

# A Knowledge-Based Framework for Automating HAZOP Analysis



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## Final Report

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## 2. List of Publications and Presentations

### Journal Publications:

1. R. Vaidhyanathan, and V. Venkatasubramanian, "Digraph-based models for automated HAZOP analysis", *Reliability Engineering and System Safety*, 50, 33-49, 1995.
2. R. Vaidhyanathan, and V. Venkatasubramanian, "A semi-quantitative reasoning methodology for filtering and ranking HAZOP results in HAZOPEXpert", *Reliability Engineering and System Safety*, 53, 185-203, 1996.
3. R. Vaidhyanathan, V. Venkatasubramanian, and F. T. Dyke "HAZOPEXpert: An expert system for automating HAZOP analysis", *Process Safety Progress*, 15(2), 80-88, 1996.

### List of Conference Presentations and Publications:

1. R. Vaidhyanathan and V. Venkatasubramanian, "Developing an expert system for HAZOP analysis", *AIChE Meeting*, Atlanta, GA, April 1994.
2. V. Venkatasubramanian and R. Vaidhyanathan, "HAZOPEXpert: An expert system for HAZOP analysis", *Fifth International Conference on Process Systems Engineering (PSE'94)*, Kyongju, South Korea, Vol. II, En Sup Yoon (Editor), pp. 1117-1121, June 1994.
3. V. Venkatasubramanian and M. L. Preston, "Perspectives on Intelligent Systems for Process Hazards Analysis", *Proceedings of the International Conference on Intelligent Systems in Process Engineering (ISPE'95)*, Snowmass, CO, July, 1995 (Invited Paper).
4. R. Vaidhyanathan and V. Venkatasubramanian, "Digraph-based models for automating HAZOP analysis of chemical plants", *AIChE Meeting*, Miami Beach, FL, Nov 1995.
5. R. Vaidhyanathan and V. Venkatasubramanian, "HAZOPEXpert: An intelligent system for performing automated HAZOP analysis", *Process Plant Safety Symposium*, Houston, TX, Apr 1996.
6. R. Vaidhyanathan and V. Venkatasubramanian, "Experience with an expert system for automated HAZOP analysis", *European Symposium on Computer Aided Process Engineering*, Rhodes, Greece, May 1996.



## Invited Seminars:

Seminars of this work were delivered at the following institutions:

University of Lund, Lund, Sweden, Aug 1994

Eli Lilly & Co, Indianapolis, IN, Oct 1994

Dow Elanco, Indianapolis, IN, Oct 1994

G. D. Searle and Co., Chicago, IL, March 1995

Honeywell Technology Center, Minneapolis, MN, April 1995

Imperial College of Science, Technology and Medicine, London. U.K, June 1995

Loughborough Institute of Technology, Loughborough, U.K, June 1995

Imperial Chemical Industries, Runcorn, U.K., June 1995

Exxon Engineering & Research, Florham Park, NJ, Sept 1995

Indian Institute of Technology, Madras, India, Jan 1996

University of Edinburgh, Edinburgh, Scotland, March 1996.

Gensym Corporation, Cambridge, MA, Oct 1996

Air Products and Chemicals, Allentown, PA, Feb 1997

### 3. Significant Findings

Automating HAZOP analysis is achieved by understanding the different types of expertise required for performing HAZOP analysis and developing a framework for representing and reasoning with this knowledge. One important requirement of the framework is the ability to reuse a major portion of this knowledge so that it can be applied for a variety of chemical plants and not require complete reacquisition for every new flowsheet. The results produced by the automated system must have the look and feel of the HAZOP analysis performed by a team of experts. The system must include the capability to explain its reasoning about how a particular hazard might arise. The other important questions concern complexity and scalability issues for large industrial-scale processes.

We have demonstrated that the knowledge required for HAZOP analysis can be separated into process-specific and process-general knowledge. The process-specific knowledge includes the process piping and instrumentation diagram (P&ID) and the process material properties. Experts use mental models while performing HAZOP analysis which comprise of cause-and-effect type knowledge of process units which are process-general and applicable to a wide variety of flowsheets. We have shown that these mental models can be represented using directed graph-based qualitative models of process units, called HAZOP-digraph (HDG) models. We have also shown how these HDG-models can be developed for common process units. We also developed bi-directional message-passing based inference methods for the control of reasoning. These methods use the HDG-models to propagate process deviations and interact with the process-specific knowledge to determine abnormal causes and adverse consequences of deviations. We also solved associated problems concerning cyclic loops among process variables due to recycle and control loops.

