Risk Management for Safety Operation Utilizing Virtual Reality Simulation Supported By Intelligent HAZOP Analysis

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This thesis has been submitted to the Graduate School of Natural Science and Technology, Okayama University, Japan, as a partial fulfillment of the requirement for the degree of Doctor of Engineering.

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Abstract

Ensuring safe operability and minimizing risk is the key component to prevent negative impact in all industries dealing with toxic, reactive, flammable and explosive materials. HAZOP (Hazard and Operability), a preliminary and systematic approach for identifying hazards has been unquestionably successful in reducing incident of hazards by mitigating the consequence of major accident in the industrial process facilities. However, laborious work, time and cost are the shortcoming in performing and maintaining HAZOP analysis. Many research works on HAZOP automation are available, yet the traditional approach is still widely used by plant operators. The traditional method only covers parts and aspects of a specific plant type rather than generalizing to fit many plant types. In HAZOP analysis of chemical process industries (CPI), process analysis can be divided into two groups - defined or routine process, which roughly occupies 60-80% and predefined or non routine process, which occupies 20-60% of HAZOP analysis. Thus leading towards the significance of having safety information as update and accessible as possible.

In recent years, computer hardware capable of developing and running virtual reality model has become more affordable for middle and small scale CPI. Consequently, virtual reality has been proposed as a technological breakthrough that holds the power to facilitate analysis. The ability to visualize complex and dynamic systems involving personnel, equipment and layouts during any real operation is a potential advantage of such an approach. With virtual reality supporting HAZOP, analysis which often solely relied on expert imaginative thinking in simulating hazard conditions, will aid understanding, memory retention and create a more interactive analysis experience.

In focusing assessment for safety operator and safety decision maker, we present a web-based HAZOP analysis management system (HMS) to help HAZOP team and related individuals to perform revision, tracking and even complete HAZOP analysis without management bureaucracy. Besides, depending solely on expert imaginative thinking of scenario using P&ID, this work will develop a dynamic visual model which brings to the user a different view of consequent and subsequent to an accident and will further enable three dimensional analyses of effects. This approach will prevent 'miss looks' due to

‘paper-based’ view.

We also present Virtual HAZOP Training system, a risk-managing virtual training concept supported by intelligent HAZOP proposed to eliminate analysis redundancies and bring static ‘paper-based’ analysis to more dynamic and interactive virtual analysis simulation. However, the efficiency of VR simulator depends on the scenario accuracy to the real world that can be simulated. We introduce the system’s artificial intelligent engine responsible for retrieving the most accurate and highest possibility ‘to-happen’ scenario case. A fuzzy – CBR method enables the engine to classify and use real past scenarios combined with suitable parameters in creating a defined scenario. This method resolves issues in balancing between computational complexity and knowledge elicitation

Reactor section in a vacuum gas oil hydrodesulphurization (VGO HDS) process is used as the case study to illustrate the performance of the proposed system. The wide usages of HDS unit in the petroleum refining industry play important roles in chemical plant incidents happening worldwide. HAZOP analysis management system in average manages to reduce more than half the time required in performing HAZOP analysis compares to traditional method. With the proposed system, operator is able to optimally use safety information in HMS to prevent common and repetitive mistakes. Virtual process and accident simulator available in virtual HAZOP training system help to improve safety operator estimate overall impact towards equipment, operator and environment during process 20-35% better.

This system is expected to be the main foundation for Virtual Reality simulator research in analyzing accident caused by human factor. Asides providing better and healthier working environment, negative profitability impact which influence not only the company that runs it but also the world economy due to byproduct shortage, can be avoided.

Preface

This thesis summarizes the result of research work that has been carried out from April 2007 to date at Advanced Safety System Laboratory in the department of Intelligent Mechanical at Okayama University.

We address the need of developing computer-aided tools and components generally in process hazard analysis focusing on assisting safety operator. Their responsibility of ensuring safety is an important issue in process design and operation in the chemical process industry (CPI). It is even more critical for modern chemical manufacturing processes, which are either operated under extreme conditions to achieve maximum economic profit, or are highly flexible. The importance of safety analysis in process operation is well recognized after occurrence of several tragic accidents that could have been avoided by adequate process safety analysis. To ensure safe operation, process hazard analysis (PHA) is very important to proactively identify the potential safety problems and recommend feasible mitigation actions. Among the available PHA techniques, hazard and operability (HAZOP) analysis is the most widely used one in the CPI. Due to information structures of HAZOP analysis, we found that it is essential to restructure information management and delivery method from experience safety operator toward new safety operator. Virtual reality technology impose in this thesis improve effectiveness for new safety operator to train on safety analysis without endangered or halt plant operation

In this research emphasis is placed on the understanding of the very nature of the domain from a holistic perspective which considered that information requirement in the safety analysis might resemble those in operations. We layout this thesis in such way in order to provide useful foundation to develop a complete chemical plant safety management system, as a part the health, safety and environment (HSE) that assist and manage all safety aspect within the chemical plant. The approach used in this study comes in two folds :(1) utilization of previous experience reasoning in supporting safety decision and safety procedure development. (2) Formulate the contextual and conceptual models with virtual experience aiding imaginative thinking effectiveness.

Without any doubt getting the whole picture has provided a great deal of insight toward the understanding of safety operator problem at hand and its relations with other parts of the whole.

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In doing this research, I have inevitably drawn on a very wide range of resources. It is perhaps appropriate here to pay a general tribute to all authors who have contributed to the progress of my research and development of simulation system.

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Abbreviations

AI	Artificial Intelligence
AHA	Automatic Hazard Analyzer
ANSI	American National Standards Institute
CCPS	Center for Chemical Process Safety
CIA	Chemical Industries Association
CHAZOP	Control or (Computer) Hazard and Operability analysis
COMHAZOP	Computer program as an aid for HAZOP studies
ETA	Event Tree Analysis
FMEA	Failure Modes Effects Analysis
FRR	Facility Risk Review
FTA	Fault Tree Analysis
HAZAN	hazard analysis
HAZOP	hazard and operability study
HAZROP	Hazard, Reliability, and Operability Analysis
HDG	HAZOP-Digraph Model
HRA	Human Reliability Analysis
HSE	Health and Safety Executive
ICI	Imperial Chemical Industries
IPL	Independent Protection Layers
ISA	International Standards Association
MHA	Major Hazard Analysis
OSHA	Occupational Safety and Health Administration
PHA	Process Hazard Analysis
P&IDs	Piping & Instrumentation Diagrams
CBR	Case-Based Reasoning
DBMS	Database Management Systems
HMS	HAZOP Analysis Management System
VR	Virtual Reality
FL	Fuzzy Logic

Glossary

Accident: An unplanned event or sequence of events that results in undesirable consequence. An incident with specific safety consequence or impacts.

Availability: The ability of an item to be in a state to perform a required function under conditions at a given time interval, assuming that the required external resources are provided.

Bureaucracy: the combined organizational structure, procedures, protocols, and set of regulations in place to manage activity, usually in large organizations.

Consequence: The direct, undesirable result of an accident sequence usually involving a fire, explosion, or release of toxic material.

Consequence Analysis: The analysis of the effects of incident outcome cases independent of frequency or probability.

Event: An occurrence related to equipment performance or human action, or an occurrence external to the system that causes system upset.

Event Sequence: A specific, unplanned series of events composed of an initiating event and intermediate events that may lead to an incident.

Failure Mode: A symptom, condition, or fashion in which hardware fails. A failure mode might be identified as loss of function, premature function, or a simple physical characteristic.

Fault: The state of an item characterized by inability to perform a required function, excluding the inability during preventive maintenance or other planned action.

FMECA: A variation of FMEA that includes a quantitative estimate of the significance of the consequence of a failure mode.

Function: The normal or characteristic actions of an item.

Initiating Event: The first event in an event sequence and can result in an accident unless engineered protection systems or human actions intervene to prevent or mitigate the accident.

Item: Any part, component, device, subsystem, functional unit, equipment or system that can be individually considered.

Operating Time: The time interval during which an item is in an operating state.

Reliability: The probability of an item to perform a required function, under given conditions, for a given time interval.

Risk: The combination of the expected frequency and consequence of a single accident or a group of accidents.

Risk Assessment: The process by which the results of a risk analysis are used to make decisions, either through relative ranking of risk reduction strategies or through comparison with risk targets.

Risk Management: The systematic application of management policies, procedures, and practices to the tasks of analysis, assessing, and controlling risk in order to protect employees, the general public, the environment, and company assets.

Risk Measures: Ways of combining and expressing information on likelihood with the magnitude of loss or injury.

Safety System: Equipment and/or procedures designed to limit or terminate an accident sequence, thus mitigating the accident and its consequences.

Safety Operator : person who is in charge of ensuring safety before, during and after operation.

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Chapter I

GENERAL INTRODUCTION

General Introduction

1.1 General Overview of Research Problem

To compete in the ever – expanding global market as well as to meet increasingly tighter safety and environmental constraints, process industries are being compelled to ensure safer, operable and reliable plants and process that result in safer high-quality product in shorter time and lesser cost. Therefore, different approaches are needed that address all these requirements throughout the plant process from the eyes of safety personnel.

Safety personnel are individuals whose responsibility is to ensure safety before, during and after operations. Depending on country or companies, a different term is used to describe individual whose tasks involve safety management. Safety officer, safety operator, safety engineer and health and safety executive (HSE) are among the common designations for the personnel in charge of safety management. In this thesis, we will use the term safety operator. Unlike field operator, whose work task is running the operation, safety operator has to know all aspects of the operations to make safety decisions, layout safety procedures and other related tasks. In general, safety operator can be categories into two, depending on their overall task. By referring Figure 1.1, the first category is a safety operator whose main task is a field operator; while the second category is a safety operator who belongs to a safety department with task specifically on safety management. In general case of the first category, the most experienced and the most senior operators are given the responsibility to outline procedures for emergency. The advantage is that operators become expert on every aspect of the operation under his/her supervision. However, the expert operator is faced with over task which results in working tension. Technical know-how and the acquired experience will also be jeopardized incase the operator decide to leave the company. Japanese companies are a common example of companies using the first category of safety operator. In other countries like Europe, oil and gas companies have their own safety department which responsible for overall safety of the company. These safety operators are required to have the deep knowledge of every aspect of the company operations and as a result, they receive off site training such as offered by Occupational Health & Safety Advisory Services (OHSA) institute. The advantage of such training is that documentation - procedures manual are well organized. Invariably, this prevents knowledge and skill acquisition as every safety procedural step has been detailed thereby undermining the capability of the operator in responding to emergency risk operations. Consequently, acquiring operation skills in risk management is far from the field operator.

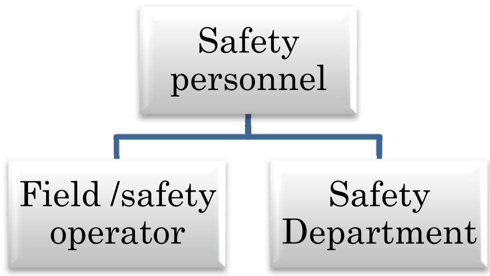

Fig 1.1 Safety personnel classifications.

Risk as defined by OHSAS is the product of the probability of a hazard resulting in an adverse event and the severity of the event. Most human activities involve specific risks. The risk profiles of industries change with time as certain hazards are overcome, new ones appear. The main hazards of the process industries arise from the escape of process materials, which may be inherently dangerous or become dangerous being present at high pressures and high or low temperatures. A review of worldwide chemical or chemical related incidents that have had major impacts on surrounding communities is summarized in table 1.1. This suggests the need for improved approaches to the handling of hazardous materials [1].

As chemical industries become increasingly complicated and automated, the gap between safety operators and processes becomes wider. Safety operators lose the ability to analysis real processes as field operator manipulate plants through control panels, which include switches, alarms, recorders, monitors, and many other instruments. It is difficult for them to understand all the knowledge about relevant processes and emergency situations. Accidents in chemical processes arise mostly from operator error [2].

To reduce these errors in operating procedures, effective analysis methods must be developed. In the past the objective of safety operator analysis was only to prevent direct damage and to reduce the loss of lives and property from accidents but at present, it includes the wider meaning of developing human resources and increasing the productivity, safety and efficiency of industries. The importance of safety operator education is emphasized now more than ever.

Process Hazard Analysis (PHA) has always been considered an important factor in staying competitive in a global economy. Safety operator need to remain up to date with the latest methods and technology. Most people would agree that safety training is important, but there is an obvious cost in developing or purchasing safety training. Companies also lose productive operator time while they sit through the training; not to mention travel costs if the training is not offered locally [3].

Safety Training should involve an introduction to basic hazards and plant procedures in which the flammability, toxicity and the corrosive properties of chemicals are discussed. Also the use of personal protective equipment, fire alarm systems and work safety processes should be incorporated. The safety operator should be assigned to a particular plant to work alongside an experienced operator, in order to receive practical instructions in all aspects of plant operations, including safety and emergency processes. These safety training methods in combination with available process hazard analysis can be used to help the safety operator to understand specialized aspects of process hazards such as emergency safety and permit-to-work systems.

Three-dimensional simulation systems allow users to navigate in any direction within a computer-generated environment, decide what actions to take and immediately see the impact of those actions [4]. These virtual reality systems allow safety operator to walk around the plant, see all the equipment that constitutes the process, have the possibility of starting, running and shutting down equipment and responding to error conditions without causing any damage to the equipment or harm to themselves.

Table 1.1: Selected major incidents

Incident	Impact
Flixborough in United Kingdom (1974) **Vapour cloud explosion**	28 fatalities on-site; $232 million damage; damage to homes off site
Seveso in Italy (1976) **Toxic material release**	Widespread contamination on-site and off-site
Bhopal in India (1984) **Toxic material release**	300 fatalities, $20 million damage, mostly offsite

Mexico City LPG (1984) **LPG Explosion**	2500 fatalities many others injured off-site
Chernobyl in Ukraine (1986) **Fire and radiation release**	31 fatalities; 300 square miles evacuated; widespread contamination
Sandoz warehouse Switzerland (1986) **Toxic material release**	Major impact on ecology of Rhine River
Shell Norco refinery in United States (1988) **Vapour cloud explosion**	7 fatalities on-site; neighbouring town evacuated; damage exceeded $50 million; widespread damage to homes off-site

The human and economic costs of accidents worldwide can be shocking. In 2004 industrial workplace accidents killed one person every two hours and injured one person every five seconds. The cost of accidents at work and occupational diseases ranged for most countries from 2.6 to 3.8% of Gross National Product [5]. Up to 85% of accidents can be traced back to human & organizational factors causes:

- *Unclear management structure, unavailability of information,*
- *Lack of coordination,*
- *Ineffective training,*
- *Procedure difficult to use,*
- *Inadequate investigation for the causes of most recurring problems,*
- *Deviations from safety procedures are among the main causes.*

Unfortunately, safety operators are the one who will be blamed for this. Safety operators' occupation description is direct or indirectly related to the above causes.

It is believed that virtual reality can be successfully applied to improve analysis and hazard awareness issues in the field of chemical engineering. Chemical Blue Chip Companies have utilized virtual reality technology for a long time for field operators training module. Virtual reality can offer the potential to immerse personnel into an interactive and well controlled virtual world containing simulated hazards. This may operate as an enhancement to existing process hazard analysis (PHA) method especially HAZOP. While HAZOP undeniably has successfully managed to mitigate major accident, HAZOP analysis done by human teams has the following shortcomings: time consuming, laborious, expensive and inconsistent. To solve these problems, various model and/or rule-based HAZOP expert systems have been developed during the last one decade [6]. These systems, however, can only address "routine" or process-generic HAZOP analysis. In the chemical process industries (CPI), "routine" HAZOP analysis roughly occupies 60-80% while "non-routine" or process-specific HAZOP analysis occupies 20-40%. Due to the lack of learning capability of the current HAZOP experts systems, the knowledge of non-routine analysis could not be formulated and reused for similar chemical processes, and the "non-routine" HAZOP analysis still needs to be addressed by human experts. The major problem with HAZOP expert system proposed in [1] is design to fit general plant instead of plant type specific. This leaves incompleteness of HAZOP analysis.

A normal practice of CPI is to record all near miss cases or accident cases for future reference. These cases sometime can be traced back from five to even ten years ago. In this dissertation, we propose a system that can manipulate and take advantages of this information in completing HAZOP analysis. Because of these cases are past histories they are more reliable compare to expert knowledge. We used risk factor as an indexing mechanism for setting cases priority in order to assist safety operator in deciding responses upon emergency.

From an interview with safety operators, we found several issues arise from the operator view point that never been discussed in past research in the safety domain. These issues are: Inadequate safety training, management bureaucracy, Miss looks and access limit.

Inadequate safety training, in the recent world economy parlance, does not imply that experienced employee had to be laid off or willingly quit for better salary pays. It has been a big problem for any industries that rely on the experience workers when to lose this valuable human asset. New hired field operator will learn from senior and more experience operators while in some chemical plant, virtual training or off-site training also available for them to accelerate the learning process. However, for safety operator, this kind of training is not widely available for them. Often, safety personnel solely rely on an old guide book for learning.

With regards to problem of management bureaucracy, in standard plant, process hazard analysis normally kept by the safety department or human resource department depending on production scale. Due to safety analysis documentation nature, the possibility that this documentation be revised or referred often is low. The troublesome procedure faced by the operator in terms of form filling, permission request for using or modifying leading obsolete analysis constitutes a bottleneck. The possibility of the revision of the documentation is only during a safety audit which is dependent on the plant management itself which is every quarter year to one year.

Prior to HAZOP analysis, preparation including brainstorming, site visit and information gathering are conduct. During the analysis itself, HAZOP team will use P and ID and their expert creative imagination to simulate the possible sequence and consequent. This action often results in overlooking mistakes where the location of real physical equipment is influencing the environment. The phenomenon is referred to as Miss looks in industrial operations. An example is, heat from heat exchanger may leak to a nearby container belonging to a totally different process line or overlapping pipes and equipments. This can only be noticed by being on the site while doing the analysis.

Consequently, the primary issues addressed by this research are to propose mechanisms and develop implementation of system to assist safety operator in managing safety information as well as use the information effectively during critical time.

1.2 Research Objectives

The overall aim of this work is to investigate and develop risk management system using virtual support and artificial intelligence techniques to improve safety analysis. We are focusing to assist safety operator to manage safety information, especially on how to reuse past near miss and accident cases to increase safety awareness. Deciding a risk level for scenario was never an easy task for safety operator. Qualitative factor that contribute to risk factor are converted to quantitative value therefore helping safety operator to make the right decision to react judging by the risk value. We facilitate decision making by proposing visual support in a form of 3D model and virtual reality simulation that can be molded in such a way that can penetrate safety operator mind. This has involved the development of emergency scenarios for application in the chemical process industry during hazard and operability analysis (HAZOP). It is believed that the use of such systems will increase safety awareness and knowledge of safety procedures and therefore hopefully lead to reducing the plant accident rate.

The specific objectives can be classified in the following way:

- To facilitate risk estimation for safety recommendation.
- To integrate intelligent system into HAZOP to give learning capability to traditional HAZOP.
- To improve the HAZOP analysis quality continuously during practice.
- To take the advantages of other safety information such as near miss and accident cases to assist safety analysis.
- To investigate the general suitability and potential of virtual reality technology for safety audit application in the field of chemical engineering
- To develop a range of virtual chemical plants environments in which to train safety operators for a range of different scenarios
- To identify components and characteristics of the HAZOP processes to be simulated in the virtual world for adequate realism and training acceptance
- To develop a complete but easy to use system of HAZOP analysis for a range of chemical plant scenarios.

1.3 Research Methodologies

Hazard and Operability (HAZOP) which undoubtedly is the most widely used process hazard analysis is chosen to provide safety analysis information. Process Safety Management, within which the HAZOP discipline is a key component, has been unquestionably successful in reducing the incidence and mitigating the consequences of major accidents in all industries dealing with toxic, reactive, flammable and explosive substances. There has not been quite another Flixborough much less a Bhopal type incident since the widespread advent of these procedures. This means protecting the communities adjacent to such facilities as well as the workers within them. Incompleteness and inconsistence of HAZOP analysis is covered by using proposed Fuzzy-CBR method - a hybrid of fuzzy logic and case base reasoning technique used in this research for indexing and retrieving similar cases for a future analysis. In safety domain, risk factor is very important in making decision. As we are in the safety domain and not soft-computing domain, the proposed approach enables us to apply fuzzy and case base reasoning for separate knowledge representation. A proportional risk assessment is suggested to be indexer for the case base, where case with higher risk value is priorities for action. While HAZOP analysis information, near miss, accident case and past scenario are knowledge case base representation. Virtual reality is responsible for bringing safe analysis experience to safety operator without endanger or giving negative impact on overall plant operability. The integration of these three methods as shown in Figure 1.2 are applied into the proposed HAZOP analysis management system, and virtual HAZOP analysis system produces an intelligence risk management tools for safety personnel. HAZOP analysis management system is used to manage and manipulate safety information while virtual HAZOP analysis assists safety operator to perform HAZOP analysis with virtual reality support.

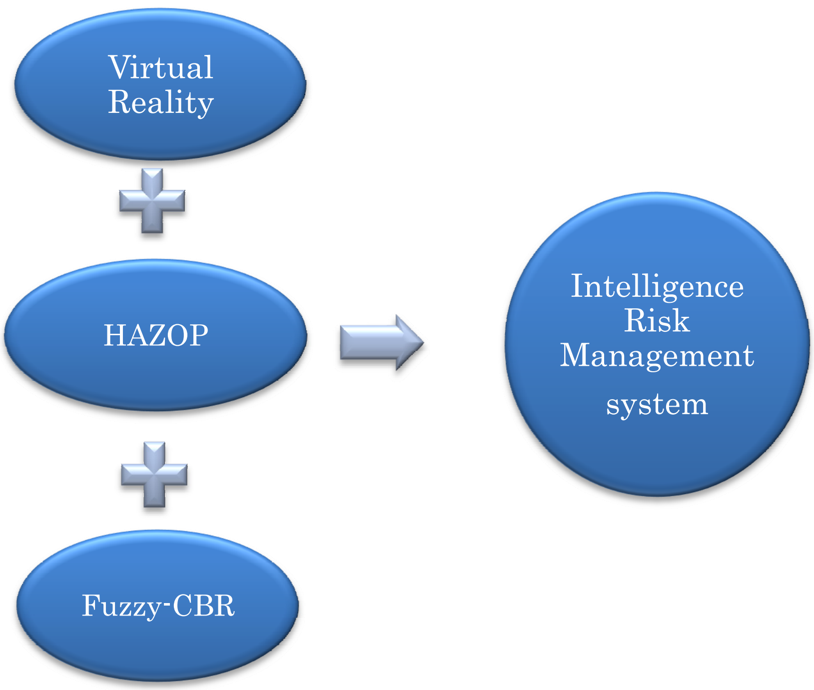

Fig. 1.2 Intelligent Risk Management System

Figure 1.3 shows the relationship between proposed methodologies. Information from HAZOP and previous safety cases such as near miss cases are managed and manipulated by fuzzy-CBR. Similar case within case base is compared to HAZOP case. If suitable, the case from case base will be used to improve HAZOP case description. Fuzzy-CBR is dynamic while the rules of decision making is not static and thus can be adjusted according to operator need. For example, to retrieve and reuse case from case base, similarity index must be between 0.8 and 1.0, which mean almost the same. However, case base with a small number of cases can be benefited by widening the similarity index from 0.5 to 1.0, which will include more results. Accurate and high precession is achieved by indexing and matching only the most similar cases. This retrieved cases are associated with keyword, which used by virtual reality scenario as parameters. This scenario will be used to help safety operator visualizes HAZOP scenario.

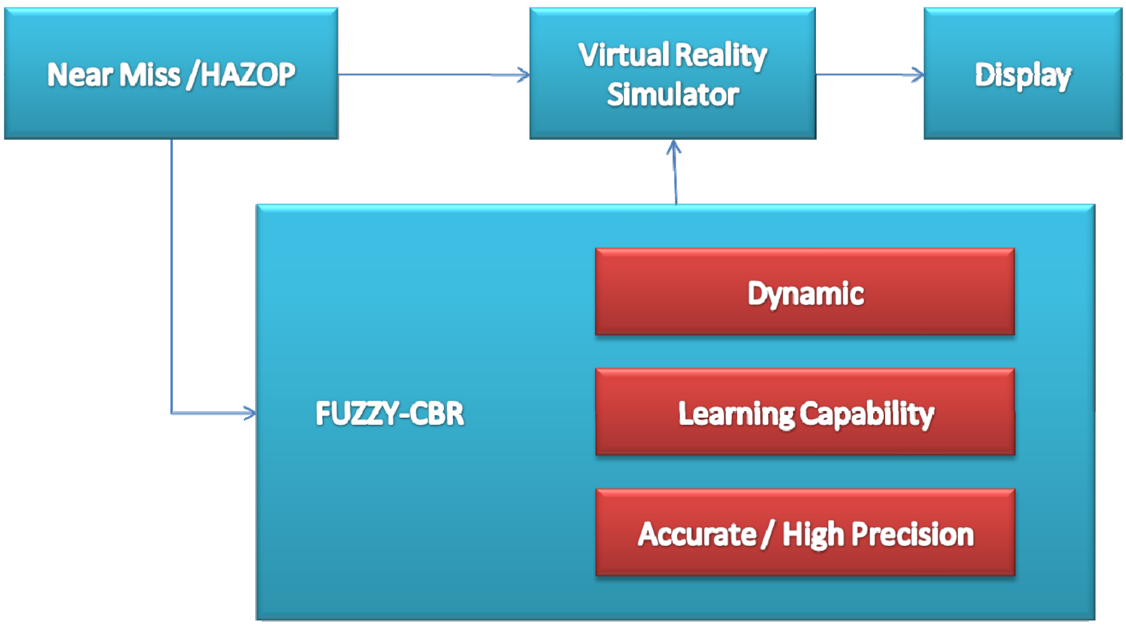

Fig. 1.3 Relationship between methodologies

1.4 Research Significance

This research work contributes to the HAZOP analysis in chemical process industry using intelligence system. As mentioned before, the quality of HAZOP analysis depends on the knowledge and experience of the HAZOP team. Therefore, incompleteness and inconsistence usually are the drawbacks with regards to

HAZOP done by human teams. Given the enormous amounts of time, efforts and money involved in performing HAZOP, there exists considerable incentive to develop intelligent systems for assisting the process hazards analysis of chemical process plants. An intelligent system can reduce the time, efforts and expense involved.

Learning to predict and prevent chemical process hazards is an essential part of the safety operator education. However, taking advantages of available safety information was not a simple task. While others similar research focusing on safety training for field operator, this research is focusing on assisting new-to-experience safety personnel to be able to handle emergency situations effectively and at the same time able to profitably minimize the negative impact on life in case of unavoidable accident incidence. The light weight and portability of developed system expected to mould safety operator mind set to a new level. Compare to field operator, safety operator unable to fully master every aspect of the plant. Without real situation emergency training of every part of the plant, it is difficult for safety operator to make important decision regarding safety and develop safety procedures based only on previous PHA. Developed risk management system in this research is hoped to assist safety operators to be able to see beyond their imagination.

The unique contributions of this research work are as summarized below.

- This work combines virtual reality simulation with HAZOP for providing virtual model support in assisting HAZOP analysis. The integrated system now helps HAZOP team to see different perspectives that were impossible with the pipe and instrument diagrams (PID). Hitherto, there has not been a similar work combining virtual reality simulation with HAZOP analysis in this manner.

- Fuzzy-CBR method - a hybrid of fuzzy logic and case base reasoning technique is used in this research for indexing and retrieving similar cases for a future analysis. This helps in overcoming the incompleteness and inconsistence of conventional

HAZOP analysis method. In this new integrated system, safety information is stored in single case base where accident data from past long years can be easily reused. The proposed information management system serves as a supplement for continuously improving quality of HAZOP analysis during practice.

- ❖ The virtual analysis environment proposed in this thesis interfaces with various safety information modules. This newly designed user interface system provides support for retrieval of information on pipe and instrument diagram from database. The new system is different from common virtual reality simulation where users interact with and immerse into the system during practice.

It is worth noting that consistence and completeness are critical in HAZOP analysis because neglect of any potential hazard may even result in disasters. Investigation results of past industrial accidents, e.g. the tragic BP Texas city plant accident occurred in March 2005, have proven that poor quality of PHA is a major root cause of accidents occurred in the CPI.

1.5 Justification for the research studies

Risk management undeniably is a crucial part in any industrial system/plant involving hazard materials and processes. HAZOP, the well established risk assessment and process hazard analysis method, require different aspects of improvement to increase safety information completeness and usability. There is a need for effective utilization and management of HAZOP information as these safety information are required as long as the plant operate. In safety domain, risk is used as the key in prioritizing action in ensuring process safety. However, deciding a risk level for a process/scenario is a time consuming task. A team of safety analysts would agree a process is a high risk process, but how high the risk is still debatable. Is it a high risk, a very high risk or an unacceptable kind of risk is difficult to be agreed by everyone in the team? This risk level will determine what action ought to be taken. Deciding the risk level would consume time even for a single process. Hitherto, there is no method to model risk that suits every safety operator decision. Risk matrix only addresses the direct byproduct of risk component which will not address safety operator rules. Therefore, a concept of fuzziness is required to govern the rules in risk estimation. Hitherto, virtual aid such as virtual reality or virtual model has never been used to facilitate HAZOP analysis. Virtual aid is established to be a profound medium in current process safety training for operators. Low cost per performance of this technology enables everyone to enjoy the virtual aid benefit. When these two concepts are combined, it is expected to increase HAZOP expert system efficiency. Fuzzy-cbr proposed in this thesis with virtual aid; provide tools to assist HAZOP study with reliable reasoning for analysis result.

1.6 Organization of the Dissertation

Chapter one is the general introduction which consists of the research problem overview which highlights the weakness in present chemical safety analysis and consequently leads to setting research objectives about improving overall HAZOP analysis experience. The impact of final product towards enhancing plant safety is suggested in this Chapter. Chapter two discusses available literature relating to hazards and safety in the chemical industries. Chapter three deals with the theoretical framework in which Hazard and operability (HAZOP) methodology is employed as a foundation for Process Hazard Analysis (PHA) technique. Modifications of the conventional HAZOP towards more versatile and intelligent PHA used in this research are explained. Following is the artificial intelligence hybrid methods of fuzzy logic and case base reasoning, method of analogical reasoning which is common and extremely important in human cognition is introduced. Here we explain how fuzzy-CBR is applied in the proposed system. Chapter four is on the development of intelligence risk management system – an intelligent HAZOP Analysis Management System which treats in detail the development and work flow of HAZOP Analysis. Introducing the service of web based interface enable portability and easiness when performing HAZOP analysis, whether for record tracking, updating/ revising or even new analysis record. Following is Virtual HAZOP training system which presents three dimensional models to be used for safety training. Enhancing this safety training is an integrated HAZOP database which helps in retrieving most possible and real scenario. This is achieved by using operator selection and comparing it to previous scenario. Parameters of previous scenario are extracted and reused by the system to retrieved new scenario. Chapter five considers the application to industrial safety management and presents a case study of Vacuum Liquid Gas Hydrodesulphurization model with highlights of some of the issues and problems relating to operation especially issues relating to plant operator training and safety. The final part of this dissertation is the Conclusions and Future Research Work. It draws the conclusions arising from this work and states some recommendations for the use of HAZOP, fuzzy-CBR and virtual reality in chemical engineering industries and in chemical engineering education. The possible future research works and work in progress is reviewed.

Chapter II

PRELIMINARIES AND BASIC CONCEPTS IN RISK MANAGEMENT

Preliminaries and Basic Concepts in Risk Management

2.1 Introduction

This chapter discusses available literature relating to hazards and safety in the chemical industries. It also provides a short description of a number of incidents in order to show the consequences of such events. Furthermore, it considers some of the main hazards in the chemical industries and discusses the process safety issues while indicating methods to avoid and anticipate catastrophic events for chemical plants. The definitions of risk and safety management stated in this chapter outline the differences. In chemical process industries, safety management systems (SMS) are more preferred in terms of overall purpose. Risk management system proposed in this thesis has never been discussed in any literature of safety concern. However, similar systems employing risk assessments to ensure safety are available with different process hazard analysis (PHA).

2.2 Safety in Chemical Industry

2.2.1 Safety Culture

The increasing size and complexity of industrial processes creates increased scope for major disasters, leading to greatly increased public concern about industrial safety. The last century has seen series of such disasters worldwide.

There is a widespread concern over the hazards of chemicals, not only to those who work with them but also to the environment and the general public. Unless a chemical plant is well designed, it is very difficult to prevent dangerous materials from releasing. Safety in chemical industries cannot be treated as a separate subject such as design, production or maintenance, but depends inextricably on both the technical competences and safety awareness of all staff and employees [7]

Process safety has advanced over the last thirty years. In the 1970s the introduction of a number of checklists, such as the development of HAZOP studies and the Dow's Fire and Explosions Index constituted a major breakthrough in the history of industrial safety. Dow's Fire and Explosions Index is a checklist method of hazard identification, which provides a comparative ranking of the degree of hazard posed by particular design conditions and its third edition is published as a manual by the American Institute of Chemical Engineers [8] In the 1980s came an increase in the regulation of chemical plants which culminated in an overall socio technical and audit approach covering all aspects of design, operation and management of chemical plants [9].

The extent to which health and safety thinking is reflected in business activities and decision-making is an important determinant of effectiveness. The practical implications of safety policies must be thought through so as to avoid conflict between the demands of policy and other operational requirements. Management decisions were insufficient attention or weight given to health and safety leading to [9]

- ❖ Unrealistic time scales for the implementation of plans which put pressure on people to reduce supervision;
- ❖ Work scheduling and rosters which fail to take account of problems of fatigue;
- ❖ Inadequate resources being allocated to training;
- ❖ Organizational restructuring which places people in positions for which they have insufficient experience;
- ❖ Jobs and controls systems which fail to recognize or allow for the fact that people are likely to make mistakes and might have difficulties communicating with one another.

Beyond the technical issues, the influence of human error in the chain of events leading to accident and failures in the organization as well as management of safety issues, emerge strongly from inquiries. The most detailed set of safety rules and procedures are meaningless unless they are implemented and kept under regulatory review. It is essential that the immediate causes of accidents are seen in the wider context of the organization and management climate in which they occur and it is important to focus on the design of systems and equipment in order to minimize the potential for human error.

The twelfth edition of Marsh and McLennan's annual review analyzes the largest chemical industry losses, which refer to the cost of injuries and damage, since 1959 [11].Most of these losses occurred in oil refineries while the highest average losses occurred in natural gas processing plants. Mechanical failure of equipment was the most frequent of these causes. Most of these could have been avoided by proper inspection and maintenance. The next most frequent cause was stated to be operational errors, which could have been avoided by providing more effective training of operators.

Piping systems, which include hose, tubing, flanges, gauges, strainers and expansion joints were the most frequent origin of loss. The low frequency of losses originating at pumps and compressors was unexpected [8]

The public no longer regards processes industries as something remote from them, run by operators with an incomprehensive language of their own, but they consider them capable of giving rise to events which may directly affect ordinary people. Public opinion in the majority of countries is concerned about industrial accidents and their effects and will not tolerate fatalities on the scale that once existed.

2.2.2 Hazard in Chemical Industries

A hazard is a physical situation with a potential for human injury, damage to property, damage to the environment or some combination of these. Hazards do not only involve process plant and associated materials but also major structures, and materials, which release ionizing radiation [7]. The hazards, which are commonly identified in chemical industries, can be grouped in several different categories. These categories include electrical hazards, health and occupational hygiene hazards, chemical reactions hazards, explosion and fire hazards, operational and control hazards and hardware hazards.

2.2.2.1 Electrical hazards

Electricity is a safe and efficient form of energy and is a convenient source for lighting, heating and power. The proper use of electricity is not dangerous but if out of control, can cause harm to human in form of electric shock. In the United

Kingdom every year up to fifty people may be killed and up to a thousand are injured at work as a result of electrical accident [11].

2.2.2.2 Health and occupational hygiene hazards

Health and occupational hygiene is the science of anticipating, recognizing and controlling workplace conditions that may cause workers' injury or illness. Major workplace risks can include chemical, biological, physical and ergonomic hazards. Harmful chemical compounds in the form of solids, liquids and gases exert toxic effects by inhalation, absorption or injection. Airborne chemical hazards exist as concentrations of mists, vapors, gases, fumes or solids. The degree of worker risk to any given substance depends on the nature and potency of the toxic effects and the magnitude and duration of exposure. Information on the risk to personnel from chemical hazards can be obtained from a material safety data sheet, which is a summary of the important health, safety and toxicological information on the chemical or mixture's ingredients [12].

Biological hazards include bacteria, viruses and other living organism that can cause acute and chronic inflection by entering the human body. Occupations that deal with plants or animals or their products or with food processing products may expose workers to biological hazards. It is essential for an industry to provide proper ventilation, appropriate personal protective equipment such as gloves and respirators and adequate infectious waste disposal systems [12].

Physical hazards include excessive levels of electromagnetic radiation, noise, illumination and temperature. In occupations where there is exposure to radiation time distance and shielding are important tools in ensuring worker safety. Danger from radiation increases with the amount of time one is exposed to it. Hence, the shorter the time of exposure, the smaller the radiation danger will be. Distance, also is an available tool in controlling exposure to radiation and the radiation levels from some sources. It can be estimated by comparing the squares of distance between the worker and the source. Shielding involves the placing of protective materials between the source and the person to absorb partially or completely the amount of radiation [13].

Noise, another significant physical hazard can be controlled by installing equipment and systems that have been engineered, design and built to operate quietly or by enclosing or shielding noisy parts and by providing hearing protective equipment to personnel.

The part that lighting plays in ensuring a safe and healthy place of work is increasingly recognized. The standard of luminance required depends on the visual efficiency necessary for the tasks involved and the decisions should be based on the recommendations of the code for lighting produced by Illuminating Engineering Society [12].

2.2.2.3 Chemical reaction hazards

A chemical reaction that goes out of control and runaways can create a serious incident with the risk of injury to people and damage to property and the environment. The reactivity of chemicals in process industries is a potential process hazard. The chemical reactivity of any substance should be considered in the following contexts [8].

- Its reactivity with atmospheric oxygen
- Its reactivity with elements and compounds with which it is required to react in the process
- Its reactivity with water
- Its reactivity with itself
- Its reactivity with other materials with which it may come in contact unintentionally in process
- Its reactivity with materials of construction

Most hazards are caused by reactivity with atmospheric oxygen and the majority of problems arise from oxidative self-heating. In most continuous organic chemical reactors, which operate under pressure, air is automatically excluded. In some cases more stringent measures are taken not merely to prevent air entering the plant while it is running but also to remove it before the plant starts up and to remove oxygen from materials entering the process.

The reactivity between reactants in processes must be carefully studied and considered when a reaction system is designed, both from thermodynamic and kinetic aspects. From the safety point of view, it is extremely important whether a reaction is strongly exothermic, moderately exothermic, mildly exothermic, thermally neutral or endothermic. Exothermic reactions are usually difficult to control in continuous process involving gases and liquids and are most difficult to control in batch processes where the entire charge of reactants is added at the start of the batch, where both liquids and solids are present. An exothermic reaction can lead to thermal runaway, which begins when the heat produced by the reaction exceeds the heat removed. The rates of most reactions increase rapidly with temperature leading to the danger of their getting out of control, with large rises in temperature and pressure and loss of containment of the process material.

