# NEW TRENDS FOR CONDUCTING HAZARD & OPERABILITY (HAZOP) STUDIES IN CONTINUOUS CHEMICAL PROCESSES

# NEW TRENDS FOR CONDUCTING HAZARD & OPERABILITY (HAZOP) STUDIES IN CONTINUOUS CHEMICAL PROCESSES

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de ben segur que es superarà

jordi

# RESUM

El capítol I introdueix la temàtica de la recerca, i després de definir el concepte de *Seguretat de Processos*, progressivament analitza els escrits regulats (d'Estats Units i Europa) que hi ha presents a l'actualitat, detallant específicament les mancances i buits d'informació relacionats amb la primera etapa de la gestió del risc de les industries de procés: la identificació de perills. Es conclou que hi ha absència de criteris per aplicar les tècniques que tenen la intenció d'investigar què és el que pot anar malament (situacions perilloses).

El capítol II específicament defineix el sistema de gestió del risc tecnològic que cal analitzar a les industries de procés. A partir d'aquesta definició, es justifica que l'etapa d'identificació de perills és el pilar de tot el sistema. Finalment, es mencionen algunes de les tècniques d'identificació més utilitzades, els anomenats *Process Hazard Analysis (PHA)*, i es detallen les seves mancances i fortaleses, característiques que han acabat definint la temàtica específica de la Tesis. Concretament, es dóna èmfasis a la tècnica anomenada *HAZard & OPerability (HAZOP) study*, objecte principal de la recerca.

El capítol III defineix l'abast, el propòsit i els objectius específics de la recerca. La intenció d'aquest capítol és donar resposta a les següents qüestions: el perquè de la recerca, quins elements han estat inclosos i què s'ha considerat per tal d'assolir les conclusions de la Tesis.

El capítol IV descriu l'estat de l'art de la literatura relacionada amb el HAZOP, i revisa referències bibliogràfiques tals com llibres, conferències, i publicacions procedents de revistes científiques. Aquesta revisió no només permet classificar les diferents línies de recerca relacionades amb el HAZOP, sinó que també permet assolir un coneixement profund de les diferents particularitats de la pròpia tècnica. El capítol finalitza amb un conjunt de mancances tant de gestió com tècniques, així com les necessitats de recerca que poden millorar la implantació dels estudis HAZOP a la industria de processos químics continus.

El capítol V analitza la informació que ha estat recopilada durant la fase experimental de la tesis. Les dades procedeixen de la participació en cinc estudis HAZOP (durant les fases de preparació, organització, execució i redacció) aplicats a la industria de refineria del petroli. En aquest sentit, el capítol V realitza una anàlisi estadística d'aquestes dades per extreure'n conclusions quant a la preparació, organització i execució d'estudis HAZOP.

El capítol VI estableix el conjunt d'accions que s'ha de tenir en compte per tal d'assegurar que un estudi HAZOP estigui ben organitzat i executat, en funció dels resultats obtinguts en el capítol V i de l'experiència assolida al llarg del desenvolupament d'aquesta Tesis. Com a punt de partida, es defineix un Sistema de Gestió del propi HAZOP, i a partir de les seves fases, es desenvolupa una metodologia que pretén donar suport a tots aquells punts febles que han estat identificats en capítols anteriors del present escrit. Aquesta metodologia té la intenció de donar suport i guia no només als líders del HAZOP, sinó també a qualsevol part interessada en aquesta temàtica.

El capítol VII descriu les conclusions de la recerca. Les conclusions en primera instància enumeren les mancances quant a definició de criteris a seguir de diferents regulacions que apliquen a la Seguretat de Processos. Seguidament, es mencionen les limitacions de la pròpia tècnica HAZOP, tant des del punt de vista de gestió com tècnic, i finalment, es descriuen quins són els criteris establerts per donar solució a totes aquestes febleses que han estat identificades.

L'Annex I és una recopilació de diferents criteris que han estat desenvolupats al llarg de l'escrit en forma de taules i figures. Aquestes han estat ordenades cronològicament d'acord amb les diferents fases que defineixen el Sistema de Gestió HAZOP. En aquest sentit, l'annex I té la intenció de convertir-se una guia concisa i pràctica, preparada i pensada per ésser utilitzada directament a camp, per aquelles parts interessades en liderar estudis HAZOP.

L'annex II recopila informació relacionada amb aspectes clau de seguretat i medi ambient que cal tenir en compte en diferents tipus d'unitats de refineria. Aquesta informació pot ésser considerada com a un suport per tal de motivar el "brainstorming" dels diferents membres que conformen l'equip HAZOP.

L'Annex III recopila les dades de les diferents variables que han estat considerades a la fase experimental de la recerca. Addicionalment, s'adjunten un conjunt de figures que mostren l'estadística elemental d'aquestes variables.

