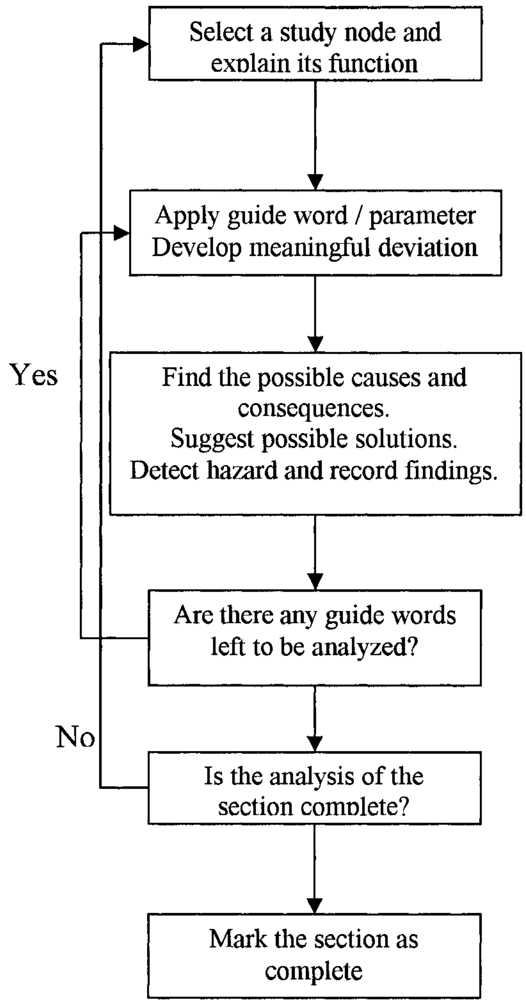

Figure 1.1: Typical HAZOP analysis used in a process facility

- The results of the automated study can be an aid for manual HAZOP analysis thus saving the overall time to conduct the study.
- It can be an aid for an operator in a chemical plant as a decision support.
- The study is easier to track thus making it more focused.
- The results of the study can be stored for later use or printed in a reported format.

1.4 FAULT PROPAGATION AND KNOWLEDGE BASE IN HAZOP

Two aspects of automated HAZOP analysis are fault propagation and knowledge-base. A fault in a process facility is a weakness or an error within the system that may arise as a result of an equipment failure, human error or a reaction in chemicals used within the system. Fault produces results that are a deviation from the original intention of the design of the process plant. Certain faults may not be hazardous for certain equipment but become fatal when it propagates to other equipment. The recent BP refinery accident (Purvis & Herman, 2005) can be taken as an example of how a small failure in one equipment can cause a huge accident that affects the entire process facility. The BP refinery in Texas consists of operations involving an isomerization unit. The Isomerization unit converts raffinate, a low octane blending feed, into higher octane components for unleaded regular gasoline. The accident involved the Raffinate Splitter tower and the blowout drum, which is part of the conversion procedure. The event started unrolling when the level detector failed to find the right level of liquid hydrocarbon entering the Raffinate Splitter tower. The automatic valve, which was supposed to route the excess liquid out of the tower, also failed. The liquid built up in the tower and exerted great pressure through the pipes on the emergency relief valve 150 ft below. As a result, three emergency valves opened and liquid began flooding the blow down drum at the other end of the isomerization unit. Some liquid overflowed from the blow down drum into a process sewer but the high level alarm on the blow down drum did not go off. The drum filled completely and a geyser-like eruption occurred from the top of the blow down drum. The eruption lasted about one minute and liquid fell to the ground creating a large flammable vapor cloud resulting in a huge explosion.

The basic concept of fault propagation used in HAZOP analysis differs from the one used in fault tree analysis. In a fault tree (Lapp and Powers, 1977), the analysis centers on the identification of the failure of the Top event. A fault in a fault tree can propagate from any Basic event to the top event which identifies the ultimate failure of the system. The fault propagation between the Basic and Top event is represented using logic gates. However, the propagation of fault is limited within the top event only (i.e., a single piece of equipment). On the contrary, the automated tool described in this paper identifies the propagation of fault (deviation) to any number of pieces of equipment. For example, if equipment is affected by the deviation "MORE PRESSURE", then the HAZOP analysis performed would be able to determine other equipment that is affected and could be a cause of hazard due to "MORE PRESSURE" from the original faulty equipment. It may be possible that some equipment may not be affected as a result of the deviation propagation. But the expert tool would be able to identify the influence of the propagation of deviation to neighboring equipment. Figure

1.2a and 1.2b represent the conceptual difference of fault propagation used in fault tree analysis and an automated HAZOP analysis tool. The example illustrates the fact that the fault propagation using fault tree analysis in Figure 1.2a can only identify the fault within the lamp and cannot identify what other hazard can occur as a result of lamp failure. Figure 1.2b shows the propagation of deviation and its effect on equipment in a typical process facility as a whole.

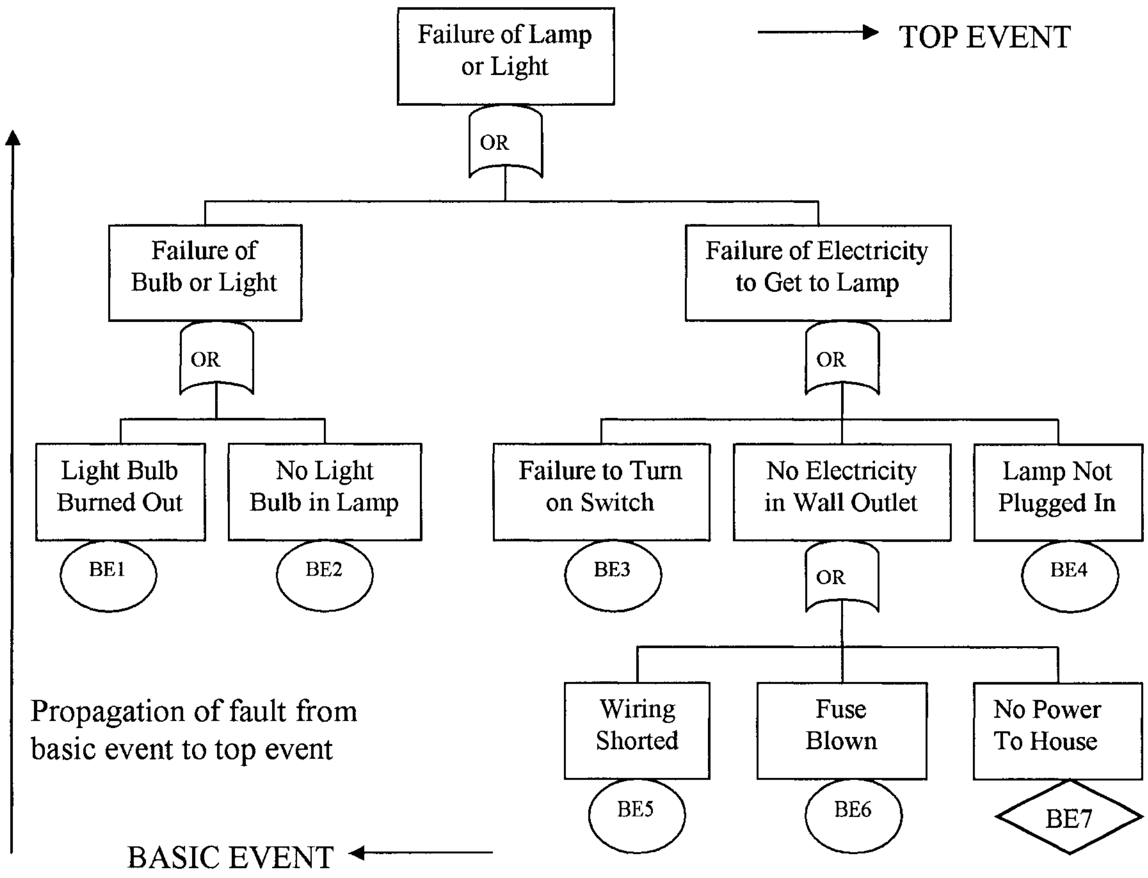

Figure 1.2a: Fault tree for failure of lamp to light

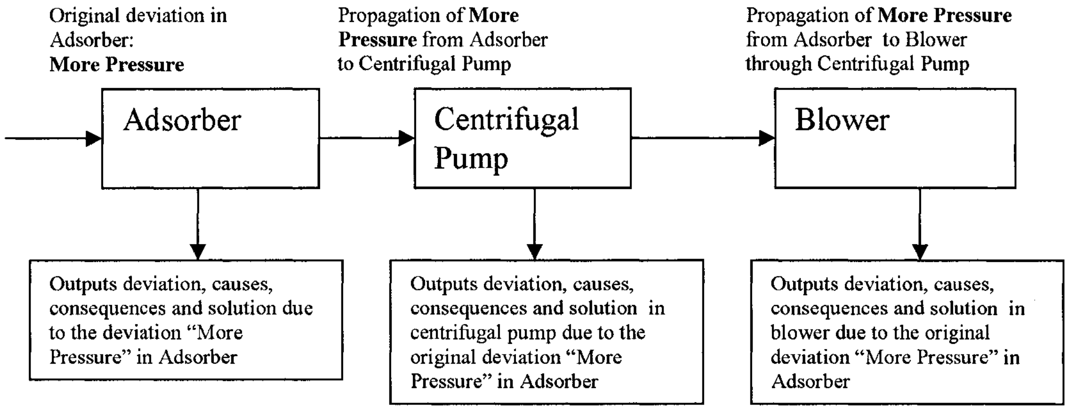

Figure 1.2b: Fault propagation using HAZOP analysis in a typical process facility

A knowledge base is a collection of information set up in a pre-defined format which can be retrieved and used for HAZOP study. This information is gathered from past HAZOP analysis performed on equipment. This knowledge is stored in a database which can be extracted when required. Data can be added by the user to derive meaningful results from automated HAZOP analysis. The addition of data can be specific to the process facility structure.

1.5 OBJECTIVES OF THE RESEARCH

The objectives of this research are as follows:

- Develop an algorithm that would enable propagation of fault among equipment combining the forward and backward search techniques and identify propagation of deviation to all downstream equipment.

- Conduct automated HAZOP analysis in a process facility with the aid of a knowledge base.
- Develop user friendly automated HAZOP analysis software which would integrate the knowledge base and fault propagation algorithm to identify hazard in a process facility.
- Conduct a real life case study to demonstrate application and effectiveness of the developed system.

1.6 ROADMAP

The chapters of the thesis are divided as follows. Chapter 2 describes the past automated HAZOP analysis tools. The features of each tools is described followed by their limitations. It then proposes a new expert tool ExpHAZOP+ which attempts to overcome some of the previous limitations described in the chapter. Chapter 3 describes the three aspects of the developed tool ExpHAZOP+ which are the graphical user interface, the knowledge base, and the inference engine. Each of these aspects of ExpHAZOP+ is described in detail. Chapter 4 describes the fault propagation algorithm and also how the algorithm uses the equipment database to automate the system. This chapter also describes the modules used to develop the expert system. Chapter 5 describes a case study in which the result of the ExpHAZOP+ analysis performed using the expert system is shown. Furthermore, it shows that the result of the expert system matches the result of ExpHAZOP+ analysis performed using an existing methodology. Chapter 6 draws conclusions and suggests some future improvement. Related references are provided at the end.

CHAPTER 2

PAST EXPERT TOOLS FOR HAZOP AUTOMATION

2.1 REQUIREMENTS OF AN EXPERT TOOL

HAZOP analysis should be thorough and exhaustive. The HAZOP team cannot afford to overlook even the "routine" causes and consequences which occur in the process units which are common to many process facilities. Some of the commonly found units are pipes, valves, pumps, controllers, sensors, instruments etc. The functionality of these units does not vary much from one process facility to another. Thus the result of the analysis performed on these units in one process would change very little if applied in another process. In that sense the analysis of such units are "routine". On the other hand there are complex units such as reactors and their support systems, settling tanks, vessels and their protective devices, heat exchangers, distillation columns, etc. These types of units are often unique in their functionality based on the type of process facility. Analyses of such units are difficult to automate and do not fall under any repeatable generic approach.

In manual HAZOP analysis a considerable amount of expert manpower time and effort has to be spent in dealing with the analysis of such "routine" process units. Thus an automated HAZOP analysis system will reduce the workload of the experts considerably, enabling them to concentrate on the HAZOP analysis of the more complex process units.

The guide word in HAZOP analysis is a systematic and logical procedure that makes automation possible using the knowledge-based systems approach. It is important to recognize that HAZOP analysis requires a combination of many different types of expertise, some of which are specific to the process plant under consideration. 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 the analysis. The abnormal causes for the process variable deviations considered during HAZOP analysis are not only process generic equipment failures and operator errors, but also the properties of the process materials present. Similarly, the adverse consequences of the process variable deviation also depend upon the properties of the process materials present in the process facility. In addition, the P&ID of the plant is used for the propagation of the process variable deviations.

It is desirable to develop an automated HAZOP analysis system that is context-independent so that it can be used for performing the analysis on a wide variety of processes. Automated HAZOP analysis should also be able to find the process-specific hazards for the various processes. This requires the user using the system to input the process specific knowledge. The process specific analysis is then performed using this updated knowledge. In the following sections, the various approaches taken in the past to automate the HAZOP analysis using intelligent systems are reviewed.

2.2 Identification of hazard by fault propagation

Parmer and Lees (1987a & 1987b) were the first to automate HAZOP analysis using a rule-based approach. They applied their automated tool for the hazard identification of a water separator system. The knowledge required for propagating faults (initiation and termination) in each process unit is represented by qualitative propagation equations and event statements. The initiation event statements described the initiation of a fault in a malfunctioned unit, the propagation equations described the propagation of faults through a normal operating unit and the termination event statements described the termination of a fault in a unit causing the unit to malfunction.

The initial event statements are of the form, "initial fault → process variable deviations", the qualitative propagation equations are of the form, "process variable deviation → process variable deviation", and the terminal event statements are of the form, "process variable deviation → terminal fault". The initiation and the termination statements are the causes and consequences respectively, determination of which is the goal of the HAZOP analysis procedure. The process materials properties and their susceptibility to cause a fault or hazard are also represented in the system. Using this information the specific realizations of hazards due to generic faults like "leak" are found.

The decomposition of the P&ID into process units is done at a coarser level. The P&ID of the plant was divided into lines consisting of pipes and other units (such as pumps, control loops valves, etc., through which a process stream passes) such as vessels. The control loop which consists of the 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. A line consists of pipe-work and other units through which a process stream passes between vessels. The causes 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 the immediate 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. The computer method generated a more exhaustive list of results compared to the conventional analysis performed by the HAZOP team. Thus there is need for the development of pruning rules and further enhancement using the expert systems approach.

2.3 The Expert System HAZOPEX

A rule-based expert system prototype called HAZOPEX was developed using the KEE shell by Karvonen and co-workers (1990). The HAZOPEX system's knowledge base consisted of the structure of the process system and rules for searching causes and consequences. The rules to search potential causes are of the type, "IF deviation type AND process structure or conditions

THEN potential cause". One important drawback of these rules is that the condition part of the rules depends on the process structure. For example, for a process variable deviation in a line, the rules for finding the causes has to check what unit is connected upstream and will then find the appropriate causes. This increases the number of rules required as the number of process units increases, thereby limiting the generality of the system. Also in HAZOPEX, 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. HAZOPEX's knowledge-base consisted of 330 rules for searching causes of deviations and 20 rules for finding consequences. In addition, the knowledge-base of HAZOPEX did not have the process material property information for finding process-specific consequences. 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 checklist for the user.