2.2.2.4 Explosion and fire hazards

The term explosion is used to describe incidents where there is a rapid release of energy, which causes a significant blast wave capable of causing damage. The gases in a chemical explosion, which is formed as a result of chemical reactions, expand rapidly due to a sudden increase in temperature, thereby increasing the pressure relative to the surrounding atmosphere. The damage which arises from an explosion may be caused either by the effect of a blast wave or by projected fragments or items of equipment. All chemical explosions are very fast; they give out heat, and make a loud noise. They fall into two classes:

- Explosive deflagrations, which are caused by chemical reactions, which are passed through the deflagrating materials at well below sonic velocity. They develop an appreciable pressure producing a blast wave with the potential to damage and the burnt products move in the opposite direction from that of combustion wave.
- Detonations are caused by very rapid chemical reactions which pass through the exploding materials at speeds of 1-10km/s. High pressures are developed and the burst products move in the same direction as the combustion wave.

Explosives, which normally detonate, are termed high explosives such as TNT (trinitrotoluene) and have high shattering power even when unconfined.

Fire is a process of combustion characterized by heat or smoke or flame or any combination of these.

2.2.2.5 Operational and control hazards

There have been a number of recent and well-publicized accidents in which human error has played a prominent part. For example, in Texas City in 1969 the operators opened an escape valve in the overhead product line of a butadiene plant which was placed on total reflux whilst other parts were being serviced. As a result an unstable compound, vinyl acetylene, concentrated in the bottom of the column. Eventually two tones of vinyl acetylene in the liquid phase detonated, scattering large pieces of the column up to 900 meters and the fire burned for 60 hours [14].

In order to understand the contribution of human behavior to the risk of accidents it is essential to examine the errors people make and what leads to such errors. The reduction of human error probability can lead to a reduction in the probability of accidents in chemical industries.

A useful classification framework identifies the human errors as slips-lapses, mistakes or violations. Slips or lapses typically occur through lack of attention or from stressful situations with the result that individuals fail to achieve what they intend to do. Slip or lapse human errors include forgetting to turn off power, becoming inattentive to important safety checks or forgetting important steps in work procedures, which may cause equipment damage [13].

Mistakes can result from incorrect decisions, poor communications and infrequently practiced operations. Typical mistakes include failure to appreciate the dangers of equipment and materials used, misunderstanding of operational procedures and emergency situations or failure to realize the implications of a process plant. Individual or team training is the most effective way to reduce these mistakes. Virtual reality training systems can help trainees to learn from their mistakes without causing any damage to equipment or themselves.

Violations are deliberate decisions to break agreed procedures. They can be associated with a steady drift into unacceptable attitudes, or can be deliberate acts by a workforce to adopt unsafe and unapproved practices. Some violation human errors include the deliberate use of unauthorized lifting equipment, the breaking of rules for an electrical unit or deviation from permitted work process. The study of the relationship between employees and the equipment with which they work in parallel with the physical environment in which man-machine system operates is extremely important for the safe and effective operation of process industries.

2.2.2.6 Hardware hazards

Even in the best designed machinery, plants failures can occur. If the cause of failure is investigated, the repetition can be normally prevented. Modes of failure relate to the type of stress under which the component has been working and the characteristic features of failures due to tension, compression, shear and torsion are well known. Sometimes the failure is related more to the operating process than to the stress. When in particular, there is repeated stress cycling of a part, it can subsequently leads to fatigue failure [13].

2.2.3 Risk Assessment and Hazard Identification

Risk is the likelihood of a specified undesired event occurring within a specified period or in specified circumstances. It may be either the frequency (the number of specified events occurring in unit time) or the probability (the probability of a specified event following a prior event), depending on the circumstances [8].

Cooper and Chapman [10] define risk as the exposure to the possibility of economic or financial loss or gain, physical damage or injury, or delay, as a consequence of the uncertainty associated with pursuing course of action.

A further definition of risk, which is used as the basis of many risk assessment techniques, is similar to the one quoted by Horton [13] and says that the term risk is used to cover the combination of an unfavorable result and the possibility of its occurrence. It is used as the recognition of future uncertainty and implies that a given set of circumstances has more than one possible outcome.

2.2.3.1 Risk Assessment

Improvement in safety performance has often meant seeking to reduce the number of potential accidents. The process of risk assessment attempts to minimize or eradicate the probability of an accident occurring. Risk assessment has been used informally throughout history, whenever there is a decision to be made, or an action taken there is always an associated risk. The outcome of the decision is in the future and is therefore uncertain, different actions might mean different outcomes while some outcomes might be more desirable than others.

The wide variety of industrial activities has created a wide variety of different definitions and hence a blur between terms such as risk assessment, risk analysis and risk estimation. Jones [8] gives one of the clearest definitions:

- ❖ Risk assessment is the quantitative evaluation of the likelihood of undesired events and the likelihood of harm or damage being caused together with value judgments' made concerning the significance of the results.
- ❖ Risk analysis is an imprecise term that infers the quantified calculation of probabilities and risks without taking any judgments' about their relevance. As such it is equivalent to risk estimation.

The assessment of risks is necessary in order to identify their relative importance and to obtain information about their extent and nature. This will help in deciding on methods of control. Knowledge of both areas is necessary to identify where to place the major effort in prevention and control, and in order to make decisions on the adequacy of control measures [12]. Assessing risks will demand a thorough knowledge of all the activities and working practices. The knowledge of the employees and safety representatives involved often proves valuable. Competent people should carry out risk assessments, and professional health and safety advice may be necessary in some cases [12].

Determining the relative importance of risks involves deciding on the severity of the hazard and the likelihood of occurrence. There is no universal formula for rating risk in relative importance but a number of techniques have been developed to assist in decision-making.

2.2.3.2 Hazard Identification

The identification of hazards is the vital element of risk analysis and its effectiveness requires a deep understanding of the process, which is clearly dependent on the knowledge, experience, engineering judgments and imagination of the team to whom the task is assigned. It can also be seen as a useful discipline in its own right. For example, identifying hazards at an early stage will often allow them to be eliminated by a modification of the design or system [13]. Hazard identification is the process of determining what hazards are associated with a given operation or design, as it is operating. In existing operations, hazard identification is performed periodically to determine the implications of changes to process knowledge and to recognize changes to process, equipment and materials.

2.2.3.3 Reliability and failure analysis

Reliability can be defined as the probability that a component will perform a required specified function. This may depends on the components success in commencing to operate when required, continuing to operate subsequently, not operating on demand, and not continuing after the demand has ceased. The reliability of a multi-component system depends on the incidence of failures in the components. Data on such failure may be fitted to statistical distributions for use in reliability analysis [8].

2.2.3.4 Fault Tree Analysis (FTA)

Fault Tree Analysis is the technique that can be used to determine failure sequences and probabilities in complex systems. In a FTA a logic diagram or "fault tree" is developed to determine the causes of an undesired event. A fault tree may be constructed for virtually any undesired event that can occur within the system. Once an undesired event has been selected, it is shown at the top of the diagram and all the circumstances that lead to it are determined by reasoning backward from this event. These circumstances are then broken down into events that can produce them, and so on. The process is continued until all events that can ultimately lead to the undesired event are identified. Special symbols are used in FTA to represent events and their logical relationships. Circles, rectangles, diamonds and house-shaped Figs are the symbols which are used for events and indicate certain characteristics about them. Other symbols, called "logic gates" show the manner in which events at one level of fault tree combine to produce an event at the next higher level [8].

2.2.3.5 Failure Mode and Effect Analysis (FMEA)

Failure Mode and Effects Analysis is based on identifying the possible failure modes of each component of a system and predicting the consequences of the failure. In this procedure each item used in the system, which might include the people, equipment, materials, machine parts or environment, is listed on an FMEA. The analyst should consider the exact modes in which each item can fail. For example if a control valve fails to open it could result in too much pressure or the wrong ratios of flow [8]. The analysis is continued by determining the effects of each failure combination. Both the effects on other items within the system and those on overall system performance are considered and evaluations are then made concerning the seriousness of each failure or failure combination. Finally, the means of detecting each failure is determined and any additional remarks regarding the failures are recorded [6].

2.2.3.6 Hazard and operability analysis (HAZOP)

The most widely known technique is that published by H.G. Lawley and later by the Chemical Industries Association in the United Kingdom under the title "A guide to hazard and operability studies" [7]. Hazard and operability studies can be applied to existing process plants, in particular when modifications are being considered, but are most effective when carried out at a design stage where a wide range of possible actions still exist. The method uses guidewords such as "too much" and "too little", which can be applied to the process parameters to generate "what if" questions. The guidewords that are used must be relevant to the stage of design and must be sufficiently comprehensive to be capable of identifying the hazards involved. While this method can be used without direct reference to engineering standards, it requires a broad documentation of the points studied to demonstrate the quality of the study. Experience has shown that this technique is most effective when carried out by a team of designers, operators, and other specialists as appropriate, at a series of study meetings [6].

2.3 Review of Risk Management Systems

Intensive search of risk management system in safety domain give almost no concrete result. While risk management in other domain such as financial, give many well established systems such as credits risk management system. Risk management and safety management are used in various ways and are often seen as identical. The IEC-standard [15] defines *Risk management as the systematic application of management policies, procedures and practices to the tasks of analyzing, evaluating and controlling risk.*

In several types of industry, the word "safety" is preferably often used. *Safety management may be defined as the aspect of the overall management function that determines and implements the safety policy. This will involve a whole range of activities, initiatives, programs, etc., focused on technical, human and organizational aspects and referring to all the individual activities within the organization, which tend to be formalized as Safety Management Systems (SMS).*

In both these definitions, there are points of departure with regards to the policy of the company. That is in line with both quality and environmental standards. An example [16] is the environmental management system which is a part of the overall management system that includes organizational structure, planning activities, responsibilities, practices, procedures, processes and resources for developing, implementing, achieving, reviewing and maintaining the environmental policy.

These three definitions are based on the existence of policy, consequently there is no safety management if a policy is lacking. All the three are also normative, saying how it shall be done. Such definitions might be acceptable in high-risk industries, where such practices are common and compulsory.

However, many companies do not have a formulated policy (especially SME), but they have safety management to deal with their hazards, in one way or another. Accordingly, there is a need for a comprehensive and descriptive definition. One suggestion for a simple definition of occupational health and safety management—a systematic way of managing the occupational health and safety risks of a company [16].

Nevertheless, management can exist without being "systematic", which is related to some kind of norm. This leads to a suggestion of a simple definition: Safety management as a way of managing the hazards (safety risks) of a company.

2.4 Summary

The dangerous nature of the chemical industry and the accidents, which had occurred in the past, in particular those caused by human errors, are placing increasing emphasis on improving safety training on chemical process plants. There is a need for continuous updating and upgrading of chemical process education and training methods. As automation and mechanization increase in complexity, the human interface with systems becomes critical if safe and effective performances are to be achieved. The term risk management system proposed is not common in safety domain. Chemical process industries and similar fields prefer the safety management system to extending the process of managing activities, initiatives, programs, etc., which focused on technical, human and organizational aspects and referring to all the individual activities within the organization. Risk management system used in this thesis refer to the systematic application of management policies, procedures and practices to the tasks of analyzing, evaluating and controlling risk to assist safety operator.

Chapter III

THEORETICAL FRAMEWORK

Theoretical Framework

3.1 Introduction

In the previous Chapter we stated problem faced by safety operator in the process of safety knowledge acquisitions. We respond to the magnitude of this challenge through the creation of a technology allowing safety factors expertise to be widely available to safety personnel by embedding a Virtual environments experience during safety analysis. In order to achieve this objective, a widely used hazard and operability study (HAZOP), which unquestionably is successful in reducing hazard incidents by mitigating the consequence of major accident in the industrial process facilities, has been chosen as a safety analysis method. We improve the existing HAZOP analysis by incorporating an artificial intelligence method, fuzzy-CBR, thereby giving the traditional HAZOP an ability of self learning. Incompleteness of HAZOP analysis are solved by adding all available safety information such as near miss case and previous accident cases into HAZOP using proposed reasoning method. Fuzzy-CBR, a combination of two well-known techniques for imbedding intelligence system is used in this research for two reasons. 1) Fuzzy logic has ability to help safety operator in translating linguistic risk component such as probability and severity of harm into risk value that can be used to decide actions priority. 2) CBR as a reasoning technique provides solid ground that decision are made based on real situation from past and not just another mathematical assumption.

A risk estimation technique which we call proportional risk assessment is proposed for calculating quantitative value of risk to provide a logical system for safety operator to set priorities for attention to hazardous situations. This value is used as a weight for case representation in case base. The proposed idea of assisting traditional HAZOP analysis process from using P&ID (Pipe and Instrument Diagram) and imaginative thinking to use recent Virtual technology.

This research has been inspired by VIRTHUALIS project which suggests implementation of safe analysis into virtual environment. VIRTHUALIS is the largest European Research Project of Industrial Safety, which aims at producing an innovative technology that integrates Virtual Reality and Human Factors methods, with the objective of improving safety in production plants and storage sites. The VIRTHUALIS Project (Contract no. NMP-515831-2) started on 1st May 2005, and are set out to run for four years. A network of European experts in the Human Factor (HF), Virtual Reality (VR) and Process Industry domains have been clustered in centers of references in order to produce fit-for-the-purpose tools. 28 Partners from 12 different European countries are currently taking part in the Project. The overall objective of the VIRTHUALIS project is to reduce hazards in production plants and storage sites by addressing end-users' practical safety issues through the development of an affordable and accessible technology and related tools. The new technology will be achieved by merging Human Factors (HF) knowledge and Virtual Reality (VR) technologies. [17]

3.2 HAZOP

The foundation of HAZOP analysis of industrial process operations addresses the questions: what could go wrong, how would we know and what could we do about it? Process Safety Management, within which the Hazard and Operability (HAZOP) discipline are a key component, has been unquestionably successful in reducing the incidence and mitigating the consequences of major accidents in all industries dealing with toxic, reactive, flammable and explosive substances. There has not been quite another Flixborough much less a Bhopal type incident since the widespread advent of these procedures. This means protecting the communities adjacent to such facilities as well as the workers within them.

The concept of HAZOP study first appeared with the aim of identifying possible hazards present in facilities that manage highly hazardous materials. The purpose was to eliminate any source leading to major accidents, such as toxic releases, explosions, and fires. However, over the years, HAZOP's application readily extended to other types of facilities because of its success in identifying not only hazards, but also operational problems. Thus, HAZOP was adopted for medical diagnostic systems, road-safety measures, and hazard analysis in photovoltaic facilities, among others. This diversity of usage illustrates how HAZOP has been considered as a powerful technique to improve many kinds of systems. There has been continuous progress over the years in using HAZOP and major publications as in Figure 3.1, highlight its success and consolidation as the most systematic, rigorous, though, and universally used hazard identification technique.

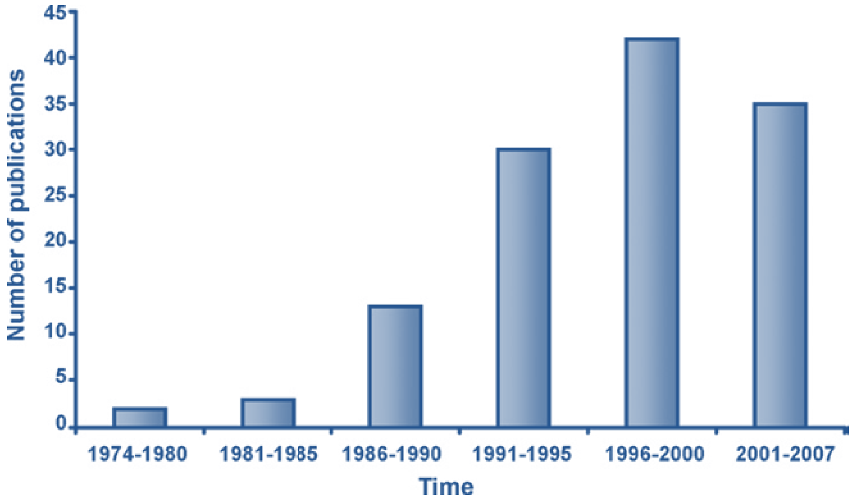

Fig. 3.1 Trend of related-HAZOP publications

Over these years, improving HAZOP by imbedded experts system and automating it stimulates most researcher interest as shown in Figure 3.2; this trend prompts this research in seeking the effectiveness of automated HAZOP. From reviewing past automated HAZOP systems including the system developed by previous researchers in this laboratory; we conclude that an assisted HAZOP analysis would be more efficient and reusable due to easy adaptation for plant specification. This will be elaborated in the following section. First the core concept of hazard and operability analysis itself will be reviewed.

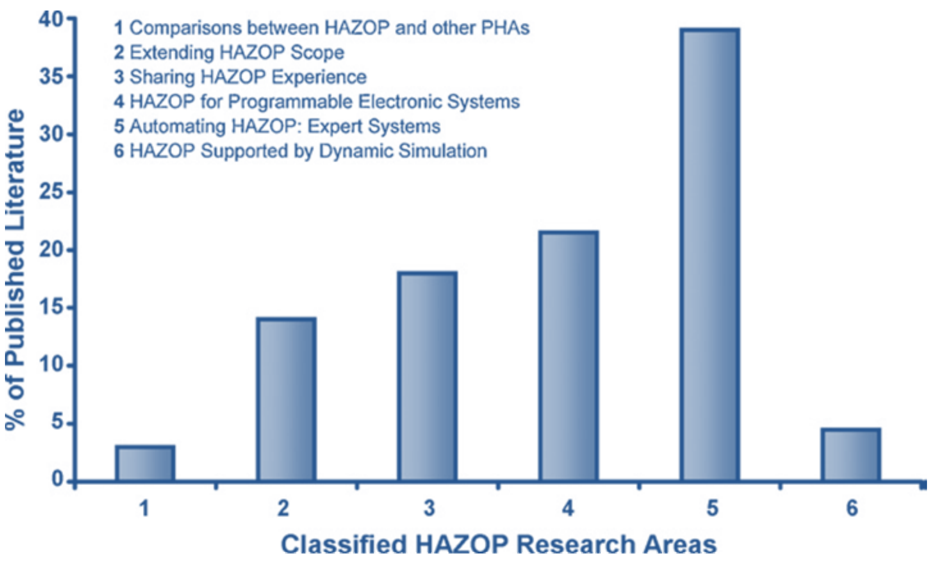

Fig. 3.2 HAZOP research lines proportion.

3.2.1 Hazard and Operability analysis

The HAZOP process is based on the principle that a team approach to hazard analysis will identify more problems than when individuals working separately combine results. The HAZOP team is made up of individuals with varying backgrounds and expertise. Aside from safety operator, the expertise including field operator is brought together during HAZOP sessions and through a collective brainstorming effort that stimulates creativity and new ideas, a thorough review of the process under consideration is made.

The HAZOP team focuses on specific portions of the process called "nodes". Generally, these are identified from the P&ID of the process before the analysis begins. A process parameter is identified, say flow, and an intention is created for the node under consideration. Then a series of guidewords is combined with the parameter "flow" to create deviations. For example, the guideword "no" is combined with the parameter flow to give the deviation "no flow". The team then focuses on listing all the credible causes of a "no flow" deviation beginning with the cause that can result in the worst possible consequence the team can think of at the time. Once the causes are recorded the team lists the consequences, safeguards and any recommendations deemed appropriate. The process is repeated for the next deviation and so on until completion of the node. The team moves on to the next node and repeats the process as shown in Figure 3.3.

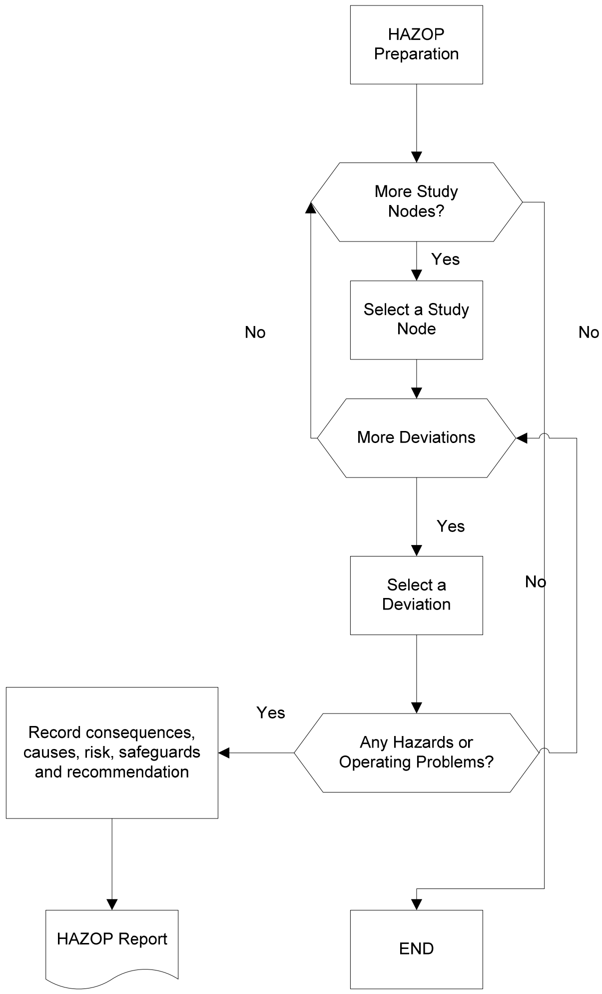

Fig. 3.3 HAZOP study procedure

HAZOPs concentrate on identifying both hazards as well as operability problems. While the HAZOP study is designed to identify hazards through a systematic approach, more than 80% of study recommendations are operability problems and are not, of themselves, hazards. Although hazard identification is the main focus, operability problems should be identified to the extent that they have the potential to lead to process hazards, result in an environmental violation or have a negative impact on profitability.

3.2.2 HAZOP Responsibilities

3.2.2.1 Process Hazard Analysis (PHA) Team Leader

The HAZOP team leader works with the PHA coordinator in defining the scope of the analysis and selection of team members. He or she will direct the team members in gathering of process safety information prior to the start of the study. The leader will plan the study with the PHA coordinator and schedule team meetings. He or she leads the team in the analysis of the selected process keeping team members focused on discovering hazards associated with the process and directs the team scribe in recording the results of the team's findings. The leader will ensures that the analysis thoroughly covers the process as it is defined at the start of the hazard analysis and ensures that the study is completed in the time allotted during the planning stage. He or She writes a report detailing the study findings and recommendations the group makes and reports the findings and recommendations to management officer. He will field any follow-up inquiries by project implementation regarding the study recommendations.

3.2.2.2 Engineering Experts

The engineering experts or field operator assigned to the process hazard analysis may include some or all of the following: a project engineer, a machinery engineer, an instrument engineer, an electrical engineer, a mechanical engineer, a safety engineer, a quality assurance engineer, maintenance engineer or technician and a corrosion/materials engineer. These individuals will be responsible for providing expertise in their respective discipline as it applies to the hazard analysis of the process being studied. These individuals are responsible for attending the initial hazard analysis kick-off meeting. They are also required to be available to the team as required with the understanding that the team leader will give adequate advance notice when their expertise is required. They are required to provide documentation of any existing safeguards and procedures.

3.2.3 Technical Approach to HAZOP

The HAZOP process creates deviations from the process design intent by combining guide words (No, more, less, etc.) with process parameters resulting in a possible deviation from design intent. For example, when the guide word, "no" is combined with the parameter, "flow", the deviation, "no flow" results. The team should then list all credible causes that will result in a no flow condition for the node. A list of guide words with simplified acronym used in this research is given below.

Table 3.1 list of guideword in HAZOP study

Parameter / Guide Word	More	Less	None	Reverse	As well as	Partly	Other than
Flow	high flow (HiFL)	low flow (LoFL)	no flow (NoFL)	reverse flow (RvFL)	deviating concentration (DcFL)	Contami nation (CtFL)	deviating material (DmFL)
Pressure	high pressure (HiPR)	low pressure (LoPR)	Vacuum (VcPR)		delta-p (DlPR)		Explosion (ExPR)
Temperature	high temperatu re (HiTP)	Low temperat ure (LoTP)					
Level	High level(HiLV)	low level(LoL V)	no level (NoLV)		different level (DfLV)		
Time	too long / too late (TlTM)	too short / too soon (TsTM)	sequence (SqTM) step (SpTM) skipped (SkTM)	Backwards BkTM)	missing actions (MaTM)	extra actions (EaTM)	wrong time (WrTM)
Agitation	fast mixing (FmAg)	slow mixing (SmAg)	no mixing (NmAg)				
Reaction	fast reaction / runaway (FsRC)	slow reaction (SlRC)	no reaction (NoRc)				unwanted reaction (UwRC)
Start-up / Shut-down	too fast (TfSu)/(Tf	too slow (TsSu)(T			actions missed (AmSu)/(AmSd		wrong recipe WrSu/WrSd

	Sd)	sSd)			)		
Draining / Venting	too long (TlDV)	too short (TsDV)	None (NnDV)		deviating pressure (DpDV)	wrong timing (WtDV)	
Inertising	high pressure (HpIN)	low pressure LpIN	None NNIN			Contami nation (CtIN)	wrong material WmIN
Utility failure (instrument air, power)			Failure (FlUF)				
DCS failure			Failure (FiDC)				
Maintenance			None NNMc				
Vibrations	too low (TlVR)	too high (THVB)	None NnVB				wrong frequency (WFVB)

If a particular parameter does not change from one node to the next then it is not necessary to repeat all of the deviations that were considered in the previous node. Merely refer to that case in the deviations column of the node presently being considered.

3.2.4 Consequences and Safeguards

The primary purpose of the HAZOP is the identification of scenarios that would lead to the release of hazardous or flammable material into the atmosphere, thus exposing workers to injury. In order to make this determination it is always necessary to determine, as exactly as possible, all consequences of any credible causes of a release that are identified by the group. This will serve a twofold purpose. One, it will help to determine a risk ranking in HAZOPs where multiple hazards are uncovered by the group so that priority can be established in addressing the hazard. And two, it will help making the determination as to whether a particular deviation results in an operability problem or hazard. If the team concludes from the consequences that a particular cause of a deviation results in an operability problem only, then the discussion should end and the team should move on to the next cause, deviation or node. If the team determines that the cause will result in the release of hazardous or flammable material, then safeguards should be identified.

Safeguards should be included whenever the team determines that a combination of cause and consequence presents a credible process hazard. What constitutes a safeguard can be summarized based on the following general criteria:

1. Those systems, engineered designs and written procedures that are designed to prevent a catastrophic release of hazardous or flammable material.
2. Those systems that are designed to detect and give early warning following the initiating cause of a release of hazardous or flammable material.
3. Those systems or written procedures that mitigate the consequences of a release of hazardous or flammable material.

The team should use care when listing safeguards. Hazards analysis requires an evaluation of the consequences of failure of engineering and administrative controls, so a careful determination of whether or not these items can actually be considered as a safeguard must be made. In addition, the team should consider realistic multiple failures and simultaneous events when considering whether or not any of the above safeguards will actually function as such in the event of an occurrence.

3.2.5 Extending HAZOP Identification Scope

Comparing the structure and systematic execution of HAZOP and FMEA easily affirms that both techniques work similarly. While the hazard-identification stage in HAZOP is based upon using established guidewords and parameters for generating deviations of the design intent, FMEA considers the failure modes of specific equipment. This close relationship between HAZOP and FMEAs' definition features and their results generated much research on combining the two in studies to increase the efficiency and improve the quality of both reviews, focusing on their identification of hazards, operability problems, and reliability. Post [14] suggested techniques for combining reliability studies and PHAs, based on HAZOP and FMEA techniques, by reviewing the development of these methodologies and suggesting how to integrate the two types of studies.

Trammel and Davis [18] combined the strengths of the HAZOP and FMEA methodologies to maximize their effectiveness, employing the hybrid PHA methodology to identify design weaknesses and to increase system uptime in semiconductor manufacturing process.

Burgazzi [20] determined the uncertainties of passive systems by comparing the findings from two hazard identification methods to assess the main sources of physical failures. FMEA analyzed the systems/components' reliability (well-engineered safety components), while HAZOP identified the reliability of physical phenomena (physical-phenomena stability). The author stated the need to include FMEA in analyses of passive components. While this technique enabled the identification of the most relevant uncertainty sources of the passive system's performance and generated a set of critical parameters, HAZOP helped in qualifying and eventually confirming the outcome of the earlier study.

3.2.5.1 Considering qualification

Many authors attempted to extend the HAZOP application from identifying hazards to evaluating their impacts. Bendixen and O'Neill [19] considered HAZOP and FTA as the best combination PHA techniques to do so. Their experience on conducting QRAs confirmed uncertainties in their execution. They concluded that a thorough HAZOP, linked carefully with the FTA, minimized the contributions of uncertainty from three areas of the QRA:

(1) Which initiating events must be considered?
(2) What is the frequency of occurrence of these initiating events? and
(3) Which criterion was to be applied in consequence modeling estimation?

Ozog et al. [15,16] confirmed that this same combination was the most effective way to identify, quantify, and control risks. They believed that HAZOP is the most versatile technique for hazard identification in new and existing facilities, and that FTA is the most appropriate hazard-quantification technique.

Demichela et al. [22] developed the Recursive Operability Analysis (ROA), for the safety analysis of plants with multiple protection levels activated by the same process variable. They explored complex pathways by linking HAZOP results and FTA development, thereby effectively constructing accidental sequences that might lead to the top event (TE). The thermodynamic study used as the basis of ROA verified its successful application and showed which protection systems were effective against a given TE.

Shafaghi et al. [23] specifically considered the combination of checklists and HAZOP, applying this hybrid PHA technique to assess the hazards of an absorption heat pump. The objective of using a checklist is to identify major areas needing attention and/or further consideration; it is limited to certain questions and does not provide a mechanism for investigating problems. The authors showed that with a checklist for preliminarily recognizing hazards, HAZOP successfully identified many types of risks, sources of non-optimum system reliability, and also improvements in the heat pumps' design.

3.2.5.2 The human factor

In this section, we cite work on possible hazardous situations caused by human errors. These situations should be seen as human process interaction (e.g., accidents that could be prevented by better training or instructions, better methods of operation, better design). Since standard HAZOP assessments focus only on the malfunction of equipment and process variables, methodologies were developed to consider human-machine interfaces, organizational style, management attitudes, procedures and training, and batch processes and pipeless plants. The importance of this work is reflected in the fact that between 50 and 90% of operational risk is attributable to human error [24]. Schurman and Fleger [25] proposed a novel method for incorporating analysis of hazards introduced by human error into standard HAZOP by adding a new set of guide words (such as missing, mistimed) and parameters (person, information, action) to focus on management and organizational factors that can contribute to risk. Their method employs conditional reliance on procedure/training as safeguard.

Baybutt's [24] new approach for delineating human-failures and human-factors issues that influence the hazardous scenarios revealed by PHA entails identifying types of human failures analogously to generating conventional HAZOP deviations. Human failures are identified by conceptually combining elements of three simple lists to prompt the PHA team in considering all the people involved with the process and their roles, the various functions they may perform, and the different types of errors they may make the combination (Person–Facility Aspect–Failure Type) producing the looked-for deviations (i.e., specific human failures). Aspinall [26] also focused on addressing human factors in HAZOPs, and then restated the basic principles of HAZOPs in order to show how the established guide word-driven method could be used for human factors issues. The author illustrated how to proceed in any stage of a process lifetime and strongly strengthened the importance of a clear design intention (or activity intention) for defining additional deviations for human factors investigation. Rasmussen and Whetton [27] suggested considering the process plant as a socio-technical system, linking hardware, software, operations, work organization, and other safety-related aspects. Their work described the first stage of a hazard identification process to identify critical areas and the need for further analyses. Managerial vulnerabilities and organizational failures significantly contribute to causing accidents. Kennedy and Kirwan [28] discussed the requirement to develop a modified HAZOP for detecting specific safety-management vulnerabilities that could fail in practice; to carry out a HAZOP of safety-management systems required new, different information from that of traditional studies. Accordingly, they supported their proposal by functional task descriptions and decision-action diagrams, offering examples of this type of information, and defining the study's procedures, group selection, and the required guidewords. They validated their new approach by comparing the results obtained by MORT and FMEA.

Further, they cited many references on safety-management systems issues. From a different point of view, but covering the same time-management requirements, Patkai [29] considered the need for a data-management tool for aiding the HAZOP process. He justified the tools and methods he developed by generating more structured data, and collecting it for additional developments. Thus, safety experts could utilize the tool for HAZOP data-management and not only represent data intuitively, but search for important information from the analysis.

3.2.5.3 Specific HAZOP modification

Particular PHAs must consider different objectives, purposes, and scopes. Specific safety analyses might focus only on detecting major process hazards, such as fires, explosions and toxic releases. Baybutt [30] discussed the requirement for a specific PHA technique that directly and exclusively addressed major process accidents. HAZOP can be time-consuming as it aims to identify operability problems in many nodes. Major Hazard Analysis (MHA) begins by considering the first subsystem, and then moves directly to identifying the causes of scenarios originating in that node and resulting in the loss of containment; Baybutt gives a typical list of categories of initiating events. The results from this methodology can be linked with subsequent analyses, such as LOPA and QRA. Hence, the methodology is structural, matching “enabling events” and “scenarios”, thereby affording a fuller description of the hazard scenario. Grossmann and Fromm [31] offered an alternative to undertaking full HAZOP studies by excluding irrelevant and trivial questions. They stated that in assessing an established process, about 90% of the questions revealed no new information on the risk because it already was known, or the special combinations or process properties and malfunctions were not safety-relevant. Without sacrificing the principles of HAZOP, they overcame this disadvantage developing a special form of safety review, viz., “Mini-HAZOP”. The main difference from a full-scope HAZOP was its restriction to meaningful combinations of guidewords.

Finally, focusing on HAZOP documentation, due to the amount of information and cause-consequence pairs highly related to abnormal situations in process facilities, previous researchers Suzuki et al. [33] developed a HAZOP based operator decision support system (implemented by using Microsoft Access) with the aim to predict possible hazards. This tool could support operators to take corrective actions against abnormalities. The authors extended the HAZOP features by adding database with valuable information to be used for maintenance personal and operators.

3.2.6 Automated HAZOP: Expert System

The development of expert systems for automating HAZOP undoubtedly was the most wide-ranging research related on HAZOP topics. HAZOP can be a difficult, time-consuming and labor intensive activity, and many researchers have attempted to develop expert systems to resolve these drawbacks. In this section, we discuss the global efforts made towards this goal, arranging the studies under specific topics and authors.

Parmar and Lees [28] were among the first authors attempting HAZOP automation. They described a method of modeling fault propagation for hazard identification implemented in a computer-based interactive facility. They used a rule-based approach to automate HAZOP, and demonstrated its application identifying hazards in the same water separator system used by Lawley [29]. One year later, Heino et al. [30] established a rule based expert system called HAZOPEX, an advanced development environment consisting of a Lisp workstation (Symbolics) and a hybrid expert system shell (KEE). In addition to Common Lisp, Flavors and Windows, its numerous extensions offered the possibility of using object hierarchies, rules, truth maintenance, world-based alternative exploration, predicative calculus language, and interactive graphics equipped with picture – and image – libraries.

Wang et al. [31] developed knowledge-based simulation architecture as a tool able to allow a HAZOP expert to build and modify simulation models at a simulation-language independent level and without the constant presence of a simulation software expert. Its application was focused on large-scale process plant modeling. Another knowledge-based system, embodied in HAZID [32] was developed, tool which included the screening process designs at an early stage, the initial evaluation of proposed process modifications and the analysis of human team performance. The main feature of HAZID was the no possibility for interaction at run-time, excluding user control over the generation of cause-consequence links.

Heeyeop et al. [30] developed a system open-ended and modular in structure to make it easy to implement wide process knowledge for future expansion. The tool had a frame-based knowledge structure for equipment failures and process properties, as well as rule networks for consequences reasoning which used both forward and backward chaining. One important factor to consider in managing HAZOP studies is the time required to execute the entire analysis. Freeman et al. [30] made the first attempt to plan HAZOP studies with an expert system, setting up a way to estimate how long and how many work-hours a HAZOP study takes. They based their estimate on the number of major equipment items to be analyzed, the system's complexity, and the experience of the HAZOP team leader. Five years later, Khan and Abbasi [32] improved this model, adding new factors and variables. The proposed model takes into account four different parameters (preparation time, meeting time, delay and report writing); and uses multivariable empirical equations. Additionally, the preparation and study time are function of three parameters: number of P&IDs, complexity of P&IDs and the skills of the team leader.

Venkatasubramanian and his colleagues published numerous papers within the framework of automating HAZOP. First, Venkatasubramanian and Vaidhyanathan [34] developed a knowledge-based system, called HAZOPExpert that was implemented using an object-oriented architecture Gensym's G2 expert system shell. HAZOPExpert had some disadvantages in representing the process-generic HAZOP models of the process units. Likewise, Vaidhyanathan and Venkatasubramanian [34] devised an approach to address these difficulties, introducing a representation called HAZOP-Digraph Model (HDG), defining a digraph as a representation tool that offers the infrastructure for graphically representing the causal models of chemical process systems so that they will be transparent to the user. Further, the basic HAZOPExpert generated many more consequences compared to those identified by the expert team. Accordingly, the authors proposed a semi-quantitative reasoning methodology to filter and rank those consequences. For batch procedures, Srinivasan and Venkatasubramanian [35] integrated Petri nets –mathematical languages used for modeling discrete event systems – and subtask digraphs to account for the operational procedures required in batch processes; their system was called Batch HAZOPExpert. Other researchers worked to improve particular features both for continuous – and batch – processes, and for management requirements [36]. Srinivasan and Venkatasubramanian [37,38] automated HAZOP analysis of batch chemical plants. Firstly, the authors presented the knowledge representation framework by combining high-level Petri nets and digraphs with object-oriented knowledge representation for the development of a flexible and user-friendly system called Batch HAZOPExpert (implemented in G2). Finally, the authors described the system features and its performance on an industrial case study. The same authors [39] expanded the scope of PHA automation, not only for hazard identification, but also covering the entire PHA process.

They proposed an integrated framework and a knowledge-based system, called PHAzer. The system uses qualitative digraph based models of unit operations to identify hazards, dynamic mathematical models to perform detailed safety evaluation, and digraph and fault tree models to synthesize and analyze fault trees. Khan and Abbasi also published much work on automating HAZOP. Their first paper [40] analyzed the conventional HAZOP, identifying several factors affecting its effectiveness and reliability; they concluded that its conventional structure must be modified to ensure fast, efficient, and reliable results. They described their approach for optimizing HAZOP studies (OptHAZOP) that rests upon expert system knowledge. This base comprised a large collection of facts, rules, and information on various components of process plants, such as process deviations, their causes, and their immediate consequences for various components. To improve their first version, they generated new knowledge-based software tool, termed TOPHAZOP to speed up the OptHAZOP [41]. It identified general and specific causes and consequences of all probable process-deviations. The whole expert system (the so-called EXPERTOP) consisted of the following main modules: Knowledgebase, inference engine, and user interface. Finally, Khan [42] proposed a knowledge-based expert system for automating HAZOPs for offshore process facilities.