Finalment, es llista la Nomenclatura, les Referències, i les Abreviacions i Acrònims que han estat utilitzats i citats al llarg del desenvolupament de la memòria de la Tesis.

# SUMMARY

Identifying hazards is fundamental for ensuring the safe design and operation of a system in process plants and other facilities. Several techniques are available to identify hazardous situations, all of which require their rigorous, thorough, and systematic application by a multi-disciplinary team of experts. Success rests upon first identifying and subsequently analyzing possible scenarios that can cause accidents with different degrees of severity. While hazard identification may be the most important stage for risk management, it depends on subjectivity issues (e.g., human observation, good judgment and intuition, creativity, expertise, knowledge) which introduce bias. Without a structured identification system, hazards can be overlooked, thus entailing incomplete risk-evaluations and potential loss. The present Thesis is focused on developing both managerial and technical aspects intended to standardize one of the most used techniques for hazard identification; viz. *HAZard & Operability* (HAZOP) *study*. These criteria have been carefully implemented not only to ensure that most of the hazardous scenarios will be identified, but also that *US OSHA PSM Rule*, *EPA RMP*, and *Seveso Directive* requirements will be accomplished.

Chapter I pioneers the main research topic; from introducing the process safety concept up to the evidence of more detailed information is required from related regulations. A review of regulations (i.e., US, Europe legislation) focused on Hazard Identification has been conducted, highlighting, there is an absence of specific criteria for performing techniques intended to identify what can go wrong.

Chapter II introduces the risk management system required to analyze the risk from chemical process facilities, and justifies that hazard identification stage is the Process Safety foundation. Hereafter, an overview of the key Process Hazard Analyzes (PHA) has been conducted, and the specific HAZOP weaknesses and strengths have been highlighted to establish the first steps to focus on.

Chapter III establishes the scope, the purpose and the specific objectives that the research covers. This chapter answers the following questions on the spot: why the present research is performed, which elements are included, and what has been considered for acquiring the final conclusions of the manuscript.

Chapter IV gathers HAZOP-related literature from books, guidelines, standards, major journals, and conference proceedings with the purpose of classifying the research conducted over the years and finally define the HAZOP state-of-the-art. Additionally, and according to the information collected, the current HAZOP limitations have been emphasized, and thus, the research needs that should be considered for the HAZOP improvement and advance.

Chapter V analyzes the data collected while preparing, organizing, executing and writing HAZOPs in five petroleum-refining processes. A statistical analysis has been performed to extract guidance and conclusions to support the established criteria to conduct effectively HAZOP studies.

Chapter VI establishes the whole set of actions that have to be taken into account for ensuring a well-planned and executed HAZOP study, i.e. the HAZOP Management System. Both technical and management issues are addressed, criteria supported after considering the previous chapters of the manuscript. Chapter VI itself is the result of the present research, and could be used as a guideline not only for team leaders, but also for any related party interested on performing HAZOPs in continuous chemical processes.

Chapter VII states the final conclusions of the research. The interested parties should be released about the hazard identification related-gaps present in current process safety regulations; which are the key limitations of the HAZOP study, and finally, which are the criteria to cover the research needs that have been found

Annex I proposes the key tools (tables, figures and checklists “ready-to use”) to be used for conducting HAZOPs in continuous chemical processes. The information layout is structured according to the proposed HAZOP Management System. This information is intended to provide concise and structured documentation to be used as a reference book when conducting HAZOPs.

Annex II is intended to overview the most relevant petroleum refining processes by highlighting key factors to take into account in the point of view of process safety and hazard identification, i.e. HAZOP. In this sense, key health and safety information of specific petroleum refining units is provided as a valuable guidance during brainstorming sessions.

Annex III illustrates the complete set of data collected during the field work of the present research, and also analyzed in Chapter V of the manuscript. Additionally, it depicts a statistical summary of the key variables treated during the analysis.

Finally, the Nomenclature, References, and Abbreviations & Acronyms used and cited during the manuscript have been listed. Additionally, a Glossary of key terms related to the Process Safety field has been illustrated.

“Learning from experience is a lantern on the stern, illuminating the hazards the ship has passed through. It is essential to do so as we may come the same way again. However, we should also have a lantern on the bow, so that we can see the hazards that lie ahead.

HAZOP is a lantern on the bow”

(Trevor A. Kletz)

While subjectivity introduces uncertainty on the overall risk management procedure, and specially when identifying possible hazardous scenarios; it should also be emphasized that human creativity and decision-making are major strengths of safety issues. Knowledge; expertise and freedom for creative thinking are added-values for hazard identification. While expert systems development has undoubtedly helped process analysts to better understand the process facilities nature, and also interactions between modes of failures, causes and consequences; in my opinion, I will always state the necessity of human thoughts for identifying what can go wrong. This is my opinion, and this work, my contribution.