2.4 Identification of hazards using qualitative simulation

Waters and Ponton (1989) developed a quasi-state qualitative simulation approach based on the earlier work of De Kleer and Brown (1984). They found the approach to be highly combinatorial thus restricting its practical usefulness. Their qualitative simulation approach will explore all behaviors that are consistent with the initial state of the system and the input deviations. But many of these explored behaviors will not be useful from a safety perspective. Their qualitative simulation program was written in PROLOG and implemented on a Sun 3/50 workstation. They reported that the time taken to perform qualitative simulation substantially exceeded that required for a numerical simulation involving considerable detail for the simple systems tested.

2.5 Inductive and Deductive Reasoning Approach

Nagel (1991) developed an inductive and deductive reasoning based approach to automatically identify potential hazards in chemical process facility. The approach identified hazards that may occur due to hazardous reactions in the process facility and the requisite conditions that enable the occurrence of these reactions. It further inquires design or operational faults which could cause these hazards. This is a reaction-based hazard identification approach. The catalytic production of aniline from nitrobenzene and hydrogen is given as an example, for which the system automatically identifies possible top level hazards. Language for Chemical Reactivity (LCR) is used to describe chemicals, properties and reactions. The paths connecting the root causes to the top level hazards, for the given P&ID and operating conditions are found using a deductive reasoning approach. The modeling language, MODEL.LA (MODELing LAnguage) developed by Stephanopoulos et al. (1990) is used to describe processing systems, unit operations, operating conditions and behavior. Topological fault trees are constructed based on the results obtained by the above reasoning procedure. The application of this approach was limited to hazards where chemical reactions are involved. Thus this approach is not as general or as useful as conventional PHA approaches.

2.6 Qualitative Hazard Identified System

A prototype hazard identification system, called Qualitative Hazard Identifier (QHI), was developed by Catino and Ungar (1995). QHI works by exhaustively positing possible faults from a library, automatically building qualitative process models, simulating them and checking hazards. One main difference between the QHI algorithm and the HAZOP analysis procedure is that QHI's analysis starts with the faults whereas the HAZOP analysis starts with process deviations. Although this is an efficient approach requiring only forward simulation to determine immediate deviation and hazards, as compared with the HAZOP analysis which requires both a simulation to determine the hazards and a fault diagnosis to determine the faults, the QHI approach requires the library of faults to be complete.

In QHI the model of a given physical system is built by choosing the physics and chemistry from a predefined library of fundamental physical and chemical phenomena such as heat and mass transfer, chemical reaction and phase equilibrium. This modeling approach was implemented using the Qualitative Process Compiler (QPC) developed by Crawford and associates (1990). The qualitative simulation of these models thus generated is performed using the QSIM algorithm of Kuipers (1986) and possible behaviors are determined. Perfect controller and pseudo steady-state assumptions were used in order to simplify the complexity of the qualitative simulation. The plant P&ID,

the substances present and assumptions about operating conditions are the information that has to be input into the QHI system for performing the PHA.

The QHI algorithm was applied for the hazard identification of the reactor section of a nitric acid plant. For this case study, QHI evaluated the effects of the faults leaks, broken partially and completely blocked filters and pipes, controller failures leading to valve failures, etc. The number of behaviors generated by qualitative simulation of a fault ranges between 10 and 1600, with 40 and 100 behaviors for most of the faults. For some of these faults the simulation and hazard identification were completed in a matter of seconds whereas for many others, QHI took hours to days to complete. Also, for some faults, the memory on a Sun SparcStation was exhausted and the QHI could not identify the hazards. This is an important drawback for this approach as it is too fine-grained for industrial-scale applications and thus restricts the generality of its use.

2.7 Operability Study Expert System

A prototype expert system for operability study which uses "fault propagation decision tables" of process units was described by Shimada, and associates (1994). The plant structure (P&ID) and reaction types were input to the plant specific knowledge base of the expert system. The "process words" (process variables) and "guide words" (deviations) and the decision tables of the units formed the generic knowledge base. The process unit decision tables are qualitative, casual input-output variable relation, fault propagation models, which were similar to those used by Parmer and Lees (1987a and b). The system was implemented in PROLOG and sample results were presented for the HAZOP analysis of the Solvay Process for manufacturing sodium bicarbonate. There was no mention of the process material property knowledge, which is an important part of HAZOP analysis needed to identify process hazards. Thus this expert system only identifies operability problems due to faults and not the hazards in the plant due to process material properties and process deviations. Also, the HAZOP results produced by the expert system are in the form of "qualitative cause/consequence equation record sheets", which were not user friendly. There was no discussion on how these record sheets output by the system could be converted to the normal text form to be used by conventional HAZOP team.

2.8 Knowledge-based Prototype

Suh, Lee and Yon (1997) developed a knowledge-based 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 was developed using object-oriented language – C++ based on PC. However, only models of pipe, valve, heat exchanger, tank mixer, control valve and pump had been developed. Models for other process units were under programming.

2.9 HAZOP analysis for a complex process

An expert system was developed by Venkatasubramanian and Vaidyanathan (1995, 1996) in object-oriented architecture with G2 expert shell system. Both this approach and the one described next uses the idea of the separation of the knowledge required to perform HAZOP analysis into process specific and process general knowledge. This expert system further uses Diagraph-based (directed graph) HAZOP models of the process units to derive an input-output relationship among equipment. The process specific knowledge consists of process material properties and process P&ID. The process general knowledge consists of HAZOP digraph models of the process units which are signed directed graph based on qualitative casual models developed specifically for HAZOP identification. This is by far the most extensive automated HAZOP analysis tool developed so far and applied successfully on real-life process facilities. However the system requires large memory which restricts running of the system only on mainframe or large machines. It handles up to 12 process units. The knowledge-base creation is complex and is difficult for modification by an ordinary user.

2.10 The Knowledge-base Expert System TOPHAZOP

Khan and Abbasi (1997) proposed a knowledge base software tool, called TOPHAZOP, for conducting automated HAZOP analysis. The knowledge base consists of two main branches: process-specific and process-general. The process-specific knowledge base has been classified into two main groups: objects (process units) and its attributes (process parameters), 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. The system is developed under an object oriented environment using C++ language and can run on commonly used desktops. However TOPHAZOP does not indicate the interactions between parameters and deviation propagation to the downstream process units, which might lead to incomplete HAZOP analysis.

2.11 Limitations of Past Attempts

Even as each of these attempts has added to the precision and sophistication in automating HAZOP, a great deal remains to be done. For example, the following limitations besiege each of the past attempts:

- The majority of the developed expert tools were dependent on the process facility structure. There was no general way to apply the expert tool developed for one particular process facility to another.
- There was more emphasis on the identification of causes of deviations rather than the effect (consequences) of these deviations.
- The acquisition of knowledge was limited to only four types of equipment (storage vessel, pipe lines, operational unit, and control systems). The

systems neglect typical process operations such as mass transfer, heat transfer, reaction, etc.

- There is no direct avenue to study fault propagation (deviation propagation) from one unit to another.
- Large volumes of data regarding process and equipment must be keyed-in for analyzing a single deviation.

2.12 Proposed Expert Tool ExpHAZOP+

This proposed work attempts to overcome some of these limitations specially applying the expert tool to all process facility regardless of the process structure and fault propagation. Part of the proposed work is the development of a unique algorithm for fault propagation. The algorithm is unique as it can identify fault propagation to all downstream units which was not achieved in the previous systems. It would also add an efficient knowledge base with an emphasis on the consequences of deviation. The proposed system would be suitable for an ordinary user, as opposed to an expert, to dynamically update process specific knowledge to the knowledge base. This would enable the user to perform a modified HAZOP analysis. The expert system is named ExpHAZOP+. The proposed expert tool would overcome the limitation of the past tools by allowing propagation of deviation to all downstream units. ExpHAZOP+ consists of three components: the Graphical User interface, Knowledge base, and Inference Engine. Details of these components will be elaborated in the following chapter.

CHAPTER 3

ExpHAZOP+ METHODOLOGY

3.1 optHAZOP METHODOLOGY

ExpHAZOP+ has its roots from the optHAZOP (optimum HAZOP) procedure originally developed by Khan and Abbasi (1997). The optHAZOP is a HAZOP study procedure that uses a developed expert knowledge base (information base). This information base is a collection of facts, rules and information regarding various components of a process facility. The information can be used for basic recommendations to give effective and reliable results.

The algorithm for the optHAZOP procedure is presented in Figure 3.1. The main element of the optHAZOP procedure is a knowledge based software tool which is needed to identify all probable deviations in the functioning of a process facility. This knowledge base software cuts the total study time by more than 45% compared to the conventional manual HAZOP procedure. The knowledge base reduces the expert manpower required by manual HAZOP analysis. This enables the HAZOP study to be performed more economically.

ExpHAZOP+ enhances optHAZOP by uniquely identifying the propagation of deviation in any number of pieces of equipment in any section of the process facility. It also applies the concept of an information base described in optHAZOP.

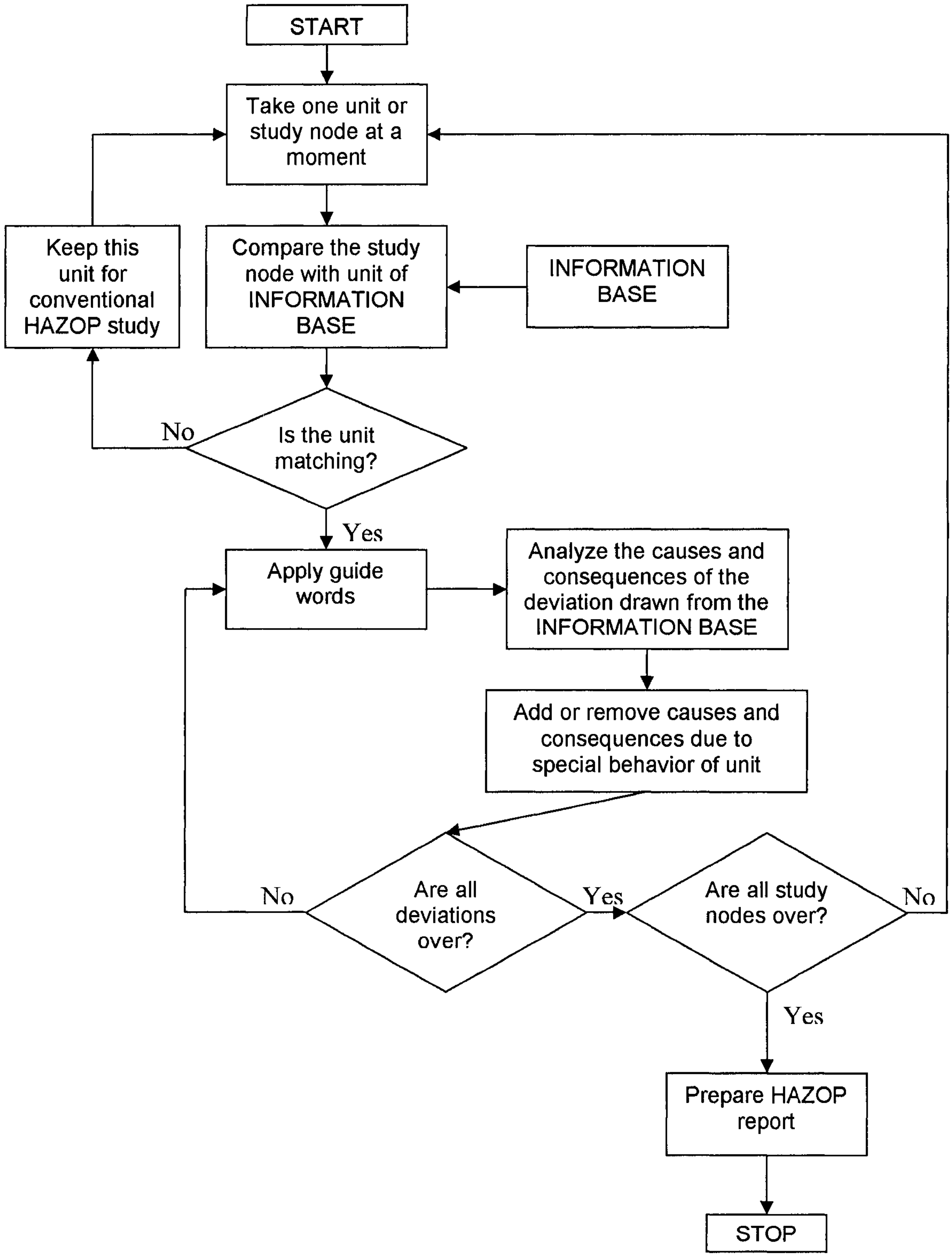

Figure 3.1: The optHAZOP methodology

3.2 ARCHITECTURE OF ExpHAZOP+

The architecture of ExpHAZOP+ consists of the following three components, a graphical user interface, a knowledge base and an inference engine. The object oriented architecture of ExpHAZOP+ is presented in Figure-3.2. The figure shows the interconnection between the three components.

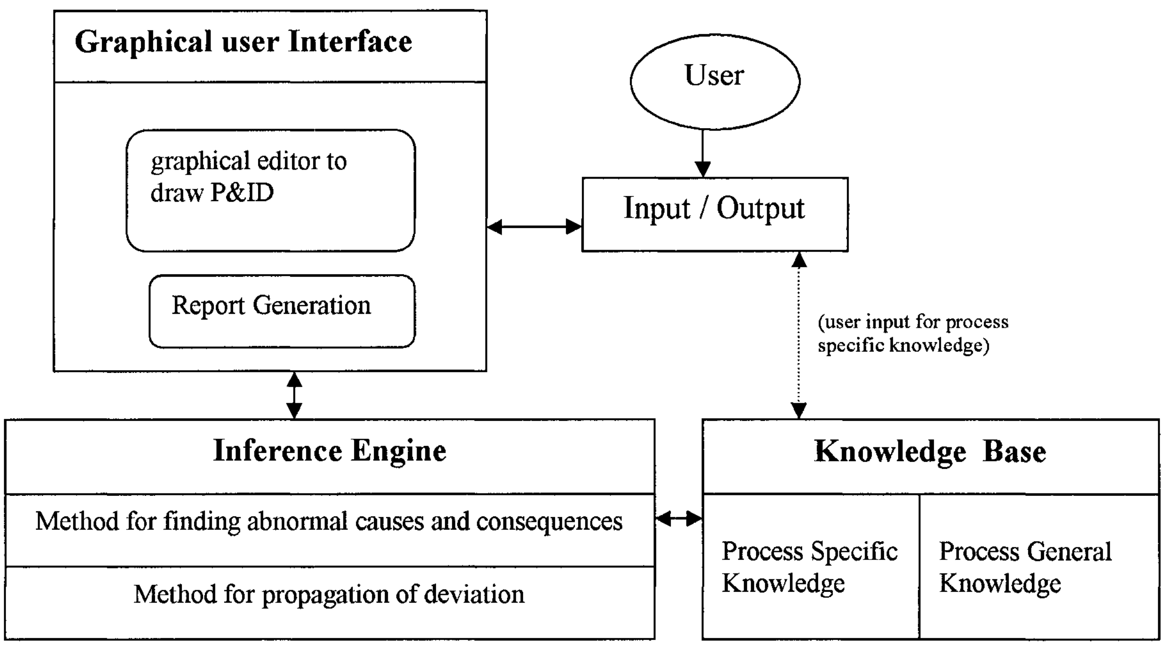

Figure 3.2 The architecture of ExpHAZOP+

3.2.1 GRAPHICAL USER INTERFACE (GUI)

The graphical user interface consists of an open interface in which the user has the option to perform a HAZOP analysis by drawing a P&ID diagram using existing equipment or perform the analysis using his own defined equipment. Each piece of equipment is connected to its own database. The database consists of process general knowledge for the equipment. When a user interacts with equipment for HAZOP analysis, a list of related process variable deviations is displayed. When a user selects a piece equipment or a group of equipment with corresponding process variable deviation, the causes and consequences related to the process variable deviation is displayed on a separate screen.