3.2.7 HAZOP supported by dynamic simulation

Currently, ongoing work is applying process simulation in safety-related studies. Combining process-simulation features with hazard-identification techniques delivers invaluable results for safety examinations. This methodology's purpose is to determine risk from operational disturbances, and to develop means for effective risk reductions [43]. Eizenberg et al. [44] introduced HAZOP into process-safety education, both for educational purposes and training operators. Combining HAZOP with dynamic simulation could offer students the means for exploring the consequences of emergencies. They might try various strategies for dealing with the event, and rapidly assess the effectiveness of their postulated responses in preventing a component failure, culminating in a serious accident. Further, in quantifying HAZOP by dynamic simulation, the possible process deviations can be examined and threshold values identified that might lead to potential hazard scenarios. Thus, Ramzan et al. [45] introduced a systematic methodology, supported by dynamic simulation and conventional HAZOP, for finding operational failures and analyzing the effects of design improvements in a safety system. Whereas conventional HAZOP covers both safety and operational failures, dynamic simulations guide safety teams towards generating optimization proposals for systems. The application of this methodology was illustrated in a separate paper [46]. Labovsky´ et al. [47] integrated a mathematical-model approach with HAZOP analysis. They initially applied the methodology of a chemical reactor, highlighting the combination as a useful tool for equipment in all steps of its design, not only during its operational stage. The mathematical-model revealed deviations from normal operating conditions, and analyzed device's response.

Later, the methodology was applied in a MTBE production unit to illustrate the importance of both steady-state analysis and the deviations dynamical response. This approach could serve directly for examining the safety of industrial equipment, or might function as a robust basis for a subsequent conventional HAZOP study.

3.3 Intelligent HAZOP

The definition of intelligent is having the faculty of reasoning and understanding, displaying or characterized by quickness of understanding and good judgment [48]. One of the important challenges in automating HAZOP analysis is handling the huge amount of process specific information which is required as the input for performing HAZOP. It is desirable to develop a system that is context-independent so that it can be used for the HAZOP analysis of a wide variety of processes and will also be able to find the process-specific hazards for the various processes. This was a major hurdle that posed difficult conceptual and implementation challenges that thwarted the attempts towards automation. These systems, however, can only address "routine" or process-generic HAZOP analysis. "Routine" HAZOP analysis means that its reasoning logic can be applied to different processes while the "non-routine" HAZOP analysis means that its reasoning logic is process specific or plant specific. Generally, an analysis of deviations generated by using guidewords "other than", "as well as" and part of" are "non-routine". As a result, these kinds of deviations are hardly addressed in literature about HAZOP expert systems. In the CPI, "routine" HAZOP analysis roughly occupies 60–80% while "non-routine" HAZOP analysis occupies 20–40% [49]. Due to the lack of self-learning capability in existing HAZOP experts systems, the knowledge of "non-routine analysis" can be hardly formulized and reused for similar chemical processes, and the "non-routine" HAZOP analysis still needs to be addressed by human experts.

As distinguishing point from previous mention of automated HAZOP system, intelligent HAZOP proposed in this thesis utilized artificial intelligence technique of hybrid fuzzy logic and case based reasoning. This technique which elaborated in the next section is responsible for selecting the most promising information from HAZOP database for estimating risk. Reasoning from past experience and cases facilitates learning capability of intelligent HAZOP. This type of reasoning is more reliable and trusted by safety operator due to existed previous cases. Experts often find it easier to relate stories about past cases than to formulate rules. Similarly it is true in the HAZOP analysis domain that rules or models are hard to construct to automate "on-routine" analysis. Table 3.2 is HAZOP analysis information while Table 3.3 is Near miss, accident case or process case recorded during operation. With suitable reasoning method, information in Table 3.2 can improve operation description of HAZOP thus making HAZOP analysis one more step to completeness as shown in Table 3.4.

Table 3.2 HAZOP analysis information

Process	Deviation	Cause	Consequent
Feed to Heater	No Flow	Pipe blocked or broken	Material Damage in heater

Table 3.3 Real operation cases with HAZOP parameters

Process	Deviation	Cause	Consequent	Attributes / similarity
Feed to Heater	No Flow	In previous pipes, blockage, breakage	In F401, empty, temperature increases, breakage, fire, explosion, leakage of H2	Strings / 0.5
Feed to Heater	No Flow	From feed section, feed oil doesn't flow	In R401, empty, no reaction To E404, reactor effluent doesn't 'flow	Strings / 0

Feed to Heater	No Flow	Pipe blocked or broken	Material Damage in heater	Strings / 1

Table 3.4 Improved HAZOP analysis information

Process	Deviation	Cause	Consequent
Feed to Heater	No Flow	Pipe blocked or broken From feed section, feed oil doesn't flow	Material Damage in heater In F401, empty, temperature increases, breakage, fire, explosion, leakage of H2 In R401, empty, no reaction To E404, reactor effluent doesn't 'flow

3.4 Fuzzy - Case Base Reasoning (Fuzzy-CBR)

Fuzzy logic (FL) and case-based reasoning (CBR) are two well-known techniques for the implementation of intelligent systems. These techniques share some common concepts: both involve selection, ranking, and aggregation of several alternatives for solving a particular problem. However, there are certain aspects in which the two approaches are distinct from each other, and have their own advantages and drawbacks. FL, for instance, simplifies the process of knowledge representation by employing the concept of a linguistic variable; a variable that can assume linguistic values like hot, near, and high. Linguistic variables, implemented with the help of fuzzy sets greatly reduce the system's knowledge base as an entire range of parameter values can be compactly represented by a single fuzzy set. FL uses these linguistic variables to define the system's knowledge base as a collection of fuzzy IF–THEN rules. The linguistic interface and simplified knowledge representation make FL an attractive choice for intelligent system implementation.

However, one hurdle in the adoption of FL for intelligent system implementation is the difficulty of *knowledge elicitation*. FL-based systems obtain domain knowledge from domain experts to prepare the rules in the system's knowledge base. Nonetheless, there is no easy way to map the experts' knowledge to the system's rules. There are a lot of hedges that qualify the experts' decision making process which cannot be captured by the system's parameters. CBR gets around this knowledge elicitation problem by keeping a historical repository of experience. Unlike the FL case, the database in a CBR-based intelligent system is composed of *cases*—comprising of (values of) input parameters encountered in the past and the corresponding system output. Any new input parameter configuration is decided upon by comparing with all the existing cases and using the most similar case to guide the output decision. This decision and the corresponding input values are made part of the knowledge base for use in future decision making. Thus the knowledge base and accuracy of the system grew with experience. Conversely, a growth in knowledge base size also means a growth in the system's complexity in the context of computational time and memory requirements. As each encountered cases is represented by its own set of crisp values for the parameters, an exponential growth in the size of the knowledge base is required to handle all possible cases. By comprising a blend of FL and CBR can lead to a solution where the two approaches cover each other's weaknesses and benefit from each other's strengths.

3.4.1 Case Base Reasoning

A CBR system emulates the natural human instinct of 'reasoning from past experiences' [50]. A CBR system model is built around a knowledge base of past cases, called the *case base*. Each entry in the case base contains an n-tuple of input variable values $(u_{1i}, \ldots, u_{ni})$, u_{ji} being defined over the space U_j, $j = 1, \ldots, n$, along with an m-tuple $(v_{1i}, \ldots, v_{mi})$ value of corresponding output variables with v_{ji} being defined over the output space V_j.

Given a new case $c = (u^*_1, \ldots, u^*_n)$ the case-based reasoner compares c against all cases in the case base, generating a collection of matching scores $[m_{1i}, \ldots, m_{ni}]$ for each entry in the case base, indicating the degree to which each attribute in the ith case entry matches the corresponding input attribute. The matching values in each case are aggregated to find the overall similarity of the case with the input. The case(s) with the highest level of matching is (are) used to generate the system output.

CBR has been historically represented by a four step cycle proposed by Aamodt and Plaza in 1994 [49]. The four steps, called the four REs as shown in Fig. 3.4 are widely acknowledged. CBR offers several benefits for intelligent classification systems. Kolodner et al. in [50] gives a comprehensive list of CBR advantages. Some of these are summarized below:

- ❖ It facilitates the knowledge acquisition process by avoiding the time required to elicit the solutions from the experts.
- ❖ It provides a means for evaluating solutions when no algorithmic means of evaluation is available.
- ❖ CBR-based classification does not need complete understanding of the domain.
- ❖ It allows the system to learn from past experiences.

However, there are also some sensitive issues facing the deployment of CBR. Some of these issues are:

- ❖ How to best represent the cases?
- ❖ How to avoid the exponential growth in size of the case base as the number of known cases increases?
- ❖ How to represent a domain containing multimedia objects like sound and images?

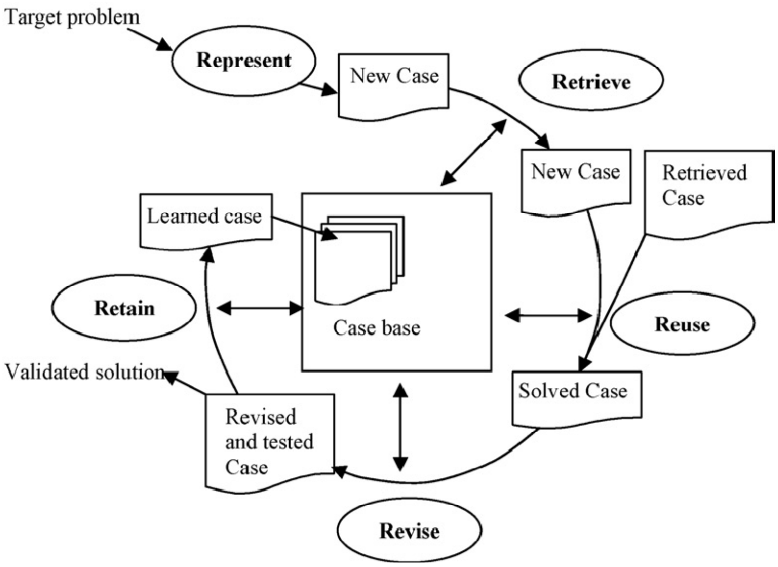

Fig 3.4: R4 cycle in case base reasoning

3.4.2 Fuzzy rule-based system

An FL-based system model is a knowledge-based system comprising of rules of the form:

Rui : *IF* X_1 *IS* F_{1i} *AND* . . . *AND* X_n *IS* F_{ni} *THEN* Y *IS* G_i

where X_j, $j = 1, \ldots, n$ are called the *antecedent variables*, each defined over a space U_j . Similarly, Y is the *consequent variable* defined over the space V. Each F_{ji} is a linguistic term expressed by defining fuzzy subset over the corresponding U_j. For any $u_j \in U_j$, the degree of membership $\mu F_{ji}(u_j)$ shows the degree to which u_j is compatible with the term F_{ji} . Similarly, G_i is a linguistic term expressed by means of a fuzzy subset over V. For any $v \in V$, the degree of membership $\mu G_i(v)$ is the degree to which v conforms to the concept G_i.

The process of reasoning with FL is as follows: given an input $X_j = u^*_j$ we calculate the degree of compatibility of

X_j with each rule (or the firing level of each rule) as:

$\varphi_i = \min \mu A_{ji}(u^*_j)$

The firing levels of all the rules are combined to calculate the system output, given by the fuzzy subset O defined over the output space:

$\mu_O(v) = \max[\varphi_i]$

Optionally, the resulting fuzzy set is defuzzified to get a single value for the output. Fig. 3.6 shows the process involved in FL-based reasoning.

As a decision making technique, FL has several advantages, like:

- FL avoids the need for rigorous mathematical modeling.
- It mimics human decision making while handling vague concepts.
- FL can be used to infer from imprecise information.
- FL offers improved knowledge representation in terms of linguistic and qualitative variables.
- FL can be used to model complex, non-linear systems.

FL however has certain limitations as well. Some of these are:

- FL needs a knowledge elicitation step to gather knowledge from domain experts.
- FL does not provide a mechanism to learn either at the design phase or during use.

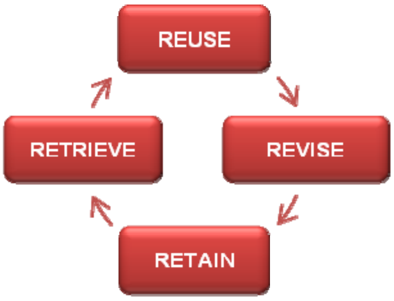

Fig 3.5 CBR cycle

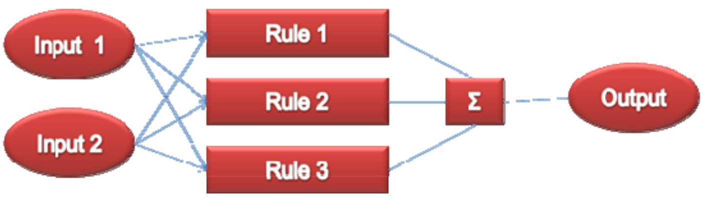

Fig. 3.6 Fuzzy rule-based systems.

3.4.3 Fuzzy-CBR

It is now a well-received argument that a combination of CBR and FL can result in systems that are more efficient and more manageable than the standalone techniques. FL can be used to build CBR systems with a tolerance for imprecision, uncertainty, approximate reasoning, and partial truth, in order to achieve tractability, robustness, low solution cost, and closer resemblance to human decision making [53].

The use of combined FL/CBR systems goes back to the early 1990s, when CBR systems with fuzzy attributes using fuzzy pattern matching were introduced. One of the earliest hybrid CBR/FL systems is the *ARC* system [54] which uses fuzzy features to represent a prototype class of cases. The system uses a fuzzy pattern matching algorithm to find the most similar class to the input case. The *BOLERO* system [54] integrates case-based and rule-based knowledge representation for medical diagnosis. The system stores past knowledge of solved instance using linguistic terms represented by fuzzy sets. The *CARS* [60] system represents cases and problems by means of fuzzy attributes. For the retrieval step, this system calculates the fuzzy similarity measure between attributes based on fuzzy algebra. The similarity is expressed by means of linguistic fuzzy terms *no-match*, *partial-match*, or *complete-match*. *PROFIT* [64] is a fuzzy-CBR system for estimating value of residential property for real estate transactions. It uses fuzzy predicates to express similarity between the comparable properties. The resulting property value estimate is qualified by a fuzzy confidence measure. Further detail of FL/CBR convergence can be found in [62].

3.4.3.1 Fuzzy-CBR representation

In the safety domain, risk factor is the primary key on deciding action to be taken in preventing an accident. We suggest proportional risk assessment as a measure for calculating the quantified risk due to a hazard. This can be calculated by:

$$\text{Risk factor} = \text{Probability factor} \circ \text{Severity of harm factor} \circ \text{Frequency factor} \quad (3.1)$$

Fuzzy set of risk factor is a byproduct (Mamdani method) of the probability factors fuzzy set, severity of harms factors fuzzy set and frequency factor fuzzy set.

In soft-computing domain, case base are consider fuzzy set itself. We are in safety domain thus using fuzzy as indexing mechanism is consider as fuzzy-CBR technique. When indexing case base priority in CBR, risk must be the factor to consider. The weight of risk factor is on the severity factors. For example, a line of hot pipe if a burst occurs will give the severity of harm of death, but because of active precaution and prevention such as having temperature control and insulators, the heat can be dispensed. Therefore, the frequency of exposure is low; the same goes to probability of hot pipe burst which also low. A direct calculation of risk should give low risk. However, in real chemical process industries, the weight is given to severity of harm; as a result the risk is considered as high as the possibility of the insulator fails still exists. This is due to no inspection and maintenance. Operator would not be aware of these possibilities.

3.4.3.2 Fuzzy Knowledge acquisition

Knowledge is formulated using severity factor, probability factor and frequency factor to obtain the risk factor. This factor is implemented using natural linguistic variable that represents state classification; severity factor is classified into five *area S={Very Low, Low, Medium, High, Very High},* probability factor *P={ Low, Medium, High}*, frequency factor *F={Very Low, Low, Medium, High, Very High}* and risk factor R ={Very Low, Low, Medium, High, Very High}. The classification can be implemented using fuzzy set representation. The use of fuzzy set to represent knowledge only becomes expedient as one does not have enough information to assign elements into sets. By using fuzzy, qualitative knowledge can be mathematically modeled and numerical approach can be used to estimate fault propagation along the process. In this paper, the fuzzy represent is assumed to be triangular; for it has the advantage of simplicity and is commonly used in reliability analysis [84] Construction of fuzzy representation is generalized using linguistic variables identified by safety expert or experience safety operator in operating plant. The triangular representation can be shown in Figure 3.7, 3.8, 3.9 and 3.10.

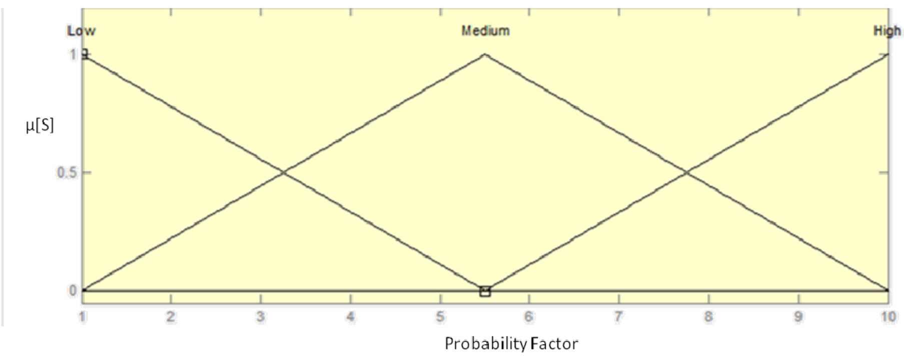

Fig. 3.7   Fuzzy set of Probability Factor

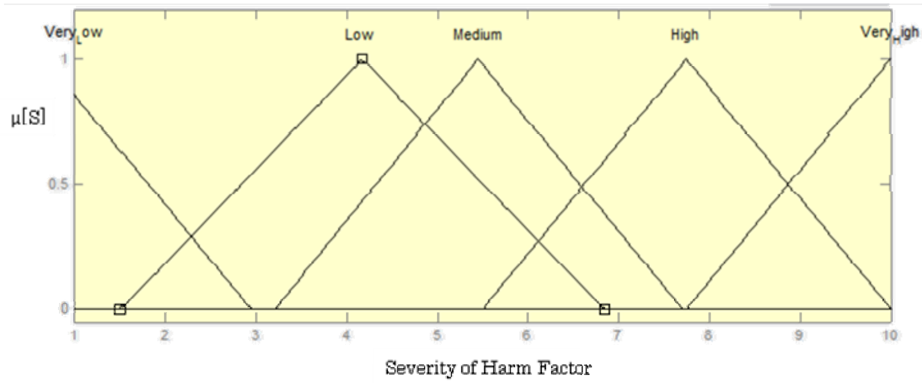

Fig. 3.8 Fuzzy set of Severity of Harm Factor

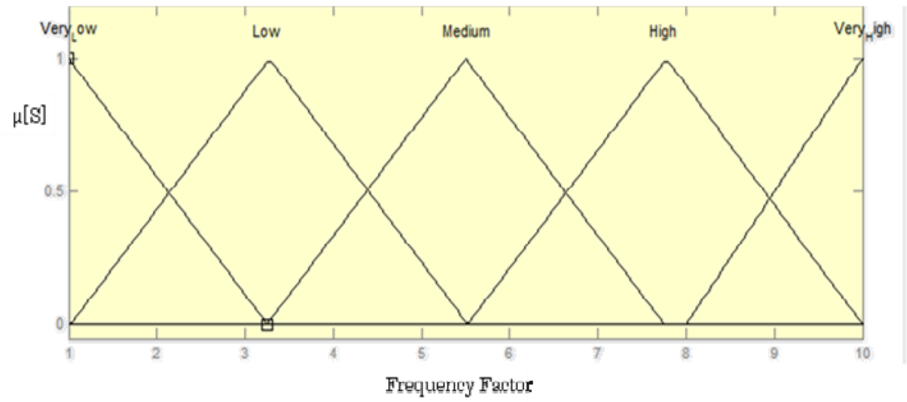

Fig. 3.9 Fuzzy set of Frequency Factor

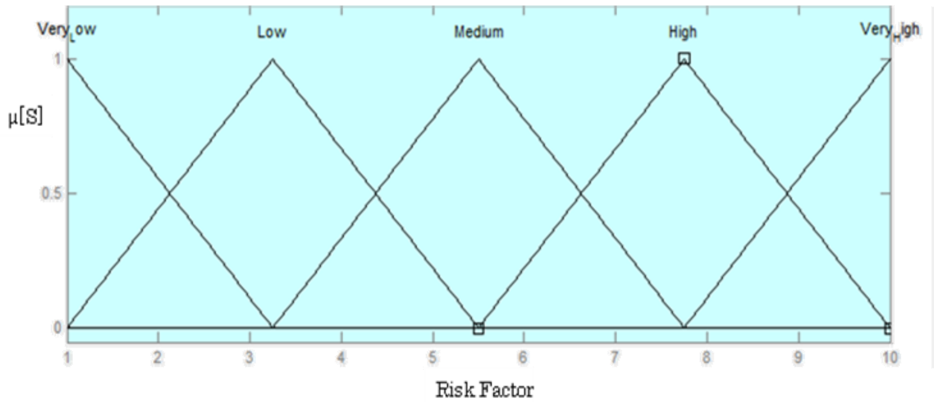

Fig. 3.10 Fuzzy set of Risk Factor

In Figure 3.7, 3.8, 3.9 and 3.10, fuzzy sets are designed to conform to natural condition during operation. Membership function μ(x) is arranged from 0 to 1 which represents the possibilities of case. After knowledge is elaborated into fuzzy sets information and its membership, knowledge connection phase is established using rules that restrict connection between three inputs (Probability factor, Severity of harm factor and frequency factor) and one output (risk factor).

3.4.3.3 Membership function

Membership function shows the characteristic of fuzzy set and as a translation over a universe of discourse U. This is associated with variable x, with membership degree between 0 and 1.

$$\mu(x): U = [0,1] \tag{3.2}$$

The membership function is assumed to be the degree of possibilities of variables that indicate true value of variable. This variable can have difference value, for example the term of probability factor may be:

$$\text{Probability} = \{Low, Medium, High\} \tag{3.3}$$

Triangular curve representation is defined as union of two linear lines that can be shown in Figure 3.11

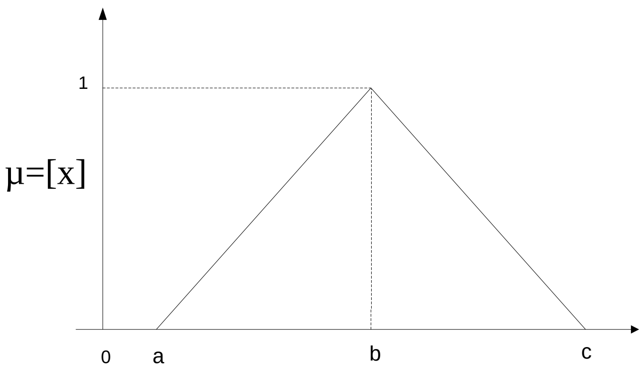

Fig. 3.11 Triangular curve

Membership representation in Figure 3.11 can be expressed as follows:

$$\mu(x) = \begin{cases} 0; & x \le a \text{ or } x \ge c \\ (x-a)/(b-a) & a \le x \le b \\ (b-x)/(c-b); & b \le x \le c \end{cases} \tag{3.4}$$

Variable of membership function will vary from Low, medium, and high. Fuzzy representation of probability shows the uncertainty condition that may occur during process. If hazard can be mitigated, it is not usually “low risk”; it possibly gives the impacts such as severity of injuries to operator. This condition may happen due to risk in transitional condition from medium to high condition. Analysis should be done to ensure how safe the action when mitigating hazard.

Linguistic variables can be used to construct a model for risk index based on manipulated variables via probability, severity of harms and frequency index. Membership function and fuzzy system can describe HAZOP more qualitatively with indexing the risk variable.

3.4.3.4 Fuzzy inference and indexing

In this section, fuzzy inference algorithm is introduced to manipulate cases raking and indexing. A fuzzy inference offers the connection using IF THEN rules,

$$\textit{IF \{Severity\} AND \{Probability\} AND \{Frequency\} THEN Risk} \qquad (3.5)$$

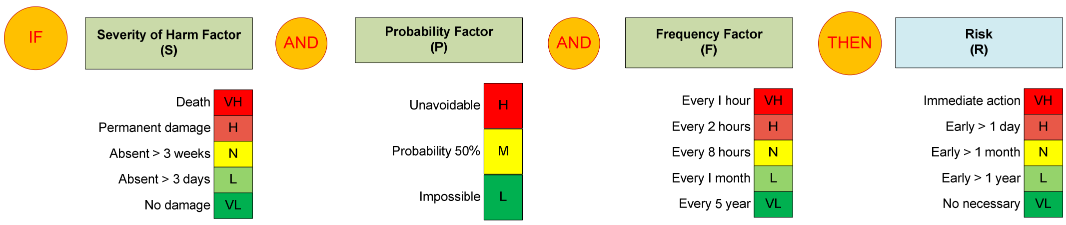

Fig. 3.12 Membership set linguistic value of severity of harm factor(S), probability factor(P), frequency factor(F) and output risk (R)

Figure 3.12 shows the definition of fuzzy set in real world.

Example of IF –THEN rules in risk indexing:

IF (Severity is Low) AND (Probability is Low) AND (Frequency is Very Low) THEN (Risk is Very Low)

IF (Severity is Very High) AND (Probability is High) AND (Frequency is Very Low) THEN (Risk is Very High)

IF (Severity is Low) AND (Probability is Low) AND (Frequency is Very High) THEN (Risk is Medium)

IF (Severity is Medium) AND (Probability is High) AND (Frequency is Very Low) THEN (Risk is Very High)

IF (Severity is High) AND (Probability is Medium) AND (Frequency is High) THEN (Risk is High)

IF (Severity is High) AND (Probability is High) AND (Frequency is Very Low) THEN (Risk is Very High)

IF (Severity is Very Low) AND (Probability is Medium) AND (Frequency is Very Medium) THEN (Risk is Medium)

It can be shown that severity factor, probability factor and frequency factor are premise part, while risk factor is consequence part. The rules are applied due to dealing with uncertain condition when there is not enough exact information for estimating risk for taking action. The inference technique shows the appropriate technique to estimate the status of case safety.

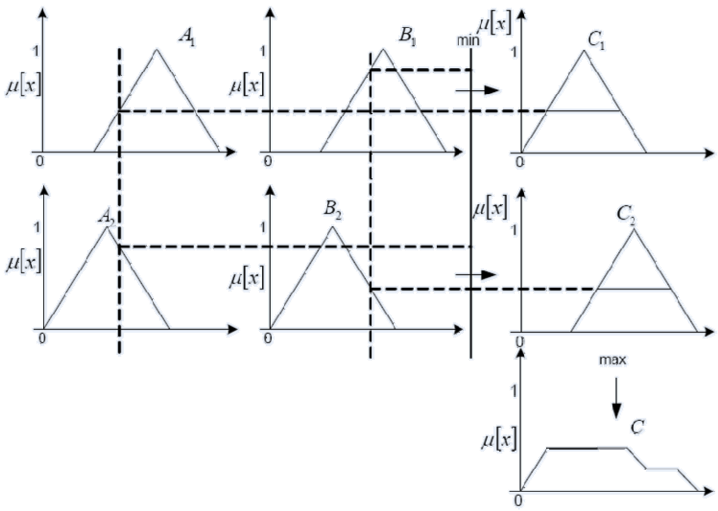

Fig. 3.13 Fuzzy inference for two input one output system.

Fuzzy inference will combine list of rules and match input in all IF-part. The combination of the inputs will activate the rules in antecedent part and formulate fuzzy conclusion set. As an example, in Figure 3.13, it is shown how fuzzy inference manipulates two inputs and converts the result to an output. Naturally, this method is implemented when many inputs are combined to give output. Suppose, if there are n input variables and m rules, using max-min rule known as Mamdani approach, the pair of antecedent that perform output fuzzy variable is given by:

$$\mu_{C_n^m} = \min\left\{\mu_{A_n^m}(x), \mu_{B_n^m}(x)\right\} \tag{3.6}$$

After converting fuzzy input, membership function of the fuzzy output set can be obtained by:

$$\mu_C(x) = \max\{\mu_{C^1}(x), \mu_{C^2}(x), \ldots \mu_{C^m}(x), \} \tag{3.7}$$

The membership function for output shows min-max rule, matching inputs and aggregation of output THEN part (consequence).

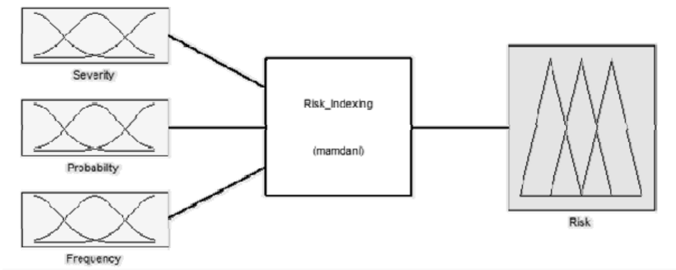

Fig. 3.14 Relationship between input member set and output

The fuzzy-CBR engine module is the core of the indispensable phase of CBR systems, i.e. and retrieval. The proposed Fuzzy-CBR technique used in this research do not used fuzzy technique in finding similarity between cases. This is due to qualitative nature of HAZOP analysis cases. Fuzzy is basically used in indexing and raking cases. Case with higher raking is prioritized as representative case within hierarchical structures of the database.

When a new scenario case (deviation) analysis problem is presented to the system, the fuzzy-CBR engine is activated. The engine starts from selecting the corresponding scenario case in sub case base that fits the problem through the hierarchical indexing mechanism, the fuzzy indexing. Within the chosen sub-case base, all past scenario cases are compared with the new problem, and scored based on the similarity-based case retrieval algorithm that is described in the following to find the closest-matching cases.

To define the similarity between the past scenario case and new problem, a measure is needed first to assess the closeness between the attributes belonging to them. Basically there are five types of attributes for each case: object such as equipment, string such as the material name, numeric such as operating temperature of equipment, interval-numeric such as design parameters and set object such as materials.

The similarity of string attributes is simply calculated by string matching algorithm. If string attributes are same, then their similarity is 1, otherwise 0.

$$Sim\,(A, B) = (A = B)\,?\,1 : 0 \tag{3.5}$$

In a scenario case, all numeric attributes are transformed to nonnegative values. For example, the temperature unit is Kelvin temperature while the absolute pressure is used to represent pressure attributes. The mathematics similarity formula for non-negative numeric attributes x_i and y_i is:

$$sim(x_i, y_i) = \frac{1-|x_i - y_i|}{\max(x_i, y_i)} \tag{3.6}$$

Where *sim*(.) is similarity between sets. Usually, there is more than one material involved in a piece of process equipment. Comparison of scenario cases usually requires comparison of the material sets present in the equipments where the cases originate. Assume there are two material sets A and B, which belong to two different cases, respectively. Set A contains *m* materials: M_{A1}, M_{A2}... M_{Am}, and set B contains *n* materials: M_{B1}, M_{B2}. . . M_{Bn}. Then the similarity of A and B could be computed by equation (3.7)

$$Sim(A,B) = \frac{\sum_{i=1}^{N} S_i}{\max_i^N (m,n)}$$

Where

$$N = Min(m,n) \tag{3.7}$$

S_i is the maximum similarity between the ith material in one set and each material in the other material set, $1 \le i \le N$.

If N = m then,

$$S_i = \mathrm{Max}_{j=1}^{n}\{sim(M_{Ai}M_{Bj})\} \tag{3.8}$$

If N = n then

$$S_i = \mathrm{Max}_{j=1}^{m}\{sim(M_{Ai}M_{Bj})\} \tag{3.9}$$

In equation (3.8) and (3.9), sim($M_{Aj,}M_{Bj}$) represents the similarity between material M_{Ai} and material $M_{Bj,}$ which can be computed by equation (3.10).

$$sim(M_{Ai}M_{Bj}) = \sum_{k=1}^{K} (W_k sim(att_{Aik} att_{Bjk}) \tag{3.10}$$

where *K* represents the number of index attributes of a material, W_k represents the weight of the *k*th index attribute, $1 \le k \le K$, att_{Aik}, att_{Bik} are respectively the *k*th numeric index attributes of materials M_{Ai} and M_{Bj}, and sim(att_{Aik}, att_{Bik}) can be calculated by Equation (3.6)

The similarity algorithm of interval-numeric feature is extended-Euclidian algorithm. Suppose there are two interval numeric attributes A= [a_1,a_2], B = [b_1,b_2], then their similarity can be calculated as follows:

$$Sim(A,B) = \frac{(a_1b_1 + a_2b_2)}{\max((a_1)^2 + (a_2)^2, (b_1)^2 + (b_2)^2} \quad (3.11)$$

HAZOP cases have object attributes such as equipment and materials. The object similarity calculation takes advantage of the chemical process ontology if ontology is available. We propose this similarity for future use. The path length measure is used to calculate the object similarity [65]. It essentially computes the similarity between two object nodes by counting the numbers of nodes on the shortest path between them in the ontology hierarchy. The shortest path includes both the object nodes. Mathematically, the similarity of two object nodes A and B using the path-length measure (path) is defined as:

$$sim(A,B) = 1/p \quad (3.12)$$

Where p is the number of nodes on the shortest path between A and B within an ontology hierarchy.

For example, in the equipment ontology, if equipment A is a subclass of equipment P (subclass is equivalent to a is-a relationship in ontology), and equipment B is a subclass of equipment Q while equipment P and equipment Q are two subclasses of equipment O. The shortest path from equipment A to equipment B is A-P-O-Q-B. There are five nodes on the path. Therefore, the similarity of equipment A and equipment B is 1/5.

Finally the Case similarity is the sum of each case attributes similarity multiplied by its weight which is determined by domain expert. The weights are adjustable.

$$Sim(caseA, caseB) = \sum_{i=1}^{N} S_i \frac{1}{W}$$

(3.13)

3.4.4 Case Base representation

Construction of the case base to a large extent determines the intelligence level of a CBR system. Each case instance generally consists of two parts: the problem and the solution, the problem part contains the HAZOP analysis background information of a particular deviation while the solution part describes its abnormal causes, adverse consequences, risk, safeguards, recommendations and some other auxiliary stored in a relational database in which each case holds a unique identification number. To facilitate the similarity-based case retrieval that is described in the following section, a hierarchical case structure is introduced as a method to partition a huge number of cases into multiple hierarchical subordinate case bases (Sub Case Base). This HAZOP analysis cases can be categorized by the types of the chemical processes specified in the process ontology, by the equipment types specified in the equipment ontology if the ontology exists, else according to respective chemical process and equipment specification database.

This hierarchical case structure is important features for quick and accurate retrieval of past cases [70]. Each case in the case base is defined by arrangement of four major categories: equipment with its design parameters, materials contained in the equipment, operating conditions, and stream context conditions. The equipment design parameters such as design pressure and design temperature describe the equipment where the deviation being analyzed occurs. The equipment type must be available in the equipment specification database or equipment ontology if available. Each case contains a list of materials presented in the equipment. Hazardousness related physical–chemical characters of materials such as flash point, boiling point and toxicity are distilled from database to represent the material characters. Operating conditions include parameters such as operating temperature, pressure and level. The stream context conditions reflect the equipment types of both upstream and downstream of the equipment. Each complete problem and solution are giving weight as shown in Table 3.5 for Probability Factor(P), Table 3.6 for Severity of harm factor(S) and Table 3.7 for Frequency Factor (F).

$$R = P \circ S \circ F \tag{3.11}$$

Where R is the fuzzy set of risk, P is the fuzzy set of probability factor, S is fuzzy set of the severity of the harm factors, F is the fuzzy set of frequency (or the exposure) factor. The relation (3.11) provides a logical system for safety management to set priorities for attention to hazardous situations. The validity of these priorities or these decisions is obviously a function of the validity of the estimates of the parameters P, S and F, and these estimates, apparently very simple, require the collection of information, the visit of the workplaces and the discussion with the workers about their activities [71]. The weakness CBR arises with the complexity of case base. This is due to an exponential growth in the size of the knowledge base. Risk factor for each case is used as raking mechanism for the case base. Similar case in hierarchical case structure with higher risk factor is prioritized as case representative.

Table 3.5: Gradation of the probability factor in association with the undesirable event

Probability Factor(P)	Description of undesirable event
10	Unavoidable
9	Almost assured
8	Frequent
7	Probable
6	Probability slightly greater than 50%
5	Probability 50%
4	Probability slightly less than 50%
3	Almost improbable (or remote)
2	Improbable
1	Impossible

Table 3.6 Gradation of the severity of harm factor in association with the undesirable event

Severity of harm factor(S)	Description of undesirable event
10	Death
9	Permanent total inefficiency
8	Permanent serious inefficiency
7	Permanent slight inefficiency
6	Absence from the work >3 weeks, and return with health problems
5	Absence from the work >3 weeks, and

	return after full recovery
4	Absence from the work >3 days and <3 weeks, and return after full recovery
3	Absence from the work <3 days, and return after full recovery
2	Slight injuring without absence from the work, and with full recovery
1	No one human injury

Table 3.7 Gradation of the frequency (or the exposure) factor in association with the undesirable event

Frequency Factor (F)	Description Of undesirable Event
10	Permanent presence of damage
9	Presence of damage every 30 s
8	Presence of damage every 1min
7	Presence of damage every 30 min
6	Presence of damage every 1h
5	Presence of damage every 8h (or 1 working shift)
4	Presence of damage every 1 week
3	Presence of damage every 1 month
2	Presence of damage every 1 year
1	Presence of damage every 5 years

Table 3.8 Estimation of linguistics risk factor to urgency level of required action.

Risk Value (R)	Urgency level of required actions
Very High	Immediate action
High	Required action earlier than 1 day
Medium	Required action earlier than 1 month

Low	Required action earlier than 1 year
Very Low	Immediate action is not necessary but it is required the event surveillance

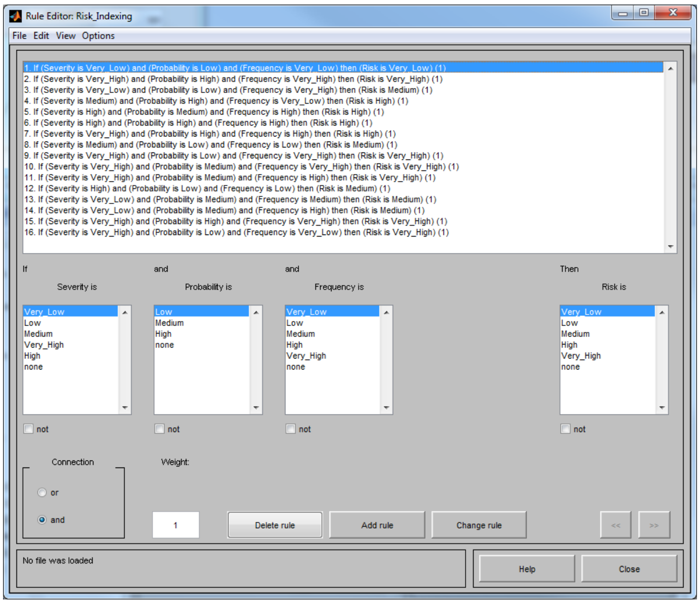

Fig. 3.15 IF-Then rules setting windows in Matlab

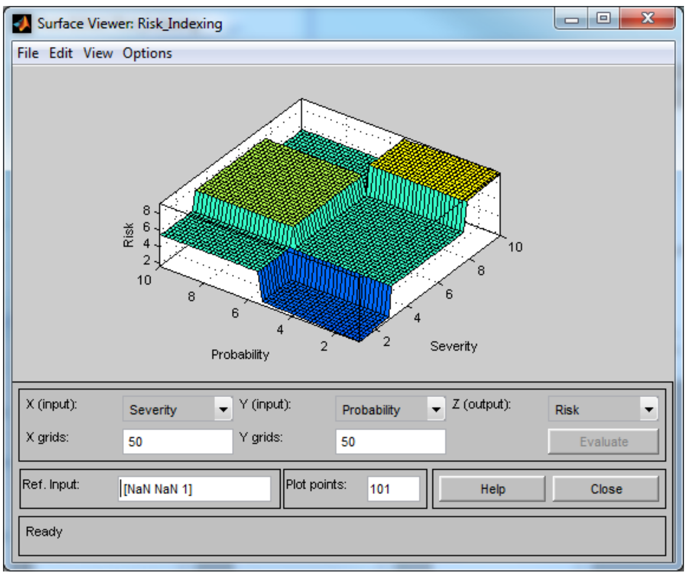

Fig. 3.16 surface show relationships between severity, probability and risk.

