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

September 2010

Nan Bin Mad Sahar

The Graduate School of

Natural Science and Technology

(Doctor Course)

OKAYAMA UNIVERSITY

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.

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.

Table of Contents

Table of Figures

List of Tables

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.

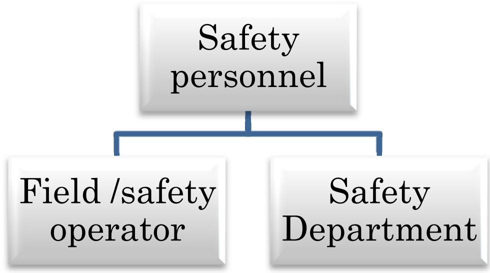

Fig 1.1 Safety personnel classifications.

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.

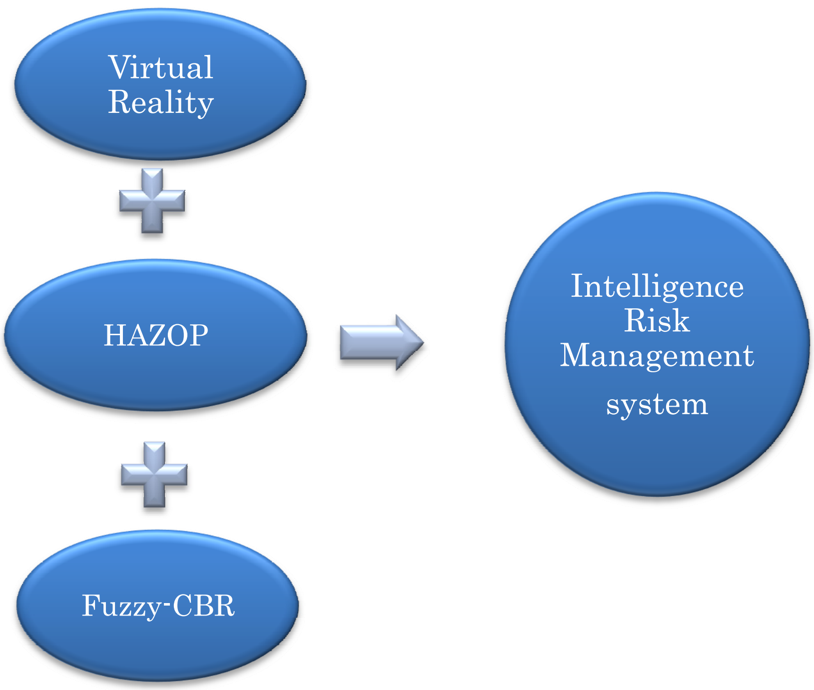

Fig. 1.2 Intelligent Risk Management System

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.