To perform a user-defined HAZOP analysis, the user needs to define his equipment. This is done by providing the name of the equipment, an equipment picture, the deviations related to the equipment as a result of abnormal causes and adverse consequences. The graphical user interface will prompt the user again and again until he finishes entering his data. This data is directly updated in the database in a table format with the other existing equipment table. Upon completion of user data and drawing P&ID, the user selects the section of the P&ID in which HAZOP analysis is required. This section is called the study node. The study node is denoted by drawing a rectangular region in the graphical user interface. The output for the analysis is the deviation with causes and consequences. The user has the option to store the analysis for later user or output it for Report Generation. The Report Generation outputs the result of the user defined HAZOP analysis in MSWord format.

The graphical user interface also allows the user to perform some general functions such as saving and opening a particular P&ID, adding captions to equipment and lines for identification, etc. Figure 3.3a shows an example of a typical graphical user interface with process general equipment. It also shows the menus related to the equipment. Figure 3.3b shows the entering of data by

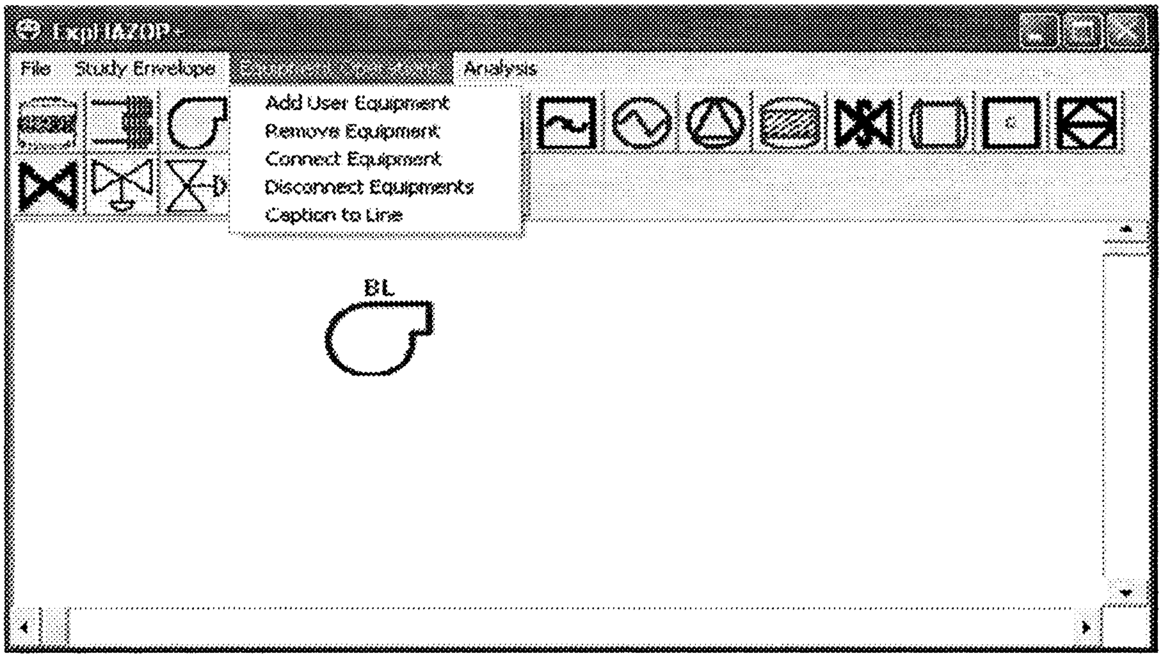

Figure 3.3 a The Graphical User Interface with menus (GUI)

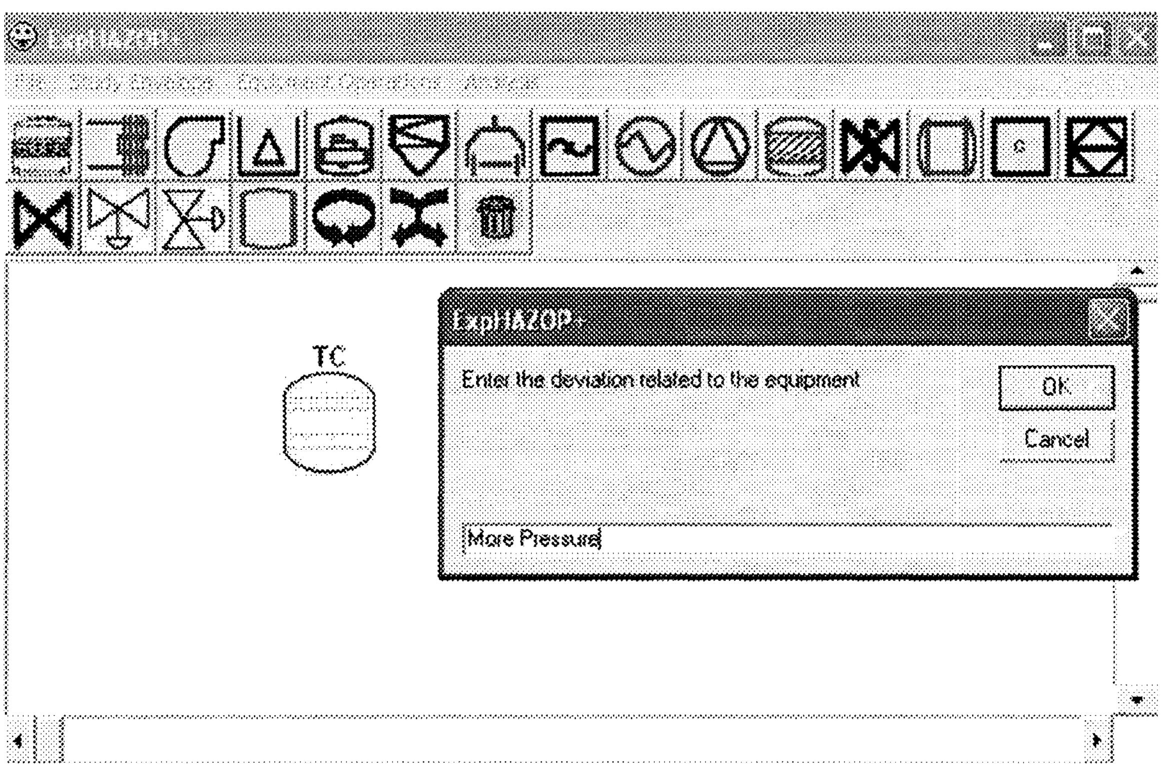

Figure 3.3 b The GUI with process specific equipment

the user from the GUI for process specific equipment. Figure 3.4 shows the connection between the graphical user interface and the knowledge base. It shows the procedure in which the inference engine performs a search in the knowledge base and outputs the result of the search to the graphical user interface.

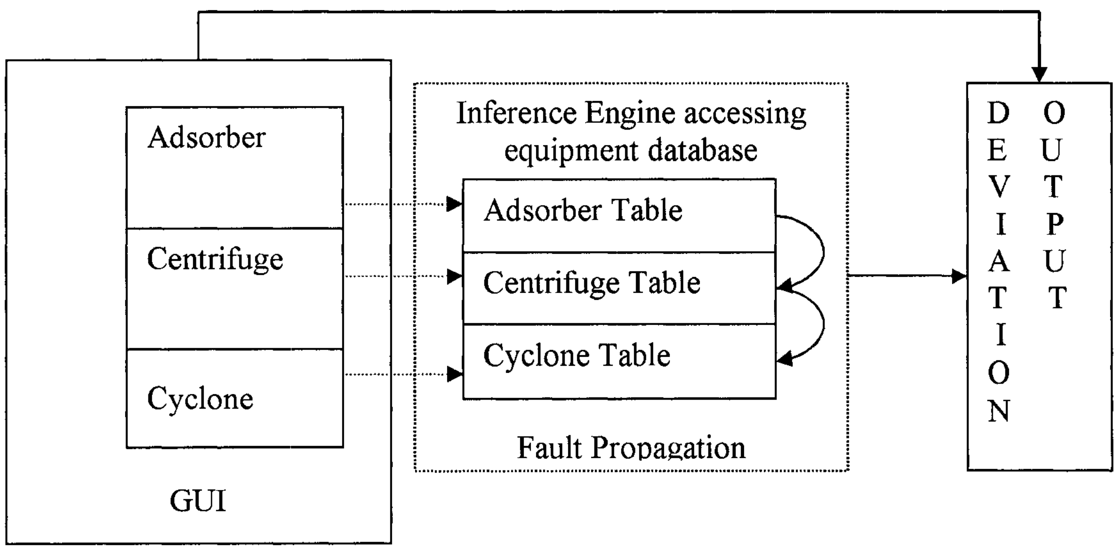

Figure 3.4: Connection between the GUI and knowledge-base

3.2.2 KNOWLEDGE BASE

The knowledge base (Khan and Abbasi 1997, 2000) consists of information derived from past HAZOP analyses related to process operation, process equipment, operating problems, failure mode and failure frequencies. The information is developed using practical industrial case studies of various process facilities. If the information is properly presented and maintained, it can be used for a long period of time and also for other safety related study purposes. Based on the collected information, a computerized knowledge base is built using MS Access as the back-end and Visual Basic as the front-end.

One of the observations in developing the knowledge base from studying past accidents in process facilities is that the causes for equipment failure do not vary much from one process facility to another even though the consequences may vary based on the structure and operation performed in the process facility. The consequences are functions of process types, process conditions, and chemicals in use. The inclusion of recommendations in an expert system to overcome or reduce the consequences will not be effective as the recommendation will be based on the type of failure, the consequences and economic feasibility. However a general set of recommendations for various failure scenarios of a particular component can be developed in the knowledge base. These recommendations will serve as a base to find out more economically feasible and reliable recommendations.

The acquisition of knowledge used in ExpHAZOP+ encompasses process equipment as well as process operations. The knowledge base is characterized in seven different operations commonly present in a process facility. Each operation and the equipment required to perform the operation in the ExpHAZOP+ knowledge base are categorized as follows:

- *Mass transfer operation*: units involving the transfer of one or more component from one stream to another stream (e.g. extractor, adsorbers, dust collectors, electrostatic, precipitators, filters).

- *Heat transfer operation*: units involving the transfer of heat from one stream to other stream (e.g. air cooled exchangers, carbon block exchangers, shell and tube exchanger, plate and frame exchangers etc.).
- *Mass and heat transfer combined*, units involving both chemical and heat transfer (e.g. distillation columns).
- *Reaction*: units involving chemical transformations including oxidation (e.g. continuous stirred-tank reactors, plug flow reactors, autoclaves).
- *Transportation*: units involving transfer or movement of chemicals from one place to another (e.g. piping, compressors, pumps, valves).
- *Storage*: storing bulk quantities of chemicals (e.g. vessels).
- Other physical operations, such as mixing, compression, relief venting, purging, relief device etc.

An operation may encompass one or more pieces of equipment. For example transportation units consist of piping, compressors, pumps and valves. The knowledge base incorporates 19 different pieces of equipment related to the process facility. The equipment are: adsorber, air cooled exchanger, blower, carbon block exchanger, centrifuge, compressor, cyclone, distillation column, dust collector, electrostatic precipitator, extractor, filter heat exchanger, piping, pump, reactor, temperature sensor, temperature controller and valve.

The architecture of the knowledge base is shown in Figure 3.5 (Khan and Abbasi 1997, 2000). This figure describes the hierarchy or the organization of the knowledge base. In this figure, each piece of equipment consists of a set of deviations. Each set of deviation consists of a set of causes. Each cause corresponds to a consequence. An example of the equipment adsorber is represented in the MS Access database is shown in Table 3.1. The knowledge for all equipment either general or specific is entered in the same format i.e. the equipment name, corresponding deviations, causes and consequences. The equipment tables are connected by means of the common deviations (generic or specific) entered by the user.

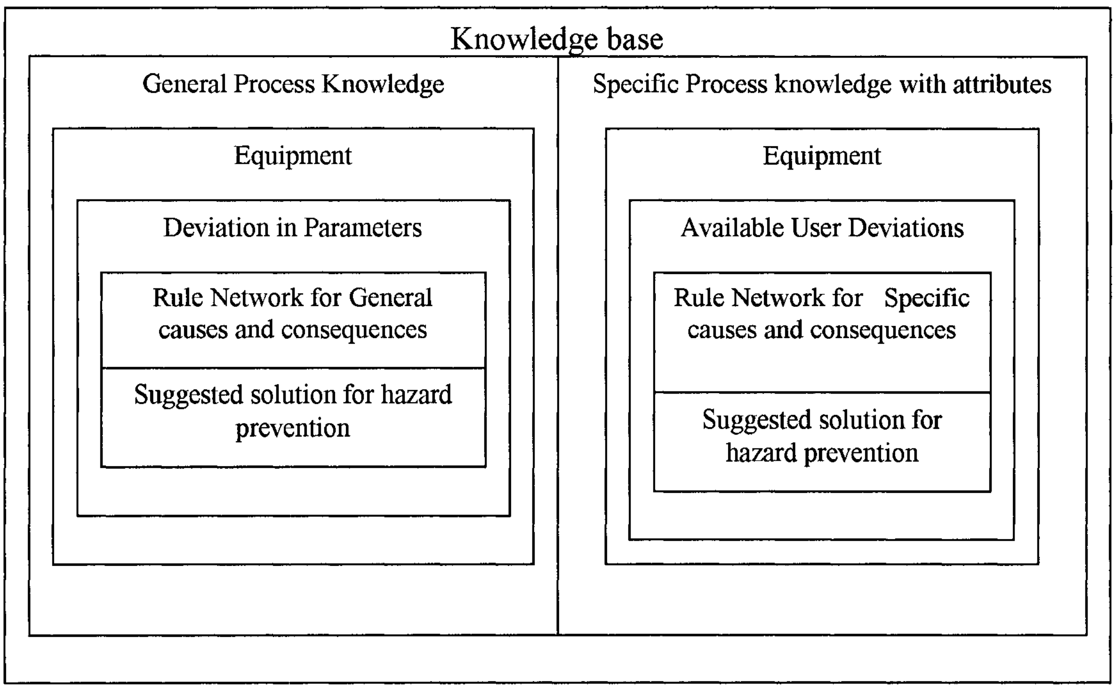

Figure 3.5: The architecture of the knowledge base

3.2.2.1 PROCESS GENERAL KNOWLEDGE

The process general knowledge is the information that has been collected over years for a particular equipment independent to the operation it involves. There is no attribute attached to the equipment. It consists of equipment deviations with corresponding generic causes and consequences. The process generic knowledge is gathered based on the following data:

Table 3.1: Representation of an adsorber database

adsorber					
ID	item	deviation	causes	consequences	cause_id
1	adsorber	More pressure	Migration of internals into lines	blockages / rupture	1
2	adsorber	More pressure	Blockage of packing / trays	rupture	2
3	adsorber	More pressure	Process liquid reintroduced into improperly cooled adsorber	vaporization of the process liquid	3
4	adsorber	More pressure	loss of vacuum	Liquid/vapor decomposition initiated by high temperature	4
5	adsorber	More pressure	air leakage into equipment operating under vacuum	Autoignition/deflagration of vapor	5
6	adsorber	Less pressure	Uncontrolled condensation/ absorption of vapor phase component	rupture	6
7	adsorber	More temperature	exposure of packing internals with flammable material to air during maintenance or by air leakage into equipment operating under vacuum	fire	7
8	adsorber	More temperature	Poor vapor flow distribution through adsorbers	hot spots and fire	8
9	adsorber	Wrong composition	Insufficient or excessive fractionation	compositions outside of metallurgical limits (e.g., corrosion)	9
10	adsorber	Wrong composition	Excessive vapor flow	carryover of liquid to undesired location	10
11	adsorber	Wrong composition	High concentration of flammables in the inlet stream to a carbon bed adsorber	deflagration	11

1) Equipment and their capacities.