Our investigation of large-scale flowsheets identified that strict qualitative reasoning could lead to ambiguous values for process variables. In such cases, with strict qualitative reasoning, the worst case scenario has to be assumed, which would generate more consequences that realistically possible. We developed a novel semi-quantitative and order-of-magnitude reasoning methodology which uses quantitative information in the form of the design specifications and normal operating conditions of the process units and the quantitative properties of process

materials to filter and rank the adverse consequences found by strict qualitative reasoning.

We have tested these techniques by developing an knowledge-based system, called *HAZOPExpert*, to perform automated HAZOP analysis. *HAZOPExpert* has been implemented in an object-oriented architecture. The user interacts with the system through an intelligent graphical user interface which includes the P&ID graphical editor, the HAZOP model library of process units and the HAZOP results windows. This greatly simplifies knowledge-acquisition for a given process. A process variable deviation can be initiated by the user using a pull-down menu. *HAZOPExpert* performs the HAZOP analysis and displays the results in the HAZOP results windows. *HAZOPExpert* can also export the results into spreadsheeting software and format it as the standard HAZOP results table.

We tested the *HAZOPExpert* system with the aid of five complex, real-life, industrial case studies. All these case studies have been reviewed using HAZOP analysis by our collaborators from Arthur D. Little and Co. This is a very important issue from the industrial perspective. We compared *HAZOPExpert's* results with those obtained by the team of HAZOP experts for all the case studies. These investigations showed that *HAZOPExpert* was able to identify all the abnormal causes and adverse consequences that were found by the HAZOP team. The strictly qualitative *HAZOPExpert* generated more HAZOP results than those recorded in a conventional HAZOP analysis performed by experts. *HAZOPExpert* with the semi-quantitative filtering achieved a significant reduction in the number of consequences while identifying all the causes and consequences identified by the HAZOP team. We have demonstrated that a knowledge-based system can successfully perform a fast, systematic, thorough and detailed analysis of routine process hazards in complex, industrial-scale continuous chemical processes, thus reducing the time and massive effort involved in performing a HAZOP review.

#### 4. Usefulness of Findings

Occupational safety and health hazards pose threats to an estimated 20 million workers in the manufacturing sector in the United States. Industrial statistics show that even though major catastrophes and disasters of chemical plants may be infrequent, minor accidents are very common, occurring on a day to day basis, resulting in many occupational injuries, illnesses, and costing the society billions of dollars every year [CMA, 1991]. For example, in 1983 alone over 3000 job-related deaths and an estimated 4.9 million job-related injuries and illnesses occurred [Bureau of Labor Statistics, 1985]. It is also estimated that the annual cost to society of work-related injuries, illnesses, and deaths has nearly tripled from \$11.5 billion in 1972 to \$33.0 billion in 1984 [National Safety Council, 1985; McGraw-Hill Economics, 1985].

The occurrence of several catastrophic accidents in the refining and chemical industries during the 1980s has intensified public concern about process safety. The chemical industry, the federal government, and many state governments have responded to address these concerns in the form of new guidelines and requirements. The recently published final *Occupational Safety and Health Administration (OSHA)* standard on process safety management, Rule 29 CFR 1910.119 [OSHA, 1992], requires the use of a process hazards analysis (PHA) technique for the identification of hazards for process systems containing toxic substances and/or flammable process materials above specified threshold quantities. OSHA estimates that such a process hazards analysis will be required at approximately 25,000 existing plant sites in the U.S. and for all the new ones that are built or retrofitted in the future [Freeman et. al., 1992]. At a typical plant site, five to ten different PHA studies will be needed to comply with the OSHA standard. This comprehensive mandatory review of process hazards will *directly impact* on the safety of about *one million workers* who are employed in the chemical industry, and many millions of people residing in the neighboring communities surrounding chemical plants [CMA, 1991]. It is estimated that about 100 million person-hours and 10 billion dollars might have to be spent using the current PHA approaches to meet this new regulation [Freeman et. al., 1992].

This project is aimed at the prevention of accidents in the industry by developing an automated, intelligent HAZOP analysis system which can make the HAZOP analysis

more thorough and detailed, minimize human errors and free the team to concentrate on the more complex aspects of the analysis which are unique and difficult to automate. The research carried out in this project leads to a better understanding of the complexities involved in the design of knowledge-based, intelligent computer systems that have the potential to effectively identify the hazards in chemical plants. In this project, our significant findings demonstrated that knowledge-based systems can successfully identify all the causes and consequences of process deviations through a thorough and detailed analysis. We showed that the expertise required for HAZOP analysis can be separated into process-specific and process-general knowledge. The process-general knowledge remains fixed irrespective of the process plant under consideration, and the process-specific knowledge can be acquired separately and easily using a graphical user interface for each process plant. We also showed how the process-general causal knowledge can be represented using HAZOP-Digraph models of process units. Our work also described how the complexities due to controllers and cyclic loops in complex, industrial processes can be effectively handled by using variable deviation propagation strategies.