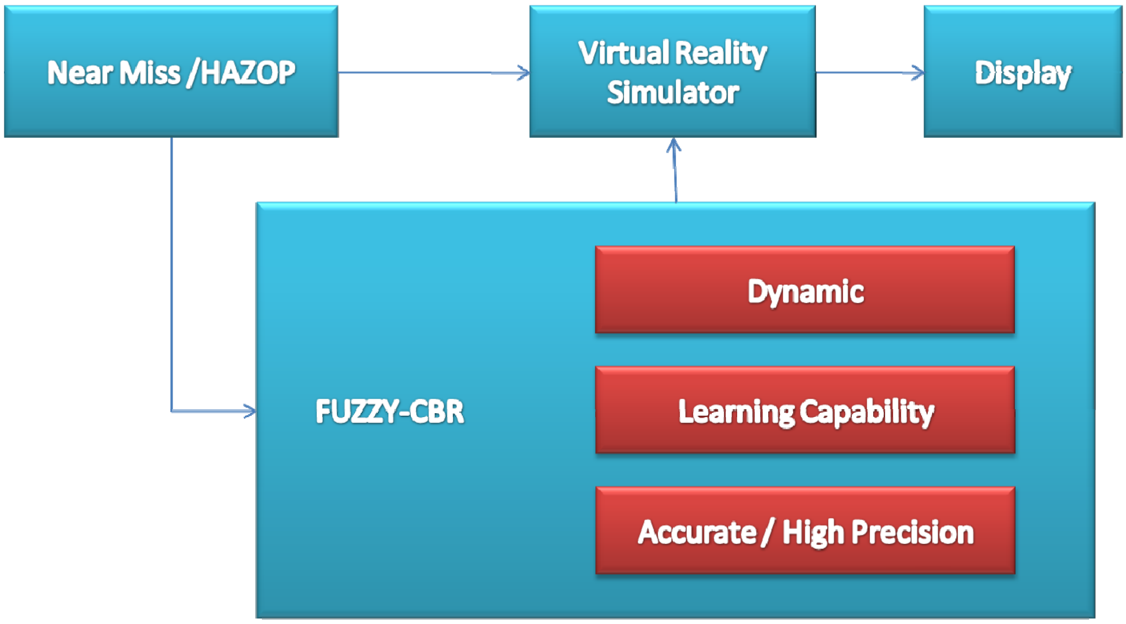

Fig. 1.3 Relationship between methodologies

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,

References

[1] King R. and Hirst R. (1998). Safety in Process Industries, Arnold, London

[2] Goh, S., Chang, B., Jeong, I., Kwon, H., and Moon, I., (1998), Safety Improvement by a Multimedia Operator Education System, Computers Chem. Eng., Vol.22, Suppl., pp.S531-S536

[3] Burton A., Hollands, R., Denby, B., Phillips R. and Weyman R., (2001), The use of virtual reality as a tool for teaching and testing hazard awareness in the construction industry, (awaiting publication)

[4] Goh, S., Chang, B., Jeong, I., Kwon, H., and Moon, I., (1998), Safety Improvement by a Multimedia Operator Education System, Computers Chem. Eng., Vol.22, Suppl., pp.S531-S536

[5] Eurostate for human factor, http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/themes

[6]Venkatasubramanian, V., Zhao, J., Viswanathan, S.,2000. Intelligent systems for HAZOP analysis of complex process plants, Computers & Chemical Engineering 24: 2291-2302

[7] King R. and Hirst R. (1998). Safety in Process Industries, Arnold, London

[8] Jones D., (1992). Nomenclature for Hazard and Risk Assessment in the Process Industries, Institution of Chemical Engineers, United Kingdom.

[9] Wells G., (1997) Major hazards and their management, Institution of Chemical Engineers, United Kingdom

[10] Health and Safety Executive (HSE), Successful Health and Safety Management, 1991

[11] March and Maclennan, (1988), 100 Worst Accidents in the Process Industries.

[12] Occupational Safety and Health Administration (OSHA), (1998), Industrial Hygiene, U.S. Department of Labour, OSHA 3134.

[13] King R. and Hirst R. (1998). Safety in Process Industries, Arnold, London

[14] R.L. Post, HazRop: an approach to combining HAZOP and RCM, Hydrocarbon Processing 80 (1) (2001) 69–76.

[15] IEC (International Electrotechnical Commission), Dependability Management—Risk Analysis of Technological Systems (IEC 300– 3–9), IEC, Geneva, 1995.

[16] ISO (International Standard Organisation), Environmental Management Vocabulary (14050), ISO, Geneva, 1998.

[16] Wells G., (1997) Major hazards and their management, Institution of Chemical Engineers, United Kingdom

[17] Virthualis project, http://www.virthualis.org/project.php,

[18] S.R. Trammel, B.J. Davis, Using a modified HAZOP/FMEA methodology for assessing system risk, IEEE Transactions (2001) 47–53.

19] L. Bendixen, J.K. O'Neill, Chemical plant risk assessment using HAZOP and fault tree methods, Plant/Operations Progress 3 (3) (1984) 179–184..

[20] L. Burgazzi, Evaluation of uncertainties related to passive systems performance, Nuclear Engineering and Design 230 (1–3) (2004) 93–106.

[21] H. Ozog, L.M. Bendixen, Hazard identification and quantification: the most effective way to identify, quantify, and control risks is to combine a hazard and operability study with fault tree analysis, Chemical Engineering Progress 83 (4) (1987) 55–64.

[22] M. Demichela, L. Marmo, N. Piccinini, Recursive operability analysis of a complex plant with multiple protection devices, Reliability Engineering and System Safety 77 (3) (2002) 301–308.

[23] A. Shafaghi, F.B. Cook, Application of a hazard & operability study to hazard evaluation of an absorption heat pump, IEEE Transactions on Reliability 37(2) (1988) 159–166

[24] P. Baybutt, Layers of protection analysis for human factors (LOPA-HF), Process Safety Progress 21 (2) (2002) 119–129.

[25] D.L. Schurman, S.A. Fleger,Humanfactors in HAZOPs: guide words and parameters, Professional Safety 39 (12) (1994) 32–34.

[26] P. Aspinall, HAZOPs and human factors, in: HAZARDS XIX – Process Safety and Environmental Protection Symposium, Institution of Chemical Engineers (IChemE), Manchester, UK, 28–30 March, 2006.