2) Physical state of the chemicals.

3) Chemical (or material) characteristics such as flammability, toxicity etc.

4) Physical and chemical properties of chemicals such as vapor pressure, heat combustion etc.

3.2.2.2 PROCESS SPECIFIC KNOWLEDGE

Process specific knowledge is additional knowledge provided by an expert using ExpHAZOP+. Upon identifying the plant operations and the corresponding equipment the expert adds specific attributes and knowledge as well as additional equipment required to perform the operation. Process specific knowledge varies from plant to plant and depends on the type of operation performed in a process unit. The knowledge base in a process specific unit is classified into two main groups (Khan and Abbasi 1997, 2000):

a) Objects: developed using frame structures with attributes.

b) Causes and consequences: developed using an if-else rule network.

An analysis is then performed to invoke the causes and consequences for a particular object. The specific knowledge base consists:

1) Types of operation.
2) Equipment (operational units).
3) Operating conditions.
4) Atmospheric conditions.
5) Chemicals in use and their properties.
6) Location of units with respect to their surroundings.
7) Interaction among different units

3.2.3 INFERENCE ENGINE

The inference engine is an intermediary between the knowledge base and the graphical user interface. It acts as a search engine which searches for deviations selected by the user throughout the study node selected by the user in the GUI. The output of the search can be used to manually deduce information by an operator of a chemical plant for decision making. The inference engine uses the fault propagation algorithm described in Chapter 4 to propagate a deviation and identify the causes and consequences of the deviations.

Once the user draws the process and instrumentation diagram and selects the study node in the graphical user interface, the inference engine is used to perform a search within the equipments in the study node. The search is performed in the database tables for both process general and process specific knowledge. The search is performed based on the deviation selected by the user. An example of a deviation can be "LESS TEMPERATURE", "MORE PRESSURE" etc. The starting and the ending equipment are chosen by the user along which the deviation propagates (details in Chapter 4). Deviation propagates all the way downstream or the last equipment specified by the user. The deviation for process specific operation similarly propagates from equipment to equipment, based on the process specific deviation provided by the user. If certain equipment does not contain the user chosen deviation then that equipment does not produce an output. However as a result of propagation the next equipment which might have that specific deviation in its database will generate output. The end result identifies all the possible causes and consequences that might result in the failure of the process facility. The fault propagation algorithm procedure is described in details in the following chapter.

CHAPTER 4

FAULT PROPAGATION AND EXPHAZOP+ MODULES

4.1 DEVELOPMENT OF THE FAULT PROPAGATION ALGORITHM

A process facility consists of equipment (units) whose failure presents a hazard in the process facility and initiates a fault. Some of the general faults are blockages, leaks etc. Other faults are specific to the process facility such as a low flow rate of monoethylene glycol in a polyethylene terephthalate plant. In manual HAZOP analysis a team of experts undergoes brainstorming sessions in order to identify these faults based on the structure of the process facility. Once the fault is identified, a manual search is then performed in order to find how the fault can propagate through the pipeline and cause damage to itself and its neighboring units. It is possible that the propagation of the fault may not affect other units at all. In that case the unit itself is further analyzed and preventive measures are taken.

The central idea of fault propagation is not based on any particular propagation equation or event statement but on the basic assumption that faults can propagate through pipelines that are connected to equipment. A fault can be in the form of an increase or decrease of the set temperature, pressure, flow etc. designed to perform an operation in a process facility. The propagation of deviation through pipes is controlled by valves and sensors which have a certain limitation or capacity. When this capacity is exceeded due to an anomaly in the process facility behavior, it is possible for the deviation to propagate from one piece of equipment to another. However, to perform a HAZOP analysis based on this assumption it is necessary to identify all the connecting equipment and pipelines in which the analysis is performed. Furthermore, the knowledge associated with all the connecting equipment in the P&ID with their causes and consequences of such deviations, is also required. The knowledge base and the inference engine which performs the search have been described in Chapter 3. The fault propagation algorithm described below is the application of the inference engine in association with the knowledge base.

4.2 FAULT PROPAGATION ALGORITHM

The fault propagation algorithm consists of the following steps:

1) Identify equipment based on their operation.
2) Select the study node to perform the HAZOP analysis.
3) Identify the starting and ending equipment.
4) Select the deviation for the starting equipment.
5) Determine if the deviation is related to process generic operation.
6) Apply propagation method to identify general causes and consequences.
7) Determine if the deviation is related to process specific operation.
8) Apply propagation method to identify specific causes and consequences.
9) Move to the next equipment.
10) End the search if this is the last equipment. Otherwise repeat the procedure from step 3 – 8.

In previously developed algorithms for fault propagation the HAZOP analysis performed a forward search to find the causes of the deviation and then a backward search to find the consequences as a result of the causes. The developed algorithm combines the forward and backward search techniques by finding the connectivity of all pipes and equipment and extracting the causes and consequences for each piece of equipment. This allows the propagation of deviation of the identified fault to all downstream units. The flow diagram for the fault propagation algorithm is shown in Figure 4.1.

4.3 STEPS FOR HAZOP ANALYSIS PROCEDURE

The algorithm is part of the HAZOP analysis procedure developed in ExpHAZOP+. The complete HAZOP analysis in ExpHAZOP+ requires the following steps:

1) Development of P&ID diagram: The process and instrumentation diagram varies from one process facility to another. To perform the HAZOP the user must have all the data for equipment entered in the P&ID for a complete HAZOP analysis. If the user changes equipment at a certain point of the analysis, then that point is identified by ExpHAZOP+ so that when new equipment is replaced the analysis restarts from that point. The HAZOP analysis is performed on connected equipment as well as on single pieces of equipment. Once a P&ID is complete it is ready for HAZOP analysis.

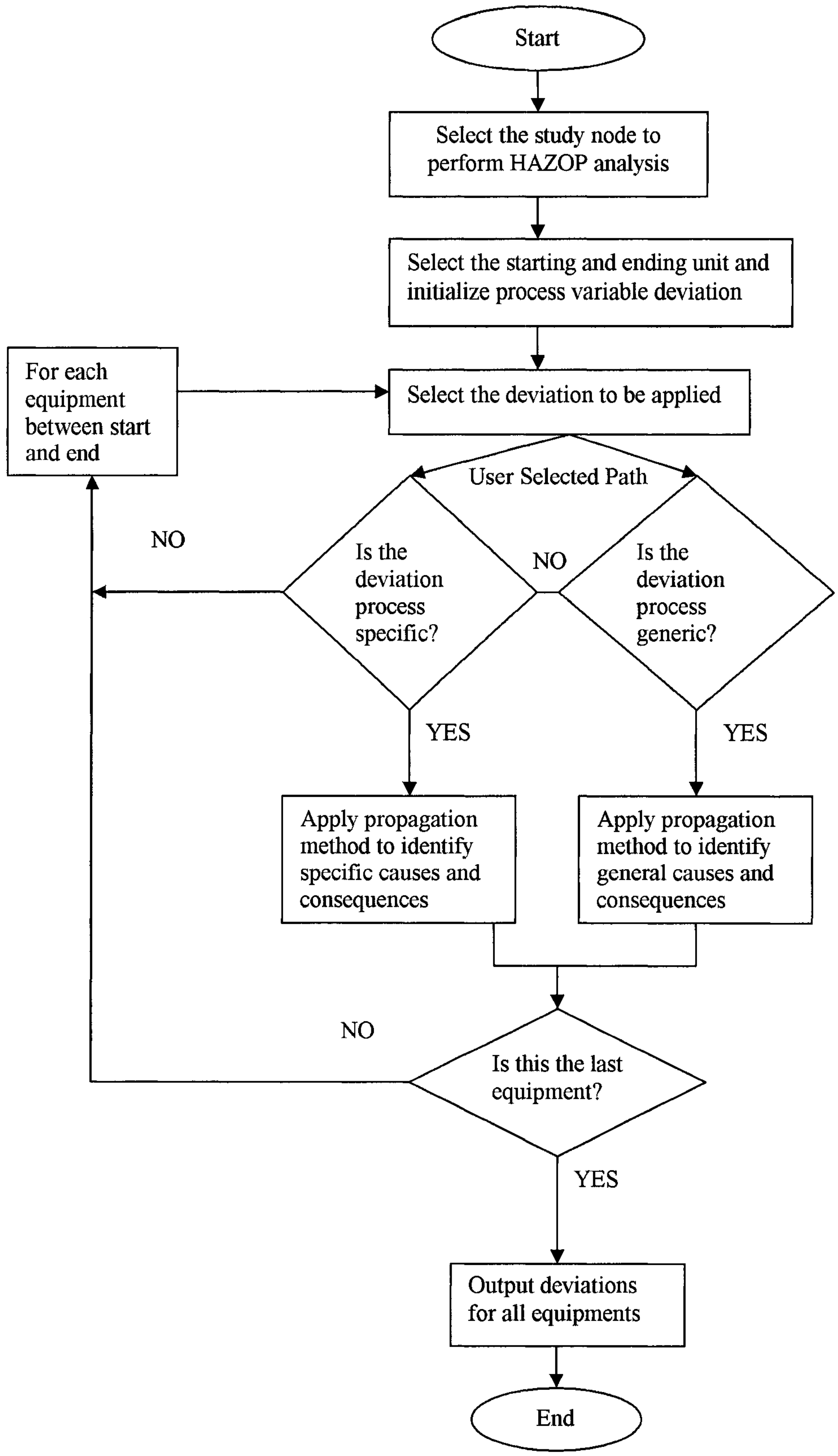

Figure 4.1: Fault propagation algorithm for ExpHAZOP+

2) Selection of process general and process specific equipment: The process general equipment is already available as menu buttons on the GUI. The database for equipment is also present in Access Database. The process specific equipment figure is entered by the user. The process specific input requirements are the same as process general equipment except that the input comes from the user. Once the user provides the required data it is automatically updated in the database.

3) Selection of a study node: The study node is selected by the user in order to perform the HAZOP analysis. All the equipment and pipes are entered in a data structure in order to identify the connectivity of the equipment and pipes inside the study node. Only the equipment inside the study nodes are considered as the starting and ending points of the analysis.

4) Creation of data structure: All the equipment and pipes along with their connectivity are stored in a collection data structure. However, only the equipment and the connecting pipes inside the study node are stored in a two dimensional array of arrays. The size of the array depends on the complexity of the connectivity of the P&ID diagram. For each connection between two equipment there will be a new row in the array. The number of columns depends on the number of downstream equipment with which the equipment is connected. The names of the equipment and pipes are also stored inside this array for identification purpose.

5) Performing HAZOP analysis: This step involves selecting the starting and ending equipment in which the HAZOP analysis is performed. The process variable deviation applied to all equipment during the deviation propagation is also selected in this step. The deviation propagation algorithm described in figure 4.1 is applied at this step.

6) Selection of path for HAZOP analysis: There can be more than one possible path from the starting equipment to the ending equipment. This path is sorted out once the user enters the starting and ending equipment for HAZOP analysis. If there is more than one path, then all the paths are shown to the user so that the user can choose his choice of path for HAZOP analysis. Upon the choice of the user, the path is sorted from the two dimensional array. The GUI will then give the user the option to choose a path of his choice for performing the HAZOP analysis. The equipment database is accessed for all equipment present in the selected path. The user then selects the path and performs the desired analysis.

7) Report Generation: In this step the final result for analysis is output in a Report format in Microsoft Word. The result of the analysis can be used by an expert to perform manual HAZOP analysis. This would enable the HAZOP analysis to be more focused and less time consuming.

4.4 MODULES IN ExpHAZOP+

ExpHAZOP+ consists of six main modules: Equipment Module, Pipe Module, Data Module, Connectivity Analysis Module, Fault Propagation Analysis Module and General Purpose Module. Each module performs a specific task, and is linked with the other modules. For example, the Fault propagation identifies propagation of deviation in equipment provided in the form of input output relations by the Data Module. The architecture and the message flow sequence in ExpHAZOP+ are presented in Figure 4.2.

4.4.1 GENERAL PURPOSE MODULE

This module deals with handling of data files, output files, and general flow of information. The general purpose module also works as a "passageway" in that it provides the necessary information to each module and sub module to carry out desired operations, and stores the results in different files. It also provides all commonly used file operations such as copying, deleting, printing and report generation of the result of HAZOP analysis.

4.4.2 EQUIPMENT AND PIPE MODULE

The equipment and pipe module consists of the general properties of equipment and pipes. For the equipment module, the properties include the storing of the equipment name, a unique tag, the height and width as well as the symbol of the equipment in the P&ID. The pipe module stores similar information as well as the tag id for the input and output equipment connected with the pipe. These features enable a user to draw a P&ID diagram. The equipment module further extends by adding features to store the user defined equipment data.

4.4.3 DATA MODULE

In this module all data relevant to equipment and pipes are stored in the data structure. A separate data structure is maintained for pipes and equipment. The equipment data structure stores the equipment name, unique tag as well as the label by which the user identifies the equipment. The pipe data structure stores the pipeline number, the input connecting equipment, the output connecting equipment, as well as the user defined label for the input and output equipment.