# TABLE OF CONTENTS

# CHAPTER I. EVOLUTION OF PROCESS SAFETY AND LOSS PREVENTION

The following contents pioneer the main research topic; from introducing the process safety concept up to the evidence that more detailed information is required from related regulations. After defining key terms related to process safety and loss prevention, three historical incidents (i.e., Flixborough, 1974; Seveso, 1976; Bhopal, 1984) have been described due to their impact on process safety evolution. Most importantly, after these disasters; public, companies, industries, and governments realized the necessity of improving safety from process facilities that manage highly hazardous materials. As the public began to mistrust the chemical industry, companies and industries worked together to establish procedures, codes and standards for improvement. Meanwhile, governments established regulations aimed at the prevention of catastrophic accidents, and the limitation of their consequences for workers, the public and the environment. Hereafter, a review of regulations (i.e., US, Europe legislation) focused on Hazard Identification has been conducted, highlighting that there is an absence of specific criteria for performing techniques intended to identify what can go wrong. This was the starting point of the research framework.

## I.1. INTRODUCTION

Process Safety is a discipline that focuses on the prevention of fires, explosions, and accidental chemical releases at chemical process facilities. It excludes classic worker health and safety issues involving working surfaces, ladders, protective equipment, etc. (CCPS/AIChE, 1993).

In 1987, Robert M. Solow, an economist at the Massachusetts Institute of Technology, received the Nobel Prize in economics for his work in determining the sources of economic growth. He concluded that the bulk of an economy's growth is the result of technological advances (Crowl & Louvar, 1990). This is especially true in chemical plants that increasingly operate at higher temperatures and pressures, more reactive chemicals, and encompass more complex, sophisticated processes. More complex processes require more complex safety technology. Thus, chemical engineers need a more detailed understanding of the fundamentals of chemical process safety. Today, safety is equal in importance to production and has developed into a scientific discipline that includes many highly technical and complex theories and practices. This term includes hazard identification, technical evaluation, and the design of new engineering features for loss prevention.

Chemical plants contain a large variety of hazards. Firstly, there are the usual mechanical hazards that cause work injuries from tripping, falling, or moving equipment. Secondly, there are chemical hazards. These include fire and explosion hazards, reactivity hazards, and toxic hazards that could lead to an incident, viz., an unusual or unexpected occurrence, which either resulted in, or had the potential to result in:

(1) Serious injury to personnel,

(2) Significant damage to property,

(3) Adverse environmental impact, or

(4) A major interruption of process operations.

Consequently, the process safety discipline is intended to prevent incidents by improving the process technology, upgrading the operating or maintenance procedures or practices, and upgrading the management systems. If incidents happened, engineers had to conduct a thorough incident investigation to determine and analyze the facts that finally caused the consequences. The main aim is to learn lessons by revealing the true underlying root causes.

While benefits from advanced technology have increased, some hazards due to our increased capabilities have presented themselves (hazards evolve at the same rate as technology). Technology has proven that it can bite back in various ways. In the computer software and hardware industry, viruses can destroy our ability to use some of our most powerful modern tools. In the telecommunications industry, equipment malfunctions can interfere with our increasingly complex communications systems. In the chemical processing industry however, the hazards of advanced technology can have catastrophic results. When something goes wrong with our technology during the handling and processing of hazardous chemicals, dramatic effects can result in multiple fatalities or injuries (Walter, 1998).

As key incidents, Flixborough, Seveso, and Bhopal are three synonyms for catastrophe. These names are inextricably linked with images of death and disastrous loss tied to the production of chemicals or oil. An objective review of the world's industrial history reveals a story punctuated with infrequent, yet similarly, tragic incidents (CCPS/AIChE, 2003). These disasters crystallized public opinion and catalyzed the enhancement of further legislation within the United States and Europe related to the chemical producing community becoming more responsible to its employees and citizens living in the chemical surroundings. Thus, governments responded with regulatory measures to prevent or minimize major accidents, but also the chemical process reacted, establishing standards, guidelines, codes, programs, and procedures for improving process safety by sharing experience and knowledge. In this sense, Table I.1[1] summarizes some of the most important industrial organizations which emerged.