We also pointed out the limitations of a strictly qualitative analysis. These can lead to ambiguities in propagation of process variable deviations and force the adoption of a conservative, worst-case outcome. This results in generation of a large number of consequences which are possible but realistically unlikely, thus leading to information overload problems. We also developed a semi-quantitative filtering and ranking methodology to overcome the above limitations. By using quantitative design and operating conditions specifications and quantitative process material property values in conjunction with HDG-based qualitative analysis, we established a novel methodology which achieves a substantial reduction in the number of consequences generated by the HAZOP system. This reduction of spurious results is very important for the practical adoption of such systems by industry.

There are still a number of research issues to be addressed to realize the full potential of knowledge-based systems for HAZOP analysis. The framework and methodologies developed in this project concentrated on HAZOP analysis of continuous process plants in steady-state operation. Since batch processes are used in large numbers in the chemical process and pharmaceutical industries, one needs to develop a knowledge-based framework that can perform HAZOP analysis for batch

processes. During batch operation the relationships between process variables keep changing and depends on the task and subtask that is being performed. Hence, the digraph-based representation is not sufficient to model the cause-and-effect relations in a batch process. Another research need is the topic of integrating qualitative analysis with quantitative mathematical, dynamic process model based analysis to obtain bounds on process variable deviations which would lead to hazardous conditions. Despite such needs for future research and certain inherent limitations, the knowledge-based system is still superior to several other alternatives for many practical problems in HAZOP analysis, as our investigation has shown.

## 5. Aims of the project and their relationship to the publications

The major aim of this proposal was to research and demonstrate a novel approach based on artificial intelligence for automating HAZOP analysis of chemical processes. The major goals of the project are described in the next paragraph.

Automating HAZOP analysis is achieved by understanding the different types of expertise required for performing HAZOP analysis and developing a framework for representing and reasoning with this knowledge. One important requirement of the framework is the ability to reuse a major portion of this knowledge so that it can be applied for a variety of chemical plants and not require complete reacquisition for every new flowsheet. Another important requirement is the ability to capture the mental qualitative, cause-and-effect models of process units used by human experts while performing HAZOP. Developing such a framework was the first aim of the project. Strict qualitative analysis can lead to ambiguous values for process variables. This can lead to generating more causes and consequences than those recorded by the team. Some of the additional results may not lead to the predicted hazardous consequence, but this can be determined only by a quantitative analysis. As the second aim, we were interested in developing strategies to overcome the limitations of strict qualitative analysis by introducing additional quantitative knowledge in the form of design and operating conditions specifications and quantitative process material property values. Testing the framework and the implementation on complex, industrial case studies and comparing the strictly qualitative and the semi-quantitative approach was the third aim of the project. Thus, the refined aims of the project were to investigate these issues to better understand the scope of knowledge-based approaches for automating HAZOP analysis.

The accomplishment of the first aim of the project with all the details are discussed in the following publication:

1. R. Vaidhyathan, and V. Venkatasubramanian, "Digraph-based models for automated HAZOP analysis", *Reliability Engineering and System Safety*, 50, 33-49, 1995.

The successful completion of the second aim is presented in the next publication:

2. R. Vaidhyanathan, and V. Venkatasubramanian, "A semi-quantitative reasoning methodology for filtering and ranking HAZOP results in HAZOPEXpert", *Reliability Engineering and System Safety*, 53, 185-203, 1996.


And finally, all the results regarding the third aim are described in:

3. R. Vaidhyanathan, V. Venkatasubramanian, and F. T. Dyke "HAZOPEXpert: An expert system for automating HAZOP analysis", *Process Safety Progress*, 15(2), 80-88, 1996.

## Equipment Purchases

1. Macintosh Computer System	#INV857097	March '94	\$6420.19
2. Macintosh Computer System	#INV857098	March '94	\$6420.19
3. Macintosh Computer System	#INV857099	March '94	\$7173.91
4. SPARC10 Computer Workstation	#INV857943	April '94	\$25460.19
5. SPARC2 Portable Computer	#INV872307	Aug '95	\$15007.71
6. MacIntosh PowerPC	#INV875235	Jan '96	\$5687.70



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