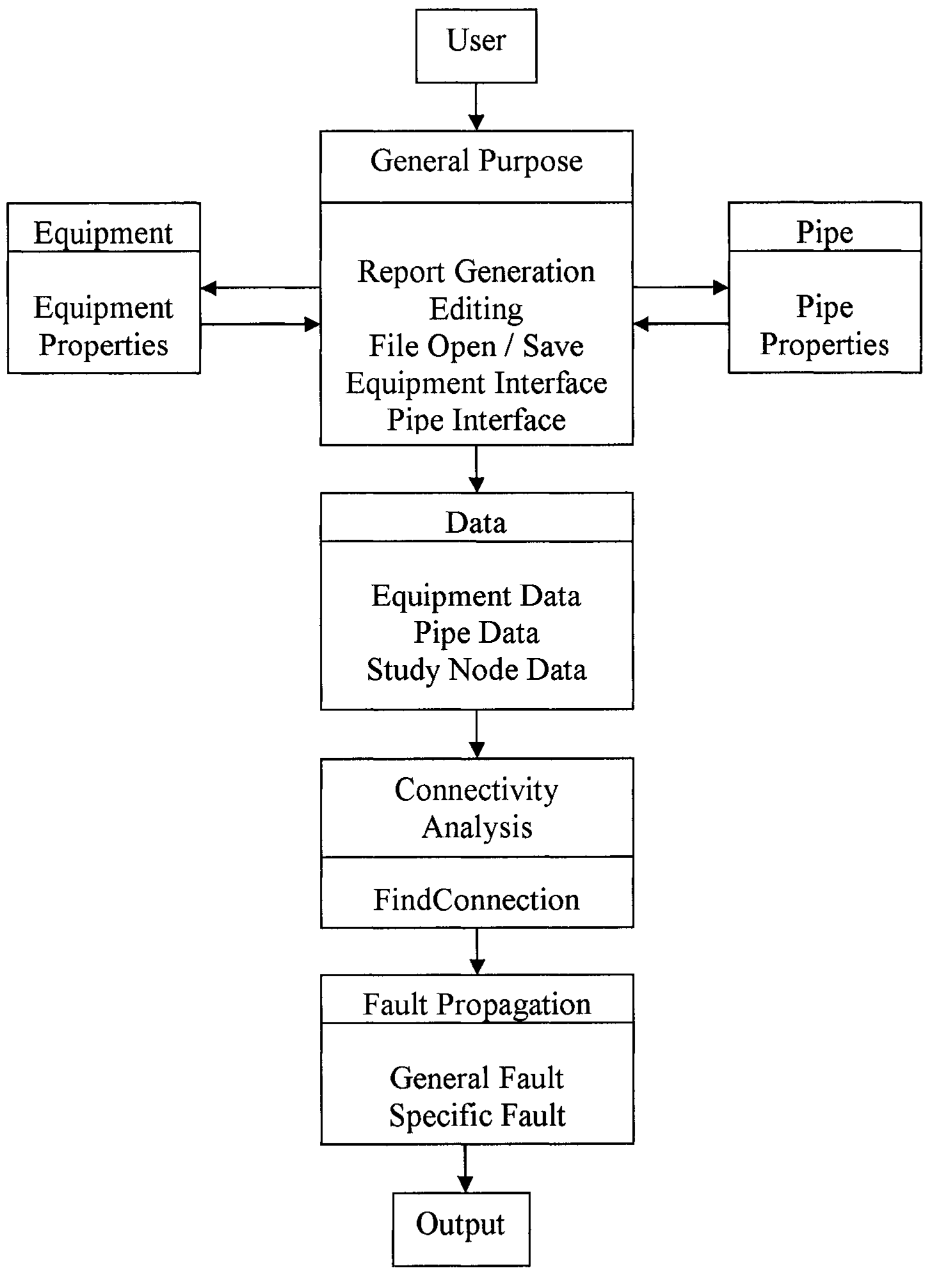

Figure 4.2: Architecture of the message flow of the modules in ExpHAZOP+

At first all the equipment and pipe data for the P&ID entered in the GUI are stored in their respective data structures. This is followed by filtering the data of the equipment and pipes lying inside the study node. This filtered data is stored separately in a two-dimensional array. This allows for faster access of data. An example data structure with a user selected study node is shown in Figure 4.3. The study node is shown in the dotted rectangle.

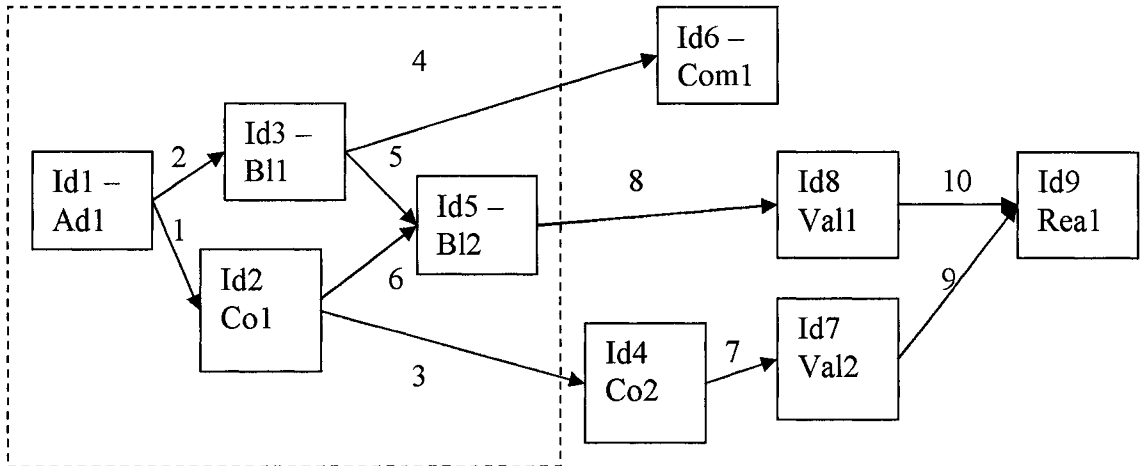

Figure 4.3. A typical GUI input for a set of equipment with their tag and label connected to a set of pipelines

In Figure 4.3, each block represents a separate piece of equipment consisting of a unique tag represented by *Id1..Id9*. The user defined label (e.g. the equipment with tag Id1 has the user defined label Ad1) is also shown along with the tag. In an actual GUI, only the user defined label is displayed. The tag is shown here for analysis purpose only. The pipeline is numbered *1..9* to identify the pipes connecting the equipment. The representation of pipeline data which is shown in Figure 4.3 is stored according to Table 4.1.

Table 4.1: Representation of the complete pipeline data entered in the GUI

Id1	Ad1	1	Id2	Co1
Id1	Ad1	2	Id3	Bl1
Id2	Co1	3	Id4	Co2
Id3	Bl1	4	Id6	Com1
Id3	Bl1	5	Id5	Bl2
Id2	Col1	6	Id5	Bl2
Id4	Co2	7	Id7	Val2
Id5	Bl2	8	Id8	Val1
Id7	Val2	9	Id9	Rea1
Id8	Val1	10	Id9	Rea1

The above data structure is filtered when the user draws a study node. The filtered data is stored in a two dimensional array as shown in Table 4.2.

Table 4.2: Filtered data obtained from study node in Figure 4.3

Id1	Ad1	1	Id2	Co1
Id1	Ad1	2	Id3	Bl1
Id3	Bl1	5	Id5	Bl2
Id2	Col1	6	Id5	Bl2

The filtered data structure is used in the *Connectivity Analysis module* .

4.4.4 CONNECTIVITY ANALYSIS MODULE

The main purpose of this module is to find all the connecting paths from the starting equipment to the ending equipment. The connectivity module uses two procedures. The *InputOutput* Procedure and the *FindConnection* procedure.

The *InputOutput* Procedure derives the tag Id of the starting and ending equipment while the *FindConnection* Procedure identifies all paths from the starting equipment to the ending equipment. The pseudo code for the *FindConnection* procedure is given below.

In *FindConnection* procedure *mArray* consist of the equipment and pipes data inside the study node including the starting and ending equipment. At first *anarrayRow* consists of only the rows in the *mArray* which has the starting equipment. *temparray* tracks the paths that are connected from the starting equipment inside the study node from *mArray.* Thus it is assured that *temparray* would only reach until the last equipment selected by the user in the *mArray.* Every time *temparray* stores a new path from the *mArray* it is updated in *anarrayRow.* In this example *mArray* is the data structure shown in Table 4.2.

Procedure FindConnections()

Repeat

While the end of **mArray** is not reached

If items in Column1 of **mArray** matches the starting equipment

Store that row for **mArray** in **anarrayRow.**

Store the equipment connected with the starting equipment in **aString**.

End While

Repeat for each item in **aString**

While the end of **mArray** is not reached

If items in Column1 of **mArray** matches the item in **aString**

Store this item in **temparray**

```
            If this is the first occurance of the item in mArray
                  Find the Row in anarrayRow in which the item be added.
                  Add the item in anarrayRow (Row)
            Else
                  Find the Row in anarrayRow in which the item be added.
                  Copy the anarrayRow(Row)
                  Add the item in the copied anarrayRow(Row).
          End If
      End If
   End While
 If there are elements in temparray
          Erase aString
          aString = temparray
          Erase temparray
End If
Until there are elements in the temparray.
End Procedure
```

Thus it is assured that all the connected paths from the starting equipment to the ending equipment are stored in *anarrayRow*. This is represented in table 4.3.

Table 4.3: All possible paths between starting and ending equipment

Id1	Ad1	1	Id2	Co1	6	Id5	Bl2
Id1	Ad1	2	Id3	Bl1	5	Id5	Bl2

The user performing the HAZOP analysis will have the option to perform the analysis on any of the two paths from *Id1* to *Id5*. Once the user selects the path the fault propagation algorithm is applied using the *Fault Propagation Module.*

4.4.5 FAULT PROPAGATION MODULE

This module applies the fault propagation algorithm in order to identify the causes and consequences of the deviation provided by the user for the starting equipment. The module uses the function *cmdPerformAnalysis* to find the propagation of deviation of the path chosen by the user. This function first distinguishes between process general and process specific knowledge. For process general knowledge it outputs the data directly from the equipment database. For process specific knowledge, the causes and consequences come from the user input which is stored in a temporary database. The data structure which gives the user an option to choose a path for HAZOP analysis in the connectivity analysis module is used to access the equipment database. The pseudo code for cmdPerformAnalysis is shown below:

Function cmdPerformAnalysis

For each equipment in anarrayRow for the user chosen row

If the equipment is user defined

Access the user defined temporary database

Output Deviation, Connecting input equipment, starting deviation, Causes and Consequences.

Else

```
            Access the equipment database
            Output Deviation, Connecting input equipment, starting
            deviation, Causes and Consequences.
        End If
    End For
End Function
```

The result of the analysis performed on the first path in Table 4.3 is shown in Table 4.4. This table shows how the deviation "More Pressure" propagates from the starting equipment adsorber (AD1) to the ending equipment blower (BL2) and outputs the causes and consequences for each piece of equipment along the way. As absorber is the first equipment in this sequence it does not have any connecting equipment.

Table 4.4: Result of the HAZOP analysis by ExpHAZOP+.

ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
Adsorber		Original deviation of More Pressure from AD1	More pressure	Migration of internals into lines	blockages / rupture
Adsorber		Original deviation of More Pressure from AD1	More pressure	Blockage of packing / trays	rupture
Adsorber		Original deviation of More Pressure from AD1	More pressure	Process liquid reintroduced into improperly cooled adsorber	vaporization of the process liquid
Adsorber		Original deviation of More Pressure from AD1	More pressure	loss of vacuum	Liquid/vapor decomposition initiated by high temperature
adsorber		Original deviation of	More pressure	air leakage into equipment	Autoignition/deflagration of vapor

		More Pressure from AD1		operating under vacuum	
ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
Compres sor	From equipment AD1 Pipe 3	Original deviation of More Pressure from AD1	More pressure	Failure of control or closure of downstream block valve, or failure to remove blind, or plugged outlet which deadheads pump	excessive temperature / mechanical damage / exothermic decomposition of fluid / ignition of fluid if shock sensitive
Compres sor	From equipment AD1 Pipe 3	Original deviation of More Pressure from AD1	More pressure	Compressor used for higher than design density fluid service especially during startup and upset conditions	mechanical damage
Compres sor	From equipment AD1 Pipe 3	Original deviation of More Pressure from AD1	More pressure	Leakage on suction side of compressor pulls air into system	flammable atmosphere
Compres sor	From equipment AD1 Pipe 3	Original deviation of More Pressure from AD1	More pressure	Exothermic decomposition of compressed fluid (e.g., acetylene)	mechanical damage
ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
Blower	From equipment CO1 Pipe 4	Original deviation of More Pressure from AD1	More Pressure	Leakage on suction side of compressor pulls air into system	flammable atmosphere

CHAPTER – 5

CASE STUDY

5.1 PROCESS DESCRIPTION

This process is originally proposed by Lapp and Powers (1977) and subsequently used by Wang (2004) in his doctoral thesis. It describes a cooling process of hot nitric acid. The nitric acid as shown in Figure 5.1 is sent to the reactor to combine with Benzene to form Nitrobenzene. The water flowing through the pump is used to cool and control the temperature of the hot nitric acid through the heat exchanger. After sensing the temperature, the temperature controller sends a signal to valve2 so as to minimize water flow. This would keep the hot nitric at a desired temperature.

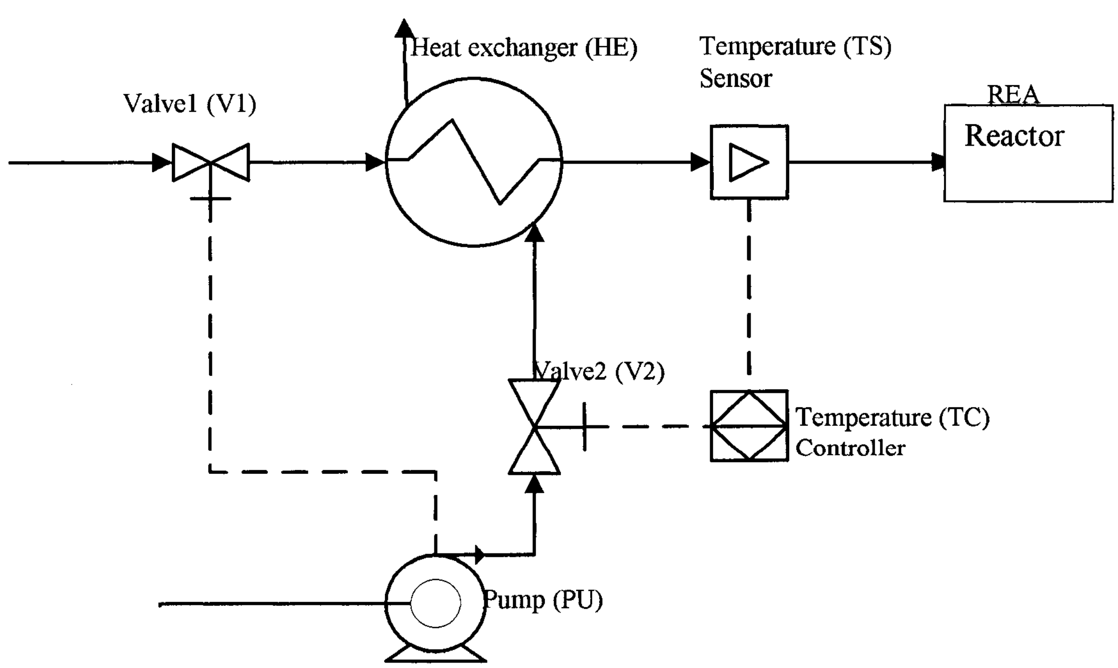

Figure 5.1: Process facility for Nitric Acid Cooling

5.2 EQUIPMENT FUNCTIONS

The functions of each of the equipment are described below.

1) Valve1 (V1): Regulates the flow of hot nitric acid into the heat exchanger.

2) Pump (PU): Maintains the circulation of water and supplies the water to the heat exchanger.

3) Heat Exchanger (HE): Lowers the temperature of the hot nitric acid using the water supplied by the pump.

4) Valve2 (V2): Regulates the flow of water entering the heat exchanger from the pump.

5) Temperature Sensor (TS): Detects the temperature of the nitric acid and sends a signal to the temperature controller if the desired temperature is not maintained.

6) Temperature Controller (TC): Controls the flow of water entering the heat exchanger by sensing the temperature from the temperature sensor and shifting the position of valve2 accordingly.

7) Reactor (REA): Assists the reaction between nitric acid and benzene to obtain nitrobenzene. The reaction must take place at a specified temperature and pressure. High temperature or pressure in the nitric acid reactor feed could cause a reactor runaway.

The control of temperature of hot nitric acid is required in order to run the process facility within safe limits. Due to this requirement, the process facility will be analyzed by investigating the effect of the process variable deviation "MORE

TEMPERATURE". The end result will show the causes and consequences of the propagation of "MORE TEMPERATURE", and how it affects equipment.