[27] B. Rasmussen, C. Whetton, Hazard identification based on plant functional modeling, Reliability Engineering and System Safety 55 (2) (1997) 77–84.
[28] R. Kennedy, B. Kirwan, Development of a hazard and operability-based method for identifying safety management vulnerabilities in high risk systems, Safety Science 30 (3) (1998) 249–274.
[29] N.I. Pátkai, Data management tool for aiding the hazard and operability analysis process, in: IEEE International Conference on Computational Cybernetics (ICCC), Budapest, Hungary, 20–22 August, 2006.
[30] P. Baybutt, Major hazard analysis: an improved method for process hazard analysis, Process Safety Progress 22 (1) (2003) 21–26.
[31] G. Grossmann, D. Fromm, HAZOP proof ammonia plant: a new way of defining a safeand reliable design, Plant/Operations Progress 10 (4) (1991) 223– 227.
[33] **K. Suzuki**, M. Ishida, I. Nojiri, Development of Operator Decision Support System using HAZOP results, in: Proceedings of the 7th International Conference on Probabilistic Safety Assessment and Management, PSAM7—ESREL 04, Berlin, Germany, June 14–18, 2004.
[34] R. Vaidhyanathan, V. Venkatasubramanian, Digraph-based models for automated HAZOP analysis, Reliability Engineering and System Safety 50 (1) (1995) 33–49.
[35] R. Srinivasan, V. Venkatasubramanian, Petri Net-Digraph models for automatingHAZOP analysis of batch process, Computers and Chemical Engineering 20 (Suppl.) (1996) S719–S725.
[36] S. Viswanathan, N. Shah, V. Venkatasubramanian, A hybrid strategy for batch process hazard analysis, Computers and Chemical Engineering 24 (2–7) (2000) 545–549.
[37] R. Srinivasan, V.D. Dimitriadis, N. Shah, V. Venkatasubramanian, Integrating knowledge-based and mathematical programming approaches for process safety verification, Computers and Chemical Engineering 21 (Suppl.) (1997) S905–S910.
[38] R. Srinivasan, V.D. Dimitriadis, N. Shah, V. Venkatasubramanian, Safety verification using a hybrid knowledge-based mathematical programming framework, AIChE Journal 44 (2) (1998) 361–371.
[39] R. Srinivasan, V. Venkatasubramanian, Multi-perspective models for process hazards analysis of large scale chemical processes, Computers and Chemical Engineering 22 (Suppl.) (1998) S961–S964.
[40] F.I. Khan, S.A. Abbasi, OptHAZOP—an effective and optimum approach for HAZOP study, Journal of Loss Prevention in Process Industries. 10 (3) (1997) 191–204.
[41] F.I. Khan, S.A. Abbasi, TOPHAZOP: a knowledge-based software tool for conducting HAZOP in a rapid, efficient yet inexpensive manner, Journal of Loss Prevention in Process Industries 10 (5–6) (1997) 333–343.
[42] W. Hangzhou, C. Bingzhen, H. Xiaorong, T. Qiu, Z. Jinsong, SDG-based HAZOPanalysis of operating mistakes for PVC process, Process Safety and Environmental Protection 87 (1) (2009) 40–46.
[43] N. Ramzan, F. Compart, W. Witt, Methodology for the generation and evaluation of safety system alternatives based on extended HAZOP, Process Safety Progress 26 (1) (2007) 35–42.
[44] S. Eizenberg, M. Shacham, N. Brauner, Combining HAZOP with dynamic simulation—applications for safety education, Journal of Loss Prevention in the Process Industries 19 (6) (2006) 754–761.
[45] N. Ramzan, F. Compart, W. Witt, Application of extended HAZOP and event-tree analysis for investigating operational failures and safety optimization of distillation column unit, Process Safety Progress 26 (3) (2007) 248–257.
[46] N. Ramzan, F. Compart, W. Witt, Application of extended HAZOP and event-tree analysis for investigating operational failures and safety optimization of distillation column unit, Process Safety Progress 26 (3) (2007) 248–257.
[47] J. Labovsky, Z. Svandová, J. Markos, L. Jelemensky, Mathematical model of a chemical reactor—useful tool for its safety analysis and design, Chemical Engineering Science 62 (18–20) (2007) 4915–4919.
[48] Nan Bin Mad Sahar, Syahril Ardi, Suzuki Kazuhiko, Munesawa Yoshiomi and 1Minowa Hirotsugu, HAZOP Analysis Management System with Dynamic Visual Model Aid,American Journal of Applied Sciences 7 (7): 943-948, 2010 ISSN 1546-9239
[49] A. Aamodt, E. Plaza, Case-based reasoning: foundational issues, methodologicalvariations and system approaches, AI Comm. 1 (1994) 35–39.
[50] J.L. Kolodner, D. Leake, A tutorial introduction to case-based reasoning, in: D. Leake (Ed.), Case-Based Reasoning: Experiences, Lessons and Future Directions, MIT Press, 1996, pp. 31–65.
[51] Barletta, B. (1991). An introduction to case-based reasoning. AI Expert, 6(8), 42–49.