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[1] Adapted from CCPS, 1992

**Table I.1.** Most important emerged industrial organizations.

| **AIChE:** American Institute of Chemical Engineers | **ANSI:** American National Standards Institute |
|---|---|
| Center for Chemical Process Safety (CCPS) | Consensus Standards on Various Subjects |
| Design Institute for Emergency Relief Systems (DIERS) | Special Publications and Handbook |
| Design Institute for Physical Property Data (DIPPR) | Technologies and Standards Development |
| Loss Prevention Symposia (Health and Safety Division) | Monthly Newsletter - ANSI Newsletter |
| **API:** American Petroleum Institute | **ASSE:** American Society of Safety Engineers |
| Process Hazards and Process Safety Seminars | Education Courses in System Safety and Accident Prevention |
| Technical Standards and Recommended Practices | Seminars (e.g., Safety Management, Chemical Process Safety) |
| Operator and Maintenance Iteming | Audio-Visual Programs (e.g., Introduction to System Safety) |
| **ASTM:** American Society for Testing and Materials | **CSB:** US Chemical Safety and Hazard Investigation Board |
| Standards Development | Investigation of industrial chemical accidents |
| Standard Technology Iteming Courses | Reports, papers about lessons learned |
| CHETAH™ Program for Estimating Physical Properties | Videotapes with accidents anatomy |
| **IEEE:** Institute of Electrical/Electronic Engineers | **IChemE:** The Institution of Chemical Engineers |
| IEEE Transactions on Reliability Special Issues | Loss Prevention Bulletin |
| Chemical Process Reliability, Safety, and Risk | Training Modules and Information exchange |
| Management Journals and Conference Publications | Conference on Major Accident Prevention |
| **CMA:** Chemical Manufacturers Association | **NFPA:** National Fire Protection Association |
| National Chemical Referral and Informational Center | Consensus Standards Related to Fire and |
| Community Awareness and Emergency Response (CAER) | Explosion Prevention |
| Management Guidelines (e.g., Manager's Guide to QRA) | Fire Safety Seminars |
| Responsible Care | Training Materials |
| **NSC:** National Safety Council | **SRA:** Society for Risk Analysis |
| CAMEO software for emergency response Management | Conferences on Risk Analysis |
| Accident Prevention Manual for Industrial Operations | Journal |

## I.2. FLIXBOROUGH DISASTER

On June 1st, 1974, at about 3:53 p.m., there was an explosion and fire at the Nypro Ltd works near Flixborough, the worst accident in the UK chemical industry. The catastrophe was initiated in section 25A, on a unit that oxidized cyclohexane with air to a mixture of cyclohexanone and cyclohexanol, known as ketone–aldehyde mixture. An accidental release of cyclohexane at approximately 9.5 bar and 155 ºC resulted in a Vapor Cloud Explosion (VCE) which caused 28 fatalities, the near-total destruction of the 24-hectare plant, severe injury to the public, significant damage to many structures in the surrounding countryside (Secretary of State for Employment, 1975), and scattered debris 32 km away (Venart, 2004).

The catastrophe was initiated during start-up while the mostly cyclohexane feedstock, inerted with nitrogen, was under hot recycle through the reactor train, R2521-R2526; when only one-third of full production flow was circulating. A couple of months before the accident, a temporary pipe assembly which was used to bridge the space between reactors R2524 and R2526 due to leakage of R2525, had been removed. The pipe was badly designed and supported, it merely rested on scaffolding. The modification made was thus much more than just a geometric alteration. Significant changes were made to the statics, the dynamics and the flow. First, due to the shape of the bridging pipe and the differences in pipe diameters, there was a coupling which latterly loaded the pipe and the bellows in the vertical direction. Second, the assembly was a mass-spring system with very little support provided by the scaffolding, especially upon vertical thermal expansion of the reactors. Finally, there were the significant discharge and flow modifications (Venart, 2004). Thus, there was an expansion joint at each end and this allowed the pipe to rotate or squirm when the pressure rose above the normal level though still below the set point of the relief valve (Kletz, 2006). Consequently, the pipe ruptured and the resultant vapor cloud found an ignition source, probably a furnace nearby (Kletz, 2001), and exploded. At the time of the incident the wind was blowing from south-southwest 4-7 $m \cdot s^{-1}$. The perceived centre of the explosion, as determined by several investigators (Foley, 1974; Artingstall, 1974; Ten-Yang, 2000) was identified as being at the roadway just in front of the Main Office.

Twenty-eight people were killed on site and 36 people were injured off site. The installation was devastated and there was extensive damage to property off site. In total 1,821 houses, shops and factories were damaged (Venart, 2004).

The Court concluded a single-step failure process occurred, an amount of 40-60 tones of cyclohexane were released, with an explosive effect of 6-16 tons of nitroglycerine. However, recent bibliography (Venart, 2004) reanalyzed the accident, and it suggests that the failure was caused by a complex two-step mechanism that resulted from the initial failure of only one bellow, a release of about 10-15 tones of cyclohexane, and the detonation of the consequent vapor cloud with an explosive effect of some 280 tones of Trinitrotoluene (TNT).