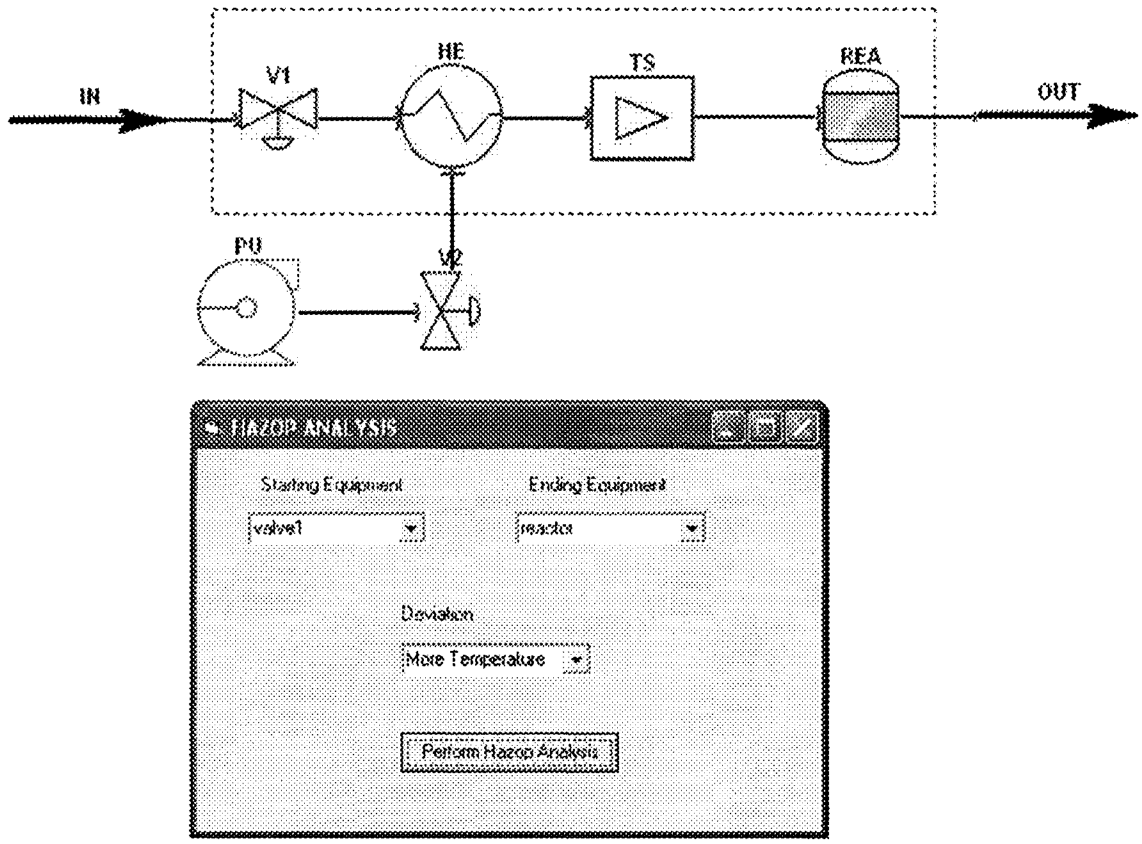

Figure: 5.2: P&ID diagram with HAZOP analysis dialogue box in the Graphical User Interface.

5.3 ExpHAZOP+ ANALYSIS OF THE NITRIC ACID COOLING

The steps taken for HAZOP analysis by ExpHAZOP+ as described in Chapter 4 are given below:

1) Development of P&ID diagram: The P&ID diagram is drawn in the Graphical user interface. The P&ID consists of all the equipment described above. The connecting pipelines are shown by arrows which indicate the direction of the hot nitric acid flow from valve1 through the heat exchanger towards the reactor. The equipment diagram is preloaded into the menu buttons. The P&ID drawn in the graphical user interface is shown in Figure 5.2.

2) Selection of process general and process specific equipment:

In this case study the equipment and their related data are already pre-loaded to perform the analysis. Hence the approach taken here is process generic.

3) Selection of a study node:

The study node in this case is selected based on the process operation. The purpose of the process is to cool down the hot nitric acid before the nitric acid enters the reactor. Thus all equipment starting from valve1 up to and including the reactor are selected as the study node.

4) Creation of data structure:

All the equipment and their connecting paths are loaded in the data structure as described in Chapter 4.

5) Performing HAZOP analysis on selected path:

The HAZOP analysis is performed by pressing the "begin HAZOP analysis" button. The starting and ending equipment are selected. The deviation "MORE TEMPERATURE" is also selected. The HAZOP analysis is then performed from the starting to the ending equipment.

6) Selection of the path for HAZOP analysis:

The only possible path for HAZOP analysis in this approach is the pipeline entering from valve1, through the heat exchanger and towards the reactor. Thus this path is chosen for HAZOP analysis.

7) Report Generation: Table 5.1 shows the result of the HAZOP analysis.

Table 5.1: Result of ExpHAZOP+ analysis for the nitric acid cooling process

ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
valve1		Original deviation of More Temperature from V1	More temperature	too hot supply of nitric acid	flow rate increases
valve1		Original deviation of More Temperature from V1	More temperature	valve1 stuck	heat exchanger temperature increase
ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
Heat exchanger	From equipment V1 Pipe 4	Original deviation of More Temperature from V1	More temperature	internal fouling occurs	Too hot reactor
Heat exchanger	From equipment V1 Pipe 4	Original deviation of More Temperature from V1	More temperature	large external temperature	Excess flow from pump
Heat exchanger	From equipment V1 Pipe 4	Original deviation of More Temperature from V1	More temperature	external fire	Temperature sensor failure
Heat exchanger	From equipment V1 Pipe 4	Original deviation of More Temperature from V1	More temperature	valve2 stuck	Temperature control failure
ITEM	CONNECTING EQUIP	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
Temperatur e sensor	From equipment HE Pipe 8	Original deviation of More Temperature from V1	More temperature	sense improperly	high temperature in temperature cooler
Temperatur e sensor	From equipment HE Pipe 8	Original deviation of More Temperature from V1	More temperature	temperature sensor stuck	improper cooling
Temperatur e sensor	From equipment HE Pipe 8	Original deviation of More Temperature from V1	More temperature	temperature sensor fails	pump load increase

ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
Reactor	From equipment TS Pipe 10	Original deviation of More Temperature from V1	More temperature	heat exchanger failure	reaction temperature increase
Reactor	From equipment TS Pipe 10	Original deviation of More Temperature from V1	More temperature	hot nitric acid flowing	reactor runaway
Reactor	From equipment TS Pipe 10	Original deviation of More Temperature from V1	More temperature	pump failure	reactor rupture
Reactor	From equipment TS Pipe 10	Original deviation of More Temperature from V1	More temperature	temperature sensor / controller failure	exceed design temperature and pressure

5.4 COMPARISION OF WANG (2004) AND EXPHAZOP+

In Lapp and Powers (1977) and Wang (2004), the nitric acid process facility was analyzed using a fault tree to identify possible failures. One of the undesired events that led to an accident in both processes was the entering of hot nitric acid into the reactor. The fault tree analysis (FTA) of their case study revealed the basic cause leading to this accident in terms of minimal cutsets (shortest route leading to an accident) of the tree. The HAZOP study procedure identifies the causes and consequences for possible failures in a process facility. The output of ExpHAZOP+, shown in Table 5.1, gives the possible causes and consequences as a result of high temperature in the reactor feed. Table 5.2 below shows a comparative analysis of Wang's approach using FTA and ExpHAZOP+ using HAZOP analysis.

Table 5.2: Comparative analysis between Wang and ExpHAZOP+

Approach	Identified basic cause leading to an undesired event as a result of the deviation, "MORE TEMPERATURE".
Wang (FTA)	V1 -> HE -> TS TS failure TC failure Large External Fire
ExpHAZOP+ (HAZOP)	*V1 -> HE -> TS TS failure TC failure Large External Fire

*Wang defined temperature deviation as +10°C.

In ExpHAZOP+, the hazard and its causes and consequences is identified by the deviation "MORE TEMPERATURE". Conversely in Wang, starting from the deviation, "MORE TEMPERATURE", the basic paths (combination of a group of basic event causes) are identified based for that deviation. Table 5.2 shows that the identified causes and consequences in ExpHAZOP+ are identical to the basic events obtained by Wang.

Table 5.1 shows that an increase in temperature in valve1 causes an increase in flow rate of nitric acid. It also causes a rise in temperature in the heat exchanger. An increase in temperature at the heat exchanger causes an increase in water flow from the pump which in turn causes the failure of the

temperature sensor and temperature controller. This failure results in the improper cooling of hot nitric acid. As a result of improper cooling the hot nitric acid entering the reactor can cause one of the following hazards in the reactor:
a) Increase in reaction temperature, b) reactor runaway, c) reactor rupture and d) an exceeding of design temperature and pressure.

CHAPTER 6:

CONCLUSION

This work was mainly focused on the development of an expert tool for automated HAZOP analysis. It discusses a new way of identifying hazard in process facilities. This approach identifies all downstream equipment and demonstrates the propagation of deviation in the case study. The result of ExpHAZOP+ analysis matches the result of Wang's (2004) approach. Wang's FTA tool identifies all possible paths that lead hot nitric flow to the reactor based on different deviations (e.g. pressure, flow etc.). ExpHAZOP+ identifies one such path by applying the deviation, "MORE TEMPERATURE". In ExpHAZOP+ if the database is updated for pressure, flow deviations etc. then it would also identify other possible causes and consequences as described in Wang's FTA approach. The limitation in Wang's approach is that the causes and consequences of the deviation, "MORE TEMPERATURE" only identify the reasons of the reactor failure. ExpHAZOP+ extends this by identifying this particular deviation can affect the reactor as well as other equipment before the propagation ends up in the reactor.

The following features were integrated in the ExpHAZOP+ as an improvement to previous expert tools described in Chapter 2.

1) Enhanced graphical user interface with user-friendly tools to perform automated HAZOP analysis.

2) User generated Knowledge-base allowing easy interface to add data.

3) Identification of propagation of deviation to all downstream units.

ExpHAZOP+ is the first step taken toward a new way to identify deviation in a process facility. Future enhancement can add the following in ExpHAZOP+:

1) Development of a relationship between causes and consequences.

2) Find the propagation of different of kind of deviation among equipment (e.g. How "MORE TEMPERATURE" in one equipment causes MORE PRESSURE in another equipment and identify the deviations of such).

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APPENDIX I: Technical Manual for ExpHAZOP+

CONTENTS

Introduction

HAZOP (HAZard and Operability) is defined as the application of a formal, systematic, critical rigorous examination to the process facility and engineering intentions of new and existing facilities to access the hazard potential of mal-operation or mal-function of individual items or equipments and the consequential effects of the facility as a whole. HAZOP can be used but not limited to identify the risks involved in a chemical plant. Towards this goal an automated tool ExpHAZOP+ is developed to identify the risks involved with its unique fault propagation approach.

System Requirements

The following system specifications are required before ExpHAZOP+ can be installed and used.

System:	Minimum Pentium II-compatible, 300 Mhz.
Operating System:	Windows 2000 or XP.
Memory:	256 MB
Disk Space:	A minimum of 12 MB.
Display:	Any display that runs under windows OS.
Printer (optional):	Required if the result of the HAZOP report is printed.
Additional Software:	Microsoft Word, Microsoft Access ODBC driver.

Setup and Installation

This instruction file contains information to run ExpHAZOP+. This includes setting up the files, copying some folders to a destination directory, menu helps as well as installing the software in your computer.

Installation of ExpHAZOP+

The installation procedure of ExpHAZOP requires the following steps: (This would allow ExpHAZOP+ to run in your computer on a windows based platform).

1) Click on the "setup" file from your CD drive.

2) A new screen will appear. Click "OK".

3) In this step another screen will appear which would offer you're a choice of installing the software in a specified directory. Indicate the directory where you want to set up ExpHAZOP+. Otherwise choose "Click this button to install ExpHAZOP+ software to the specified destination directory" and ExpHAZOP+ will be installed in your C drive.

4) Click "Continue" in this step.

5) The required files will now be copied in the destination folder. Once all the files are copied click "OK" to complete the installation process.

Setup of ExpHAZOP+

Once the installation procedure is complete, please copy the following files into your hard drive as follows:

1) Create a directory "ExpHAZOP" in your C drive if none exists.

2) Copy and Paste the folders "Database" and "JPEG" from the installation CD to the above created directory "ExpHAZOP" in the C drive.

ExpHAZOP+ is now ready to run.

Features of ExpHAZOP+

ExpHAZOP+ consists of the following three features described as follows:

GRAPHICAL USER INTERFACE (GUI)

The graphical user interface allows the user to perform HAZOP analysis by drawing P&ID diagram using existing equipments or his own defined equipment.

It further allows the user to perform some general functions such as saving and opening a particular P&ID, adding captions to equipments and lines for identification, etc.

INFERENCE ENGINE

The inference engine acts as a search engine which searches for the occurrence of a particular deviation in all the databases for all the equipments.

REPORT GENERATOR

The report generator displays the output generated as a result of the user input given in the graphical user interface and the search performed in the inference engine. The output is displayed in an MS formatted document which can be printed if required.

HAZOP Overview

This section briefly describes HAZOP, its purpose, the method that has been applied in aspect of ExpHAZOP+ and the relevant terminologies.

HAZOP is one of the most common tools to accomplish hazard assessment. The purpose of HAZOP is to reduce risks involved in a chemical plant and identify the causes and consequences of the risks involved. Manual HAZOP is expensive due to its high manpower cost and prolonged time. The purpose of automated HAZOP analysis is to reduce the time required in manual HAZOP analysis and act as an aid in the actual analysis.

ExpHAZOP+ APPROACH

Towards this goal ExpHAZOP+ is developed with a unique fault propagation approach to identify hazard, its causes and consequences. The approach is described below:

The fault propagation algorithm consists of the following steps:

1) Identify equipments based on their operations.
2) Select the study node to perform HAZOP analysis.
3) Identify the starting and ending equipment
4) Select the deviation for the starting equipment
5) Determine if the deviation is related to process generic operation
6) Apply propagation method to identify general causes and consequences.
7) Determine if the deviation is related to process specific operation
8) Apply propagation method to identify specific causes and consequences.
9) Move to the next equipment.

10) End the search if this is the last equipment. Otherwise repeat the procedure from step 3 – 8.

HAZOP TERMINOLOGIES

Some of the common terminologies associated with HAZOP study are described below:

Piping and Instrumentation diagram (P&ID): A detailed map of the entire process facility covering each and every vessel, conduit, valve, and all equipment employed in the process line.

Study Node: Any unit of the process facility within the P&ID diagram which is under HAZOP study.

Process Variable: The variables within the process facility which operates the facility. Typical process variables are temperature, pressure, flow etc.

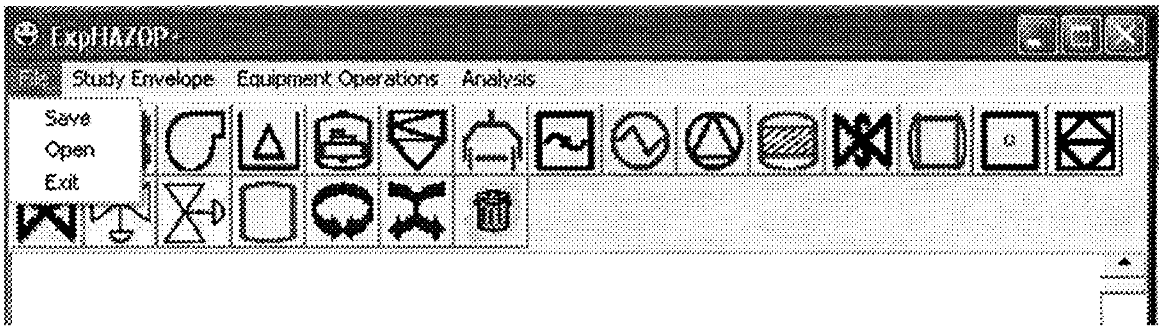
Guide Words: Helps to identify and categorize certain deviation in the process plant. Typical guide words used in HAZOP study are MORE, LESS, NO etc.