[52] Nan Bin Mad Sahar, Kazuhiko, Munesawa Yoshiomi and Minowa Hirotsugu, intelligent HAZOP for safety personnel in chemical industries with Visual Model Aid, waiting for publication
[53] Barletta, B. (1991). An introduction to case-based reasoning. AI Expert, 6(8), 42–49.
[55] Aamodt A and Plaza E. 1994 Case-based reasoning: foundational issues, methodological variations and System approaches. AI Communications 7(1), pp 39-59
[56] Aamodt A 1990 Knowledge-intensive case-based reasoning and sustained learning. Proceedings European Conference on Articial Intelligence.
[57] Bento C and Costa E 1993 A similarity metric for retrieval of cases imperfectlydescribed and explained Pro- ceedings First European Workshop on Case-Based Reasoning, ed Richter, Wess, Altho , and Maurer, Vol. 1, pp 8-13
[58] Bonissone P. 1982 A Fuzzy Sets Based Linguistic Approach: Theory and Applications Approximate Reasoning in Decision Analysis, ed M Gupta and E Sanchez, (New York: North Holland Publishing Co.), pp 329{339
[59] Dubois, D and Prade, H 1980 Fuzzy Sets and Systems: Theory and Applications (NewYork, USA: Academic Press)
[60] Soft computing in engineering design – A review Advanced Engineering Informatics,Volume 22, Issue 2, April 2008, Pages 202-221 K.M. Saridakis, A.J. Dentsoras
[61] Fuzzy similarity-based rough set method for case-based reasoning and its application in tool selection International Journal of Machine Tools and Manufacture, Volume 46, Issue 2, February 2006, Pages 107-113 Ya-jun Jiang, Jun Chen, Xue-yu Ruan
[62] S.K. Pal and S. Mitra, "Case Generation Using Rough Sets with Fuzzy Representation," IEEE Trans. Knowledge & data engineering, vol. 3, pp. 292-300, 2004.
[63] Kolodner J 1992 An introduction to case-based reasoning Articial Intelligence Review 6, pp 3-34
[64] Loss and gain functions for CBR retrieval Information Sciences, Volume 179, Issue 11, 13 May 2009, Pages 1738-1750 J.L. Castro, M. Navarro, J.M. Sánchez, J.M. Zurita
[65] Morbach, J., Yang, A., & Marquardt,W. (2007). OntoCape—A large-scale ontology for chemical process engineering. Engineering Applications of Artificial Intelligence, 20(2), 147–161
[66] Plaza E and Lopez de Mantaras R 1990 A case-based apprentice that learns from fuzzy examples Methodologies for Intelligent Systems 5, ed Ras, Zemankova and Emrich, Elsevier, pp 420-427
[67] R5 model for case-based reasoning Knowledge-Based Systems, Volume 16, Issue 1, January 2003, Pages 59-65 Gavin Finnie, Zhaohao Sun
[68] Aasia Khanum, Muid Mufti, M. Younus Javed, M. Zubair Shafiq,Fuzzy case-based reasoning for facial expression recognition Fuzzy Sets and Systems, Volume 160, Issue 2, 16 January 2009, Pages 231-250
[69] S.K. Pal and S. Mitra, "Case Generation Using Rough Sets with Fuzzy Representation," IEEE Trans. Knowledge & data engineering, vol. 3, pp. 292-300, 2004.
[70] Barletta, B. (1991). An introduction to case-based reasoning. AI Expert, 6(8)
[71] Meel, A., O'Neill, L. M., Levin, J. H., Seider, W. D., Oktem, U., & Keren, N. (2007). Operational risk assessment of chemical industries by exploiting accident databases. Journal of Loss Prevention in the Process Industries, 20, 113–127.
[73] Schofield, D., Denby, B. and Hollands, R., (2001), Mine Safety in the Twenty-First Century: The Application of Computer Graphics and Virtual Reality, Mine Health and Safety Management, Edited by Michael Karmis. Littleton, Colorado: Society of Mining, Metallurgy, and Exploration, Inc. (SME), Chapter 10. Schofield D., Fowle K.,
[74] Demel J.T. and Miller M.J, Introduction to computer graphics, 1984
[75] Dassault Systemes, (2009), CATIA, CAD software, http://www.catia.com
[76] Perrie, A., (1997) Computer Graphics, University of Wisconsin Course Notes, Spring1997 http://www.uwosh.edu/faculty_staff/perrie/371.html
[77] Hollands, R., Denby, B., Schofield, D., Brooks, G., and Burton, A., (1999) Use of Virtual Reality in Improving Safety Awareness and Performance, Proceedings of the Offshore Safety Conference, Perth, Australia.
[78] Kalawsky, R. S., (2000) Exploiting Virtual Reality techniques in Education and Training, Advanced VR Centre, Loughborough University of Technology. http://www.agocg.ac.uk/reports/virtual/vrtech/title.htm