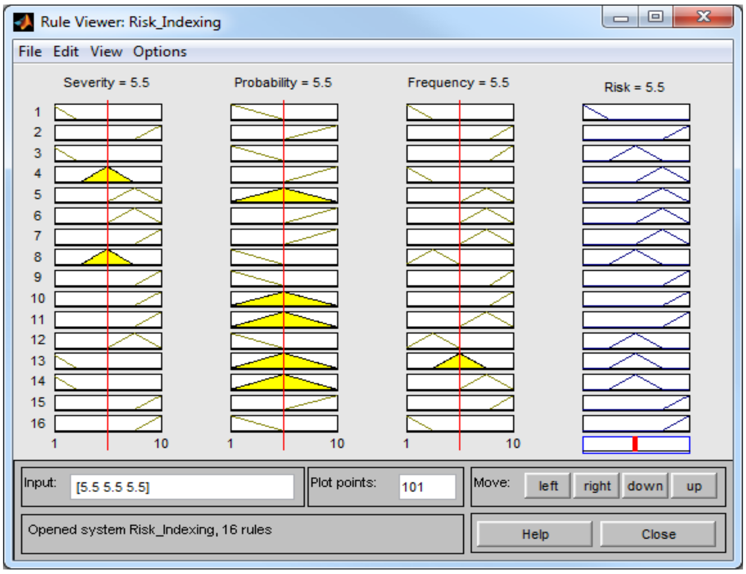

Fig. 3.17 Rule view simulate risk factor in Matlab

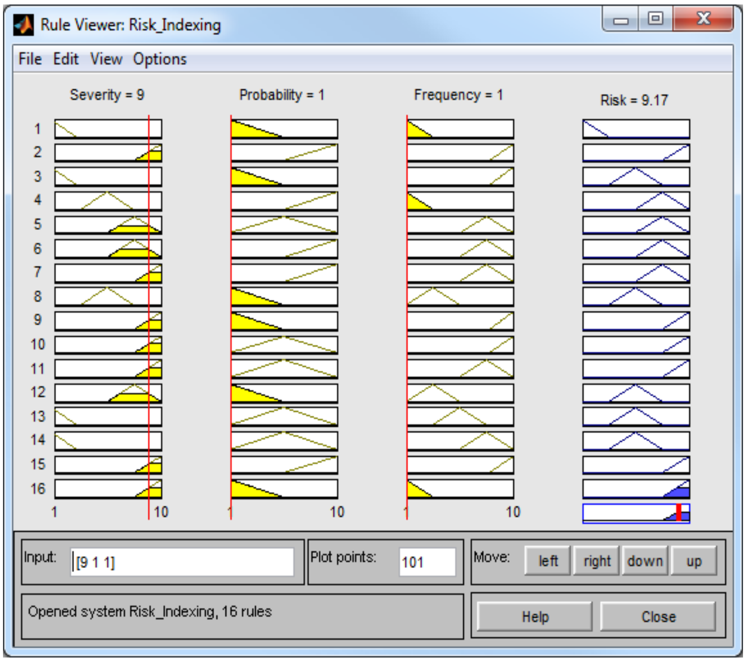

Fig. 3.18 Rule view simulate risk factor in Matlab

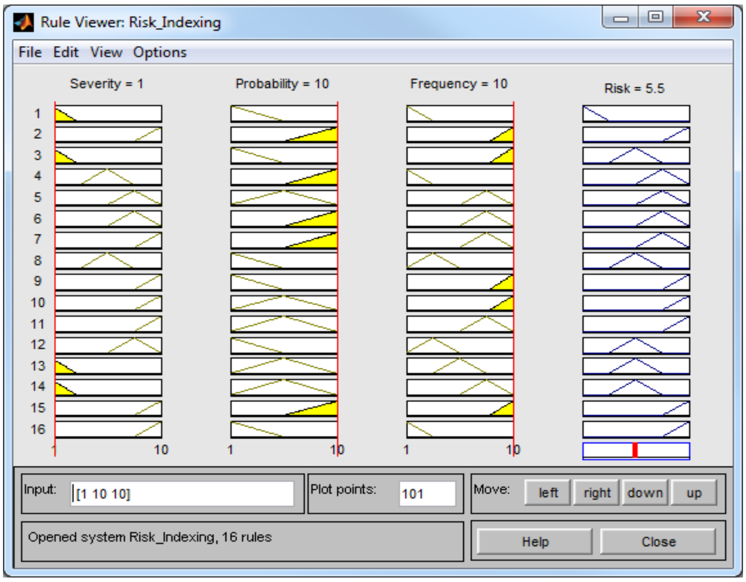

Fig. 3.19 Rule view simulate risk factor in Matlab

Figure 3.15 shows the IF-Then rules setting windows in Matlab, which govern output value. Figure 3.16 is illustrating surface indicate relationships between severity, probability and risk Figures 3.17, 3.18 and 3.19, show that the value of risk factor is not a direct product of a severity, probability and frequency factors. This value is controlled by If-then rules, which suggested by domain expert.

3.5 Application Example

Several rules have been set in order to improve pattern matching process. When registering new case, either HAZOP result or near miss case, input methods have to follow this pattern to increase matching ability rate

Parameter: Value: Unit

Table 3.9 show acceptable pattern and unacceptable input method pattern.

Table 3.9 Parameter matching ability

Matching ability	Item
Yes	reaction most active at temperature 35 Celsius

No	35 Celsius is the temperature where reaction most active
Yes	Consistence Gas supply around pressure 2.2 atm

This is the same way how HAZOP deviation are fill in, however HAZOP deviation are more forgiven as deviation are pre select using deviation parameter from the database.

Deviation: Guidewords or Guidewords: Deviation

Table 3.10 shows acceptable pattern and unacceptable input method pattern for HAZOP deviation

Table 3.10 Deviation matching ability

Matching ability	Deviation
yes	Hi flow
yes	NO flow at
no	The flow is in reverse direction

Fuzzy-CBR as described in the previous section consists of four steps of retrieve, reused, revise and retain. Below we explain how these steps are applied in this research.

3.5.1 Retrieve

Here we define set C_U=(U_1,U_2,U_3....U_n) as new case and C_{V}=(V_1,V_2,V_3....V_n) as case from case base. For every keyword in U defined by set A= (a_1, a_2, a_3...a_n), keyword in V are defined as set B = (b_1, b_2,b_3....bn). Case attributes are divided into five types: Att_{string}, $Att_{Numberic}$, $Att_{interval}$ Att_{set}, and Att_{Object} which stand for string attributes such as the material name, numeric attributes such as operating temperature of equipment, interval-numeric attributes such as design parameters, set object attributes such as materials and object attributes such as equipment, respectively. Not all attributes are available in a HAZOP case or cases in Case Base, only available attribute will be considered for similarity calculation.

In this dissertation, retrieving algorithm heavily relies on if-then programming function.

IF a_1 EQUAL TO b_1 AND a_2 EQUAL TO b_2 THEN C_{u1} EQUAL C_{v1}
RETRIVE $C_{v1.}$

String Attribute example: by using equation (3.6);

e.g. Case A= temperature increase
Case B= temperature static
IF A equal B Then true
Else false.
Where true = 1 and false = 0
Sim(Case A,Case B) = 0

Numeric Attribute example: by using equation (3.7)

Case 1 : gas flow with pressure 1.3 Atm
Case 2 : gas pressure 1.1 atm flow
Therefore sim = 1-(I1.3-1.1I 1.3) = 0.846

Interval-numeric Attribute example: by using equation (3.11)

Case 1 : reaction most active at temperature 30-35 degree
Case 2 : temperature 32-35 degree is the optimum reaction temperature
Therefore sim (case1,case2) = 30*32 + 35*35 max(2125,2249)
=0.971

Set Attribute example: by using equation (3.13)

Case 1 : FEED P401AB E401 E402 F401
Case 2 : FEED P401AB E401 E402
Sim(A,B) = 4 5 = 0.8

Object Attribute example: by using equation (3.14)

$$\text{Case 1}: \text{FEED.P401A.E401}$$
$$\text{Case 1}: \text{FEED.P401B.E402}$$
$$\text{Shortest path} = \text{num nodes} = 1/5 = 0.2$$

Example:

Item	Main HAZOP	Case Base	Attribute /similarity
Project Name	Hydrodesulphurization Unit	Hydrodesulphurization Unit	String = 1
Process Name	Flow to heater (F-401)	Flow to heater (F-401)	String = 1
Process Path	FEED>>P-401AB>>E-405>>E-401 >>F401	FEED>>P-401AB>>E-405>>E-401 >>F401	Object = 1/7
Equipment List	FEED P401AB E401 E402 F401	FEED P401AB E401 E402 F401	Set = 1
Material List	Oil Gas	Oil Gas	Set = 1
Deviation	Flow	Flow	String =1
Guideword	No	No	String =1
Cause	No gas and feed flow , •Pipes blocked or broken	In previous pipes, blockage, In previous valves, blockage	String =1 String =1
Consequence	Pipes blocked or broken, Material damages in heater Heater temperature increase 390 degree Celsius	In F401, empty, temperature increases, breakage, fire, explosion, leakage of H2 In R401, empty, no reaction Heater temperature increase 250 degree Celsius	String =0 Numeric = 0.641
Total similarity			0.8

Selection of analysis are divided into three types, predefine path analysis, predefine process analysis and new analysis or none define analysis as shown in Figure 3.20.

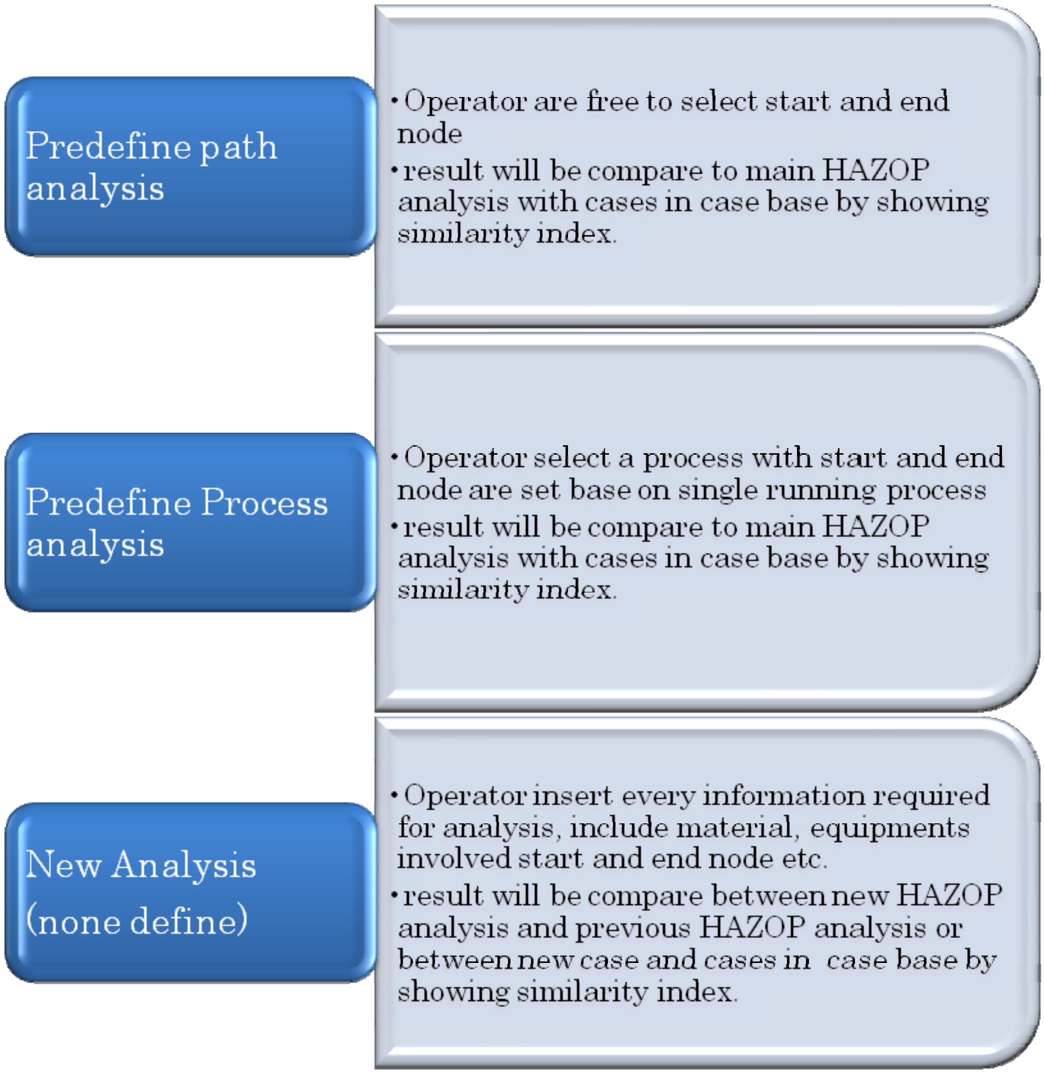

Fig. 3.20 Analysis types and its characteristic

When a new analysis problem is presented to the system, the CBR engine is activated. The engine starts from selecting corresponding case base that fits the problem through the hierarchical indexing mechanism. Operators are prompt to choose which represent their best interests.

1. Register new HAZOP analysis – this option will directly register new HAZOP analysis without having consideration for previous case. This is suitable for new database which analysis completeness state is still

at minimal.

2. Register new HAZOP analysis with previous HAZOP analysis support. This option is used when similar previous HAZOP analyses are present. Operator only have to fill a part of main parameters such as process, path, deviation etc, the system will retrieve all similar HAZOP analyses that match requested criteria.
3. Register new case - This option will directly register new case into case base without having consideration for previous case. This is suitable for new database which case base still lack of representative case.

4. Register new case with previous case of case base support - This option is used when similar previous cases are present. Operators only have to fill part of main parameters such as process, path, deviation etc, the system will retrieve all similar previous cases from case base that match requested criteria. This prevents registering case redundancy.

3.5.2 Reused Case

If retrieved case is similar to the requested criteria, which is similarity rate between 0.6 and 1.0, the previous case will be used to assist registering new case. This will save a lot of time in comparison with registering from zero bases.

3.5.3 Revised Case

Reused cases normally require revising before it can be store either into main HAZOP or case base. Revising requires domain expert decision. Adaptation and solution made is considered for applying into future cases.

3.5.4 Retained Case

After the revised case has been successfully adapted to the new case, the resulting case is stored as a new case in case base or as previous case, improvement is being based on similarity index and expert judgments.

Table 3.11 below illustrate how similarity, S_t values are used to handle reused, revised and retained cases. This values are adjustable base of safety operator experience.

Table 3.11 Similarity value toward action taken for fuzzy-CBR cycle.

Similarity	Action
$0 \leq S_t < 0.6$	Record as a new case and consider for to add to new main HAZOP
$0.6 \leq S_t < 0.9$	Only record to case base not to main HAZOP database
$0.9 \leq S_t < 1$	Ignore and retrieve similar cases from case base

3.6 Virtual reality Training

Virtual reality is a rapidly growing technology, which utilizes the increasing power of computers to simulate real or imaginary environments and situations with high degree of realism and instructiveness. It is an emerging technology with potential applications in areas such as product design and modeling, process simulation, planning, testing and verification, real-time shop floor controls, training and maintenance. One speculation on virtual reality's development in manufacturing industry is a computing architecture that could provide virtual production environments within concurrent engineering contexts to achieve zero-defect and non-risk production. In fact, virtual reality has already been applied to a wide range of problems associated with manufacturing, industrial maintenance, post-production training and customer services in areas such as visualization of complex data, robot control and remote operation of equipment, communication, training and planning, and virtual prototyping and design. The success of those applications has mostly relied on a realistic virtual environment.

Virtual reality technology is being used for training applications in a variety of process industries and fields such as military, medicine, aircraft, art and business. Virtual reality offers the potential to expose personnel to simulated hazardous situations in a safe, highly visual and interactive way. Customized simulations of chemical plants layouts, dynamic process operations and comprehensive virtual environments can be set up allowing users to move around the virtual plants, taking operational decisions and investigating processes at a glance. The consequences of both correct and incorrect decisions can be immediately fed back to safety operator giving them the opportunity to make mistakes and directly learn from them. Users can interact with the virtual worlds using a variety of hardware devices such as joysticks and data gloves, and the impression of actually being in the virtual world can be enhanced by special optical and audio devices such as head mounted displays and three-dimensional surround sound.

3.6.1 Training

Evidence from everyday life shows that well trained and careful workers may avoid injury on a dangerous job whilst untrained and careless workers may be injured under the safest possible conditions. Before any employee can work safely they must be taught safe procedures for completing their tasks. The purpose of safety training should be to improve safety awareness in employees and increase their performance on their jobs without endangering themselves and their fellow employees. Knowledge of the hazards, their effects, and the required techniques to avoid or ameliorate those effects, must be provided to all personnel in a process industry [73].

Training helps people to acquire the skills, knowledge and attitudes to make them competent in the health and safety aspects of their work. It may include formal off-the-job training, instructions to individuals and groups, and on-the-job coaching and counseling. Ensuring that people are competent may demand more than formal training, for example a period of supervised experience to practice and develop new skills.

3.6.2 Computer Graphics

A picture is said to be worth a thousand words. Computer graphics have the capability to express this statement in a modern way. Computer graphics are commonly understood to mean the creation, storage and manipulation of models and images. Such models come from a diverse and expanding set of fields including physical, mathematical, artistic, biological, and even conceptual (abstract) structures. Engineers and scientists have always capitalized on the value of pictures by expressing the results of their design work and calculations in the form of engineering drawings, charts and graphs [74]

3.6.2.1 Computer graphics history

Computer graphics has a history extending back to 1960s and has evolved through various types of technology such graph plotters, vector display systems, storage tube displays and raster based screens, which still remain the most popular methods of displaying images. The term “computer graphics” was coined in 1960 by William Fetter to describe new design methods he was pursuing at Boeing. He created a series of widely reproduced images on a plotter exploring cockpit design using a three-dimensional model of a human body. Ivan Sutherland created the first truly interactive graphics system, shown in Figure 3.20, which was called sketchpad, at MIT in 1963 for his Ph.D. Thesis

Fig. 3.21 The first interactive graphics system in 1963 [73]

Computers graphics became an important part of computing from its earliest days, but it was only in the late of 1970s and early 1980s that computer graphics became cost effective. The introduction of Cathode Ray Tubes (CRT) for displaying pictures by Tektonix in 1968, the significant drop in the cost of computer memory in the seventies and the widespread use of low priced personal computers at the beginning of the eighties led to the rapid development and the dramatic cost reductions of computer graphics. In the mid eighties, graphics moved from its status as a limited purpose tool to become an internal part of many computer systems. The Macintosh computer with its extensive use of graphics and the mouse, has helped integrate every aspect of computer use, from the developing data relationships in databases to debugging programs. Personal computers with more memory than mainframe computers of the seventies are found in most offices and homes, which make computer graphics a mainstream form of computing. Finally companies, which developed graphics software packages, have made Computer Aided Design (CAD) software being cost effective for a wide range of companies [75].

3.6.2.2 Computer graphics theory

The term "computer graphics" refers to a set of computer applications, which can be used to produce images, and animations, which would have been impossible with the technology available only a few years ago. Computer graphics uses numerical models of real world objects to create artificially created views. Each object is reduced to a representation consisting of points, edges and flat sides [77]. The kernel of three-dimensional computer graphics might be defined as the principles of modeling and rendering. Modeling is the creation of the geometry of the object to be rendered. The geometric primitives might be polygons or surface patches. The primitives might be created by defining the three dimensional co-ordinates of the vertices of the polygons or might be created via interaction with a computer program such as a CAD program or a simple program, which allows a user to create surfaces of revolution. Rendering, on the other hand, is the process of displaying the image of the object on the screen of a video display monitor, i.e. determining which pixels will be displayed and what the shade (i.e. color) of each pixel will be. Rendering might be accomplished via hidden-surface techniques, ray-tracing techniques, radiosity techniques or some combination of these methods [75]. A more advanced feature available at the higher end of the graphics market is the ability to create sequences of rendered frames and thus display these as an animation, or film.

3.6.2.3 Software and application

The first decades of computer graphics were dominated by engineering applications but since the cost of graphics systems has decreased, the number and the variety of computer graphics applications have grown. A wide range of computer graphics software is available. Today computer graphics are used routinely in such diverse areas as science, engineering, medicine, business, industry, government, art, entertainment, adverting, education, training and accident reconstruction. The following sections discuss some of the applications areas of computer graphics and present examples of such applications.

3.6.2.4 Design Engineering

A major use of computer graphics is in design processes, particularly for engineering and architectural systems. CAD methods are routinely used in the design of buildings, automobiles, aircrafts, computers and many other products. Objects in a design application are first displayed in a wireframe outline form, which shows the overall shape and internal features of objects and allows designers to quickly see the effects of interactive adjustments to design shapes.

3.6.2.5 Computer art

Computer graphics methods are widely used in commercial art applications. Artists use a variety of computer methods including special purpose hardware, artist's paintbrush programs, CAD and animation packages and desktop publishing software that provide facilities for designing objects, shapes and specifying object motion.

3.6.2.6 Presentation graphics

Another major application area is presentation graphics, which are used to produce illustrations of work or to generate slides or transparencies for use with data projectors. Presentation graphics are commonly used to summaries financial, statistical, mathematical, scientific and economic data for research and managerial papers or bulletins or various types of reports. Typical examples of presentation graphics are bar charts, line graphs, surface graphs and other displays showing relationship between multiple parameters.

3.6.2.7 Entertainment

Computer graphics methods have been widely used to make motion pictures, music videos and television adverting spots and shows. Sometimes the graphics scenes are displayed by themselves and sometimes computer generated objects are composited with the actors and live action scenes. Photorealistic rendering techniques are frequently used in advertising and television commercials. These animations can be produced by rendering each frame of a simulated motion, which are then saved as image files. When all frames in an animation sequence have been rendered, the frames are transferred to film or stored in a video buffer playback.

3.6.3 Simulation and Peripherals Technology

The model or simulation is a mathematical representation of the system being used. It needs to take account of dynamic behavior in response to the user's input. For example, a mathematical model can be produced that represents the dynamic behavior of a petrol engine under different load conditions. Very sophisticated mathematical models can be written but it is the way that these are associated with an auditory and visual representation of the system that is important [75].

It is the peripheral technologies that most people closely associate with virtual reality since they represent the user's interface with the virtual reality system. The peripheral technologies are the input and output devices, which allow the user to interact with and control the actions in a virtual reality system.

The input devices refer to the interaction devices that are used to input the position and orientations of the user's head and hand. They include a standard mouse, keyboard, joystick, space ball, touch screen monitor, data glove and tracker devices. The selection of the input devices depends on level of interaction and flexibility of movement required.

3.6.4 Virtual reality application in Training

Virtual reality is a powerful tool for training since people comprehend images much faster than they grasp lines of text or columns of numbers. Some aspects of training can be acquired in a classroom or from a book but there is no substitute for training with the real experience. It is believed that virtual reality is an excellent substitute of the real thing and many industries have produced virtual reality training simulators, which are used for planes, submarines, power plants, tanks, helicopters, ships, trains, surgery, and air traffic control. These simulators use a replica of the real operational environment and real time computer simulations to model its dynamics. Virtual reality training systems have also the flexibility to structure different training scenarios and they can monitor and measure the progress of every training session. The electronic equipment manufacturer, Motorola uses virtual reality for training its employees on new production and assembly lines in order to avoid the expense of shutting down actual production facilities. Figure 3.21 shows a screenshot from one robotic work cell from the Motorola virtual reality model of the assembly line. The virtual environment created included a conveyor system, robotic work cells for assembling pagers, a machine vision inspection system and a laser marking system for engraving identification numbers on each product [86].

Fig.3.21: Screenshot from Motorola virtual reality model [86]

3.6.4.1 Aircraft and vehicle training

This category of virtual reality application is concerned with creating a virtual environment that replicates all or some of the features involved in the operation of a vehicle or an aircraft. The real control components can be integrated with the virtual environment giving a realistic training experience. Pilots or drivers can experience the virtual reality simulation training systems without causing any harm to the vehicle or aircraft and to themselves [87]. Virtual environments have played significant roles in flight training over the past two decades and they will continue to do so in the future because their use has demonstrated significant advantages over physical scale systems. The flight simulator is one of the earliest implementations of virtual reality technology. These simulators generate a highly realistic virtual environment so that pilots trained on them may be capable of fling the real aircraft at the first attempt. Using flight simulators, pilots can be trained for new types of aircrafts and they can practice flying under emergency conditions without involving a real aeroplane or airport [88]. At the Defence Helicopter Flying School (DHFS) at Shawbury, operators use virtual reality flight simulators to train United Kingdom Royal Air Force pilots. These virtual reality training systems replicate in-flight conditions that are crucial to effective pilot training and realistically simulating scenarios including fog, rain, and snow, pilots are able to virtually experience reality, before they ever leave the ground [89]. A screenshot from such a flight simulator is shown in figure 3.22.

Fig. 3.22: Screenshot from a flight simulator [89]

3.6.4.2 Medical training

Medicine has become a computer integrated high technology industry. Virtual reality and telepresence may have much to offer with its human computer interfaces, three-dimensional visualization and modeling tools. Advanced three-dimensional modeling tools can be used to develop useful models of the human body and in the design of artificial organs. Medical professionals can use virtual reality to study the body by navigating in and around it. Telepresence techniques could allow surgeons to conduct robotic surgery from anywhere in the world offering increased accessibility to specialists. Prototypes have been tested that let the surgeons experience all the sensory feedback and motor control that would be felt in person [90] [91].The development of virtual reality training simulators can help surgeons to practice without harming animals or humans. The Human Interface Technology Laboratory (HITL) at the University of Washington has developed human controlled robot manipulators, which can provide numerous advantages in performing surgical tasks, especially in microsurgery and minimally invasive surgical procedures. Virtual interface technology combined with robotic manipulators can potentially re-map this relationship between the surgeon and patient, and thereby providing additional degrees of freedom to the surgeons' movements and senses, and close the gap between inside and outside, large and small[92].Figure 3.23 shows screenshots from this virtual reality application.

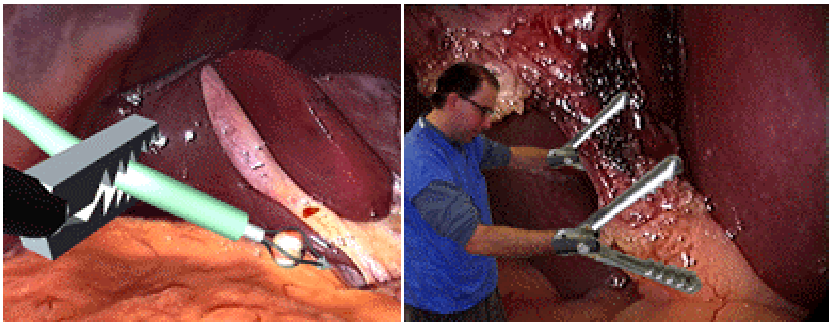

Fig. 3.23: Virtual prototyping of medical robotic interfaces [92]

3.6.4.3 Military training

One of the first areas where virtual reality found practical application is in military training and operations. One of the earliest uses of simulators in military environments was the flight trainer built by the Link Company in the late 1920's and 1930's. These trainers looked like sawed-off coffins mounted on a pedestal, and were used to teach instrument flying. The darkness inside the trainer cockpit, the realistic readings on the instrument panel, and the motion of the trainer on the pedestal combined to produce a sensation similar to actually flying on instruments at night. The Link trainers were very effective tools for their intended purpose, teaching thousands of pilots the night flying skills they needed before and during World War II. In a dynamic combat environment, it is imperative to supply the pilot or tank commander with as much of the necessary information as possible while reducing the amount of distracting information [92]. Virtual reality techniques are being explored to evaluate how today soldiers can masters new weapons and tactical procedures without the support of the physical environment. It is hoped that the virtual environment will be able to offer all the realism associated with the real world without the obvious drawbacks of cost, organization, weather, time of the day and so on. The virtual domain is repeatable, interactive, three-dimensional, accurate, reconfigurable and networkable and provides an excellent medium for military training. The Evans and Sutherland company has produced a range of computer based virtual reality systems for military planning and mission simulating. These virtual reality training applications can train personnel for security planning and scenario analysis, urban planning and law enforcement training. Figure 3.24 shows an image from a virtual reality training system used for military applications.

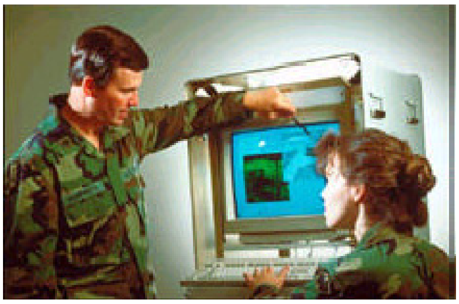

Fig. 3.24: Virtual reality training for military applications [93]

3.6.4.4 Industries

There has been number of developed hazard spotting training applications. Figure 3.25 shows an image from a hazard spotting system involving a surface mine haulage truck. This system consists of a simple truck with around twenty-five hazards, which associated, with different components of the truck. The system makes use of samples from existing training videos to explain the repercussions of missing any hazards. Whilst missing securing pins may cause the entire load bed to drop from the truck, litter around the air intake could cause the vehicle to stall, either causing the driver to lose control, or to be stuck at a particularly dangerous point on the haul road [94].

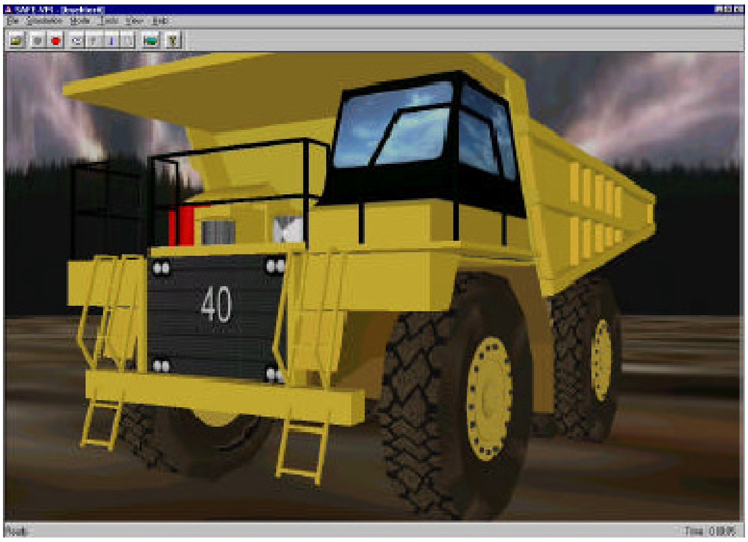

Fig. 3.25: Pre-shift truck inspection

An underground roof support application is as shown in figure 3.26. This application allows the user to perform an inspection of a section of roadway in an underground coal environment. The trainee is expected to spot a range of hazards such as badly installed roof bolts, unsupported areas, and water seepage and to identify deviations from the mines support regulations in both the roadway and at junctions.

3.6.5 Benefits and Applications

The major applications areas of virtual reality can be broadly classified into understanding, experiencing, entertainment and learning. In all four cases, virtual reality provides a safe and frequently highly cost effective environment for individuals to fulfill their professional, training or recreational needs. There are many areas where virtual reality could be used to support training. The advantages of virtual reality training compared to traditional methods of training can be summarized in the following section:

- ❖ Ability to observe system operation from a number of perspectives aided by high quality visualization and interaction [75].
- ❖ Observation of system features that would be either too small or too large to be seen on normal scale system [75].

- ❖ Ability to control timescale in a dynamic event. This feature could operate like the fast forward or rewind preview in a modern video recorder [75].
- ❖ Most people learn faster by "doing" and virtual reality systems provide much greater levels of interactivity than other computer based system. Provided that the interfaces are intuitive and easy to use then the degree of interactivity can be very beneficial [75].
- ❖ The inherent flexibility of a virtual reality system comes from the under lying software nature of the virtual environment. A virtual reality system can be put variety of uses by loading different application environments. This means that it is feasible to use a virtual reality system for a range of training applications
- ❖ The sense of immersion is a powerful characteristic in the field of engineering design and virtual reality environments provides that. For example, architecture is an area where the sense of scale is required to visualize the impact of a building design on the surrounding environment and the habitants. It is obvious that virtual reality systems are able to provide rescaling in three-dimensional designs, which is extremely important for engineering.
- ❖ A virtual training environment allows users to train themselves to engineering processes without actually being there and before plant has been built. Furthermore, the trainee is able to point out areas, which would have been very difficult to access.

Research and development into virtual reality applications can be found in many places, all over the world. The applications being developed in the field of virtual reality run across a wide spectrum, from games to construction and from business planning to flight simulations.

3.6.7 Limitations of VRT

There has been considerable speculation and enthusiasm among would-be users regarding the potential of virtual reality technology, much of it more wishful thinking than actual applications. The popular media typically make exaggerated claims about the current state of the technology. A more responsible view is that, whereas virtual reality has considerable potential for many applications in industry and commerce, it is neither appropriate nor desirable in all cases [74].

Because of its many advantages, virtual reality seems to be an ideal training medium. However, inherent to virtual reality training and education is the assumption that the training that takes place within a virtual environment transfers to the real world. Most reports regarding transfer are anecdotal and there has been insufficient effort expended toward demonstrating under what conditions transfer takes place, if at all [78].

Virtual reality is considered a valuable tool for rehearsing critical actions, in preparation for performance in the real world. It is therefore advocated for training individuals to perform tasks in dangerous situations and under hostile environments, such as in chemical plants. However, rehearsal in a dangerous situation may have unwanted consequences. The user, who makes mistakes and only experiences safe, simulated consequences, could become desensitized to, and less fearful of dangerous scenarios. This lessening of anxiety can be an important asset in enabling workers to maintain their cool under duress, but it may also lead to a loss of respect for a real-life danger, particularly where the hazard is experienced in a game format. Similarly, if occupational health and safety efforts present a virtual representation as accurate when, in fact, the simulation is not credible, the participant could leave the experience with the impression that the hazard event is really not of much concern [74].

3.7 Research Model Development

The construction of the objects used to build the virtual chemical environment are discussed and described in this section. Using a number of modeling techniques, all the objects to be used in the virtual world will be first created by using 3D Studio Max as shown in Figure 3.22. Adobe's Photoshop software was used to manipulate and design the textures, which were applied to objects. Model then are converted into two file type. Dwf file type is used in HAZOP analysis Management System (HMS). While Virtual HAZOP training system model are convert .3ds file type before imported into 3dvia virtool development system with all their texture intact. Model is hydrodesulphurization (HDS) unit used to remove sulfur (S) from natural gas and from refined petroleum products such as gasoline or petrol, jet fuel, kerosene, diesel fuel, and fuel oils. More explanation on hydrodesulphurization unit is discussed in the next chapter.

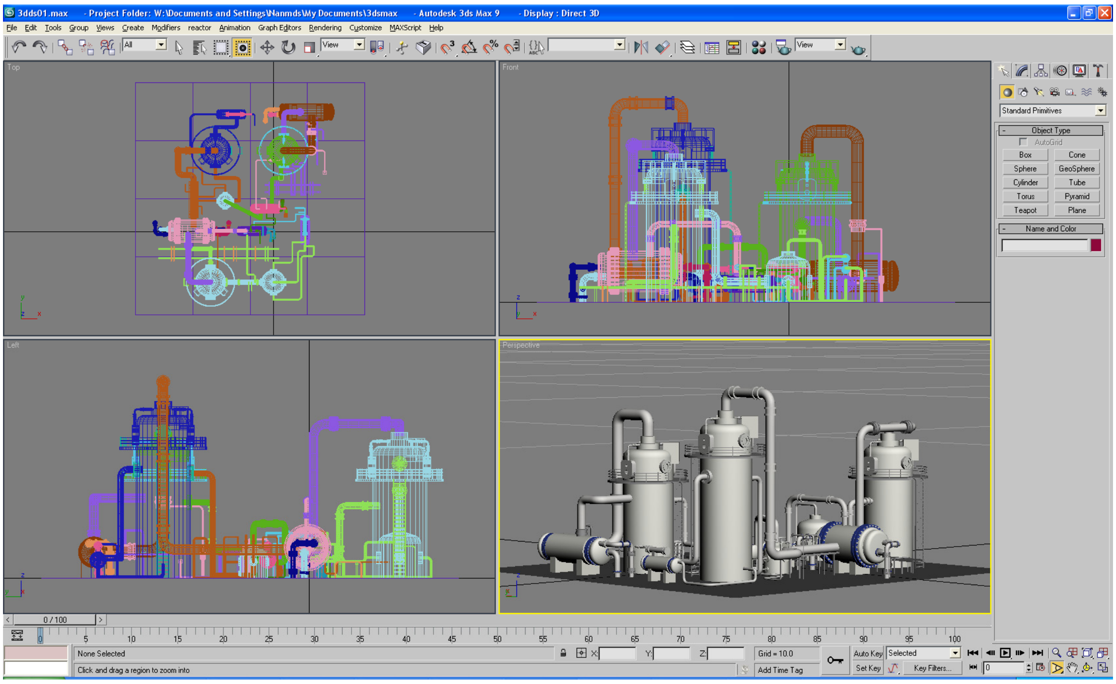

Fig. 3.22 model develop in 3d studio max

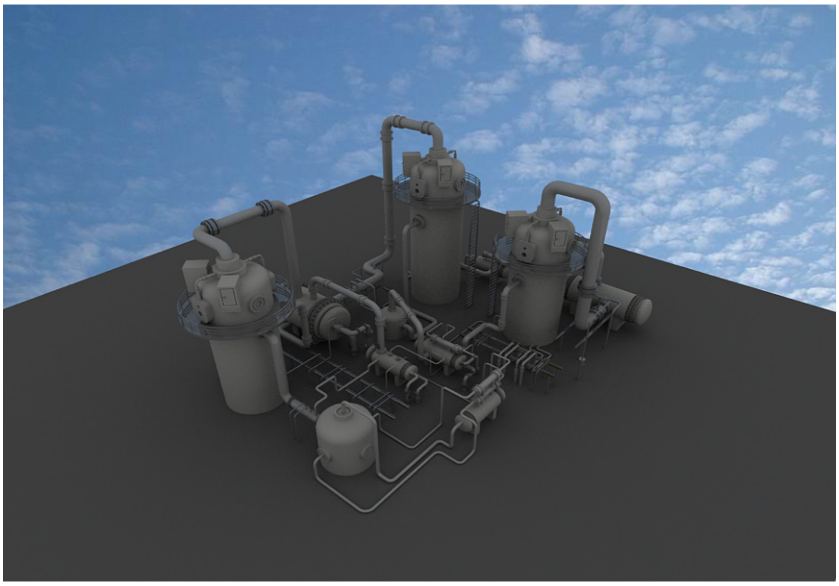

Fig. 3.23 complete rendering hydrodesulphurization unit using v-ray in 3D studio max.