Process Variable Deviation: The combination of a guide word and a process variable which makes a meaningful deviation. Example of process variable deviations are MORE TEMPERATURE, LESS PRESSURE etc.

Features of ExpHAZOP+ System

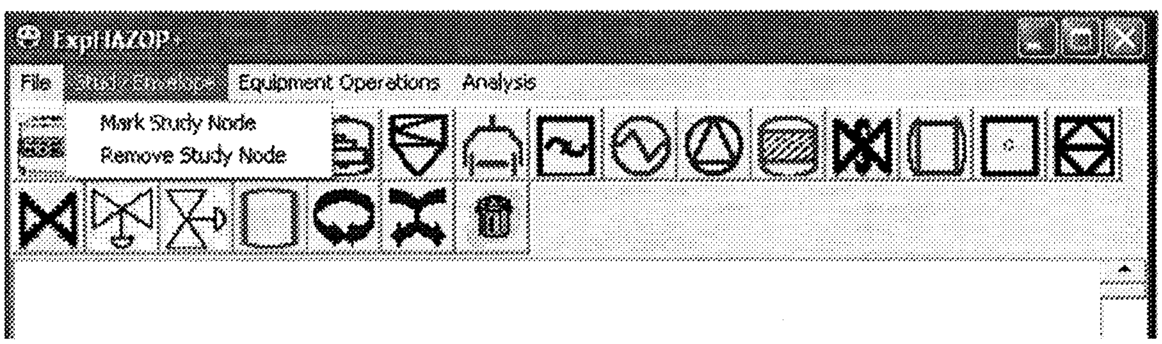
MENU FEATURES

The menus are organized as follows



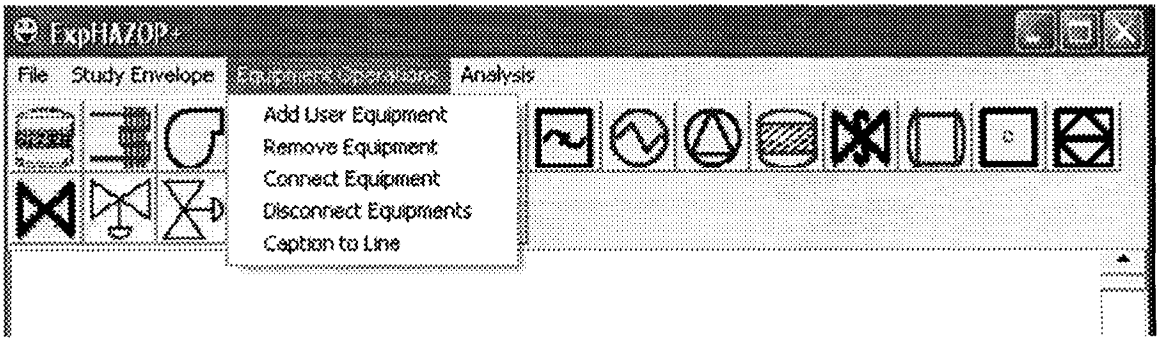
1) File: Consists of general operations for files.

- **Open:** *Opens* an existing ExpHAZOP+ file.
- **Save:** *Saves* a current ExpHAZOP+ files. The files have *".tzr"* extension.
- **Exit:** *Exits* ExpHAZOP+ software.



2) Study Envelope: Selects and deselects a study node under HAZOP analysis.

- **Mark Study Node:** *Selects* a study node for HAZOP analysis.
- **Remove Study Node:** *Deselects* a study node once analysis is complete.

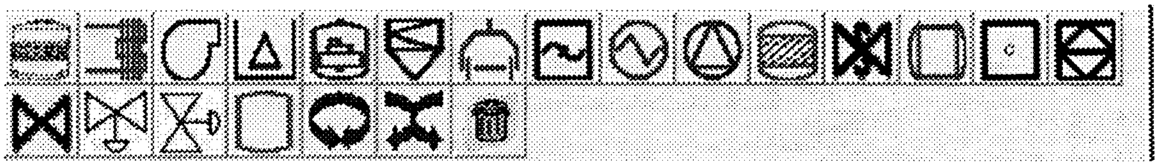


3) Equipment Operations: Consists *connecting, disconnecting* and *removal* of equipment and also *adds caption* to the connecting pipeline which connects two equipments.

- **Add User Equipment:** *Adds* user equipment depending on the process facility. The user has to enter the equipment name, deviations, causes and consequences. There will be a prompt from the GUI which will allow the user to add his own data. All data will then be updated in the Access Database in table format.
- **Remove Equipment:** *Removes* the currently selected equipment.
- **Connect Equipment:** *Connects two equipments.* The two equipments have to be selected in order to make a valid connection. The direction of connection is the order to equipment selection i.e. if two equipments are selected then the direction of deviation is from the first selected equipment to the second selected equipment.
- **Disconnect Equipment:** *Removes the connection* between two equipments. Two equipments have to be selected to make a disconnection.

- **Caption to Line:** Allows user to *add a caption* to the *pipeline* connecting two equipments. Two equipments must be selected in order to add the caption to the connecting pipeline. Caption to line is optional in this HAZOP study.

4) Analysis: Operations related to HAZOP analysis (described in detailed in the next section).

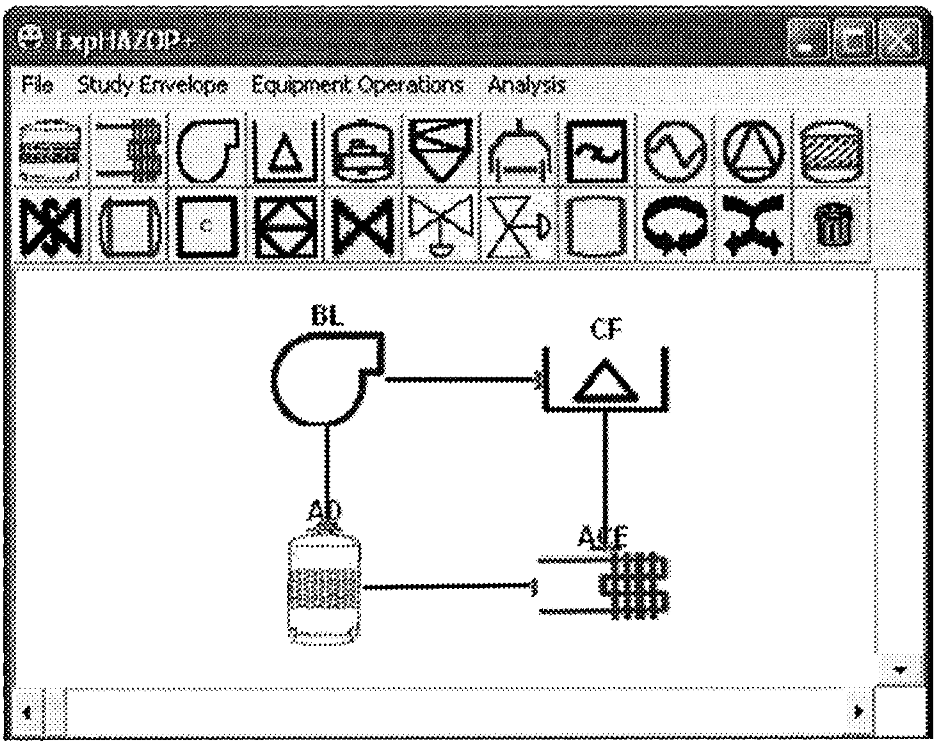


TOOLBAR BUTTON FEATURES

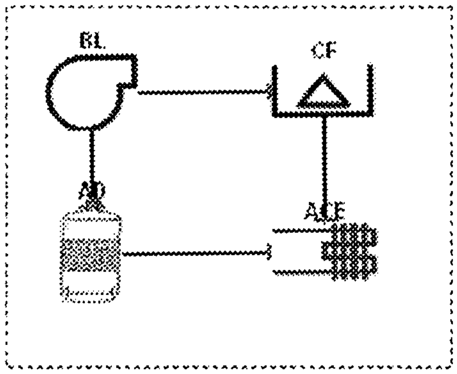
The toolbar consists of **icons (toolbar buttons)** representing *equipments*. It also consist option for *connecting*, *disconnecting* and *removing* equipments already in the menu button added for the convenience of the user. Each toolbar button consists of a tool tip text which shows the name of each equipment.

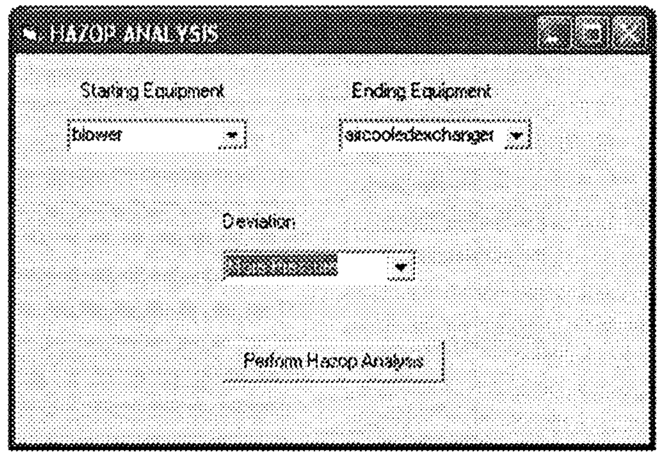
STEPS FOR HAZOP ANALYSIS

The first step for HAZOP analysis is the drawing of P&ID. This varies from plant to plant. The user can draw the P&ID according to his needs. The diagram below shows the ExpHAZOP+ software with one possible P&ID.



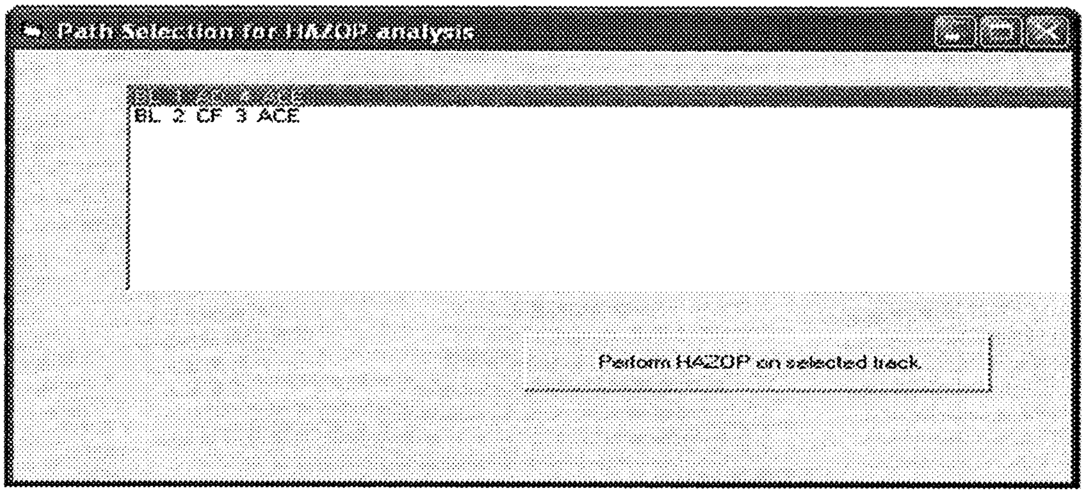
Once the drawing of P&ID is completed the next step is to draw a study node. The study node can be any particular equipment or the entire P&ID. In this case due to the small number of equipments the entire P&ID is selected as the study node. The study node is drawn using "Mark Study Node" under "Study Envelope" Menu. This would allow the user to perform HAZOP analysis once the study node is selected. The user can now begin the HAZOP analysis by selecting the "Start HAZOP analysis" under the "Analysis" Menu. A new window will open with the heading "HAZOP ANALYSIS".





In this window, all the equipments entered in the P&ID selected by the study node will automatically enter the drop down menu in the starting and ending equipment. The starting equipment is the beginning point of HAZOP analysis in the study node. The ending equipment is the ending point of analysis in the study node. The deviation is the chosen deviation in which the HAZOP analysis is performed. In the example above for the given P&ID and the study node (dotted rectangular line) the starting equipment is "blower" (with caption "BL") and the ending equipment is Air Cooled Exchanger (with caption "ACE"). All input must be entered in order to make valid HAZOP analysis. An error message would generate otherwise.

Once the input and output equipment is selected another window appears. Based on the P&ID diagram and the starting and ending equipment, this window finds all the different possible connectivity between the starting and ending point will present the user different options for connection between the input equipment and output equipment. For the above example the different possible paths to perform HAZOP analysis is shown below.



In the example above for the given input the user has to select one of the two paths to perform HAZOP analysis. The connection paths are derived from the P&ID diagram drawn by the user. In the above analysis the user selects the first path *("BL 1 AD 4 ACE").* The numbers 1 and 4 represents the pipelines connected between the equipments. Upon selected the user performs HAZOP analysis on the selected path. This outputs the result of the HAZOP as follows in this example:

ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
blower		Original deviation of More Pressure from BL	More Pressure	Leakage on suction side of compressor pulls air into system	flammable atmosphere

ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
adsorber	From equipment BL Pipe 1	Original deviation of More Pressure from BL	More pressure	Migration of internals into lines	blockages / rupture
adsorber	From equipment BL Pipe 1	Original deviation of More Pressure from BL	More pressure	Blockage of packing / trays	rupture
adsorber	From equipment BL Pipe 1	Original deviation of More Pressure from BL	More pressure	Process liquid reintroduce d into improperly cooled adsorber	vaporization of the process liquid
adsorber	From equipment BL Pipe 1	Original deviation of More Pressure from BL	More pressure	loss of vacuum	Liquid/vapor decomposition initiated by high temperature
adsorber	From equipment BL Pipe 1	Original deviation of More Pressure	More pressure	air leakage into equipment operating	Autoignition/deflagra tion of vapor

		from BL		under vacuum	
ITEM	CONNECTING EQUIPMENT	ORIGINAL DEVIATION	DEVIATION	CAUSES	CONSEQUENCES
Air cooled exchangers	From equipment AD Pipe 4	Original deviation of More Pressure from BL	More pressure	Corrosion/erosion of exchanger internals	heat transfer surface leak or rupture and possible overpressure of the low pressure side
Air cooled exchangers	From equipment AD Pipe 4	Original deviation of More Pressure from BL	More pressure	Excessive heat input	vaporization of the cold-side fluid (e.g., control system failure, cold-side blocked in)
Air cooled exchangers	From equipment AD Pipe 4	Original deviation of More Pressure from BL	More pressure	fouling, accumulation of non-condensables, or loss of cooling medium from condensing side	Loss of heat transfer capability / higher tube wall temperatures / overheating of reactive material / loss of tube strength / excessive differential thermal expansion
Air cooled exchangers	From equipment AD Pipe 4	Original deviation of More Pressure	More pressure	Cold-side fluid blocked in while	overheating

		from BL		heating medium continues to flow	
Air cooled exchangers	From equipment AD Pipe 4	Original deviation of More Pressure from BL	More pressure	Ambient temperature increase	higher vaporization rate in air heated exchanger