[79] Gary, J.H. and Handwerk, G.E. (1984). *Petroleum Refining Technology and Economics* (2nd Edition ed.). Marcel Dekker, Inc. ISBN 0-8247-7150-8.
[80] Nancy Yamaguchi, Trans Energy Associates, William and Flora Hewlett, Hydrodesulfurization Technologies and Costs Foundation Sulfur Workshop, Mexico City, May 29-30, 2003
[81] Nan Bin Mad Sahar, Syahril Ardi, Suzuki Kazuhiko, Munesawa Yoshiomi and Minowa Hirotsugu ,HAZOP Analysis Management System with Dynamic Visual Model Aid ,American Journal of Applied Sciences 2010 Volume 7 issue 7, : 943-948, June 2010
[82] Nan Bin Mad Sahar, Suzuki Kazuhiko, and Minowa Hirotsugu , Utilizing Fuzzy-CBR Methodology as an Artificial Intelligent Engine in Generating Scenario Case for Plant Virtual Reality Risk Simulation,European Journal of Scientific Research Volume 41 Issue 1, 57-71, February, 2010
[83] NAN Bin Mad Sahar, SUZUKI Kazuhiko, MINOWA Hirotsugu, Virtual Grid Risk and Safety Identification System", International Joint Seminar in Engineering IJSE 2008 proceeding, pp. 196-199, 2008.
[84] Bin Mad Sahar NAN, Asral DATU RIZAL, Kazuhiko SUZUKI, Hirotsugu MINOWA ,Managing Risk Using Virtual Reality Simulation Supported by Automated HAZOP Analysis," Asia Pacific Symposium on Safety,APSS 2007 proceeding pp. 35-38, 2007.
[85] Venkatasubramanian, V., Zhao, J., Viswanathan, S.,2000. Intelligent systems for HAZOP analysis of complex process plants, Computers & Chemical Engineering 24: 2291-2302
[86] Wilson J.R., D'Cruz M., Cobb S. and Eastgate R., (1996), Virtual Reality for Industrial Applications: Opportunities and Limitations, Nottingham University Press, Nottingham, United Kingdom.
[87] Carr, C., (1992), Is virtual reality virtual, Training and development at university of nottingham, school of chemical, environmental and mining engineering.
[88] Vince J., (1995), Virtual Reality Systems, ACM SIGGRAPH Book Series, Addison-Wesley Publishing Company, Wokingham, United Kingdom.
[89] FBS Ltd., (2001), FBS Bell 412 Simulator, Internet WWW page at URL: http://www.fbsltd.com/FBS%20Bell%20412%20Simulator%20Information.htm.
[90] Dutton, G., (1992) Medicine gets closer to Virtual Reality, IEEE Software, Sept. 1992.
[91] Nilan, M.S., Silverstain, J.L., Lankes, R.D., (1993), The VR technology agenda in Medicine, Virtual Reality 93:Special Report
[92] HITLab, (2001), Virtual Prototyping of Medical Robotic Interfaces, Internet WWW page at URL: http://www.hitl.washington.edu/research/robot/
[93] Bauman J., (2000), Military applications of virtual reality, The Encyclopedia of Virtual Environments (EVE), Produced by the students of Dr. Ben Shneiderman's CMSC 828S Virtual Reality and Telepresence Course, Fall 1993, Internet WWW page at URL: http://www.hitl.washington.edu/projects/knowledge_base/virtualworlds/EVE/
[94] Hollands, R., Denby, B., Schofield, D., Brooks, G., and Burton, A., (1999) Use of Virtual Reality in Improving Safety Awareness and Performance, Proceedings of the Offshore Safety Conference, Perth, Australia.