After reading the sequence of events that led to the final explosion, two aspects are easily questionable. First, focusing on incident causes, why was the by-pass was poorly designed and supported? Second, as a consequence, why did the explosion generate such a magnitude of impacts. On one hand, the design of the pipe was poor because there was no qualified mechanical engineer on the plant at the time. The works' engineer had left and his replacement had not yet arrived. Arrangements had been made for a senior engineer from one of the holding companies without experience to take his place. On the other hand, the explosion had those impacts because the leakage and inventories were so large, and also because the cyclohexane conversion per pass was small, thus most of the feed got a free ride and had to be recovered and recycled many times.

Flixborough destroyed the feeling of confidence that we can always keep large quantities of hazardous chemicals under control. It became apparent that we should keep the amounts in our plants as low as reasonably practicable or alternatively use safer materials instead. Inherently, safer design arrived on the chemical industry’s agenda (Kletz, 2001).

## I.3. SEVESO DISASTER[2]

On July 10th, 1976, at about 12:45 a.m., there was a toxic release at the Industrie Chimiche Meda Società (ICMESA) factory, in Northern Italy during the manufacture of 2,4,5-trichlorophenol (TCP). Parts of the small city of Seveso and of some adjacent communities were affected by the aerosol-cloud that escaped during the accident. The principal constituents of this cloud were TCP, other chlorophenols, ethyleneglycol (EG), condensation products of these compounds and the highly toxic 2,3,7,8-Tetrachlorodibenzo-p-dioxin (Cardillo et al., 1984). After the accident, investigations to establish its causes and dynamics were initiated by the competent Italian authorities, as well as by the Givaudan and Roche companies.

Based on the information available at the time of the accident from the pertinent literature and private communications, an exothermal decomposition was only to be expected to start g at 230°C with the chosen operational procedure.

The thermal stability of the reaction mixture had been confirmed many times during the numerous test runs which were carried out in both the Givaudan and Roche laboratories as well as in the plant prior to the start-up of routine manufacture. The last recorded temperature was 158°C, measured at the end of the normal work schedule and completion of the chemical reaction. The accident took place seven and a half hours later, after complete shut-down of the installation. The sequence of events could not, therefore, be related in any way to previous accidents, which had occurred in other plants and which were known from the relevant literature. In all these cases, accidents were initiated through overheating during the chemical synthesis or they were caused by still unknown reasons when different operating conditions were employed (Sambeth, 1983).

After the required hydrolysis step in the process, heating by steam was discontinued and vacuum was terminated by connection of the reactor to the atmosphere (with consequent air inlet in the reactor). Stirring was maintained during 15 minutes, and then all operations were stopped (Ferraiolo, 1979).

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[2] Adapted from Cardillo et al, 1984

At that time, the reaction mixture was about 158°C and the wet part of the reactor wall was at the same temperature as the liquid; but the upper, dry part of the wall was, at least partially, at about 300°C (Theofanous, 1983). In fact, steam at 12 bar (condensation temperature 190°C) was used, but this steam arrived at extreme heats of about 300°C to the upper part of the coil welded to the outside wall of the reactor (Theofanous, 1981). The bursting disk, set at 4 bar, ruptured seven and a half hours after operation was discontinued. According to the literature until 1976, based on n the basis of differential thermal analysis (Langer et al., 1973), chlorophenols and alkali chlorophenates should not show phenomena of instability, according to their nature, below 250-300°C. In this sense, several authors studied the thermal stability of the mixture and its components supposedly present in the reactor (Cardillo & Girelli, 1980, 1981, 1983).

The research of Theophanous, at first theoretical and later experimental, makes it possible to explain what happened in the ICMESA reactor as follows. The accident was caused by an unexpected concentration of a quantity of moderate heat in the upper layer of the unstirred liquid in the reactor. The temperature of this upper layer reached a level at which slow and weak exothermic processes, previously unknown, started.

After about 7 hours these processes contributed to the start (always in the upper layer, at about 230°C) of other and more rapid, exothermic processes, which caused the rupture of the bursting disk. Immediately, after that a large part (if not all) of the mass was affected by these processes.

Both the company and the local government were poorly coordinated, and at least a week passed before it was publicly stated that dioxin had been emitted, and another week passed before evacuation began. All these aspects generated public and government reactions, updating industrial regulations to cover major accidents.