EQUIPMENT DATABASE

The current database contains data for 19 different pieces of equipment related to the process facility. The equipment are: adsorber, air cooled exchanger, blower, carbon block exchanger, centrifuge, compressor, cyclone, distillation column, dust collector, electrostatic precipitator, extractor, filter heat exchanger, piping, pump, reactor, temperature sensor, temperature controller and valve. The equipment data table for adsorber and air cooled exchanger are given below:

adsorber

ID	item	deviation	causes	consequences	cause_id
1	adsorber	More pressure	Migration of internals into lines	blockages / rupture	1
2	adsorber	More pressure	Blockage of packing / trays	rupture	2
3	adsorber	More pressure	Process liquid reintroduced into improperly cooled adsorber	vaporization of the process liquid	3
4	adsorber	More pressure	loss of vacuum	Liquid/vapor decomposition initiated by high temperature	4

adsorber					
ID	item	deviation	causes	consequences	cause_id
5	adsorber	More pressure	air leakage into equipment operating under vacuum	Autoignition/deflagration of vapor	5
6	adsorber	Less pressure	Uncontrolled condensation/ absorption of vapor phase component	rupture	6
7	adsorber	More temperature	exposure of packing internals with flammable material to air during maintenance or by air leakage into equipment operating under vacuum	fire	7
8	adsorber	More temperature	Poor vapor flow distribution through adsorbers	hot spots and fire	8
9	adsorber	Wrong composition	Insufficient or excessive fractionation	compositions outside of metallurgical limits (e.g., corrosion)	9
10	adsorber	Wrong composition	Excessive vapor flow	carryover of liquid to undesired location	10
11	adsorber	Wrong composition	High concentration of flammables in the inlet stream to a carbon bed adsorber	deflagration	11

aircooledexchanger					
ID	item	deviation	causes	consequences	cause_id
1	Air cooled exchangers	More pressure	Corrosion/erosion of exchanger internals	heat transfer surface leak or rupture and possible overpressure of the low pressure side	1
2	Air cooled exchangers	More pressure	Excessive heat input	vaporization of the cold-side fluid (e.g., control system failure, cold-side blocked in)	2
3	Air cooled exchangers	More pressure	fouling, accumulation of non-condensables, or loss of cooling medium from condensing side	Loss of heat transfer capability / higher tube wall temperatures / overheating of reactive material / loss of tube strength / excessive differential thermal expansion	3
4	Air cooled exchangers	More pressure	Cold-side fluid blocked in while heating medium continues to flow	overheating	4
5	Air cooled exchangers	More pressure	Ambient temperature increase	higher vaporization rate in air heated exchanger	5
6	Air cooled exchangers	Less pressure	ambient temperature drop or rain	Excessive heat transfer rate	6
7	Air cooled exchangers	More temperature	External fire	loss of mechanical integrity	7
8	Air cooled exchangers	More temperature	fouling	Loss of mechanical integrity of tube	8

aircooledexchanger

ID	item	deviation	causes	consequences	cause_id
9	Air cooled exchangers	Less temperature	Low ambient temperature	fluid freezing / tube rupture	9
10	Air cooled exchangers	as well as	Mixing of fluids	exothermic reactions / phase changes / fluid system contamination due to corrosion/erosion / vibration or differential thermal expansion	10
11	Air cooled exchangers	Loss of containment	misalignment or entrance of foreign objects	Scraper punctures heat transfer surface	11
12	Air cooled exchangers	Loss of containment	impact with fan blade	Vibration/fan failure and tube rupture	12

APPENDIX II: ExpHAZOP+ Specification

ExpHAZOP+ is developed using Visual Basic 6.0. In order to run this code one must have Visual Basic 6.0. Also the following folders must be present if not if can be copied from the CD attached with this document. The folders are:
C:\ExpHAZOP\JPEG\: consist a list of equipment images used to run this program
C:\ExpHAZOP\Database\equipmentdata.mdb: consists of a list of equipment data table.
In order to run the code click on the following Visual Basic Project: Project1
The code is separated into the following forms, modules and class module:
Forms: Form1.frm, Form2.frm and Form3.frm.
Class : cBlock.cls, cLine.cls, myBlockCollection.cls, myLineCollection.cls, trigofunc.bas.

The forms and classes along with its member functions are described below:

Form1.frm

Form1 consist general functions such as toolbar properties, file properties, scrollbar properties, GUI mouse properties, equipment mouse properties, checking if certain equipment is inside a study node etc. Form1.frm also allows user the draw the Process and Instrumentation Diagram (P&ID) for HAZOP analysis. Each function in Form1.frm is described below:

FORM OPERATIONS

Private Sub Form_Load()
Loads the default values and variables in a form once it is loaded.

Private Sub Form_Unload(Cancel As Integer)
Unloads the contents of the form once the cancel ("X") button is pressed.

Private Sub Toolbar1_ButtonClick(ByVal Button As MSComctlLib.Button)
Toolbar1 describes the features in a toolbar and activates once the toolbar button has been clicked. Toolbar1 has features to add an equipment, remove and equipment, connect two equipments and disconnect two equipments.

Private Sub Picture1_MouseDown(Button As Integer, Shift As Integer, X As Single, y As Single)
Activates the MouseDown control of the Graphical User Interface (GUI).

Private Sub Picture1_MouseMove(Button As Integer, Shift As Integer, X As Single, y As Single)
Activates the MouseMove control of the Graphical User Interface (GUI).

Private Sub Picture1_MouseUp(Button As Integer, Shift As Integer, X As Single, y As Single)
Activates the MouseUp control of the Graphical User Interface (GUI).

Private Sub picid_MouseDown(Index As Integer, Button As Integer, Shift As Integer, X As Single, y As Single)
Activates the MouseDown control of the an equipment in the Graphical User Interface (GUI).

Private Sub picid_MouseMove(Index As Integer, Button As Integer, Shift As Integer, X As Single, y As Single)
Activates the MouseMove control of the an equipment in the Graphical User Interface (GUI).

Private Sub picid_MouseUp(Index As Integer, Button As Integer, Shift As Integer, X As Single, y As Single)
Activates the MouseUp control of the an equipment in the Graphical User Interface (GUI).

FILE OPERATIONS

Private Sub mnuOpen_Click()
Opens a previously saved ExpHAZOP file with .tzr extension.

Private Sub load_FILE(sFILE As String)
Loads an existing ExpHAZOP file with .tzr extension in the GUI.

Private Sub mnuSave_Click()
Saves the current content of the GUI in a file with .tzr extension.

Private Sub mnuExit_Click()
Exits the ExpHAZOP+ application.

STUDY NODE OPERATIONS

Private Sub mnumarkstudynode_Click()
Marks a study node in the GUI.

Private Sub mnuremstudynode_Click()
Unmarks a study node in the GUI.

EQUIPMENT OPERATIONS

Private Sub mnuusrequip()
Adds a user defined equipment.

Private Sub mnuconequip_Click()
Connects two equipments in the GUI.

Private Sub mnudisconequip_Click()
Removes the connection between two equipment objects.

Private Sub mnuCaptoLine_Click()
Adds a caption to the connecting line between two equipments.

Public Sub CaptiontoShape()
Adds caption to an equipment.

Private Sub mnustartanalysis_Click()
Analyze the current contents of a study node.

Private Function CheckifContainedLine(aControl As Control) As Boolean
Checks if a certain connecting line object lies inside a study node.

Private Function CheckifContainedShape(aControl As Control) As Boolean
Checks if a certain equipment lies inside a study node.

Private Sub DrawShape()
Marks a study node.

Sub AlignScrollBars(), Private Sub Form_Resize(), Private Sub HScroll_Change(),Private Sub VScroll_Change()
The following functions are used to change and control the properties of the scrollbars.

Public Function GetFirst() As Integer
Determines whether one or more equipment has been entered in the study node.

Private Sub Storeid(idindex As Integer, j As Integer)
Stores the id of the equipment entered in the GUI in an array.

Public Function Retrieveld(j As Integer) As String
Retrieves the id of the equipment entered in the GUI from the stored array.

Public Sub InputOutput(inputid As Integer, outputid As Integer)

Identifies and retrieves the id of the first and last equipment in the study node.

Form3.frm

Form3.frm takes all the input including the starting equipment, the ending equipment and the deviation for HAZOP analysis once the study node is drawn. It consists of the following functions.

Private Sub Form_Load()

Loads the default contents and variables of Form3.frm.

Private Sub Form_Unload(Cancel As Integer)

Unloads the contents of Form3.frm once the form exits.

Private Sub cmdAnalysis_Click()

This function initiates HAZOP analysis once all inputs in the input form are entered.

Public Sub SetConnection()

Calls the function FindConnection, TrinRow and AddArraytoCombo.

Private Sub FindConnection()

This function identifies all connection of all equipments inside the study node from the starting equipment given by the user.

Private Sub TrimRow()

This function removes the equipments which are connected to the first equipment but not the last.

Public Sub AddArraytoCombo()

The function below adds the equipments and the connecting pipe to the combo box from the anarrayRow. This gives the user using the system to identify which
path should he choose for HAZOP analysis.

Private Function itemexists(temparray() As Variant) As Boolean

This function identifies if an item exists in the temparray.

Form4.frm

Form4.frm gives user an option to choose a certain path for HAZOP analysis. Once the user selects the path the output for that HAZOP analysis is given in a Microsoft Word file. The functions in Form4.frm are as follows:

Private Sub Form_Load()
Loads the default contents and variables of Form3.frm.

Private Sub Form_Unload(Cancel As Integer)
Unloads the contents of Form3.frm once the form exits.

Private Sub cmdPerformAnalysis_Click()
This function performs a HAZOP analysis on a path selected by the user.

Sub ReportGenerator(strItem As String, strConnection As String, strOrigDeviation As String, strDeviation As String, strCause As String, strConsequence As String, occur As Integer)
This function generates the output in Microsoft Word of the user query. The output is shown in a tabular format. The output shows the propagation of deviation from the first equipment to the last equipment.

Trigofunc.bas

Trigofunc.bas computes the trigonometric functions required in the project.

Public Function Arcsin(X As Double) As Double
The function Arcsin computes the inverse of sine.

Public Function Arccos(X As Double) As Double
The function Arccos computes the inverse of cosine.

cBlock.cls

This class module consists of setting and storing of individual equipment properties. It consists of the following class members.

Public Property Let TagID(ByVal vData As String)
Stores the tag assigned to equipment.

Public Property Get TagID() As String
Retrieves the tag assigned to equipment.

Public Property Let shapeHeight(ByVal vData As Integer)
Stores the height assigned to equipment.

Public Property Get shapeHeight() As Integer
Retrieves the height assigned to equipment.

Public Property Let shapeWidth(ByVal vData As Integer)
Stores the width assigned to equipment.

Public Property Get shapeWidth() As Integer
Retrieves the width assigned to equipment.

Public Property Let sCaptionUpper(ByVal vData As String)
Stores the caption of assigned to equipment.

Public Property Get sCaptionUpper() As String
Retrieves the caption assigned to equipment.

Public Property Let Visible(ByVal vData As Boolean)
Stores the visibility property assigned to equipment.

Public Property Get Visible() As Boolean
Retrieves the visibility property assigned to equipment.

Public Property Let shapeLeft(ByVal vData As Double)
Stores the coordinate of the left edge of the equipment.

Public Property Get shapeLeft() As Double
Retrieves the coordinate of the left edge of the equipment.

Public Property Let shapeTop(ByVal vData As Double)
Stores the coordinate of the Top edge of the equipment.

Public Property Get shapeTop() As Double
Retrieves the coordinate of the Top edge of the equipment.

Public Sub updateShapeCaptionPos()
Updates the position of the Caption of equipments.

myBlockCollections.cls

This class represents a collection of equipments which are entered in the Graphical User Interface. Its member functions are follows:

Public Function AddShape(PICTYPE As Integer, sKey As String) As cBlock
This function adds equipment in the GUI and sets the properties of the equipment such as its width, height, name, starting position etc.

Public Property Get Item(vntIndexKey As Variant) As cBlock

This function is used when referencing an equipment element in the collection vntIndexKey contains either the Index or Key to the collection. A collection is a data structure where equipments are added.

Public Property Get Count() As Long

Counts the number of elements in the collection.

Public Sub Remove(vntIndexKey As Variant)

Removes an element from a collection.

Private Sub Class_Initialize()

Creates the collection when this class is created.

Private Sub Class_Terminate()

Destroys collection when this class is terminated.

Public Sub removeShape(Index As Integer)

This function removes currently selected equipment.

Public Function getFreeTagID() As String

This function assigns a unique id to each equipment.

Public Function getIndexFromTag(sTag As String) As Integer

This functions extracts the index number from the tag of an equipment.

cLine.cls

This class represents the contents of a connected line and its properties such as its caption, tagid of the source and destination equipment it is connected. Its member functions are defined below:

Public Property Let sCaption(ByVal vData As String)

Stores the caption of a connected line.

Public Property Get sCaption() As String

Retrieves the caption of a connected line.

Public Property Let bShowArrow(ByVal vData As Boolean)

Stores the contents of the arrowhead of a connected line.

Public Property Get bShowArrow() As Boolean
Retrieves the content of the arrowhead of a connected line.

Public Property Let sFrom(ByVal vData As String)
Stores the tag id of the source equipment of a connected line.

Public Property Get sFrom() As String
Retrieves the tag id of the source equipment of a connected line.

Public Property Let sTo(ByVal vData As String)
Stores the tag id of the destination equipment of a connected line.

Public Property Get sTo() As String
Retrieves the tag id of the destination equipment of a connected line.

Public Property Let sFromCap(ByVal vData As String)
Stores the caption of the source equipment of a connected line.

Public Property Get sFromCap() As String
Retrieves the caption of the source equipment of a connected line.

Public Property Let sToCap(ByVal vData As String)
Stores the caption of the destination equipment of a connected line.

Public Property Get sToCap() As String
Retrieves the caption of the destination equipment of a connected line.

myLineCollections.cls

This class represents a collection of lines connecting two equipments which are entered in the Graphical User Interface. Its member functions are follows:

Public Function AddLine(sFrom As String, sTo As String, bShowArrow As Boolean, Optional sKey As String) As cLine
Adds a new connecting line between two equipments. Stores line properties such as its coordinates, source equipment id, destination equipment id etc.

Public Property Get Item(vntIndexKey As Variant) As cLine
This function is used when referencing a line element in the collection vntIndexKey contains either the Index or Key to the collection. A collection is a data structure where equipments are added.

Public Function StoreCollectionItemsinArray(itemarray() As Integer, equiptag As Integer) As Variant

This function stores the entire equipment item and the connected lines in a two dimensional array mArray from the collection object mCol.

Public Property Get Count() As Long
Counts the number of elements in the collection.

Public Sub Remove(vntIndexKey As Variant)
Removes an element from a collection.

Private Sub Class_Initialize()
Creates the collection when this class is created.

Private Sub Class_Terminate()
Destroys collection when this class is terminated.

Public Sub deleteLine(xFrom As Integer, xTo As Integer)
This function deletes a connected line.

Public Sub updateLines()
This function updates the coordinates of the connected lines every time an equipment item is moved.

Public Sub AddCaptionToLine(sFrom As String, sTo As String, sCaption As String)
This function adds a caption to a line

Public Sub showArrow(lineObj As Line, arrowTo As String)
This function is called in update line and updates the position of the arrowhead each time the arrows are moved.