3.7.1 HAZOP Analysis Management System Model

HAZOP analysis management system is Web-based. Models related to case study are developed and animated in Autodesk 3D MAX 9 exported to interactive format. We choose dwf format to facilitate light file transfer web. Freewheel component by Autodesk enable model to be viewed and navigated throughout web page.

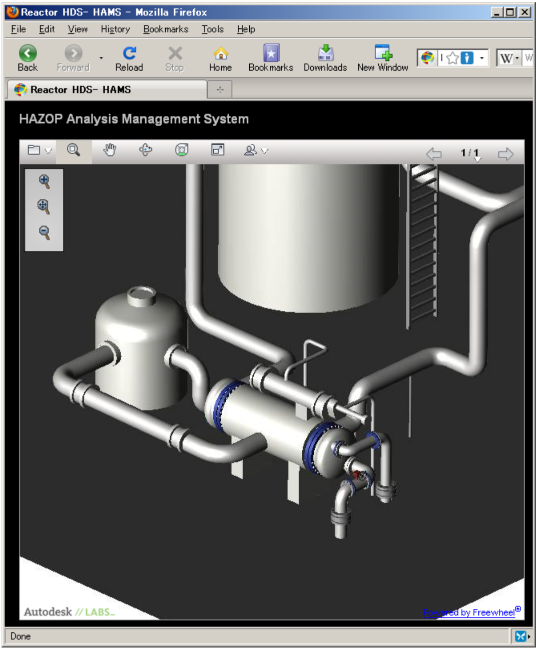

Fig. 3.24: Visual Model of HDS Reactor part.

3.7.2 Virtual HAZOP Training Model

Visual HAZOP training interface is develop using c sharp. Base model related to case study is the same as model used in HAZOP analysis Management system. Base model imported into 3DVIA virtool application to create virtual reality module.

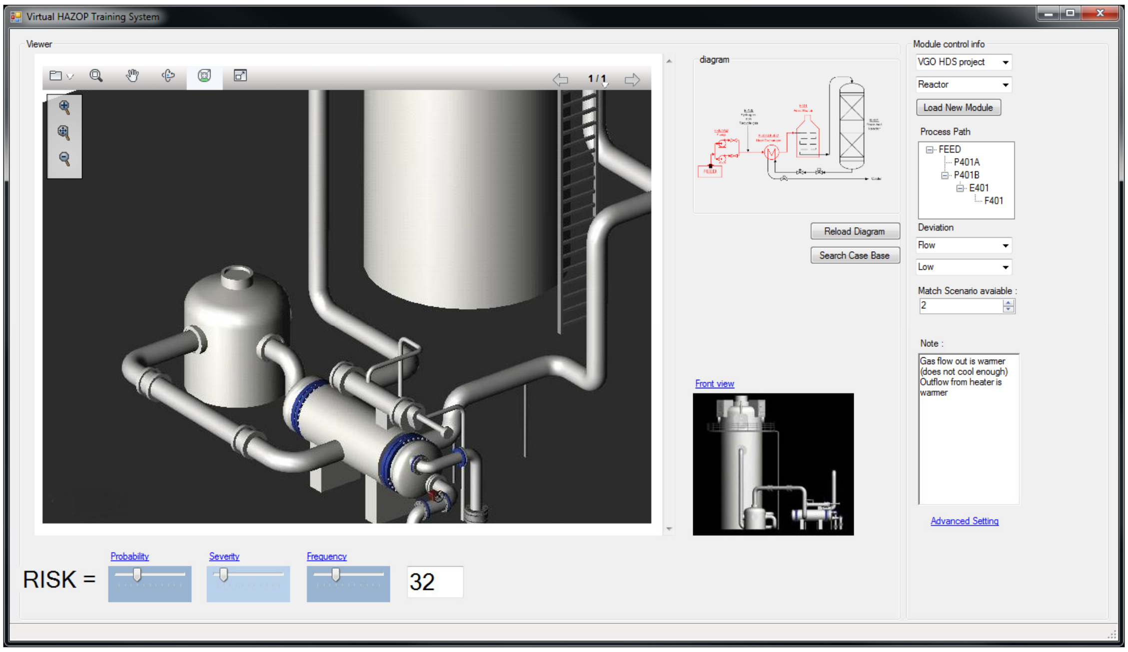

Fig. 3.25: Visual HAZOP training interface

3.7.3 Data Resources – database

HAZOP analysis data are collected from HAZOP training module and previous research data in Advanced Safety System laboratory. Accident and near miss case are collected from online sample, training module examples and safety supported system, PEC-SAFER a Japanese safety supported site for engineer in refinery. All collected cases are related to this research case study for a hydrodesulphurization unit. These cases are available in appendices.

Table 3.12: list of database table names and their function

Tables Name:	Functions
HAZOPMain	Store Main HAZOP analysis data and its properties
Casebase	Store near miss, accident cases information inform HAZOP analysis
UserMgt	Store user information and it access level
HFlist	Store information Human Factor and

	its description
ProjectList	Store project list
ProcessList	Store analysis process
PathList	Store analysis path
EquipmentList	Store equipment information, properties and status of inspection
MaterialList	Store material information and its properties
DeviationList	Level one guide word : flow, temperatures etc
GuideWord	Level two guideword : high, low etc
RiskList	Event Risk factor and description
ProbabilityList	Event occurring probability factor and description
SeverityList	Event severity of harm factor and description
FrequencyList	Event occurring frequency factor and description
HMSmodel	Store information of Visual model files used in HAZOP Analysis Management System: file name, locations etc.
VirtualHAZOP	Store information of Virtual HAZOP Training module file used in Virtual HAZOP safety training system: file name, locations etc.
PnIDlist	Store information of P&ID files: file name, locations etc.
updateList	Store timestamp and user who updated record

In the proposed system, HAZOP analysis management system and Virtual HAZOP training system share same information form database named VGO_HDS.accdb. This database is Microsoft Access database. Table 3.12 shows tables in database along with their functions. Traditional HAZOP information is stored in hazopmain table while converted HAZOP format near miss and accident cases are stored in casebase table. Figure 3.26 expresses relationship among tables in table 3.12. Available information field for each table is also shown in Figure 3.27 and Figure 3.28.

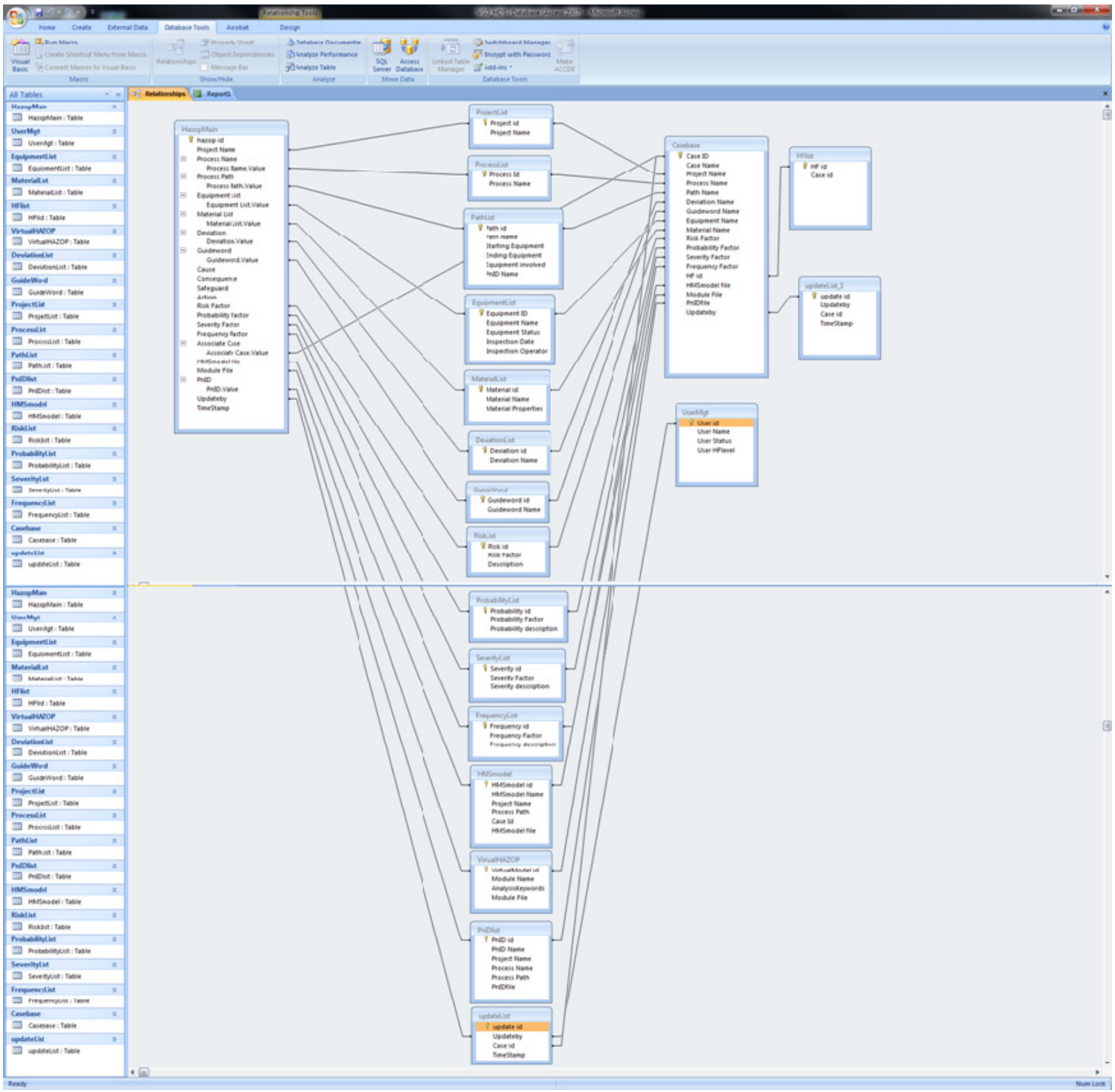

Fig 3.26: Relationship between tables in VGO_HDS.accdb

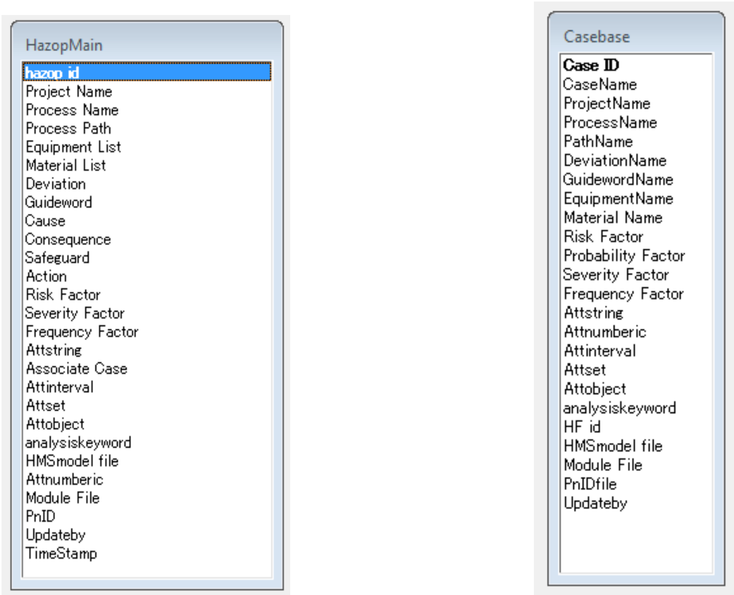

Fig. 3.27: List field of Main HAZOP table and list field of Case base

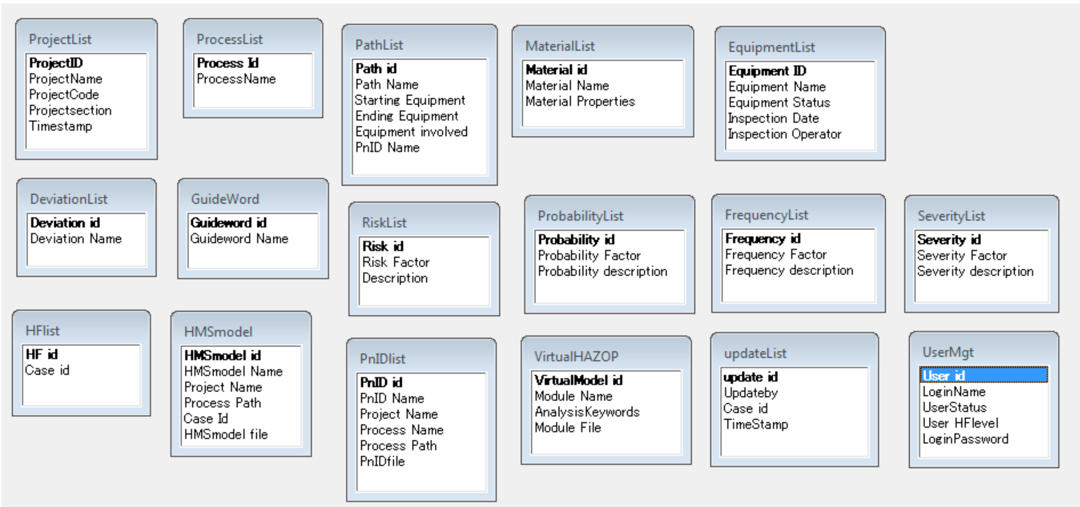

Fig. 3.28: List field of others tables

3.8 Ontology

Throughout this thesis, we used the word ontology several time in supporting HAZOP analysis. "Ontology" is a term of philosophy originally, which refers to the subject of existence. Artificial intelligence (AI) borrows the old term from philosophy and gives it new wonderful meanings. In AI, there are a number of definitions of ontology. However, the definition given by Gruber is accepted by majority of researchers: an ontology is an explicit specification of a conceptualization (Gruber, 1993).Or in layman term similar to information database but with additional of same keyword on all database. Due to no resource of real ontologies example, we described this method as a proof of concept which is, if available can be used instantly along with developed system.

Human experts are indispensable in HAZOP analysis of any chemical processes even though various expert systems can be designed to facilitate the process. Different experts especially from different organizations have different jargons with regards to the descriptions of the analysis objects and results including causes and consequences of hazards. That is to say, there is no standard to represent the HAZOP analysis domain information. This increases the difficulty of CBR for different users. To settle the terminological and conceptual incompatibility problem, require new set of ontologies to be integrated. This goes the same towards other fields. Such as Design and manufacturing which are important activities of the modern world, and the designers and manufacturers embrace globalization as part of their operational strategies, having a common view across their enterprise becomes a key factor in realizing improvements in collaboration and productivity. Design and Manufacturing interoperability is a strategy for achieving this common view and is being implemented by several enterprises and several web platforms are used to aim in this interoperability. For a successful design and manufacturing project, they need people with competence to operate and use specific equipment in all phases of the project. The equipment must be purchased, installed and understood – all without compromising that original design. If not, it can lead to negative consequences on the budget and on project schedule. Due to this, it is sometimes necessary to have a common vocabulary centered in equipment, also relating competences, processes, best practices, other equipment and other concepts. The concept of ontology embraces the followings:

- **Scope identification** – In this phase, the knowledge engineer specifies the reason why the ontology is been created, where it will be used, the processes which will be studied and the granularity of properties' description.

- **Ontology Creation** – This phase is divided into requirement specification, knowledge acquisition and representation.

The "Requirement Specification" implies the definition of questions about the domain, questions which the ontology should answer. The "Knowledge Acquisition" is responsible for the identification of domain knowledge, concepts and property identification, the relation between concepts and domains restriction. After that, in the "Representation" phase, an ontology language is chosen, and the ontology is represented in this language.

- **Integration** – During the process of ontology creation, it may be necessary to integrate the ontology which is been constructed with an already existing one, with the aim of using previous and well known concepts' definitions and relationships.

- **Evaluation** – Finally, the ontology should be evaluated by a domain expert who will validate it if it satisfies the requirements defined in the scope identification phase. This phase should also be done in parallel with the steps of the ontology creation, in an interactive process. To evaluate the ontology with the domain experts, the use of a graphic representation is extremely important.

3.9 Summary

In this Chapter, important theoretical concepts, mathematical notations and definitions that will help understanding of the discussions in the subsequent Chapters in this dissertation have been introduced. We start by explain the justification using HAZOP in this research. We show the trend of publication in HAZOP research to indicate that HAZOP is favorable PHA method for hazard identifications. Automating and combining HAZOP with an expert system is the highest percentage research focus is explained. The concept in performing a HAZOP and technical requirements explained to give understanding of HAZOP mechanism in detecting hazard and operability. Following this is literature review of previous research in extending HAZOP identification scope, automating HAZOP with expert system and supporting HAZOP with dynamic simulation. We proposed an intelligent HAZOP utilizing artificial intelligence technique of hybrid fuzzy logic and case based reasoning. This technique which then elaborated is responsible for selecting the most promising information from HAZOP database for estimating risk. Reasoning from past experience and cases facilitates learning capability of intelligent HAZOP. This type of reasoning is more reliable and trusted by safety operator due to existed previous cases and not by mathematical assumption. As the research work is in safety domain we emphasize the important of risk factor as key factor in giving prioritizing actions. We formulated a fuzzy calculation of risk using the sub component that defines risk which is probability factor (P), severity of harm factor (S) and frequency factor (F). This risk factor then is used as indexing mechanism in case base module. Risk factor provides a logical system for safety management to set priorities for attention to hazardous situations. The validity of these priorities or these decisions is obviously a function of the validity of the estimates of the parameters P, S and F, and these estimates, apparently very simple, require the collection of information, the visit of the workplaces and the discussion with the workers about their activities. Fuzzy knowledge is represent in IF-THEN rules while CBR knowledge is represent in case base module. Application example is shows to give understanding how the proposed system used the proposed method Virtual reality training concept and its signification benefit of application into safety training are discussed. Technique in model development for proposed system is explained. Following is the structure of database that stores HAZOP case, safety case base and other parameters. An otology concept also discussed to show the benefit if available to the proposed system.

Chapter IV

DEVELOPMENT OF INTELLIGENT RISK MANAGEMENT SYSTEM

Development of Intelligent Risk Management System

4.1 Introduction

In this chapter, we discuss two applications developed in order to apply the proposed methodology. HAZOP Analysis Management system and Virtual HAZOP training system are developed in order to achieve the objectives stated in Chapter One. HAZOP analysis management system is a web based application developed to manage safety information especially HAZOP analysis. Case bases are used to improve completeness of the system by adding relevant information into the HAZOP analysis case. The extended functions of the HAZOP analysis management system is the Virtual HAZOP analysis system. This system helps the safety operator to practice HAZOP analysis. The system improves operator analysis experience by imbedding virtual reality simulation. Both systems utilized fuzzy-CBR technique in case retrieving and indexing.

4.2 HAZOP Analysis Management System

This is the risk management system designed in this research for safety operations. The structure and work flow are explained in the following sections.

4.2.1 System Structure and Work Flow

User will be required to login to the designed HAZOP analysis management system as shown in Figure 4.1. Depending on user desire, three ways of performing analysis are offered. Using the same first part of fuzzy-CBR module in virtual HAZOP training system, cases with similar keywords as input from user are matching and retrieved from "casebase" table in database. A similar virtual model associated with the retrieved case is also used for giving visual aid during analysis decision. Weighted in similarity value, new case will be added to the database should no previous solution available. If the previous retrieved cases lack information, user may update the representative case for future use.

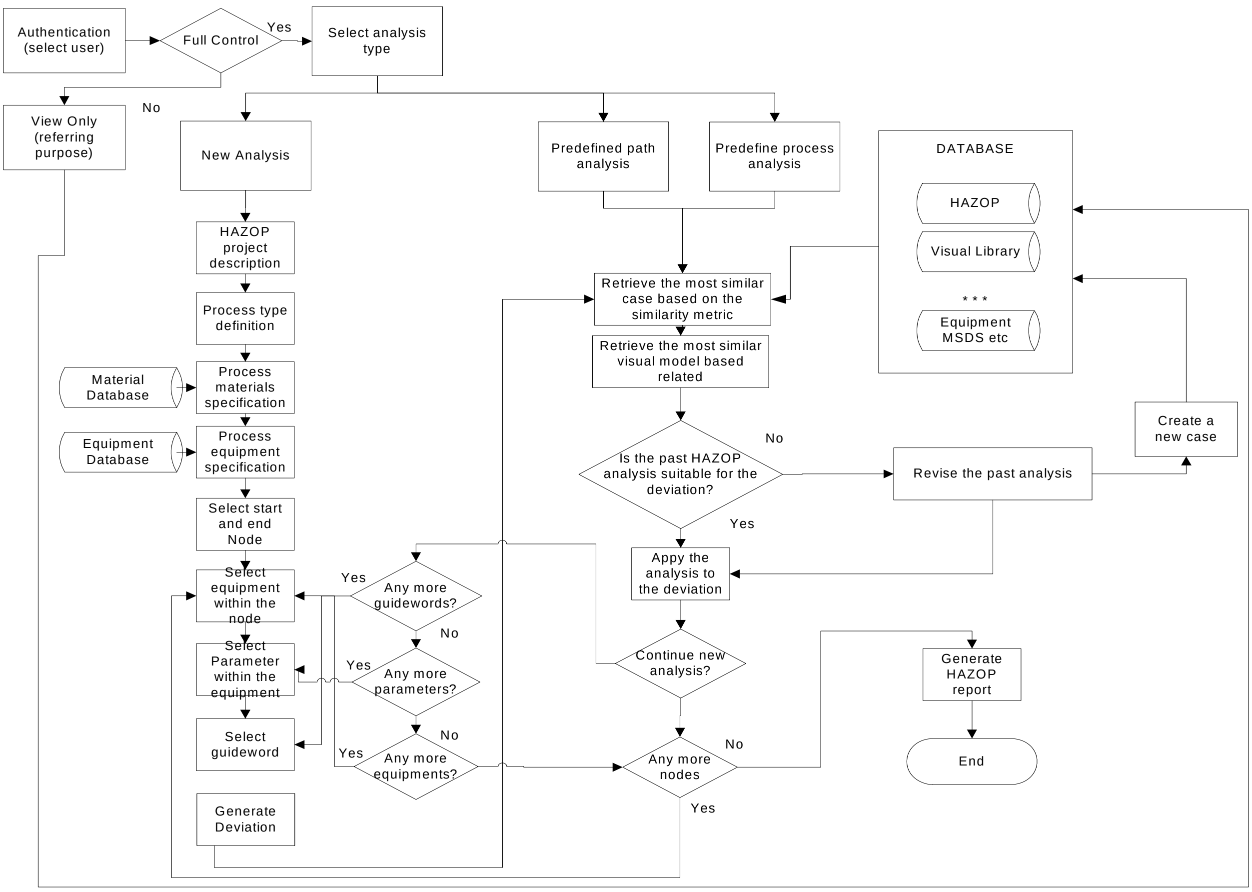

Fig. 4.1: Workflow diagram of HAZOP analysis management System

4.2.1.1 Authentication Module

This module is the gateway into the HAZOP analysis management system. Safety analysis information that can be gathered utilizing this system is highly required for security protection as this information also regarded as company trade secrets.

Referring Figure 4.2, the system starts with an authentication page. Users are filtered into three category based on the usability level:

- ❖ Admin level-this level gives a user a full access into HMS. This entitles users to run complete HAZOP analysis that includes modifying previous analysis, monitoring change and control over user access.etc. This privilege often gives to system management personnel, head of safety department and human resource.

- ❖ Analyst level – this level gives a user a limited access into HMS: basically this level has the same privilege as Admin level except user unable to maneuver other user control capability. This means that the user can only run analysis, updating record and the likes. User would neither be able to add new users nor updating their access level. This level normally granted for HAZOP member team and safety operator.
- ❖ Normal operator level -this level gives a user the privilege to view HMS report only. This access level gives permission only to view a HAZOP analysis report, which includes safety procedure and risk estimation. This level is useful for revision or learning purpose of non safety personnel such as field operator.

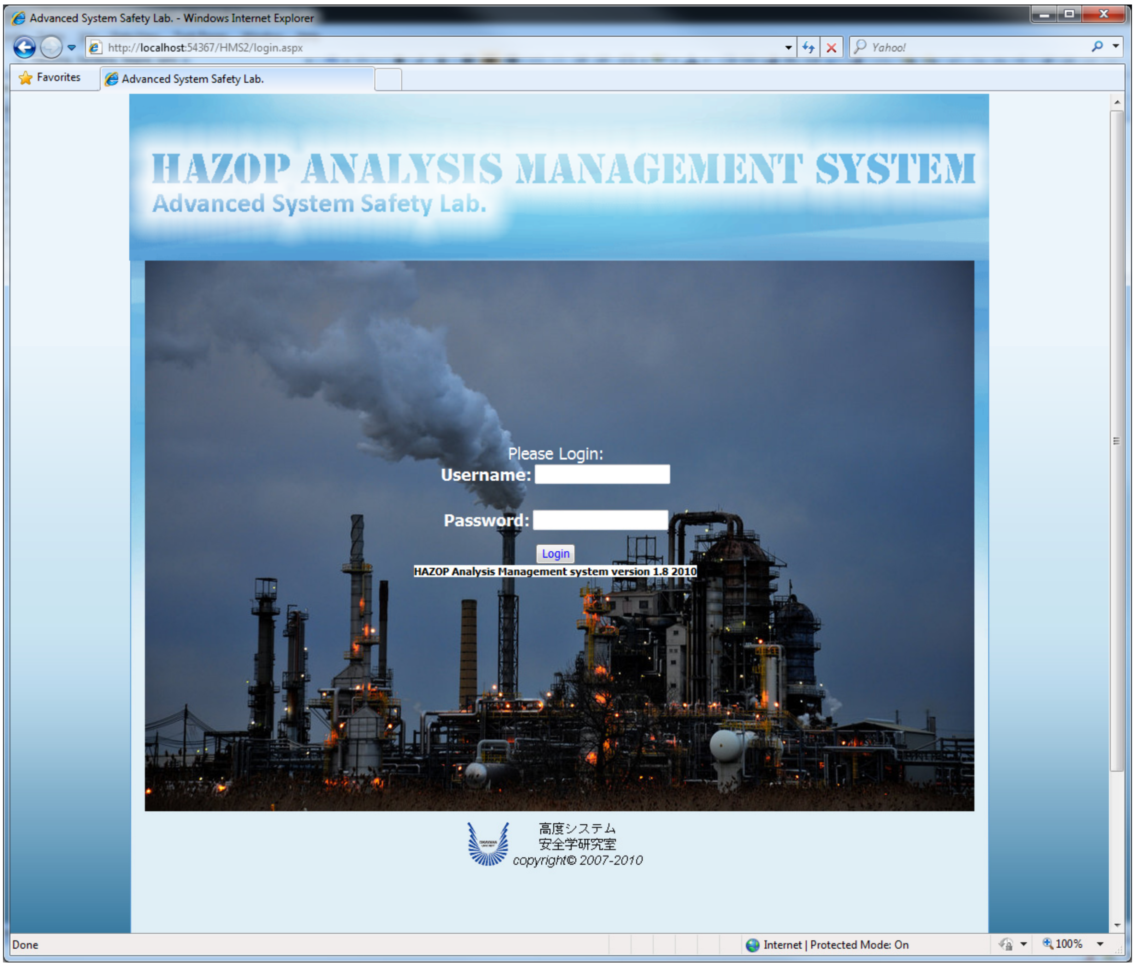

Fig. 4.2: HAZOP Analysis Management system Authentication interface.

After selecting project name and related credential information, the user then select of three analysis types they wish to do as shown in Figure 4.3

1. Predefined path analysis
2. Predefine process analysis
3. New analysis

The difference between these analyses types are explained in the next section. User name and access level is displayed on the screen along with date and time. Any changes by the user will be timestamp using above time. This enables future monitoring and tracking process of fault analysis.

Fig. 4.3: Selecting analysis type of HAZOP Analysis Management system.

4.2.1.2 Predefined Path Analysis Module

Predefined path analysis module offer user to select the path where the start node and the end node are already set according to running logic as in Figure 4.4. Using the similarity formula introduced in Chapter 3, the most similar case is retrieved from the HAZOP case base database. At the same time, visual model with the same attribute is also retrieved. This model is developed as similar as possible to the real equipment set so as to assist HAZOP analyst. Then, user can revise and reuse the past HAZOP analysis if it is suitable. If it is unsuitable, user can create a new analysis case.

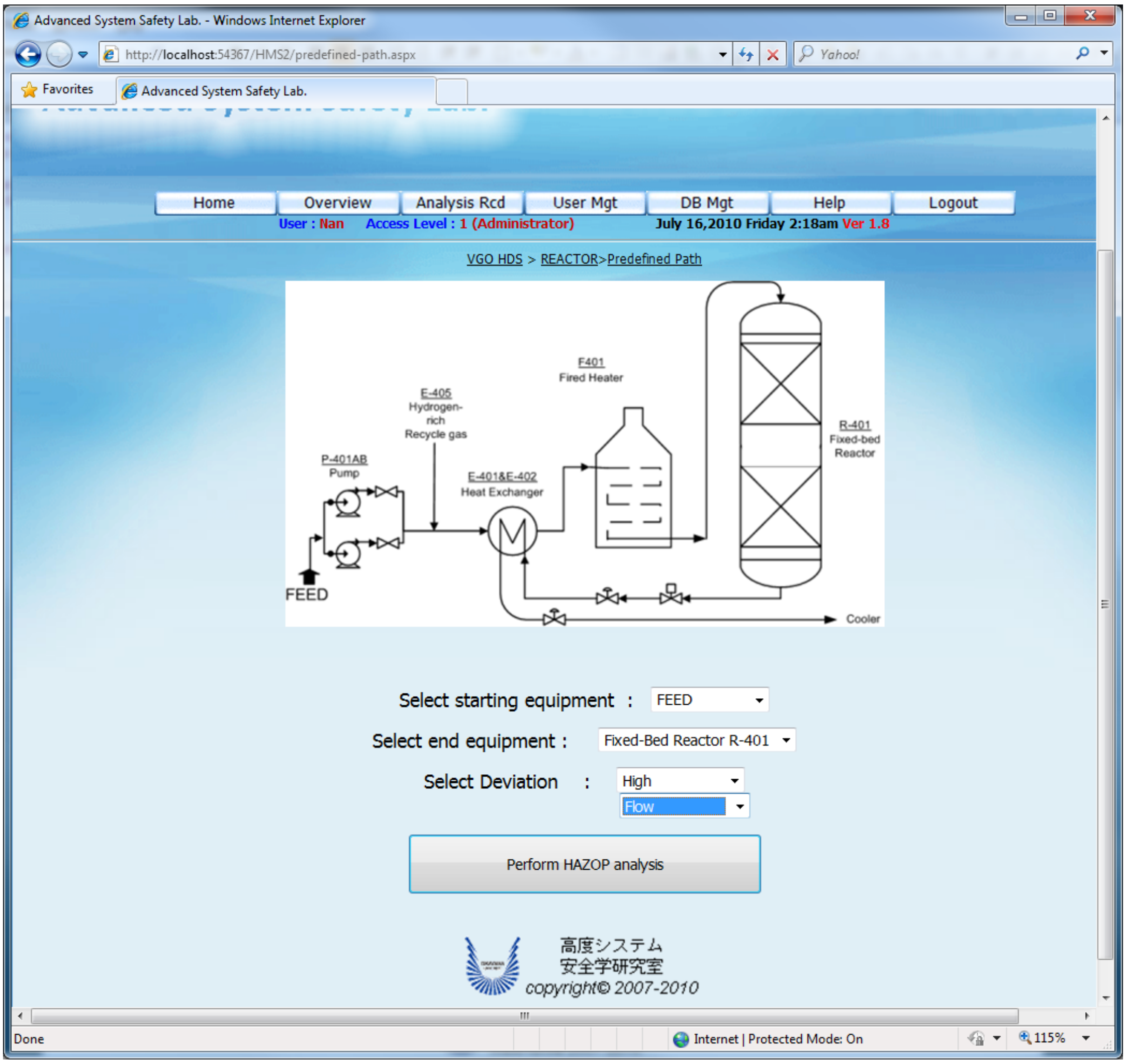

Fig. 4.4: Predefined path analysis of HAZOP Analysis Management system.

4.2.1.3 Predefined Process Analysis Module

Predefine process analysis is the same as predefined path analysis. The different is that users are offered starting node and end node based on a process rather than running logic.

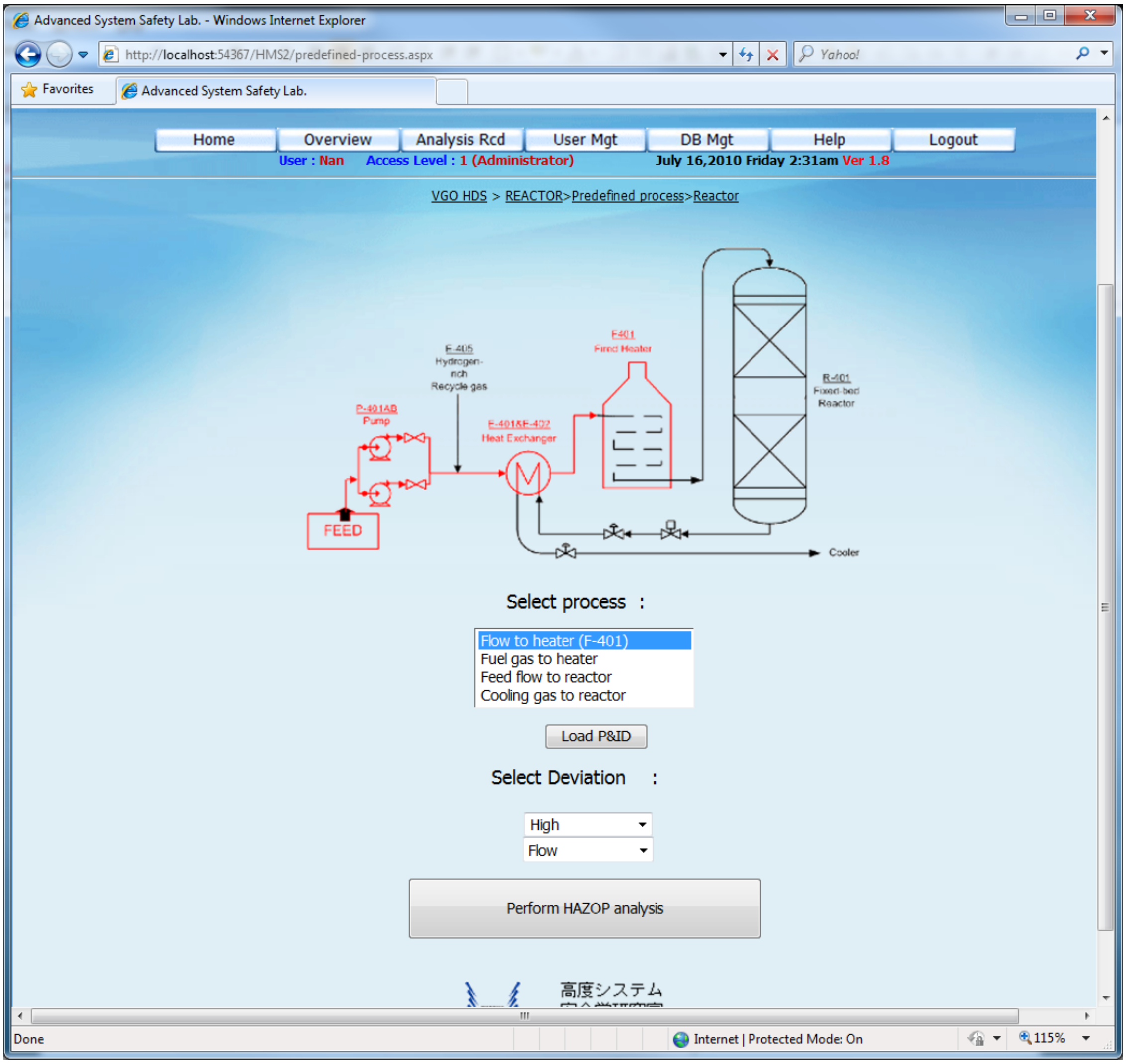

Fig. 4.5: Predefined process analysis of HAZOP Analysis Management system.

During the selection, the system automatically loads schematic diagram related to the process. Process line will be highlighted in red as shown in Figure 4.5. After selecting desire process, user identity is displayed with confirmation page of process path. As in the case of Figure 4.6, user has selected feed flow to reactor.

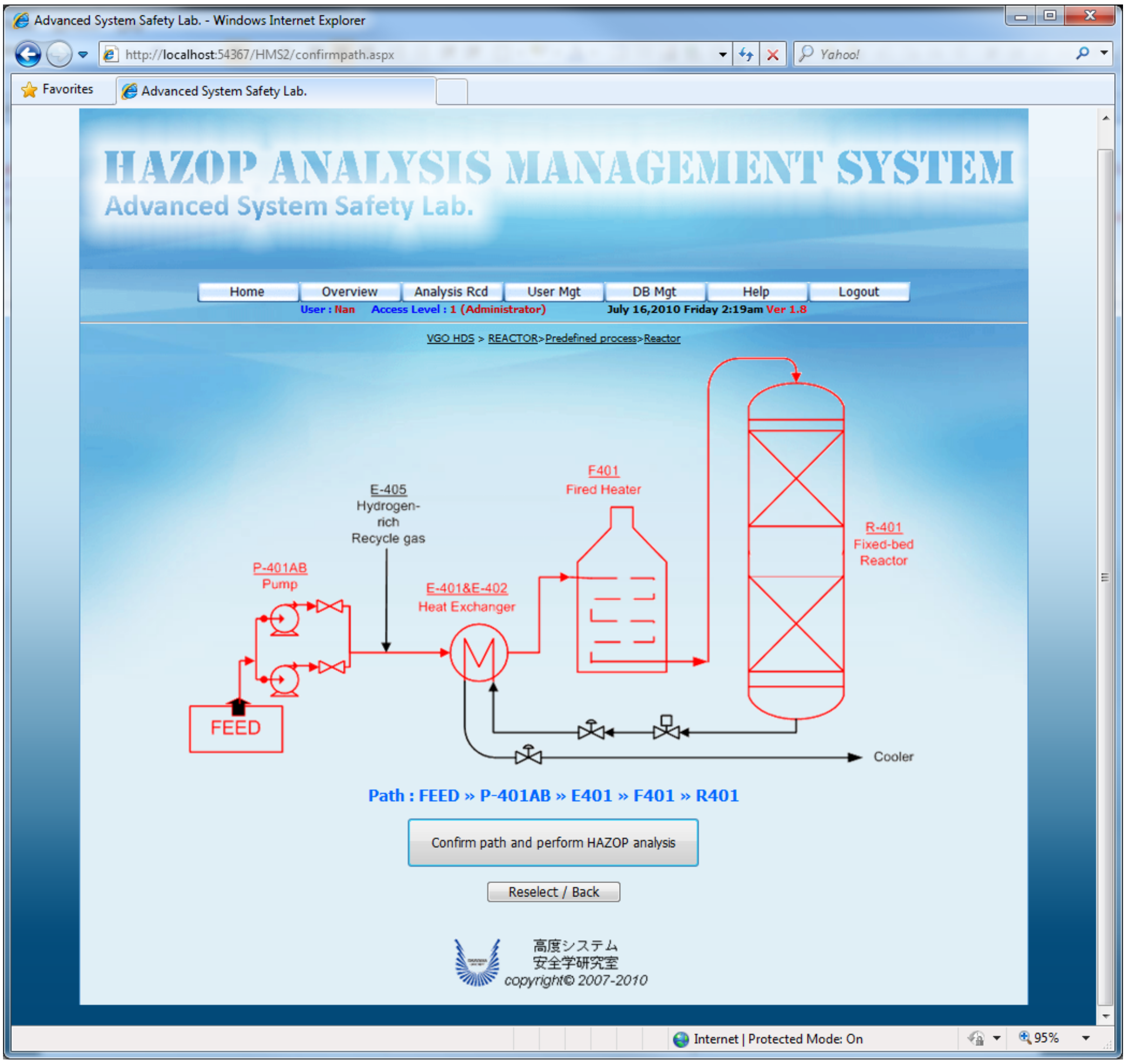

Fig. 4.6: Predefined process analysis of HAZOP Analysis Management system path confirmation page.