## I.4. FLIXBOROUGH & SEVESO'S EFFECTS

As a result of the Flixborough disaster, the Health & Safety Executive (HSE) set up a committee of experts, the Advisory Committee on Major Hazards (ACMH), to study the control of major industrial hazards and to advise on the best policy to adopt. The ACMH produced three reports, in 1976, 1979 and 1984. The first report proposed a three-part strategy for managing major hazards consisting of the following stages: identification, prevention/control, and mitigation. The first stage was the introduction of the Notification of Installations Handling Hazardous Substances Regulations 1982 (NIHHS). These required notifications to the HSE of any site at which any dangerous substance listed in the regulations was present in quantities above certain thresholds. The purpose was to secure the identification of sites having major hazard potential.

The second stage was to have been Hazard Survey Regulations requiring any occupier handling at least ten times the threshold quantity of an NIHHS substance to carry out, and submit to the HSE, a detailed survey of the hazards associated with the operations and the precautions being taken. This would have been the first part of the prevention/control strategy. However, the UK's plans to introduce regulations to implement the policy were changed when the Commission of the European Communities (CEC) signaled its intention to introduce a Directive for the control of industrial hazards following a series of major accidents in the Community. The UK strategy ever since has been to play a leading role in CEC negotiations with the aim of securing Directives, which correspond as closely as possible to UK ideas. and ideas.

The UK has had a major influence on the CEC's thinking and the strategy of identification, control and mitigation remains the basis for UK and European policy on major industrial hazards (Ron De Cort, 1994).

The problem of major hazards was becoming generally recognized in Europe due to a number of incidents. In 1966 in Feyzin, France, 17 people were killed and 80 injured when an LPG sphere exploded. In 1975, 14 people were killed in Beek, Holland when a release of propylene resulted in a large fire and explosion.

Then, in 1976 in Seveso, Italy, a major environmental disaster caused the contamination of almost 2,000 hectares of land and the deaths of more than 70,000 animals.

The outcome of the CEC negotiations was Directive 82/501/EEC, the so-called "Seveso" Directive. The Directive does not apply to all sites which present an off-site hazard. When the Directive was negotiated a conscious decision was taken to limit its scope in order not to overstretch scarce resources. This was achieved by applying quantity thresholds of dangerous substances to limit the application of certain articles of the Directive. It should be noted therefore that major accidents with off-site consequences could occur at sites which fall outside the scope of the Directive. The Directive was implemented in the UK by the Control of Industrial Major Accident Regulations 1984 (CIMAH). Hereafter, the Seveso Directive has been amended twice. The first amendment – Directive 87/216/EEC – involved the revision of some substance threshold quantities following the 1984 Bhopal. The second amendment – Directive 88/610/EEC – involved greatly increased application to storage premises after the 1986 Sandoz warehouse fire in Switzerland, a disaster which shown the dangers of pollution from stored chemicals. That incident also resulted in an increased awareness of the possibility of damage to the environment and to the trans-boundary effects of major accidents.

The interest of the CEC in the major hazards area has been maintained. A committee of competent authorities meets three or four times a year in Brussels to review experiences in member states. Discussion has centered on the way in which member states have implemented (or have failed to implement) the directives.

Major topics have included the varying criteria by which the adequacy of safety reports has been judged; the extent to which member states have established effective regimes for inspection and enforcement; the extent to which emergency plans have been implemented; reviews of major accidents which have occurred (including ones outside the Community), the lessons learned and adequacy of members states' reporting arrangement; and whether amendments to the Directive would be desirable.

Hereafter, for a number of years the UK pressed for a fundamental review of the Directive. The UK argued that the Directive was badly and confusingly worded making implementation and enforcement difficult, the annexes defining application were excessively long and complex, some of the thresholds had been set at the wrong level, and that, wherever possible, thresholds should be set at levels which produced an equivalence of harm. Finally, the CEC accepted the need for a review but took little action. In the latter part of 1989 the Council of Ministers adopted a French Government proposal that land-use planning controls should be made part of the Directive.

On 9 December 1996, Council Directive 96/82/EC on the control of major-accident hazards, the so-called “Seveso II” Directive, was adopted. Member States had up to two years to enforce the national laws, regulations and administrative provisions to comply with the Directive. From 3 February 1999, the obligations of the Directive have become mandatory for industry, as well as the public authorities of the Member States responsible, for the implementation and enforcement of the Directive. The Seveso II Directive has fully replaced its predecessor. Important changes have been made and new concepts have been introduced into the Seveso II: a revision and extension of the scope, the introduction of new requirements relating to safety management systems, emergency planning and land-use planning and a reinforcement of the provisions on inspections to be carried out by Member States.

In the light of recent industrial accidents - Baia Mare (2000), Enschede (2000), and Toulouse (2001) - and studies on carcinogens and substances dangerous for the environment, the Seveso II Directive 96/82/EC was extended by the Directive 2003/105/EC of the European Parliament and of the Council of 16 December 2003 amending Council Directive 96/82/EC.

The most important extensions of the scope of that Directive are to cover risks arising from storage and processing activities in mining, from pyrotechnic and explosive substances and from the storage of ammonium nitrate and ammonium nitrate-based fertilizers. This Directive is addressed to the Member States.

In UK, the Control of Major Accidents Hazards Regulations 1999 (COMAH) came into force on 1 April 1999 and was amended by the Control of Major Accident Hazards Regulations 2005, regulations which implemented the Seveso II Directive requirements, and replaced the Control CIMAH Regulations 1984.

However, while each Member State developed its own regulations to enforce the Seveso II Directive, the lack of a common approach still remains, generating differences between Member States and causing significantly different impacts on social, technical and financial aspects (Pey et al., 2008).

## I.5. BHOPAL DISASTER

The Bhopal tragedy was a defining moment in the history of the chemical industry. On December 3rd, 1984, at about 12.30 a.m., a runaway reaction within a methyl isocyanate (MIC) storage tank at the Union Carbide India Limited (UCIL) pesticide plant released a toxic gas cloud that killed thousands and injured hundreds of thousands. The immediate cause of the incident was the contamination of the MIC storage tank by water. This triggered a runway reaction. The temperature and pressure within the tank rose. A valve designed to prevent tank over-pressurization opened and discharged tens of tons of unreacted MIC vapor into the atmosphere within a two-hour period (Kletz, 2001). A complex set of interdependent organizational and technological factors played a critical role in the incident. Inadequate safety standards and maintenance procedures at the plant had a direct impact on the magnitude of the release. Table I.2[3] shows safety systems that should have prevented or minimized the release but were either out of order or not in full working order.

The real impact of the Bhopal disaster is the magnitude of its impacts, a fact that entails two questions on the consequences: inventory of MIC, and factory neighborhood distances. On one hand, MIC was an intermediate in the production of carbaryl, an insecticide. While it is a widespread practice to store intermediates, due to it allowing production to continue in one-half of a plant while the other half is shut down, intermediate storage is convenient but not essential, and in any case, it is better to store reduced stocks if hazardous. On the other hand, consequences would have been less serious if a shanty town had not been allowed to grow near the plant (Kletz, 2006).

After Bhopal, the public, the chemical industry and governments realized the necessity to improve process safety and loss prevention. The Public began to mistrust the chemical industry, and companies reacted accordingly by reducing stocks of hazardous intermediates or managing without them, using the intermediates as soon as they were produced, and governments started to elaborate specific regulations.

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[3] Adapted from Joseph et al., 2005

**Table I.2.** Safety systems which should have prevented or minimized Bhopal consequences.

| | |
|---|---|
| **1 Refrigeration system** | A 30-ton Freon based refrigeration system was used to keep MIC cool around 0ºC. It was shut down |
| **2 Gauges** | Gauges measuring temperature and pressure in various parts of the MIC unit were unreliable |
| **3 Temperature alarm** | The alarm on the storage tank failed to signal the increase in temperature |
| **4 Vent gas scrubber** | The MIC gas from the tank vented into the scrubber but the system was not fully operational and allowed untreated MIC gas to be released through the scrubber stacks. Even had it been operative, post-disaster inquiries revealed it was not designed to handle the large quantities of MIC released over the short duration |
| **5 Spare tank** | The storage system consisted of 3 underground storage tanks. One was supposed to be kept empty for emergency situations. However, it was not empty or could not be accessed |
| **6 Flare tower** | It was designed to burn off MIC gas, was turned off, waiting for a replacement of a corroded piece of pipe. The flare also was inadequately designed for its task |
| **7 Water curtain** | A set of water-spray pipes that shoots water about 50 feet high could have been used to knock down or control escaping gases. The water jets were turned on but they could not reach the MIC being released from the scrubber stacks at a height of 100 feet |
| **8 Tank capacity** | The recommended capacity for the MIC tanks was 50%. Tank 610 was 80% full at the incident time |
| **9 Community alarm** | The community toxic gas alarm was activated nearly an hour into the incident. It was turned off after five minutes and then turned back on after nearly another hour |
| **10 Employee Training** | Managers and workers had limited knowledge of the reactive hazards associated with MIC |

### I.5.1. Bhopal's Effects

Less than one year after Bhopal, a new accident at the Union Carbide plant in Institute, West Virginia – a chemical plant similar in design to the Bhopal facility— led to the release of a toxic mixture of methylene chloride and aldicarb oxime, resulting in the hospitalization of 134 people living in the surrounding areas (US EPA, 2000). The Bhopal and Institute accidents ultimately led to a series of changes within the US chemical industry—new management systems, different organizational structures, and more resources would henceforth be devoted to safely managing chemical process hazards.