4.2.1.4 New Analysis Module

New analysis module is responsible for new analysis, where a complete HAZOP analysis of user selected start node and end node can be performed. Process type, process material and process equipment specifications are provided to the user from the respective database. From here onward, typical HAZOP study process starts by selecting guide word and deviation and continues to similarity check as predefined process and predefined path analysis. Figure 4.7 shows one of the information entry pages of new analysis.

When a new analysis problem is presented to the system, the CBR engine is activated. The engine starts from selecting corresponding case base that fits the problem through the hierarchical indexing mechanism. Users are prompt to choose which case represents their best interests.

1. Register new HAZOP analysis – This option will directly register new HAZOP analysis without having consideration for previous case. This is suitable for new database which analysis completeness status is still at minimal.

2. Register new HAZOP analysis with previous HAZOP analysis support. – This option is used when similar previous HAZOP analysis is present. A user only has to fill part of main parameter such as process, path, deviation, etc. The system will retrieve all similar HAZOP analyses that match requested criteria.

3. Register new Case - This option will directly register new case into Case base without having consideration for previous case. This is suitable for new database in which case base still lacks representative case.

4. Register new case with previous case of case base support - This option is used when similar previous case is present. A user only has to fill part of main parameters such as process, path, deviation etc. The system will retrieve all similar previous cases from case base that match requested criteria. This can prevents user from registering case redundantly.

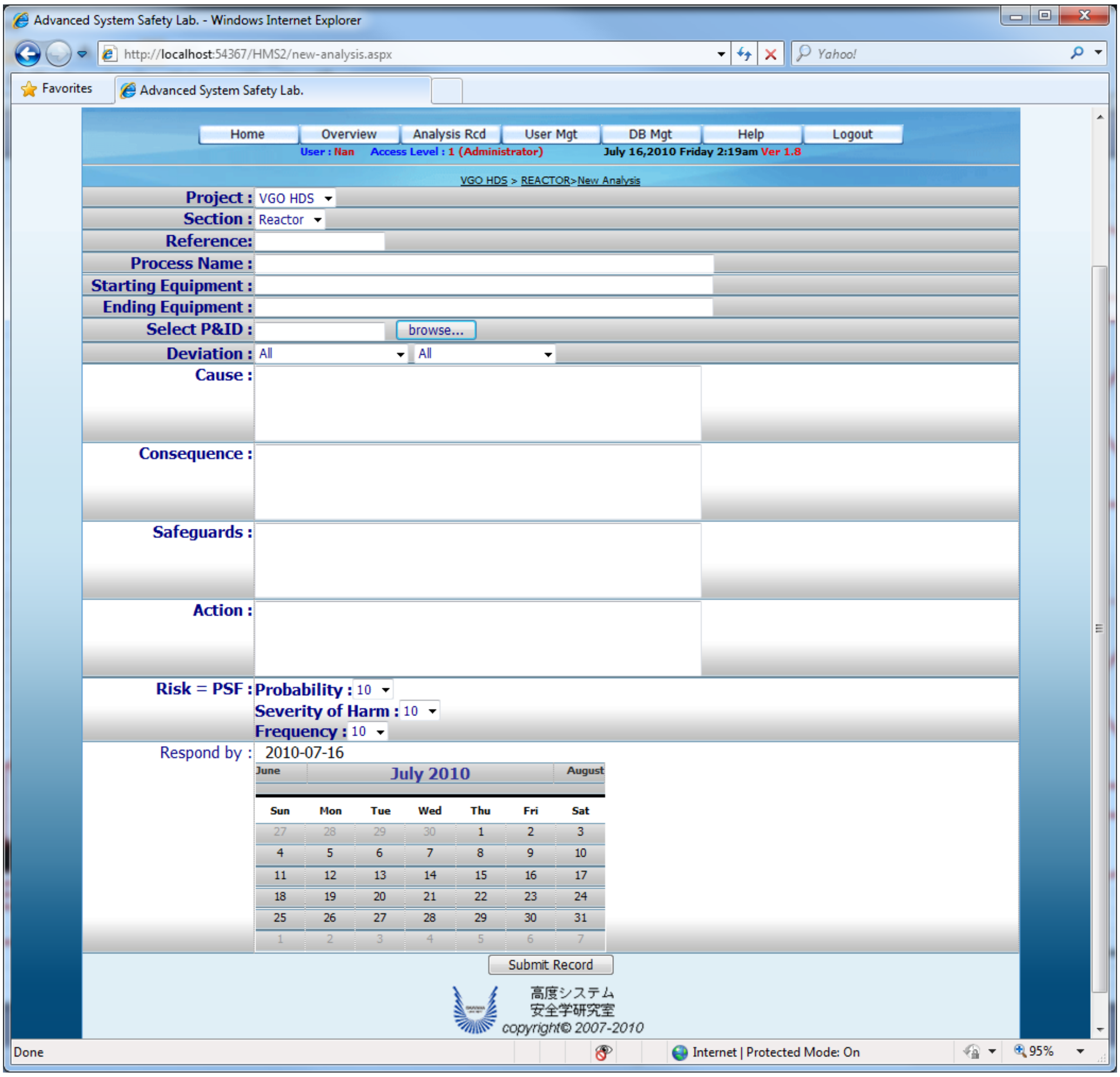

Fig. 4.7: New analysis entry page of HAZOP Analysis Management system.

4.2.2 System Result Interface

System results interface is responsible for displaying end result of selected analysis. There are two methods of displaying results. First method gives the user the ability to check new performed analysis towards currently stored analysis in HMS database. In Figure 4.8, information is divided into two parts, HAZOP analysis results and the HAZOP system analysis results. Keywords that are attached to stored cases are compared with user analysis while similarity score is displayed to the right. The page will bring the user to the editing page, that additional information or new analysis should exist.

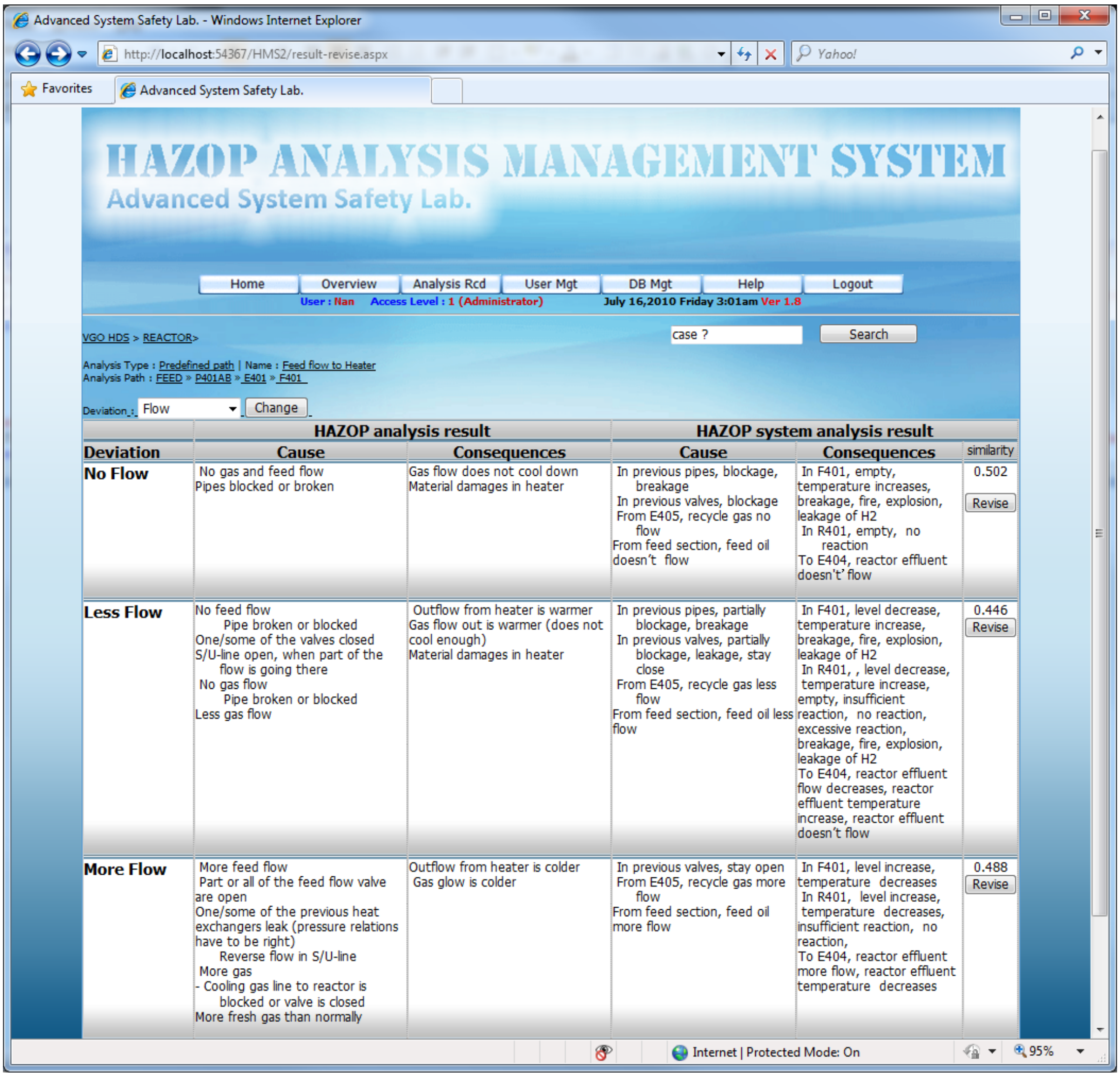

Fig. 4.8: Result comparison of analysis similarity of new case in HAZOP Analysis Management system.

Second method of displaying result is to give risk assessments in the form of Probability factors (P), Severity of hard factor (S), Frequency Factor toward Risk value (R) and Actions required for a specific deviation as shown in Figure 4.9

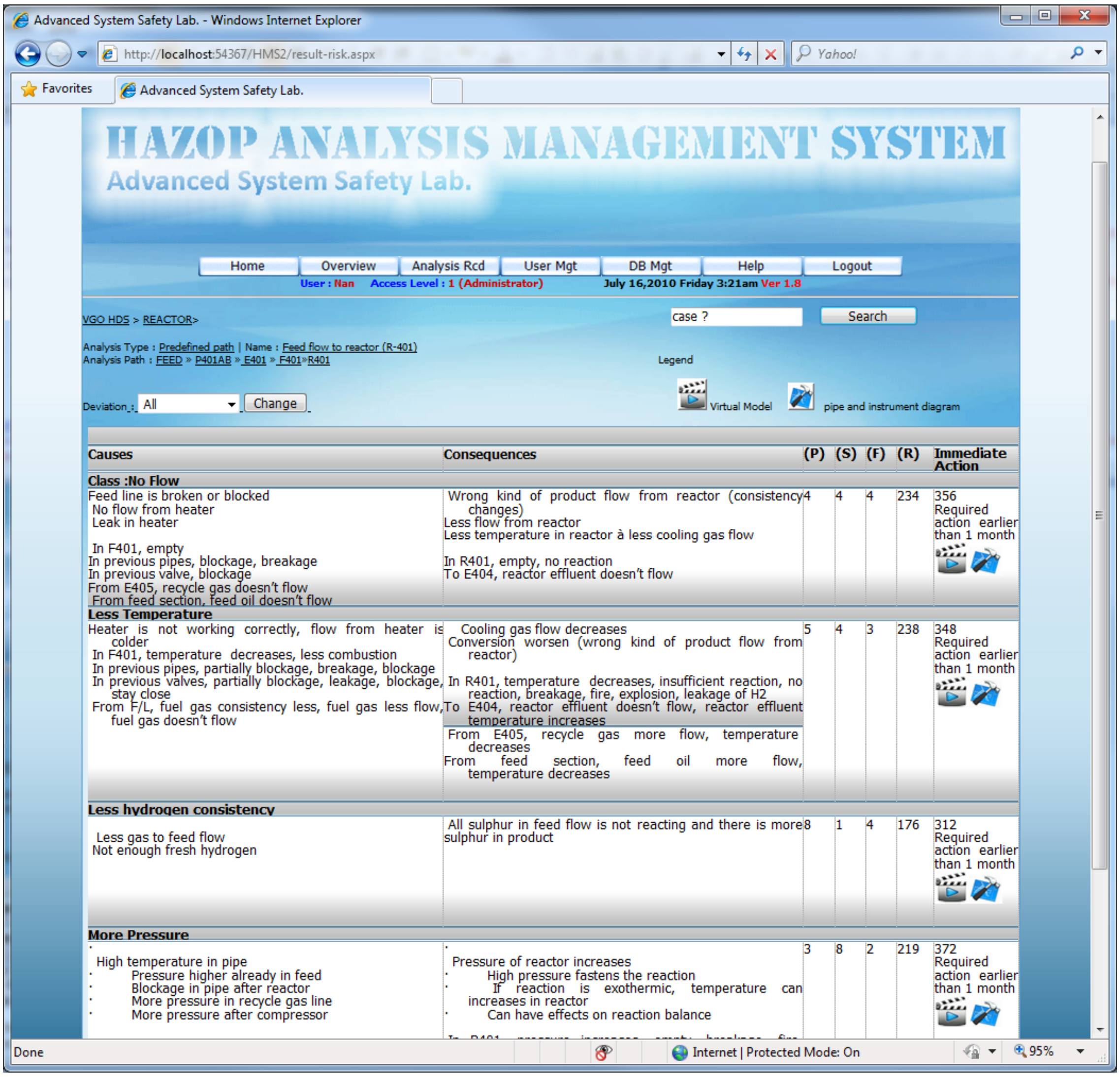

Fig. 4.9: Result with risk assessments and virtual model of HAZOP Analysis Management system.

Two icons beside the action column represent piping and instrumentation diagram (P and ID) and Visual model as in Figure 4.10. HAZOP analysis is carried out in both conventional ways and using proposed system with the time consumed for each process being calculated.

4.2.2.1 Schematic Diagram Module

Schematics diagram module is responsible for retrieving P&ID diagram used in predefined path analysis, predefined process analysis and result page. These diagrams are stored in VGO_HDS database as described in the previous chapter.

4.2.2.2 Visual Model Support Module

This is the key module differentiating this system to other expert supported HAZOP analysis system. This module is responsible for displaying related equipment models in three dimensional views. Embedded in this page is ability for user to navigate model in free form thereby enabling the user the ability to foreseeing the unexpected. This guides the analyst to having different perspectives of creative imagination. By using visual model as shown in Figure 4.10, the system allows analysts to navigate different angle and proportions that will eliminate blind spot during site visit.

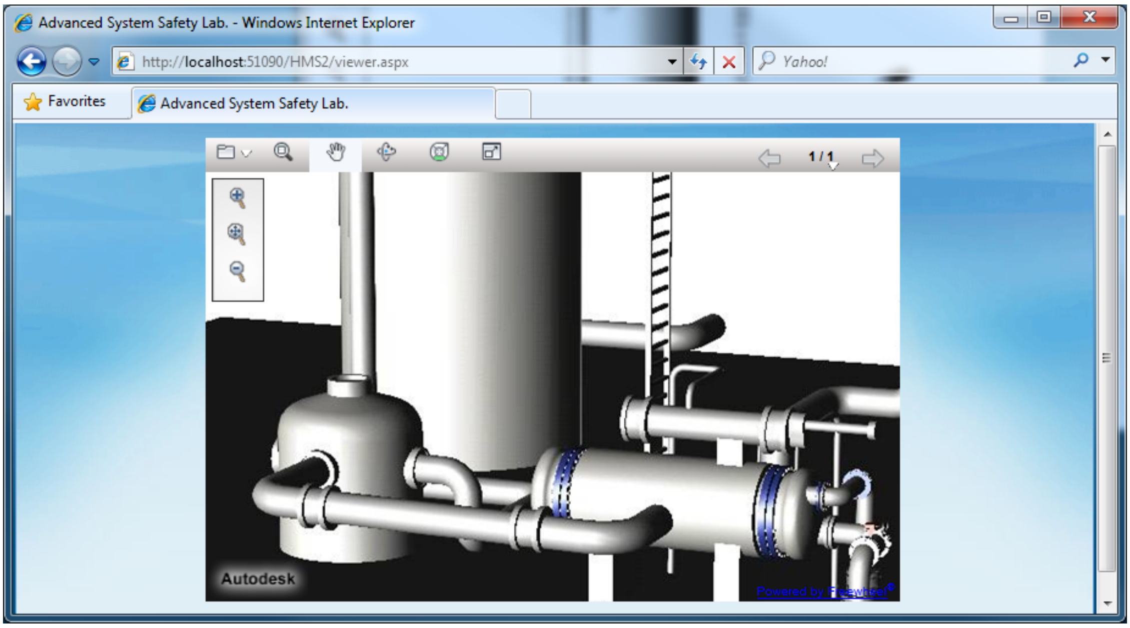

Fig. 4.10: Virtual model of HAZOP Analysis Management system.

The lightweight of this virtual model enables a low end portable devise such as personal devise assistance (PDA) to emulate this model. This allows a safety operator to bring this system on site and to make safety analyses in real time. Figure 4.11 shows HAZOP analysis management system used in portable terminal such as IPAD from Apple incorporated.

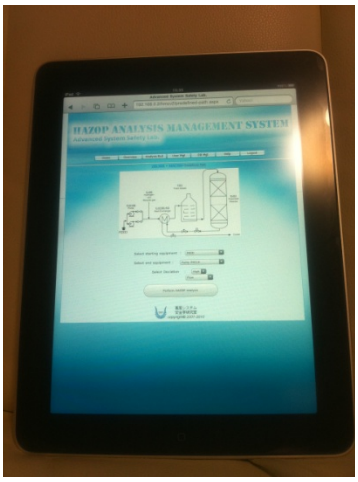

Fig. 4.11: HMS deploy on IPAD from Apple incorporated.

4.3 Virtual HAZOP Training

Chemical and petrochemical industries are well known for being prone to accidents and hazardous conditions. A complete risk management assessment system (RMAS) is compulsory for these industries in order to prevent and minimize any risk that contributes negative impact towards profitability. In recent years, high computing power and graphic visualization has become more affordable to be utilized in increasing the efficiency of RMAS. Virtual reality has been proposed as a technological breakthrough that holds the power to facilitate learning. The ability to visualize complex and dynamic systems involving personnel, equipment and layouts during any real operation is a potential advantage of such an approach. Virtual reality and multimedia training is commonly used in many industries, in aiding understanding and memory retention and creating a more interactive learning and decision making experience. The simplified concepts proposed in this thesis are illustrated in Figure 4.12. Artificial intelligent engine is the system core in providing virtual reality simulator with the right scenario case along with the right parameters that distinguish each simulation. Inputs from operator are compared between scenario case keywords. The scenario case with the highest matching rate is used to simulate real operation condition. In this thesis, due to resource constraint, parameters specification database is used instead of parameters ontology.

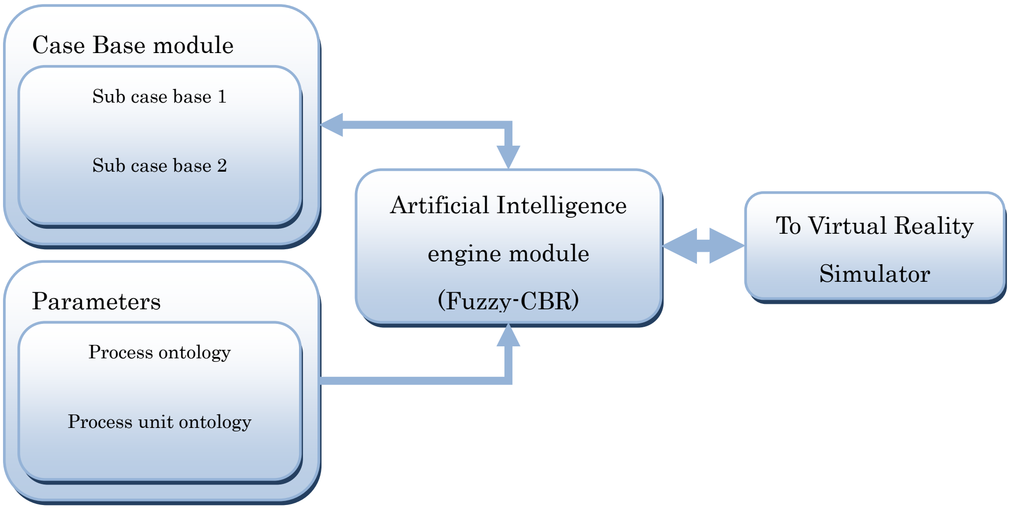

Fig 4.12: Case matching using fuzzy-CBR between user input and case base.

4.3.1 Structure and work flow

When a user interacts with VR model in simulator interface, the information such as deviation word, process path and the likes will be used by scenario generator engine to try to match with keywords in scenario case. The scenario case with the highest similarity is imported into the VR processor engine. In the case of none similar case, a new case scenario is prompted to be constructed by user for future use.

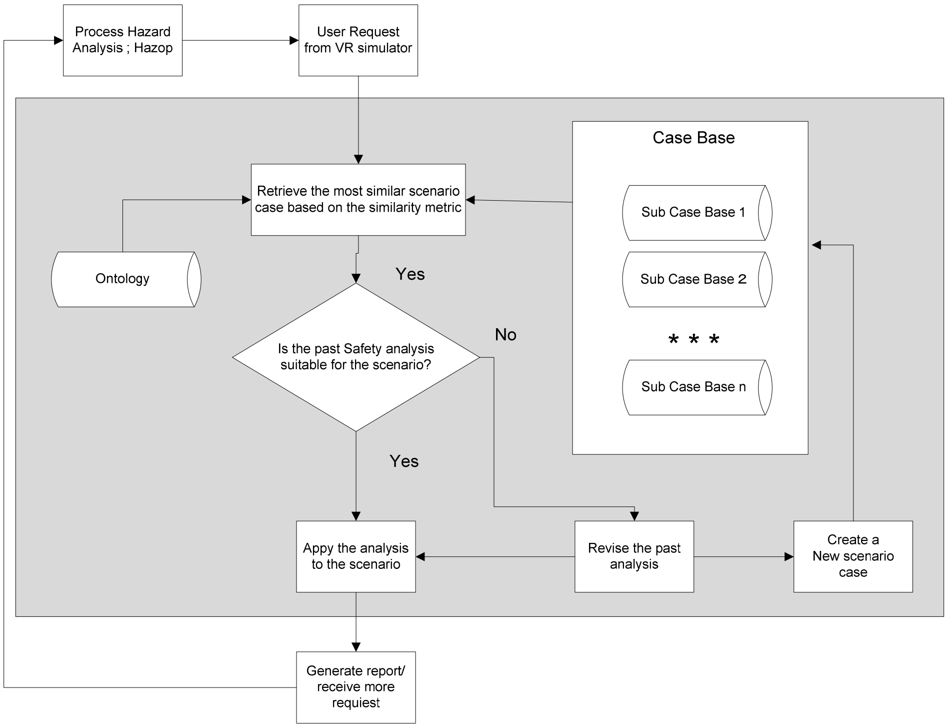

Fig 4.13: Virtual HAZOP training system workflow.

4.3.2 Interface Module

This is the module that an end user will see during safety analysis training. At the left side is the main display where all virtual reality interaction occurs. User is able to navigate using VR navigator. Simulated scenario properties are displayed based on user selection on right side. Below the process path windows, user can select different deviation. Scenario generator engine will display available scenario that match those properties. In the middle of the windows, P&ID diagram are displayed and process path are highlighted for user reference as shown in Figure 4.14.

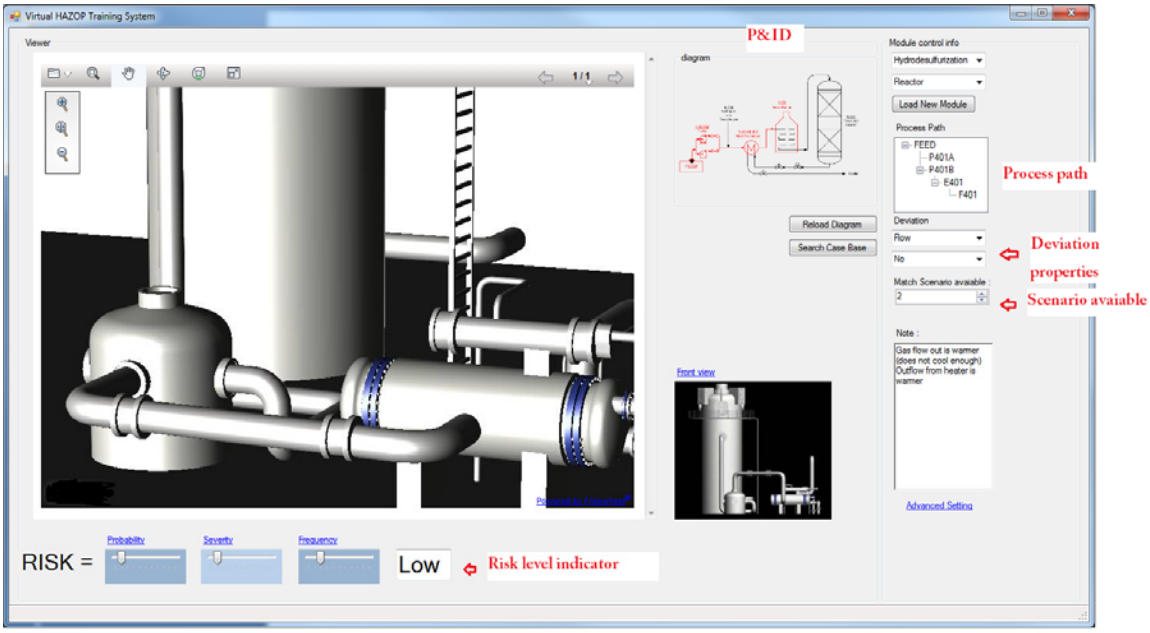

Fig. 4.14: Virtual HAZOP training system interface during properties setting.

Figure 4.15 shows virtual HAZOP training system interface during analysis with before virtual reality simulation. Risk assessments described in the previous chapter is used to display risk factor of current process. Risk factor is by product of probability, severity of harm and frequency factor using fuzzy rules. Risk factors crisp value can be display in two ways, namely, numerically or linguistically. In Figure 4.15, Virtual reality simulates a material flow slowly from heat exchanger to fired heater. This results in changing the color of the pipe connecting them into red. This is to show temperature increase, while fired heater also slowly to warming up. Without proper adjustment from user, gas that might flow or might not flow (in case of damaging fire heater) will also change color to indicate its condition. Equipment color changing is used to indicate state transaction. The principle of selecting color is depending on the virtual reality simulation model creator. There is no standard used for color selection in this research. However common sense of red color indicates hot while orange is used as an indication of warm state.

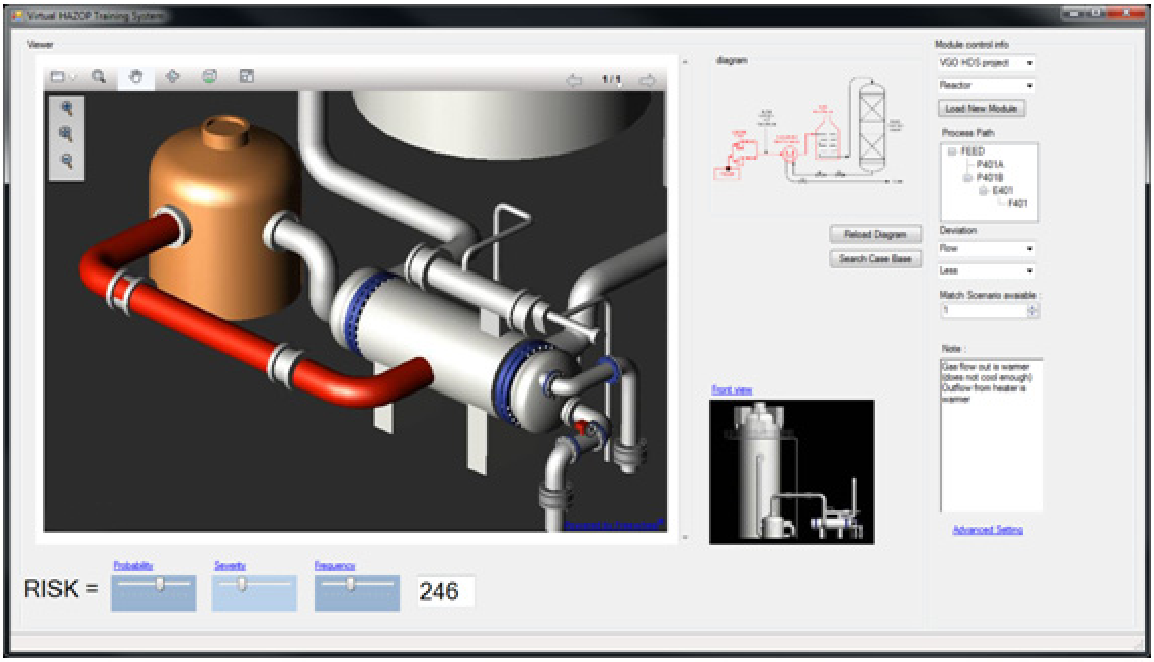

Fig.4.15: Virtual HAZOP training system interface during simulation.

4.3.3 VR Processor Engine

VR processor engine module is responsible for displaying and live rendering all feedback from the user. The system support 3DVIA Virtools .nmo as virtual reality simulation. This engine also supports the animation files created in studio 3D MAX. For future application, supporting others virtual reality file format is suggested to increase usability of the system in the real world. This engine working mechanism is very straightforward. Every virtual reality file retrieved by scenario generator engine, the VR processor engine will call all required plugs in for that type of file to be able to display to the user. Plug in for 3DVIA Virtools can be downloaded from the company website.

4.3.4 Scenario Generator Engine

Using matching fuzzy algorithm explained in the previous Chapter, user interaction such as properties input and navigating model are translated into keywords. These keywords lists are matched with keywords for each case in the case base. Scenario with most equal keywords and values are used for simulation.

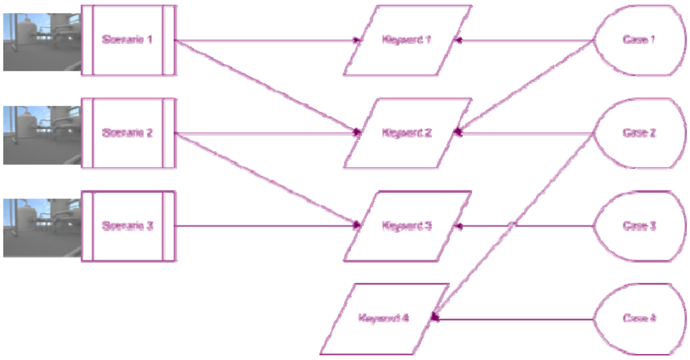

Fig. 4.16 Relationship between scenario, keyword and cases.

Figure 4.16 shows the relationship between scenario, keyword and cases. Each scenario or virtual reality simulation file is associated with several keywords. This goes the same with each case in case base. For example, scenario one shares two same keywords as case one. Therefore, case 1 can be present in virtual reality mode using the scenario one file.

4.3.5 Resource Database Management Engine

Resource database management engine is responsible for making data connection for scenario generator engine to retrieve information from database. Connection setting can be configured by editing connection type.

Below are list of available connection setting depending on which database type is used. In this research, we used connection no 2, MS Access OLE DB

1. **MS Access ODBC connection strings**

   "Driver={MicrosoftAccessDriver(.mdb)};DBQ=C:¥HMS¥VGO_HMS.mdb;Uid=Your_Username;Pwd=Your_Password;"*

2. **MS Access OLE DB & OleDbConnection (.NET framework) connection strings**

   "Provider=Microsoft.Jet.OLEDB.4.0; Data Source=c:¥ HMS¥VGO_HMS.mdb; User Id=admin; Password="

3. **SQL ODBC connection strings**
   "Driver={SQLServer};Server=150..*.*;Database=VGO_HMS;Uid=Your_Username;Pwd=Your_Password;"*

4. **SQL OLE DB connection strings**
   "Provider=SQLOLEDB;Data Source=Your_Server_Name;Initial Catalog=Your_Database_Name;UserId=Your_Username;Password=Your_Password;"

5. **SQL OleDbConnection .NET strings**
   "Provider=SQLOLEDB;Data Source=Your_Server_Name;Initial Catalog=Your_Database_Name;UserId=Your_Username;Password=Your_Password;"

After a successful connection, a record set is created from query requested by Scenario Generator Engine. This provides information exist in the database to be manipulated according to user's need.

4.4 Summary

We have developed two applications as a proof of concept of the proposed methodologies. HAZOP Analysis Management system and Virtual HAZOP training system are developed to achieve the objectives as stated in Chapter One. HAZOP analysis management system is a web based application developed to manage safety information especially HAZOP analysis. Case bases are used to improve completeness of the system by adding relevant information into the HAZOP analysis case. The extended functions of the HAZOP analysis management system is the Virtual HAZOP analysis system. This system helps the safety operator to implement HAZOP analysis with ease. The system improves operator analysis experience by imbedding virtual reality simulation. Both systems utilized fuzzy-CBR technique in case retrieving and indexing.

The advantages of the proposed HAZOP analysis management system in aiding HAZOP analysis are:

- Elimination of the management bureaucracy problems. Record tracking can easily be done without having to fill in forms or meeting with HR department to get permission. All modifications with timestamp are recorded for monitoring purpose. Access and modification permission is set and limit by user type.

- Giving analysis on different perspectives of creative imagination. By using the visual model, the system allows analysts to navigate different angles thereby eliminating blind spot.

However, the lack of ontology as described in previous Chapter to support similarity check module remains an issue in this study. Without complete ontology, it is difficult for the system algorithm to translate cases with similar meanings. Standardization during registering new cases might help reducing the problems but might equally prevent description accuracy of cases. The fuzzy algorithm used in the system only find similarities by comparing keywords associated between scenario and cases. Ability to evaluate sentences (case) with high meaning similarity is considered for future research.

The advantages of the developed specially Virtual HAZOP training system in assisting safety operator are:

- New safety operator would not have to rely solely on the experiences of safety operators to guide in a safety learning process. This gives the possibility of safety analysis skill to be transferred without expert worker commitment.
- Virtual experience enables safety operators to operate the same facilities with field operators without endangering or leaving negative impact towards overall operation.

Until the ability to integrate human factors into this training becomes possible, this training would not be able to help the safety operators to indicate field operator weakness spots for future assistance. User profiling is an absolute feature to be integrated in future research.

Chapter V

APPLICATION TO INDUSTRIAL SAFETY MANAGEMENT – A HYDRODESULPHURIZATION CASE STUDY

Application to Industrial Safety Management – A Hydrodesulphurization Case Study

5.1 Introduction

Several types of chemical processing plants have been considered to illustrate the usability of the developed safety management system as an assessment tools for safety operator. A case study of hydrodesulphurization has been considered in this Chapter to demonstrate the effectiveness of the developed system due to its wide usage and sample data availability. The hydrodesulphurization sample data is extracted from hydrodesulphurization operation training module and convert into HAZOP analysis structure.

5.2 Hydrodesulphurization

Hydrodesulphurization (HDS) is a catalytic chemical process widely used to remove sulfur (S) from natural gas and from refined petroleum products such as gasoline or petrol, jet fuel, kerosene, diesel fuel, and fuel oils.[79][80] The purpose of removing the sulfur is to reduce the sulfur dioxide (SO_2) emissions that result from using the fuels in automotive vehicles, aircraft, railroad locomotives, ships, gas or oil burning power plants, residential and industrial furnaces, and other forms of fuel combustions.

Another important reason for removing sulfur from the naphtha streams within a petroleum refinery is that sulfur, even in extremely low concentrations, poisons the noble metal catalysts (platinum and rhenium) in the catalytic reforming units that are subsequently used to upgrade the octane rating of the naphtha streams.

The industrial hydrodesulphurization processes include facilities for the capture and removal of the resulting hydrogen sulfide (H_2S) gas. In petroleum refineries, the hydrogen sulfide gas is then subsequently converted into byproduct elemental sulfur or sulfuric acid. In fact, the vast majority of the 64,000,000 metric tons of sulfur produced worldwide in 2005 was byproduct sulfur from refineries and other hydrocarbon processing plants.[80, 81]

An HDS unit in the petroleum refining industry is also often referred to as a hydrotreater.

5.2.1 History

Although reactions involving catalytic hydrogenation of organic substances were known prior to 1897, the property of finely divided nickel to catalyze the fixation of hydrogen on hydrocarbon (ethylene, benzene) double bonds was discovered by the French chemist, Paul Sabatier. Thus, he found that unsaturated hydrocarbons in the vapor phase could be converted into saturated hydrocarbons by using hydrogen and a catalytic metal. His work was the foundation of the modern catalytic hydrogenation process.

Soon after Sabatier's work, a German chemist, Wilhelm Normann, found that catalytic hydrogenation could be used to convert unsaturated fatty acids or glycerides in the liquid phase into saturated ones. He was awarded a patent in Germany in 1902 and in Britain in 1903, which was the beginning of what is now a worldwide industry.

In the mid-1950s, the first noble metal catalytic reforming process (the Platformer process) was commercialized. At the same time, the catalytic hydrodesulfurization of the naphtha feed to such reformers was also commercialized. In the decades that followed, various proprietary catalytic hydrodesulfurization processes such as the one depicted in the flow diagram below have been commercialized. Currently, virtually all of the petroleum refineries worldwide have one or more HDS units.

By 2006 miniature microfluidic HDS units had been implemented for treating JP-8 jet fuel to produce clean feed stock for a fuel cell hydrogen reformer. By 2007 this had been integrated into an operating 5 kW fuel cell generation system.

5.2.2 The Process Chemistry

Hydrogenation is a class of chemical reactions in which the net result is the addition of hydrogen (H). Hydrogenolysis is a type of hydrogenation and results in the cleavage of the C-X chemical bond, where C is a carbon atom and X is a sulfur, nitrogen (N) or oxygen (O) atom. The net result of a hydrogenolysis reaction is the formation of C-H and H-X chemical bonds. Thus, hydrodesulfurization is a hydrogenolysis reaction. Using ethanethiol (C_2H_5SH), a sulfur compound present in some petroleum products, as an example, the hydrodesulfurization reaction can be simply expressed as

Ethanethiol + Hydrogen → Ethane + Hydrogen sulfide

$$C_2H_5SH + H_2 \rightarrow C_2H_6 + H_2S$$

5.2.3 Process Description

In an industrial hydrodesulphurization unit, such as in a refinery, the hydrodesulphurization reaction takes place in a fixed-bed reactor at elevated temperatures ranging from 300 to 400 °C and elevated pressures ranging from 30 to 130 atmospheres of absolute pressure, typically in the presence of a catalyst consisting of an alumina base impregnated with cobalt and molybdenum (usually called a CoMo catalyst). Occasionally a combination of nickel and molybdenum (called NiMo) is used, in addition to the CoMo catalyst, for specific difficult-to-treat feed stocks such as those containing a high level of chemically bound nitrogen.

Figure 5.1 below is a schematic depiction of the equipment and the process flow streams in a typical refinery HDS unit.

The liquid feed (at the bottom left in the diagram) is pumped up to the required elevated pressure and is joined by a stream of hydrogen-rich recycle gas. The resulting liquid-gas mixture is preheated by flowing through a heat exchanger. The preheated feed then flows through a fired heater where the feed mixture is totally vaporized and heated to the required elevated temperature before entering the reactor and flowing through a fixed-bed of catalyst where the hydrodesulphurization reaction takes place.

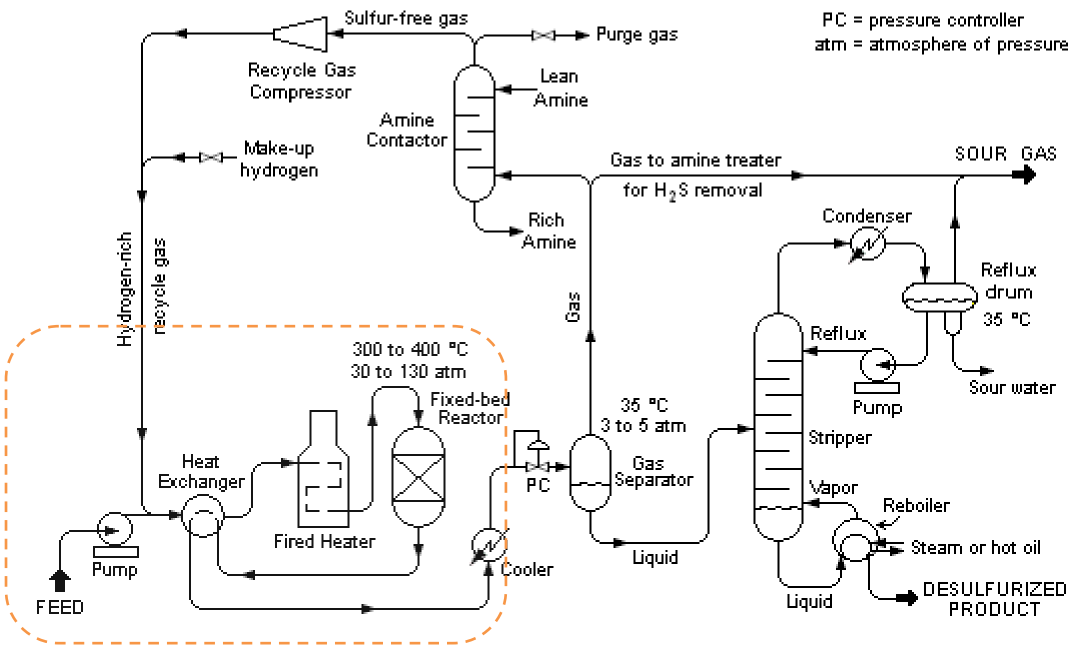

Fig. 5.1 Schematic diagram of a typical Hydrodesulphurization (HDS) unit in a petroleum refinery with reactor section highlighted.

The hot reaction products are partially cooled by flowing through the heat exchanger where the reactor feed was preheated and then flows through a water-cooled heat exchanger before it flows through the pressure controller (PC) and undergoes a pressure reduction down to about 3 to 5 atmospheres. The resulting mixture of liquid and gas enters the gas separator vessel at about 35 °C and 3 to 5 atmospheres of absolute pressure.

Most of the hydrogen-rich gas from the gas separator vessel is recycle gas which is routed through an amine contactor for removal of the reaction product H_2S that it contains. The H_2S-free hydrogen-rich gas is then recycled back for reuse in the reactor section. Any excess gas from the gas separator vessel joins the sour gas from the stripping of the reaction product liquid.

The liquid from the gas separator vessel is routed through a reboiled stripper distillation tower. The bottoms product from the stripper is the final desulfurized liquid product from hydrodesulphurization unit. The overhead sour gas from the stripper contains hydrogen, methane, ethane, hydrogen sulfide, propane and perhaps some butane and heavier components. That sour gas is sent to the refinery's central gas processing plant for removal of the hydrogen sulfide in the refinery's main amine gas treating unit and through a series of distillation towers for recovery of propane, butane and pentane or heavier components. The residual hydrogen, methane, ethane and some propane is used as refinery fuel gas. The hydrogen sulfide removed and recovered by the amine gas treating unit is subsequently converted to elemental sulfur in a Claus process unit or to sulfuric acid in a wet sulfuric acid process or in the conventional Contact Process.

Note that the above description assumes that the HDS unit feed contains no olefins. If the feed does contain olefins (for example, the feed is a naphtha derived from a refinery fluid catalytic cracker (FCC) unit), then the overhead gas from the HDS stripper may also contain some ethene, propene, butenes and pentenes or heavier components.

It should also be noted that the amine solution to and from the recycle gas contactor comes from and is returned to the refinery's main amine gas treating unit. The fresh feed is normally brought from the vacuum unit then directed into VGO hydrodesulphurization unit at 180 degrees celsius. The pressure is kept at $2kg/cm^2g$. Then, the fresh feed flow to the suction of a multistage centrifugal high heat pump, called a reactor charge pump (P-401A and P-401B). Consequently, it goes through two product heat exchangers, Feed/DSLGO Exchanger (E-401) and Feed/DSVGO Exchanger (E-402), at the pressure of $85kg/cm^2g$. The feed heat is recovered through those two product heat exchanger. After combining with the recycle gas, the feed VGO enters Reactor Charge Heater (F-401), and heats up to the desired reactor inlet temperature of 360 degrees celsius. The feed oil flows through four passes are evenly adjusted by flow controllers, which determine the total charge rate of VGO Hydrodesulphurization unit. The total recycle gas flow is adjusted by the rotation of Recycle Gas Compressor.

Once the reactor inlet temperature is heated up to the desired temperatures in the charge heater, the feed entering through the top of reactor (R-401) contains two catalyst beds with a single intermediate quench section. There are two reasons why the reactor will be divided into two beds:

(1) Generally, if the gas flow and liquid flow are both poorly distributed through the reactor, the catalyst will not be effectively utilized. To solve this problem, the reactor will be divided into two beds with a redistributor's tray in between. In this mechanism, the reactants flow to the first bed, and then are redistributed to the second bed through the redistributor's tray. In this way, despite a distribution problem with the first bed, the catalyst in the second bed still can be effectively utilized.

(2) In some cases, the reaction heat increases so high that the temperatures

across the reactor may jump up. If this happens, the reaction will become unstable and results in the temperature runway. To avoid this, the cold recycle gas is brought into the reactor redistributors section.

5.3 Reactor Part of HDS Plant Model

Developed model are base on Figure 5.2 the schematic diagram of a VGO hydrodesulphurization fresh feed of reactor section shown in Figure 5.2. The model consist two pumps named P401 A and P401B, heat exchangers named E401& E401, fired heater F401 and fixed-bed reactor R401. Reactor part of HDS plant is selected because of process analysis data availability in Advances System Safety Laboratory. There is no any other justification on selecting this section.

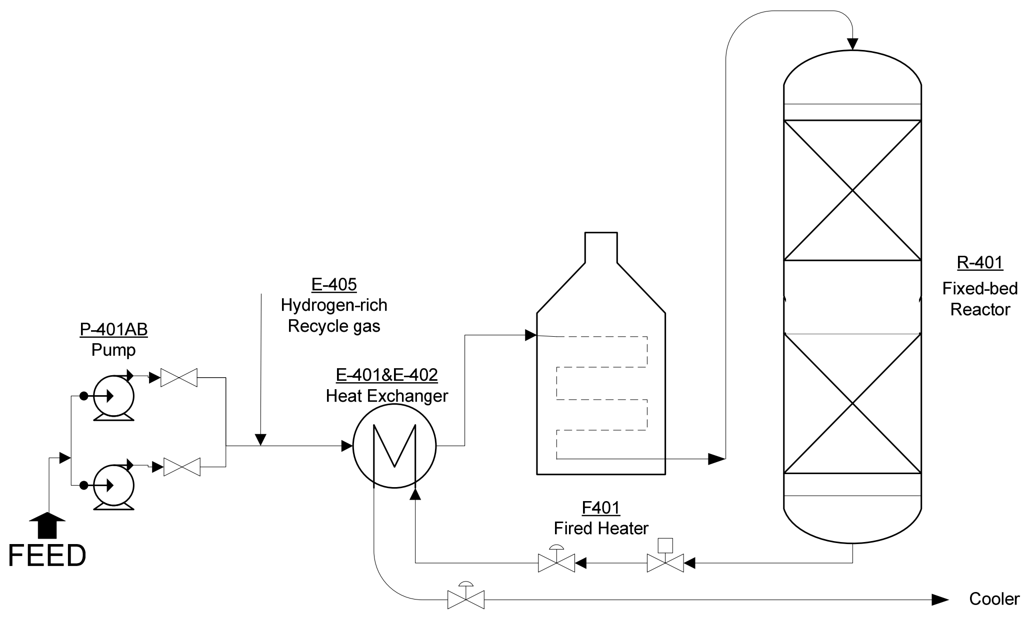

Fig. 5.2: VGO hydrodesulphurization fresh feed of reactor section

5.3.1 Model Layout

Figure 5.3 until figure 5.6 illustrates a different view angle of perspective, front left and top view respectively. Figure 5.7 illustrate the model in wire frame view.

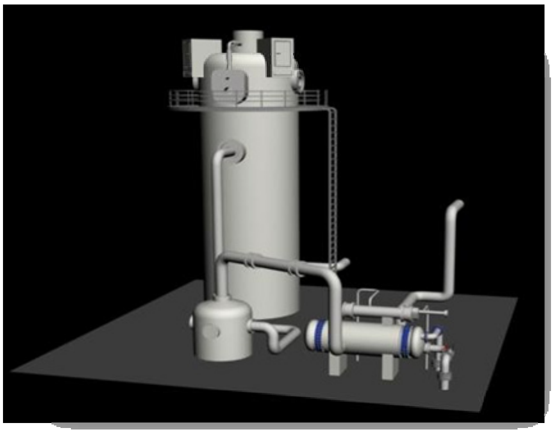

Fig. 5.3: Perspective view

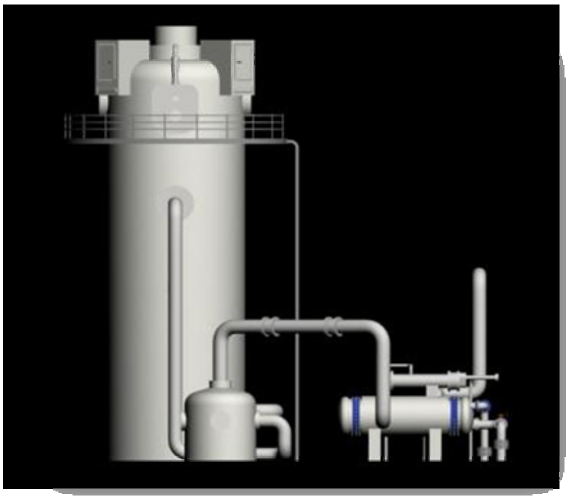

Fig. 5.4: Front view

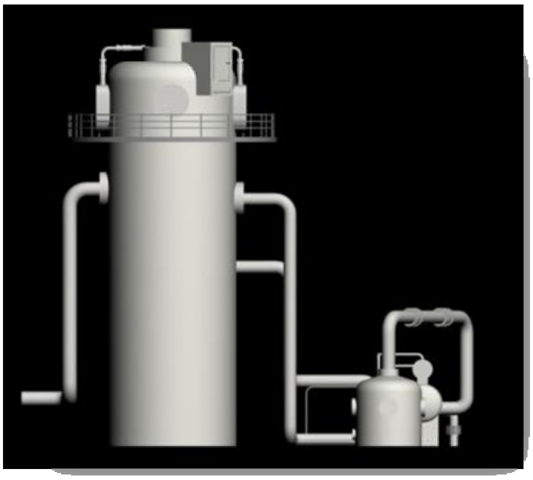

Fig. 5.5: Left view

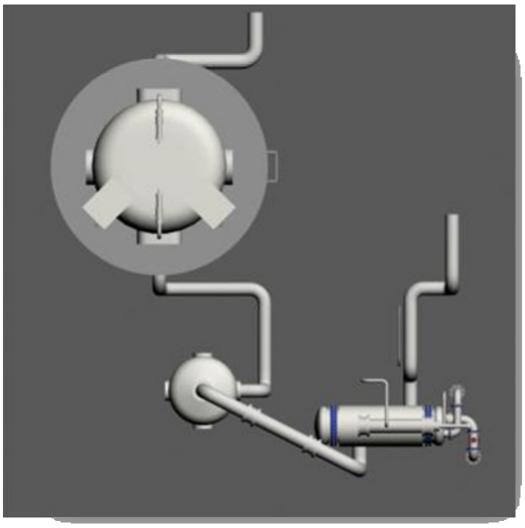

Fig. 5.6: Top view

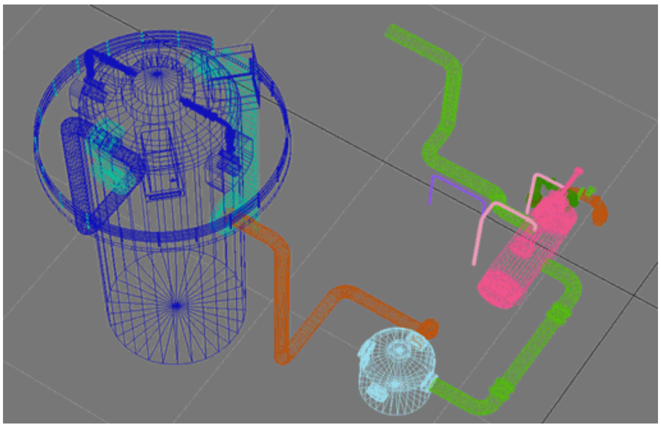

Fig. 5.7 Wire frame view

5.3.2 Development of the 3-D Model

In this section, each equipment of HDS reactor part is illustrated. Each equipment is modelled individually before combining in the reactor part model. Figure 5.8 and Figure 5.9 illustrates the HDS reactor model and HDS Heat exchanger model respectively, the largest models in HDS reactor section.

5.3.2.1 Reactors

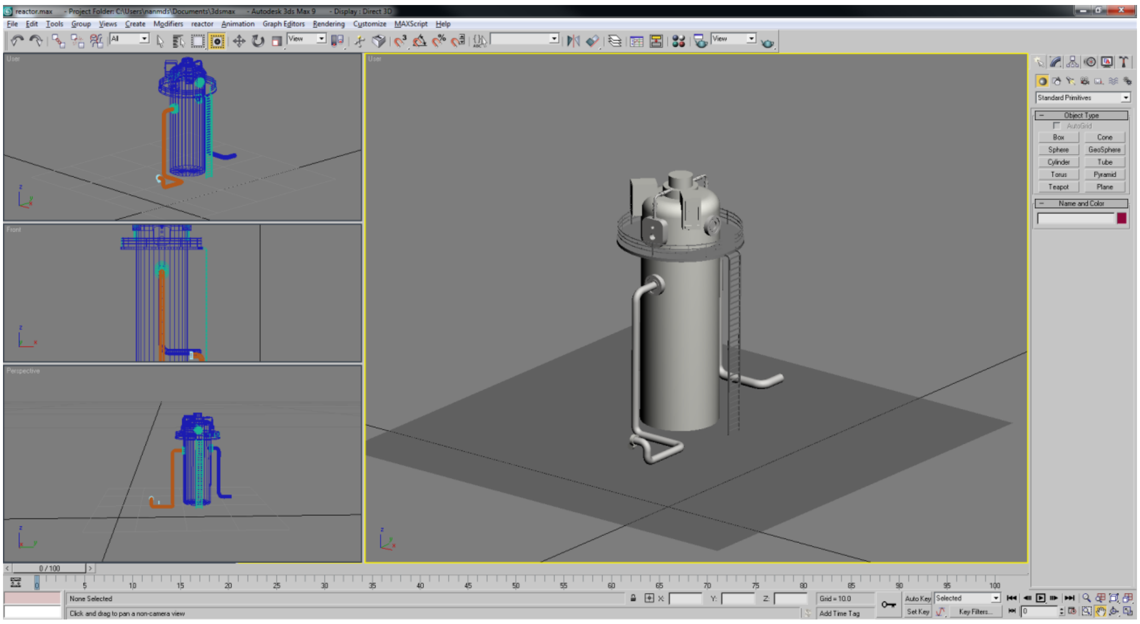

Fig. 5.8 HDS reactor model

5.3.2.2 Heat Exchanger

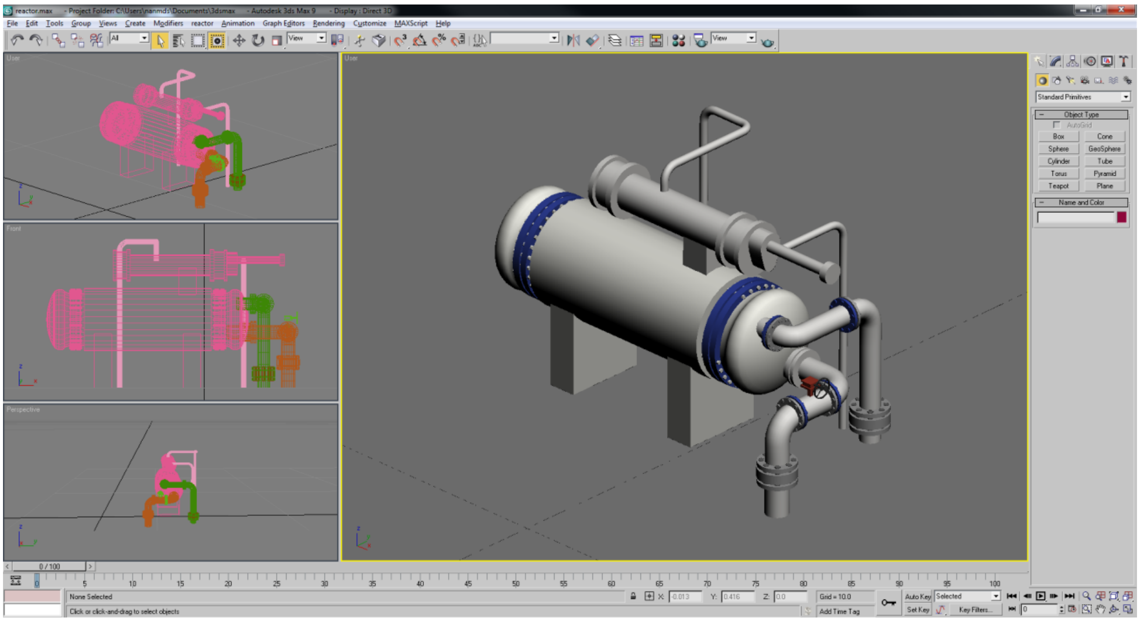

Fig. 5.9 HDS Heat exchanger model

5.3.2.3 Pumps

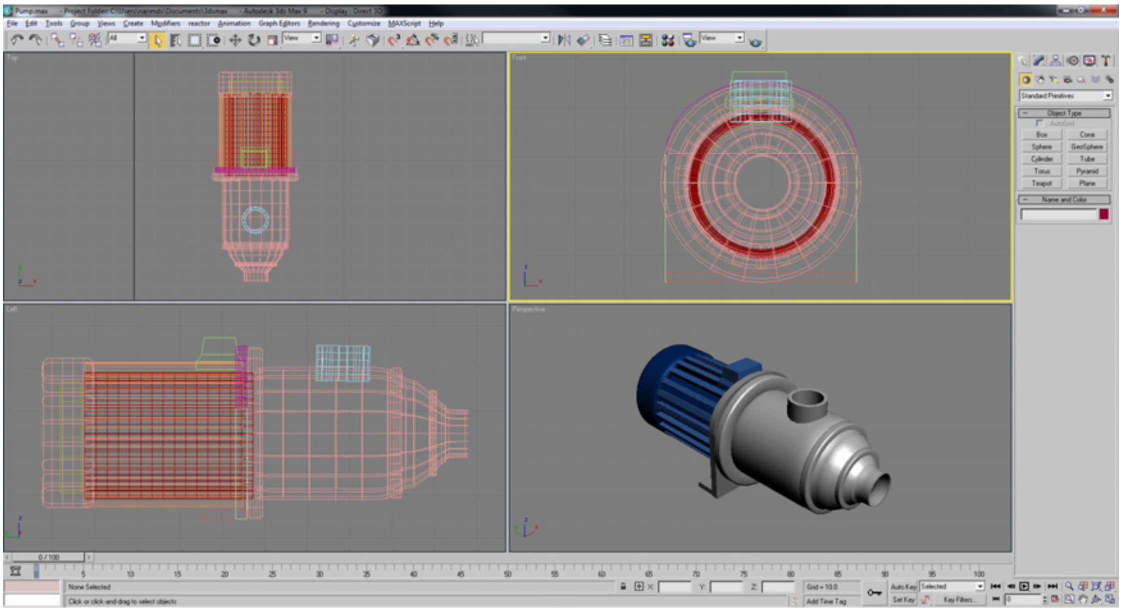

Fig. 5.10 HDS Pump model

5.3.2.4 Pipes

Figure 5.11, Figure 5.12, Figure 5.13, Figure 5.14 HDS, Figure 5.15 and Figure 5.16 are

HDS corner pipe model, HDS T junction pipe model, HDS Heat small pipe model, Heat large pipe with joiner model, HDS pipe inner model and HDS pipe with valve model respectively. This model is used to connect between model equipment. Figure 5.15 show HDS Fired heater model.

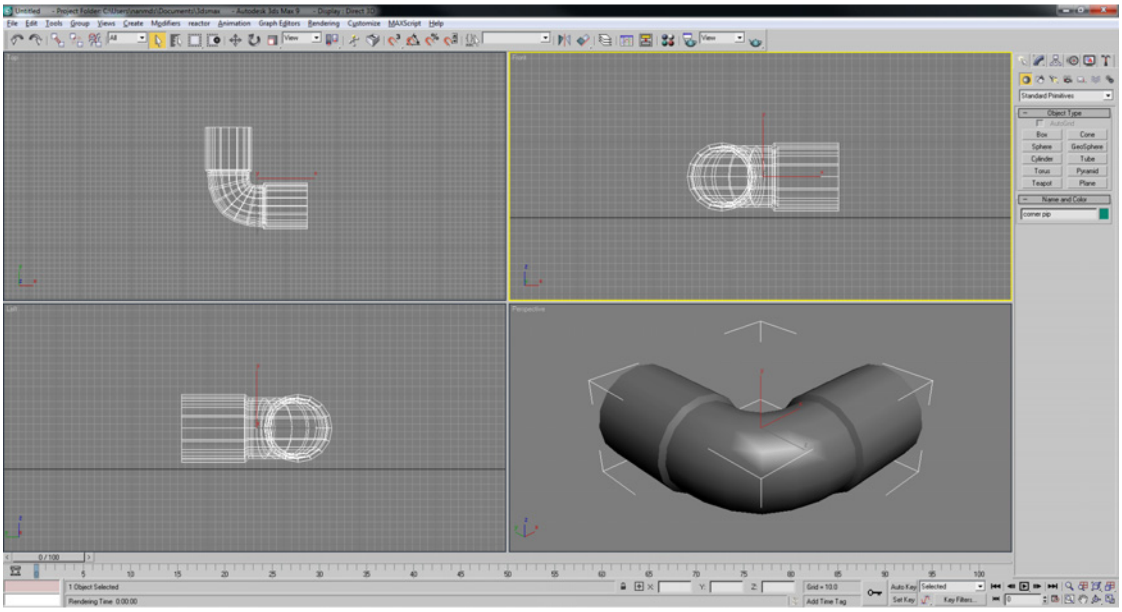

Fig. 5.11 HDS corner pipe model

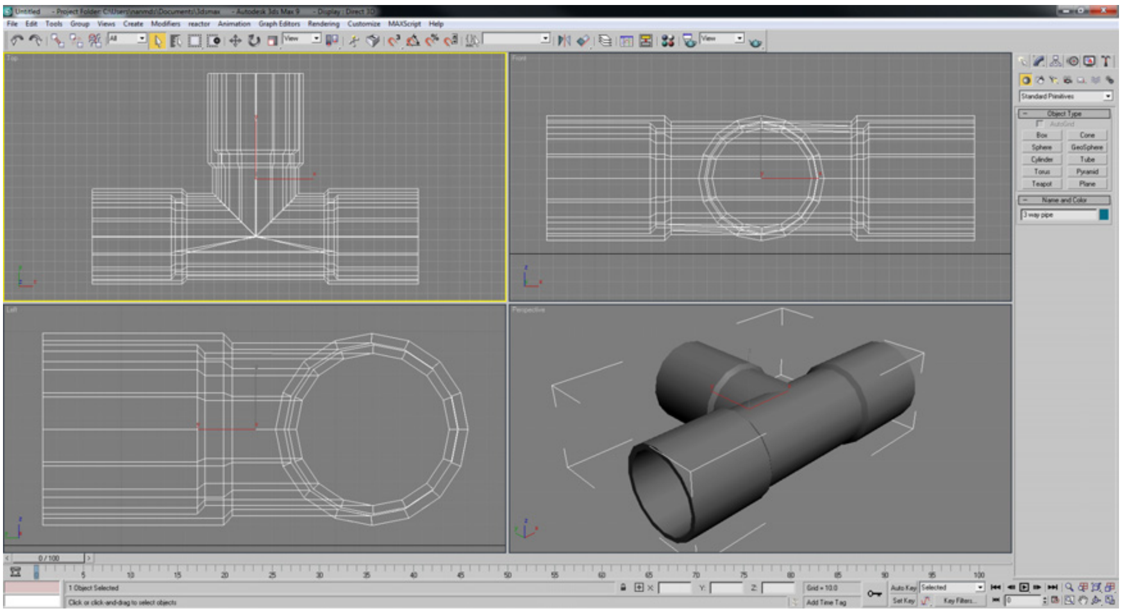

Fig. 5.12 HDS T junction pipe model

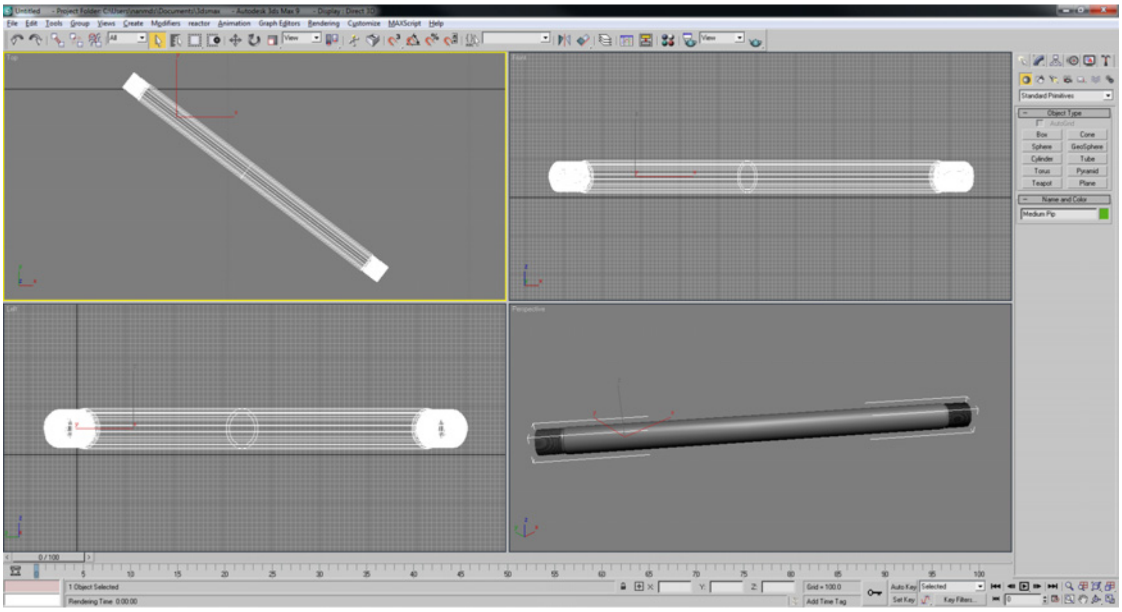

Fig. 5.13 HDS Heat small pipe model

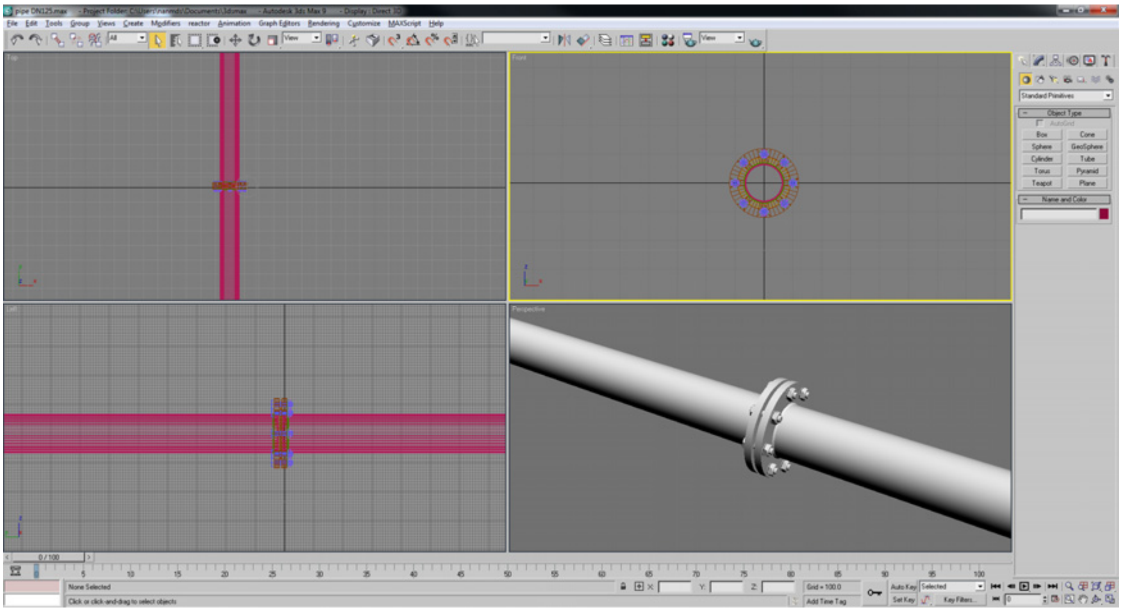

Fig. 5.14 HDS Heat large pipe with joiner model

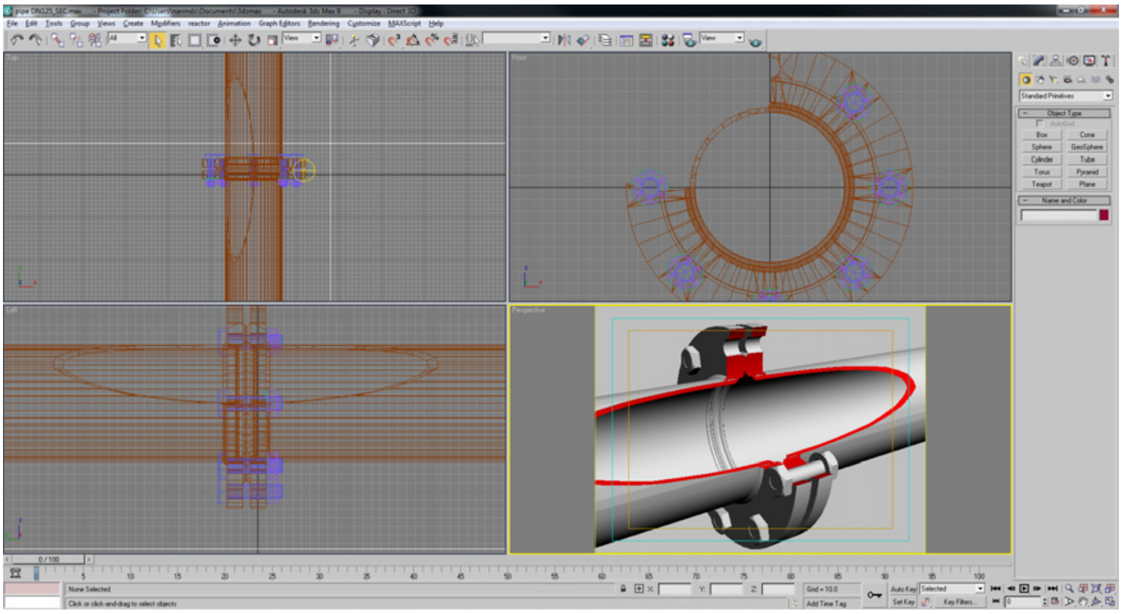

Fig. 5.15 HDS pipe inner model

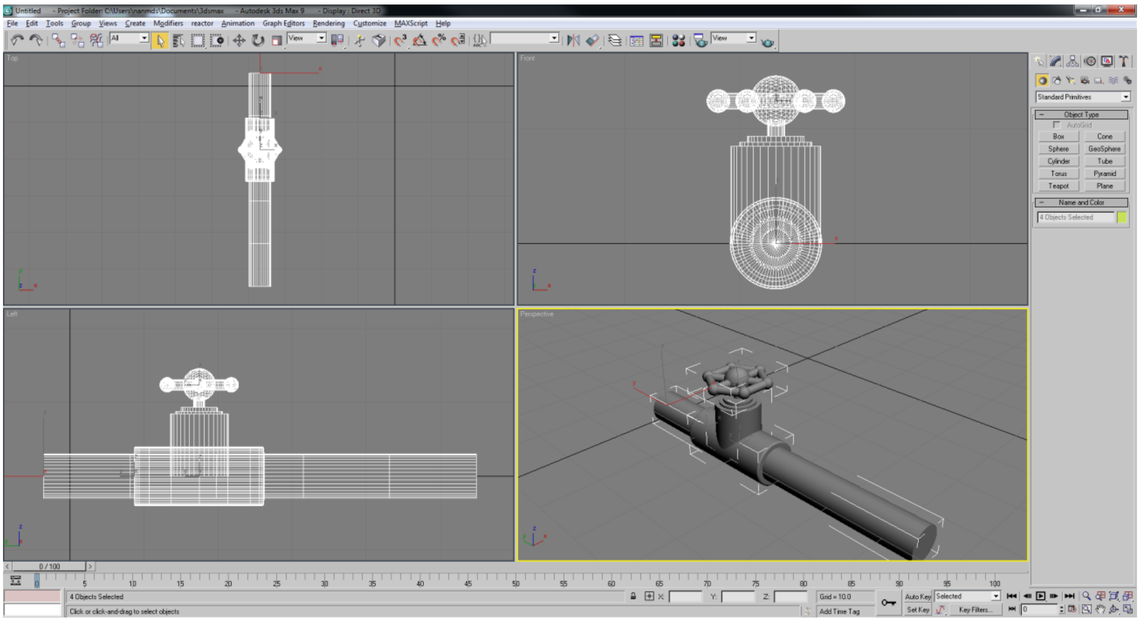

Fig. 5.16 HDS pipe with valve model

5.3.2.5 Fire Heater

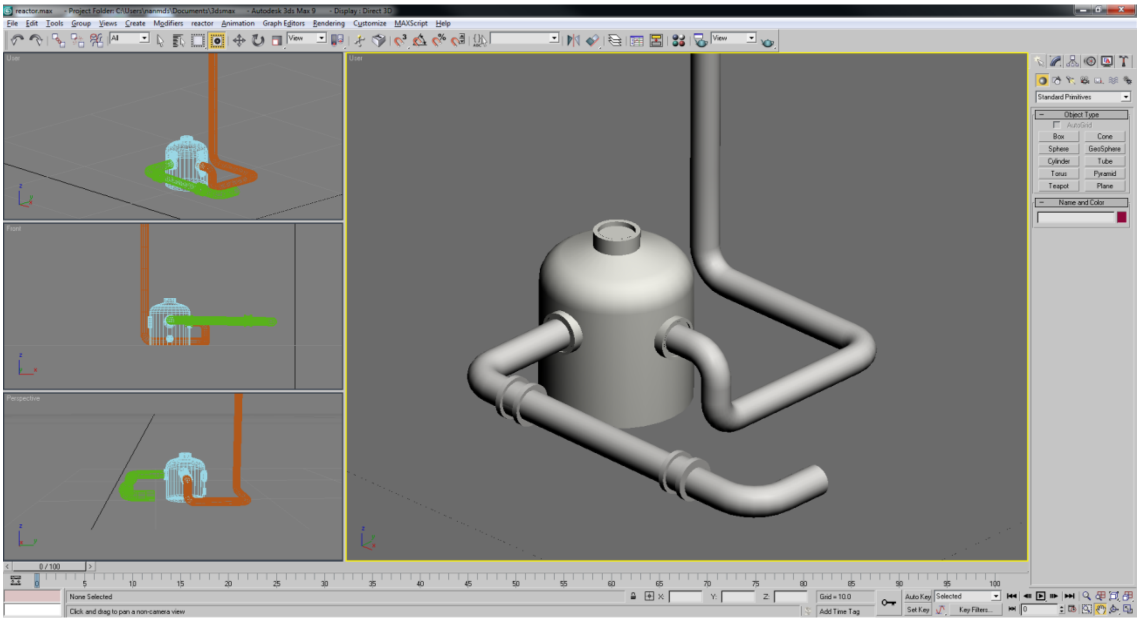

Fig 5.17 HDS Fired heater model

5.4 Discussion of Results

HAZOP analysis is carried out in both conventional ways and using the developed HAZOP analysis management system. Time consumed for each analysis method is calculated. Table 5.1 shows the comparison time consumed. The time managed to be saved depends on process complexity involving the guideword. On average, the proposed system improves 35-54% analysis time.

Table 5.1: Comparison time consumed for HAZOP analysis based on guide word between manual and proposed system supported analysis

Guide word	Manual*	System	Time saved
Flow	128 min	45 min	2.8
Temperature	90 min	39 min	2.3
Hydrogen consistency	240 min	155 min	1.5
Pressure	65 min	42 min	1.5

*: Time recorded to the nearest minute and 2 min error margin

The factors contributing to the reduction in the consumed time for HAZOP analysis are:

1) In traditional HAZOP analysis. Parameters specification has to be prepared manually. In HAZOP analysis management system, parameter specification such as equipment specification, material specification and other are stored in database. User has only to select the equipment or material name, other information regarding that parameter are retrieved into analysis form.

2) In traditional HAZOP, each new deviation of HAZOP has to be created from beginning while the HAZOP analysis management system can retrieve similar deviation case and reuse as a base for new deviation analysis.

In Virtual HAZOP analysis training, the results of the implementation of the proposed method on the case study are illustrated in Tables 5.2 and 5.3. There are around ten cases available in case base. Flow to heater (F-401) and Feed flow to reactor process part are shown in Table 5.2 and Table 5.3 respectively. Predefined scenario case is a scenario case developed as the guideline for simulator. A result retrieved from case base is a scenario case retrieved from cases stored in subset case base. This case base contains past cases that actually occurred or modified by fuzzy-CBR module into case base.

Table 5.2 Process: Flow to heater (F-401)

Class : No Flow								
Predefined scenario case		Result retrive from Case Base		(P)	(S)	(F)	(R)	Immediate Action
Causes	Consequences	Causes	Consequences					
• No gas and feed flow • Pipes blocked or broken	• Gas flow does not cool down • Material damages in heater	• In previous pipes, blockage, breakage • In previous valves, blockage • From E405, recycle gas no flow • From feed section, feed oil doesn't flow	• In F401, empty, temperature increases, breakage, fire, explosion, leakage of H2 • In R401, empty, no reaction • To E404, reactor effluent doesn't flow	5	4	3	238	348 Required action earlier than 1 month
Less Flow								
• No feed flow • Pipe	• Outflow from heater is	• In previous pipes,	• In F401, level decrease, temperature	6	3	4	246	333

broken or blocked • One/some of the valves closed • S/U-line open, when part of the flow is going there • No gas flow • Pipe broken or blocked • Less gas flow	warmer • Gas flow out is warmer (does not cool enough) • Material damages in heater	partially blockage, breakage • In previous valves, partially blockage, leakage, stay close • From E405, recycle gas less flow • From feed section, feed oil less flow	increase, breakage, fire, explosion, leakage of H_2 • In R401, , level decrease, temperature increase, empty, insufficient reaction, no reaction, excessive reaction, breakage, fire, explosion, leakage of H_2 • To E404, reactor effluent flow decreases, reactor effluent temperature increase, reactor effluent doesn't flow					Required action earlier than 1 month
More temperature								
• More temperature in feed flow • Problems in previous heat exchangers • More temperature in gas flow • Problems in previous heat exchangers • External warming	• Outflow from heater is warmer • Gas flow out is warmer (does not cool enough)	• From E405, recycle gas temperature increase • From feed section, feed oil temperature increase	• In F401, temperature increase, pressure increases, breakage, fire, explosion, leakage of H_2 • In R401, temperature increase, pressure increases, empty, insufficient reaction, no reaction, excessive reaction, breakage, fire, explosion, leakage of H_2 • To E404, reactor effluent pressure increases, reactor effluent temperature increase, reactor effluent doesn't flow	3	7	2	213	363 Required action earlier than 1 month

Table 5.3 Feed Flow to reactor (R-401)

Class :No Flow								
Predefined scenario case		Result retrive from Case Base		(P)	(S)	(F)	(R)	Immediate Action
Causes	Consequences	Causes	Consequences					
• Feed line is broken	• Wrong kind of	• In F401, empty	• In R401, empty, no reaction	4	4	4	234	356

or blocked • No flow from heater • Leak in heater	product flow from reactor (consistency changes) • Less flow from reactor • Less temperature in reactor → less cooling gas flow	• In previous pipes, blockage, breakage • In previous valve, blockage • From E405, recycle gas doesn't flow • From feed section, feed oil doesn't flow	• To E404, reactor effluent doesn't flow					Required action earlier than 1 month
Less Temperature								
• Heater is not working correctly, flow from heater is colder	• Cooling gas flow decreases • Conversion worsen (wrong kind of product flow from reactor)	• In F401, temperature decreases, less combustion • In previous pipes, partially blockage, breakage, blockage • In previous valves, partially blockage, leakage, blockage, stay close • From F/L, fuel gas consistency less, fuel gas less flow, fuel gas doesn't flow	• In R401, temperature decreases, insufficient reaction, no reaction, breakage, fire, explosion, leakage of H2 • To E404, reactor effluent doesn't flow, reactor effluent temperature increases • From E405, recycle gas more flow, temperature decreases • From feed section, feed oil more flow, temperature decreases	5	4	3	238	348 Required action earlier than 1 month
Less hydrogen consistency								
• Less gas to feed flow • Not enough	• All sulphur in feed flow is not reacting			8	1	4	176	312 Required action earlier

fresh hydrogen	and there is more sulphur in product							than 1 month
More Pressure								
• High temperature in pipe • Pressure higher already in feed • Blockage in pipe after reactor • More pressure in recycle gas line • More pressure after compressor	• Pressure of reactor increases • High pressure fastens the reaction • If reaction is exothermic, temperature can increases in reactor • Can have effects on reaction balance	• In F401, pressure increases • Form E405, recycle gas pressure increases, temperature increases • Feed oil pressure increases, temperature increases	• In R401, pressure increases, empty, breakage, fire, explosion, leakage of H2, excessive reaction, no reaction • To E404, reactor effluent pressure increases, doesn't flow	3	8	2	219	372 Required action earlier than 1 month

The risk value (R) derived from defuzzification is illustrated in Figure 5.16 right and Figure 5.16 left showing surface of the relation between Probability factors (P), Severity of hard factor (S), Frequency Factor toward Risk value (R) and Actions using Matlab fuzzy tool box. The value of risk factor is calculated as a byproduct for severity of harms, probability factor and frequency factors along with fuzzy rules. Figure 5.17 shows result of Risk factor and action value when severity factor value, probability factor and frequency factor each equals to 5. These values are used by operator to judge safety condition. Figure 5.18 shows the construction of the consequent membership function from four active rules for a system with tree inputs and two outputs.

IF {severity} AND {Probability} AND {frequency} THEN {Risk} AND {Action}

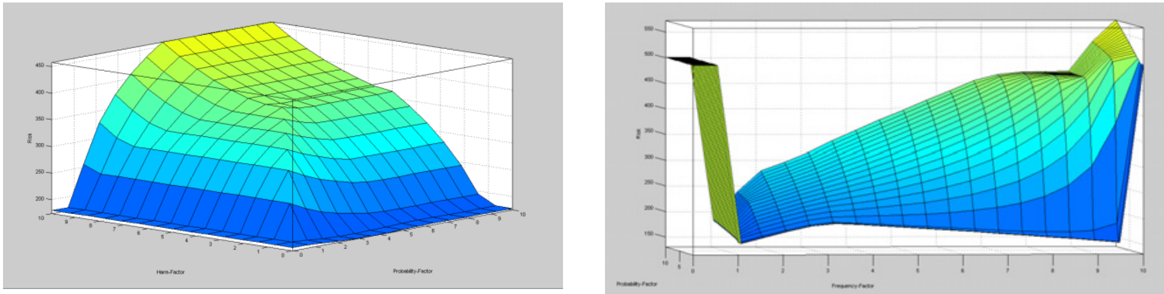

Fig. 5.18: Relation between membership function. Right: risk (R)x(F)(P),left :Risk(R)x(S)(F)

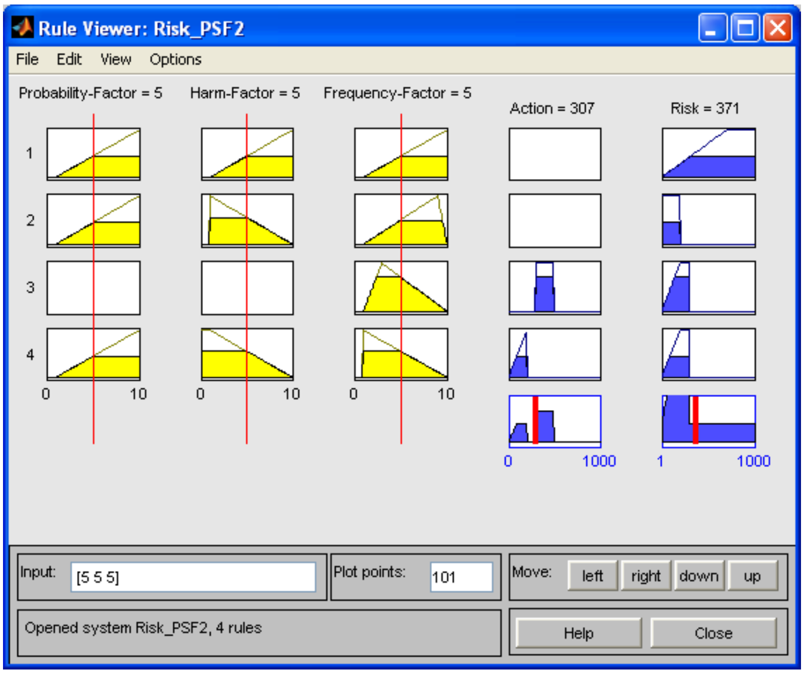

Fig. 5.19 Perform computations using fuzzy by simulation with Matlab.

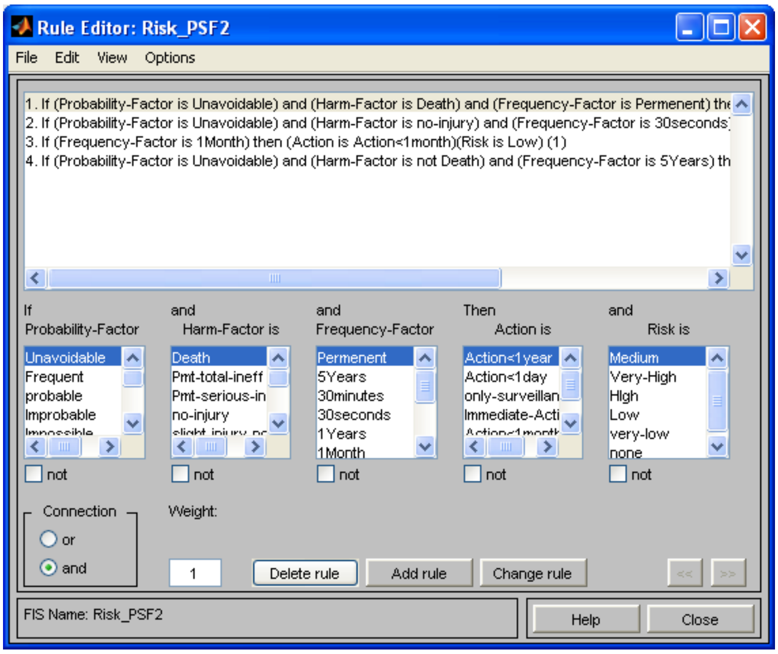

Fig. 5.20 Construction of the consequent membership function from four active rules for a system with tree Inputs and two outputs.

5.5 Summary

By using HAZOP analysis for reactor section of the hydrodesulphurization units as a case study, we have developed several models to resemble real HDS unit equipment. These models are essential to this research as to achieve the objective stated in Chapter One. The Web based HAZOP analysis management system facilitated the reduction in time consumed during the simulated process used as a case study. Besides depending solely on expert imaginative thinking of possible scenarios using P and ID, the dynamic visual model aids the safety operator to different perspectives of consequent and subsequent to an accident and enable them to analyze the system in three dimensional effects. This prevents miss looks due to a blind spot happening during site visit and HAZOP preparation. Similarity algorithm used, is responsible for ensuring accuracy in analysis tracking and in minimizing case retrieval thereby leading to a lot of time saving. We designed this system to be light and simple as a portable device to be used by the safety operator during on site analysis.

We have also illustrated the performance of Fuzzy-CBR as scenario case generation methodology by developing Virtual HAZOP training system. This method enables a virtual reality simulator to simulate a scenario case without having to develop complete scenario case for every deviation (HAZOP) and in the same time balanced to mitigate the complex computation general. Giving an opportunity for safety personnel to experience safety and operation training much like field operator have enjoyed for quite some time now. We also showed how the value of probability factors, severity of harms factor and frequency factors, are used in deciding risk for scenarios.

Chapter VI

CONCLUSIONS AND FUTURE WORK

General Conclusions and Recommendations

6.1 General Conclusions

In this work, we have stated that the chemical process industry environments are dangerous and many aspects of safety considerations must be taken into account during the operation of hazardous chemical engineering equipment. Moreover, HAZOP analysis requires high accuracy, consistencies and completeness because any ignorance could lead to catastrophic and fatal losses. Therefore, the HAZOP team must ensure that it would not lose any resources that are available to help them meet the above requirements. In addition to the specific conclusions drawn under various chapters in this dissertation, the summary of all the conclusions of the research work are as given below.

- A virtual reality technology in improving HAZOP analysis experience for safety operator has been proposed in this work. Near miss, accident cases and other safety information are now combined in a single system in improving overall quality of HAZOP.
- The proposed intelligent risk management system provided a valuable approach for training safety personnel working in dangerous workplace environment. The ability to visualize a complex and dynamic process within a virtual plant environment as obtains in the proposed system is a potential advantage of virtual reality technology.
- A web-based HAZOP analysis management system incorporated in this work assisted HAZOP team and related individuals to perform revision and complete HAZOP analysis without going through difficult procedures of fill-in request modification form. The effect in essence is that, it reduced greatly the time for navigating the process during operation.
- The dynamic visual model of the proposed management system aided the system user in carrying out three-dimensional analysis of new events without depending solely on expert imaginative thinking of scenario using P and ID. Hitherto, this type of visual ability was not possible due to blind spot syndrome happening during site visit and HAZOP preparation.

- Similarity measure and risk indexing used in this work was responsible for ensuring accuracy in analysis tracking and it minimized case retrieving cost thereby leading to time saving. Moreover, the designed system was made to be light and simple in order for safety operator to use as a portable devise during onsite analysis.

6.2 Recommendations

In this work, we have developed a system in standardizing HAZOP analysis including using expert systems. However, continuous studies still require in bringing about much improvement to the risk management system. The followings are the possible recommendations for future works:

- Related human factor issues appeared when hazard identification was focused not only on analyzing typical process deviations but also on initiating events caused by human errors. These events normally present higher frequencies of occurrence than others. While efforts have been focused on improving the expert team's motivation for finding error caused by human interferences, their integration into the HAZOP structure still remains incomplete. This is suggested for future works

- Most efforts for standardizing HAZOP studies have been done with the aim to automate its execution. Expert Systems development is the most powerful trend in the evolution of HAZOP. Disciplines such as process engineering and artificial intelligence in recent times have been merged thereby making deployment of intelligent systems a common practice. The use of Knowledge bases, Petri nets, signed digraphs and other principles has contributed to a better understanding of process industries with a focus on improving hazard identification. A considerable amount of work has been conducted in this challenging field; yet more research and application/verification of expert systems are needed to effectively apply them in hazard identification and loss prevention control.

- Future works also include improving the developed system by incorporating other hazard identification methods such as fault tree and event tree analyses. Verification of developed systems in real industrial environment is also needed in order to show its effectiveness and efficiency.

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Appendices

Appendix A: **Near Miss and Accident Case collected from PEC-SAFER Databases**

Appendix B: **List of Publications**

00018	接触水添脱硫装置の気密試験中の反応塔破裂
発災年月日	1980年4月1日
装置	灯軽油接触水添脱硫装置
運転状況	シャットダウン中(気密試験中)
特徴	気密試験中の脆性破壊

原因	事象の進展	備考
	装置定期修理終了	
	↓	
	保安検査を受ける準備として反応塔は窒素ガスによる気密試験を実施	
	↓	
①製作時に行なわれた欠陥補修溶接に用いられたD309(23Cr13Ni オーステナイト系)溶接金属部と仕様書にあるCR40Cb(13Cr フェライト系)溶接金属部あるいは母材(C 1/2Mo)との境界近傍に亀裂が生じていた。 ②亀裂が運転中に成長 ③気密試験中の内圧と残留応力によって脆性破壊 ④異種金属の溶接	内圧が55kg/cm2(設計圧力65kg/cm2)に至った時点で破裂	反応塔は当初は内張りオーステナイト系ステンレス鋼(SUS316L)であったが、多数の応力割れが発生し、フェライト系ステンレス鋼SUS405に変更している。
	↓	
	44個以上の破片(重量2～4,65kg)となって塔内充てん物とともに半径115mの範囲に飛散	
	↓	
	周辺設備や半径650m以内の民家95件に窓ガラス・建具の折損などの被害が発生	

再発防止対策

①異種金属の溶接施工方法(溶接棒の選択、溶接条件の選択)。
②内面溶接検査の定期修理でのフォロー。

安全専門家コメント

①当初のわずかな欠陥でも長時間運転で進展し、今回のような大事故につながることある。
②当該設備(高温、高圧機器、クラッド鋼)の定期修理時検査は異常がなかった箇所についても、長期間省略せず検査の要否を都度検討する。

引き金事象発生の原因	事故の引き金事象	事故に関係した直接・間接要因
・高温高圧水素ガス中で長年にわたって起動停止の繰り返しにより、溶接補修による溶接金属部と母材との異材継手境界近傍に剥離亀裂発生(製作不良) ・気密試験中の内圧と残留応力による負荷 ・異種金属の溶接 ・C-Mo鋼の水素侵食が進み耐圧壁内部に欠陥が発生、拡大(保守点検の省略)	反応塔脆性破壊	《工事・施工要因》 ・施工管理不適切

00147	ガソリン水素化脱硫装置のリボイラーフランジから漏洩火災
発災年月日	2002年11月17日
装置	ガソリン水素化脱硫装置
運転状況	定常運転中
特徴	工事・施工要因:ガスケット収納溝の不具合があり、再組み立て時に問題があったが対応せず

原 因	事象の進展	備 考
	定常運転中	
(1)事故に先立つ保守停止中の再組み立て時において、取り付けが不完全 (2)温度上昇に伴い、金属部品の冷間締め付けによるシールの締付け力が不足し漏洩が発生	↓ 高温の液体が存在するリボイラー(U字管式熱交換器)のステーショナリーチューブシートとシェルフランジ間の平面ガスケット部分から漏洩発火	
	↓ 一瞬のうちに高さ10mに達する火柱	
	↓ 消火隊始動、改質装置緊急停止	
	↓ 警察による国道の迂回路の設定	
	↓ 火災鎮火	
	↓ 緊急操作解除(窒素による装置不活性化)	

再発防止対策

(1)燃料ガスラインにつながる排出バルブを変更し、改質装置反応部の減圧速度を引き上げる。
(2)限界圧力まで使用されたバルブの交換。バルブは制御室から制御できるようにする。
(3)オペレータによる熱交換器シールベア表面検査手順の確立
・同種の操作を行なう人員に対し資格や訓練を要求。
・同種の作業を行なう外部企業のために、ガスケットベアリング表面の体系的な検査報告書を作成予定。

安全専門家コメント

・熱交換器のフランジの締付けトルクの管理基準、ガスケットの保管管理の基準を定めて確実な作業とガスケットの適正な保管管理をする。
・当該事例はフランスで発生した事故であるが、日本で発生した同じような事例がA-203にある。いずれも、ステーショナリーチューブシートとシェルフランジ間のガスケット部分から漏洩し火災となっている。ガスケット当たり面の突起(ナビン)が経年劣化で磨耗またはへたりによる形状不良を起こしたことが発端となっている。数百の事例を読み込んでいくと、世界の製油所がかかえる潜在的な弱点が見えてくる。

引き金事象発生の原因	事故の引き金事象	事故に関係した直接・間接要因
・熱交換器のガスケット収納溝の円形形状に不具合による取り付け不良 ・シールの締付け力が不足 ・再組み立て時に問題があったが対	熱交換器のガスケットより漏洩	《保守・点検要因》 ・点検・検査不良 《工事・施工要因》 ・工事検収不足 《管理・運営要因》 ・作業の基準・マニュアル類の不備・不十分

00070	水素化脱硫装置配管ベントノズルフランジのガスケット誤使用によるガス等の漏洩
発災年月日	1994年8月18日
装置	水素化脱硫装置
運転状況	装置・機器のスタートアップ中
特徴	定期修理時における仮設部材の取り替え忘れ

原因	事象の進展	備考
	定期修理で反応器出口配管側のベントノズルに仮設配管を取り付けて洗浄作業を実施	
・複数の協力会社が作業を実施 ・協力会社間の連絡の悪さ ・思い込み、認識不足	↓ 定期修理後ゴム製ガスケットを正規のSUS製に換えず残置	
	↓ ゴム製ガスケット硬化、破壊	スタートアップ後に高温高圧となる
	↓ 水素ガス・軽質油漏洩	スタートアップ2日後に漏洩
	↓ 着火防止（加熱炉遮断）、緊急停止、窒素置換	

再発防止対策

①フランジ開放、復旧作業指図書の新規制定
②工事請負者の工事管理体勢の強化
③工事担当者・協力会社に対する教育の実施

安全専門家コメント

この種の事故は事前に十分な準備があれば防止可能である。従来から行われていた個別工事毎の作業指示に加えて「フランジ開放、復旧作業指図書」を新たに作成した。それはそれで良いと思われるが、それらの間に齟齬が生じるという新たな問題も発生しかねない。従来の仕組みのどこに問題があったのか、仕組みは十分であったがそれを守らなかったのか等、なぜその仕組みが機能しなかったのか、問題点を十分に洗い出した後に総合的な対策を立てる必要がある。

引き金事象発生の原因	事故の引き金事象	事故に関係した直接･間接要因
仮設のゴム製ガスケットを正規のSUS製に取り替え忘れ	ゴム製ガスケット硬化、破壊	《人的要因》 誤操作・不作為など

00095	減圧留出油脱硫装置の熱交換器注水ノズルより漏洩火災
発災年月日	1988年5月22日
装置	減圧留出油脱硫装置
運転状況	定常運転中・ルーチン作業中
特徴	水注入箇所におけるエロージョン・コロージョン

原　因	事象の進展	備　考
	水と四硫化ソーダをノズルから注入	冷却器の腐食、汚れの原因となる硫化水素、アンモニア、シアンを取り除くため
	↓ 注水量の増加、流速の増加	
・配管内面にスケール（硫化鉄）が生成 ・溶存酸素と四硫化ソーダによる腐食性物質の生成 ・ノズル形状に起因する水流の開口部への衝突	↓ エロージョン・コロージョンの相互作用による減肉・開孔	
	↓ 高圧水素ガス噴出	
静電気火花で着火	↓ 着火	
	↓ 火災	
	↓ ・緊急シャットダウン操作 ・圧力降下操作、窒素パージ ・消火活動	
	↓ 鎮火	

再発防止対策

①検査の強化（調査部位の範囲拡大、頻度の増加）
②設備の使用状況等の変化に基づく技術検討および安全審査体制の強化
③水注入ノズルのエロージョン防止のためインナーノズル型に改造、炭素鋼の表面にアルマー加工をした配管に取替
④水または薬品注入配管に係る設計基準類の整備強化

安全専門家コメント

近年水注入箇所は、当該事例の対策にあるように、インナーノズル方式、配管内部のライニング、検査のしやすい配管変更などが進み開口事故が減った。

引き金事象発生の原因	事故の引き金事象	事故に関係した直接・間接要因
注水量の増量に伴う流速の上昇による水流の衝突 エロージョン・コロージョンを促す環境要因の存在 注入水に添加したケミカル（四硫化ソーダ）の腐食性 ボイラ給水中の微量溶存酸素とケミカルの反応にる腐食性物質の生成	エロージョン・コロージョンによる開口	《情報要因》 ﾌﾟﾛｾｽ特性・危険性の評価・検討不足 《管理・運営要因》 変更管理制度の不備・不十分 《設計要因》 機器・配管設計不良 《物質要因》 危険物質・不純物の生成・蓄積 《保守・点検要因》 点検･検査不良

00028	減圧留出油脱硫装置反応塔入口配管フランジ部からの漏洩火災
発災年月日	1989年9月27日
装置	減圧留出油脱硫装置
運転状況	定常運転中
特徴	フランジ上下部の材質の違いによる昇温時の伸びの差による開孔

原 因

・ホットボルティングでのボルト締め付け力不足
・フランジ上下部の材質の違いによる昇温時の熱膨張差によりフランジ部が開孔

事象の進展

1989年6月反応器完成
↓
1989年9月27日、反応器入口配管フランジが開孔
↓
水素・軽油が漏洩(硫化水素含む)
↓
着火
↓
火災
↓
・装置緊急停止および脱圧操作
↓
9.8MPaから0.6MPaに脱圧した時点で鎮火

備 考

（1989年6月反応器完成）運転開始時に200℃、360℃時点でホットボルティング実施

（装置緊急停止および脱圧操作）火災拡大の恐れはなく、放水による冷却を行なえば漏洩拡大のおそれ、また消火すれば硫化水素による二次災害の恐れがあるため、放水消火活動は実施せずに現場にて監視及び待機の体制をとる

再発防止対策

ホットボルティング作業を360℃を超えてから30℃毎に追加実施。
ホットボルティング作業要領の見直しと管理体制の強化。
新増設の高温高圧部のフランジ部については特別点検団を編成し定期点検を実施

安全専門家コメント

①フランジの増し締めは重要であるが、当該事例のように高温高圧の条件では、締め付け圧をどのくらいにするかを設計段階で専門メーカーの意見を聞きながら決定し、運転保全時に確実に実行することが重要である。
②脱硫装置は同じ製油所あるいは他の製油所にもあると推定されるが、類似事故防止のためホットボルティングの温度・圧力・配管口径に応じた全社的な基準を整備することが必要であろう。

引き金事象発生の原因	事故の引き金事象	事故に関係した直接・間接要因
・ホットボルティングでのボルト締め付け力不足 ・フランジ上下部の材質の違いによる昇温時の熱膨張差	フランジ締め付け力不足による開孔・漏洩	《工事・施工要因》 ・施工管理不適切 《人的要因》 ・能力・経験不足 《管理・運営要因》 ・作業の基準・マニュアル類の不備・不十分 《設計要因》 ・機器・配管設計不良

00037	減圧軽油水素化脱硫装置の運転再開中、熱交換器からガス漏洩・爆発・火災
発災年月日	1992年10月16日
装置	減圧軽油水素化脱硫装置・熱交換器
運転状況	スタートアップ中
特徴	特殊構造熱交換器のチャンネルカバー脱落

原 因　　**事象の進展**　　**備 考**

事象の進展

1. 減圧軽油脱硫装置停止し、触媒交換作業実施ご運転再開
2. 反応器及び反応器と熱交換器間の接続配管の最終段階のボルト増締め作業実施
3. 熱交換器リテーナー変形による管側シール漏れ（検知孔からの漏れ）
   - 原因：・装置の昇温、降圧および開放の繰り返しによりガスケットリテーナーの直径減少 ・ガスケットリテーナーが熱交換器本体のガスケット溝角部に乗り上げやすい状態 ・インターナルフランジセットボルトの先端のつぶれが大きくなりロックリングへの過大な荷重によりロックリングの奥側において外径が減少するように変形
   - 備考：熱交換器はBLC型で高圧に耐えられる耐圧機構と漏洩を防ぐシール機構とが別になる複雑な構造
4. 内圧によりロックリング変形飛散し、チャンネルカバー脱落
   - 原因：・検知孔からのみでは水素ガスが抜ききれなくなり、チャンネルバレルのネジ山噛み合い高さが減少し、熱交換器の内圧によりネジ山噛み合い部が塑性変形
   - 備考：・前回の開放検査時（1991年）に適切な補修を実施していなかった
5. 高圧、高温水素噴出
6. 着火
7. 爆発
8. 爆発にり隣接した他社工場およびタンクヤードの潤滑油タンク、配管類損傷
9. 潤滑油漏洩し火災発生
10. 消火活動・鎮火

再発防止対策

①同型熱交換器（BLC型）を有する事業者に情報の提供。
②当該熱交換器は特殊な構造をしているので、ガスケットリテーナーの交換など保守基準、保守計画を専業メーカーとの連携（点検・検査のポイント、部品の交換基準など）により見直す。
③保守に関して専業メーカーとの役割分担を明確にする。
④その他保安に関する各種マニュアルの見直し（高温、高圧の設備の増し締めなどの社員の立会い、ガス漏れ発生時の連絡・通報のマニュアルの作成など）。

安全専門家コメント

①高温、高圧装置の水素や軽油などを扱う装置の点検検査は細かい部品に至るまで交換・修理基準を作成しておく必要がある。
②異常が発生したことを発見するための点検による管理から、設備劣化を先取りする計画的管理が必要である。
③しばしば接点が疎かになり、そのための事故が多い。メーカーが絡む場合責任範囲を明確にする必要がある。

引き金事象発生の原因

・熱交換器が特殊構造
・昇温・昇圧の繰り返しによるガスケットリテーナー変形
・ガスケットリテーナー変形未修理

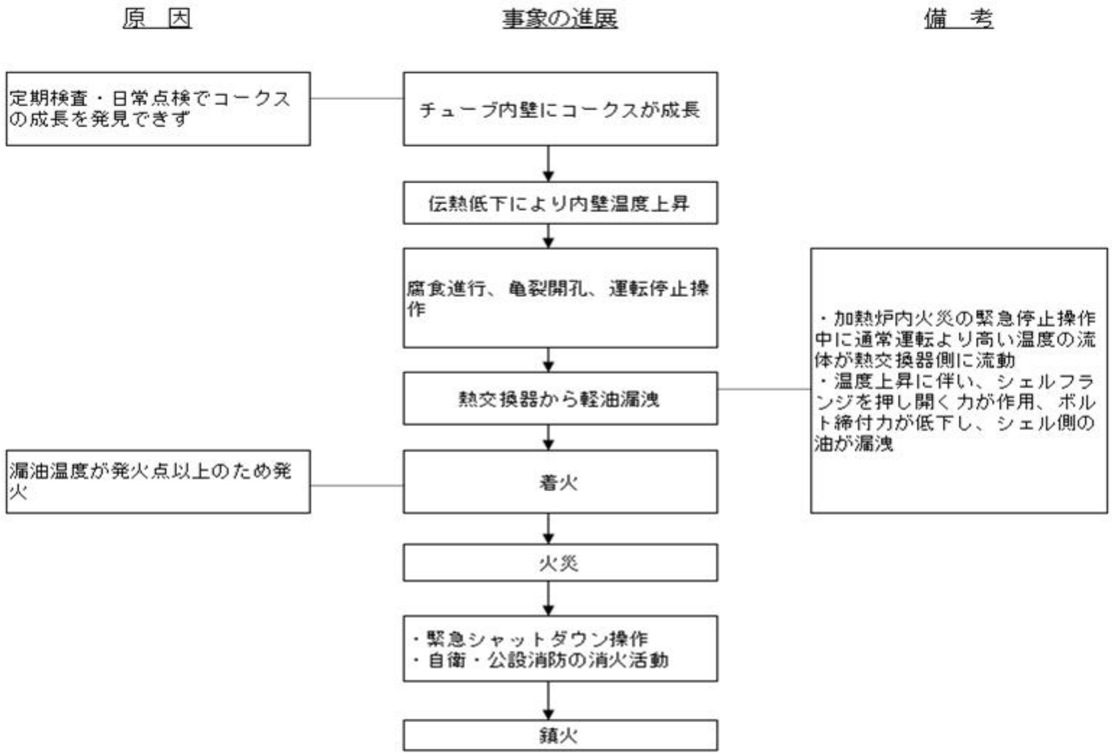
事故の引き金事象

熱交換器チャンネルカバー脱落

事故に関係した直接・間接要因

《保守・点検要因》
・保守・保全不良
・機器・配管設計不良
《情報要因》
・その他（メーカーとの情報交換不足）

00094	減圧軽油水素化脱硫装置加熱炉内チューブの亀裂火災および熱交換器漏れ火災
発災年月日	2003年4月4日
装置	減圧軽油水素化脱硫装置
運転状況	定常運転中・ルーチン作業中
特徴	加熱炉加熱管がコーキングにより開口



再発防止対策

①加熱炉管理の適正化（温度計の位置と数、炉内監視テレビの配置、過熱炉負荷の管理、バーナーの管理）
②検査ポイント決めて加熱管の温度測定を実施、傾向管理を実施
③定期的にデコーキングを実施

安全専門家コメント

正常運転中に突然、加熱炉チューブの一部が破裂する事故をどう防いだらよいか。当該事例の対策としてあがった（1）チューブ表面温度計の増設、（2）赤外線放射温度計による炉内監視、（3）適切な時期にデコーキングを実施に落ちつく。一方、突然の破裂とはいえ兆候はあるという見方をすると日常点検を工夫する必要がある。加熱炉内の点検はのぞき窓からするが、時間をとって炉内配管を10 ブロックくらいに分けて、「1ブロックはよし」というような緻密な点検をすると微妙な兆候に気づくことがある。一人ひとりが時間をかける必要はない。組織的に1日に1回綿密点検をすると決めればよい。シャットダウンシーケンスも現在は複数のケースを選択できるよう進化している。早いスピードで実施するケース、ノルマルシャットダウンに近いケース、前者は災害に拡大する恐れがあるときに用い、後者は機器の変動を許容値内にして当該事例のような事故をなくすときに用いる。発火点は引火点とは全く異なる物性値であることを知る必要がある。漏洩した可燃性液体が高温物と接触したり、断熱材に含浸して発火する事故は少なくない。

引き金事象発生の原因	事故の引き金事象	事故に関係した直接・間接要因
加熱管内面にカーボンが局所的に堆積、ホットスポットが発生管壁温度上昇による浸炭で耐食性が低下し腐食が進行	チューブ高温クリープ損傷による亀裂開口	《保守・点検要因》 点検・検査不良 保守・保全不良 《管理・運営要因》 作業の基準・マニュアル類の不備・不十分 《設計要因》 電気・計装設計不良

00021	灯油水添脱硫装置硫化水素吸収塔の液面計ガラスの破損による火災
発災年月日	1973年10月26日
装置	灯油水添脱硫装置硫化水素吸収塔
運転状況	定常運転中
特徴	パッキン挿入不良と締め付け不良によるパッキン切断

原 因	事象の進展	備 考
・パッキン挿入不良によるボルトの弛み ・無理な締め付けによるパッキン劣化。 そのためスプリングワッシャーの入っていなかったボルトとその前後のボルトに弛みが生じ、漏洩が始まり、パッキンが内圧に耐えられず切断	硫化水素吸収塔の4連式クリンガー式液面計パッキン切断	重質油脱硫工程は定期修理中であったが、系内にある硫化水素吸収塔は平常運転中であった。
	↓ 噴出	噴出したプロセスガスはアディップ水溶液及び灯油を同伴
静電気	↓ 着火	
	↓ 火災	
火災による衝撃・過熱	↓ 上下の液面計硬質ガラス二次的破損	
	↓ 火災拡大	
	↓ ・装置緊急停止（ボード） ・現場で発災塔ブロック ・緊急放出弁により降圧 （5.0MPa→0.6MPa）	
	↓ 初期消火開始 ・冷却注水 ・塔内に送水し水位を上げる	
	↓ 鎮火	

再発防止対策

設備関係：
・クリンガー式液面計全数の目視点検及び締め付けトルクの確認を実施。
・温度、圧力の厳しい条件で運転する部分に使用する液面計は差圧式液面計と交換。
・上記運転条件に満たない部分に使用するクリンガー液面計のすべてについてボールコック等の自動止弁を設置。
管理関係：
・クリンガー液面計の点検周期を4ヶ月毎と定めた。
・液面計の分解整備の際は必ずトルクレンチを使用し、不均等な締め付け防止、規定圧力を確保することとした。
・保守管理基準を見直し、液面計、フランジ部、ガス検知器等について追加することとした。

安全専門家コメント

①可燃性・毒性のガスや液体に使用する液面計はガラスタイプの型式でなく、差圧式や磁石式液面計を採用して安全化を図る。
②高所や保温に隠れた目の届きにくい場所の保全管理には、ガス検知を使用する等により漏洩の早期発見を図る。
③事故報告書によると当該設備の15m隣りで定期修理中の設備の火気使用工事（配管の切断などでガス、グラインダーなど）が行なわれていたとあるが、多少の養生では火の粉は防げない。当該事故の火源にならなかったとしても、このような作業を容認してはならない。

引き金事象発生の原因	事故の引き金事象	事故に関係した直接・間接要因
・パッキン挿入不良によるボルトの弛み ・温度・圧力の厳しい条件の所にクリンガー式液面計を使用（最新の情報により機器の更新がされていない）	液面計パッキン破断	《調達・検収要因》 ・検収ミス ・メーカー施工管理不適切 《保守・点検要因》 ・点検・検査不良 《管理・運営要因》 ・設備維持・管理基準の不備・不十分

00133	灯軽油接触脱硫装置のストリッピング塔供給配管より漏洩
発災年月日	1976年8月26日
装置	灯軽油接触脱硫装置
運転状況	定常運転中
特徴	静止機器の腐食･劣化･破損：短期間での腐食開孔

原 因	事象の進展	備 考
	定常運転中	運転を開始して6年9ヶ月経過
	↓	
	ストリッピング塔原料供給配管の保温配管外装板金の隙間から蒸気が出ているのを発見	
	↓	
・硫化水素による腐食と、低沸点成分の気化による乱流状態での侵食 ・乱流によって常にスケールが剥離されるTジョイント部で、腐食→剥離→腐食→剥離のサイクルにより、通常より高い速度で腐食が進行し、短期間で減肉した	配管Tジョイント部に腐食によるピンホール発生	
	↓	
	運転停止	
	↓	
	点検検査実施	

再発防止対策

恒久対策
・Tジョイント部の材質(SUS321TP)と形状変更(インターナルノズル)
暫定対策
・STPG38, Sch40→80に変更
・運転再開後復旧部の肉厚測定(2ヶ月間1週間毎に測定実施、その後は2週間毎に測定実施)
・検査基準の改定(側定項目、測定点など)
改定検査基準による点検を全装置で実施(肉厚測定、γ線検査)

安全専門家コメント

再発防止対策として、暫定対策は配管形状は変えずに厚肉とし検査を補強している。恒久対策は他社事例を参考にして材質(SUS321TP)と形状変更(インターナルノズル)を予定している。方針が明確に示されると現場で運転する人も安心できる。

引き金事象発生の原因	事故の引き金事象	事故に関係した直接･間接要因
・水分中に溶解している硫化水素が合流点で濃縮 ・硫化水素による腐食と、低沸点成分の気化による乱流状態での侵食	配管Tジョイント部に腐食によるピンホール発生	《物質要因》 ・危険物質･不純物の生成･蓄積

APPENDIX B: List of Publication

1. HAZOP Analysis Management System with Dynamic Visual Model Aid
Nan Bin Mad Sahar, Syahril Ardi, Suzuki Kazuhiko, Munesawa Yoshiomi and Minowa Hirotsugu.
American Journal of Applied Sciences 2010 Volume 7 issue 7, : pg.943-948, June 2010

2. Utilizing Fuzzy-CBR Methodology as an Artificial Intelligent Engine in Generating Scenario Case for Plant Virtual Reality Risk Simulation.
Nan Bin Mad Sahar, Suzuki Kazuhiko and Minowa Hirotsugu.
European Journal of Scientific Research Volume 41 Issue 1, pg.57-71, February, 2010

3.Virtual Grid Risk and Safety Identification System
NAN Bin Mad Sahar, SUZUKI Kazuhiko and MINOWA Hirotsugu.
International Joint Seminar in Engineering, IJSE 2008, June 2008.

4. Managing Risk Using Virtual Reality Simulation Supported by Automated HAZOP Analysis
Bin Mad Sahar NAN, Asral DATU RIZAL, Kazuhiko SUZUKI and Hirotsugu MINOWA,
Asia Pacific Symposium on Safety, APSS 2007, Nov 2007.

5. HAZOP Analysis Management System with Dynamic Visual Model Aid
NAN Bin Mad Sahar, SUZUKI Kazuhiko, MUNESAWA Yoshiomi and MINOWA Hirotsugu,
Tenth International Conference On Industrial Management, ICIM 2010, Sept 2010.