The first major step taken by the American industry was the formation of the Community Awareness & Emergency Response (CAER) program (Reisch, 2004). The CAER program was designed by the Chemical Manufacturers Association (CMA) to improve emergency response planning in communities near chemical facilities. Both the Bhopal accident and the accident in Institute had highlighted shortcomings in communities' awareness of chemical hazards and the effectiveness of local emergency procedures.

Under CAER, many companies initiated dialogue with key community stakeholders, and worked more closely with communities to coordinate emergency response training with local police, fire-fighters, and other emergency services. CAER also established Community Advisory Panels, comprised of plant neighbors, local leaders, emergency responders, and local educators, to address community questions about chemical companies and their operations (Belke & Dietrich, 2005).

Even before the development of CAER in the US, and before Bhopal itself, chemical manufacturers in Canada had created the 'Responsible Care' program. This began as a set of guiding principles for managing chemical producers' environment, safety, and health obligations (O'Connor, 2004). After Bhopal, the CAER program was incorporated into Responsible Care, and the program later matured into a life-cycle set of chemical hazard management guidelines designed to prevent serious chemical accidents from occurring.

In 1988, US members of the CMA adopted the core Responsible Care guidelines from Canada, and made them mandatory for CMA members in the United States. In addition to CAER, the other Responsible Care codes required participating companies to practice pollution prevention, implement process safety measures, reduce hazards in the distribution, transportation, and storage of chemicals, train employees in health and safety risks, and take responsibility for a chemical product throughout its full life-cycle of manufacturing, safe handling, distribution and sale, recycling, and disposal. The guidelines of the Responsible Care program have evolved since its inception two decades ago – the most notable recent change is the inclusion of a new Security code – but today the program continues to be a corner-stone of safety practice for the US chemical industry.

The Bhopal and Institute accidents also led to legislative and regulatory action in the United States. In 1985, the increasing public concern over chemical hazards led the US Environmental Protection Agency (EPA) to begin its Chemical Emergency Preparedness Program (CEPP) (40 CFR Part 300 & 355, 1987). CEPP was a voluntary program to encourage state and local authorities to identify hazards in their areas and to plan for chemical emergency response actions.

In 1986, Congress adopted many of the elements of CEPP in the Emergency Planning and Community Right-to-Know Act (EPCRA). EPCRA requires US states to create State Emergency Response Commissions (SERCs) and requires local communities to form Local Emergency Planning Committees (LEPCs) to prepare local emergency response plans for chemical accidents. EPCRA also requires facilities to provide LEPCs with information necessary for emergency planning, and to submit annual inventory reports and information about hazardous chemicals at the facility to SERCs, LEPCs and local fire departments. The statute also established the Toxics Release Inventory (TRI), which requires certain facilities to annually report to EPA the quantities of their emissions of toxic chemicals (Public Law 99-499, 1986). The EPCRA data are available to the public and EPA maintains a national database containing the TRI toxic chemical release reports.

As its name suggests, EPCRA promotes hazard information sharing and emergency planning. However, EPCRA does not require facilities to take any actions to prevent chemical accidents from occurring. Instead, EPCRA directed EPA to conduct a review of emergency systems to monitor, detect, and prevent chemical accidents, and to identify gaps in federal regulations. EPA initiated the Accidental Release Information Program (ARIP) to collect information related to chemical accidents and their causes. Serious chemical accidents continued to occur in the US throughout the late 1980s, and in 1990 information from these accidents prompted Congress to incorporate two new regulatory programs into the Clean Air Act (CAA) (Public Law 101-549, 1990). First, section 304 of the CAA Amendments of 1990 required the Occupational Safety and Health Administration (OSHA) to develop chemical accident prevention and emergency response regulations to protect workers at hazardous chemical facilities. OSHA responded by developing the Process Safety Management (PSM) rule (CFR Part 1910, 1992), which places accident prevention and emergency response requirements on facilities having specified hazardous chemicals above certain threshold quantities. The PSM rule went into effect in 1992. Second, section 112(r) of the amended CAA also called for EPA to develop regulations to prevent and respond to chemical facility accidents that could affect the public and environment off-site. In 1996, EPA promulgated the Risk Management Program regulations (CFR Part 68, 1996).

The Risk Management Program is similar to OSHA's PSM rule, covering many of the same toxic and flammable chemical substances, and requiring a similar set of accident prevention requirements. These requirements include using written operating procedures, providing employee-training, ensuring on-going mechanical integrity of equipment, identifying, analyzing and controlling process hazards, and the like.

Although the accident prevention program requirements of the OSHA PSM rule and EPA RMP are similar, the EPA program contains a number of additional requirements that go beyond the PSM standard. Facilities must prepare a history of accidental releases occurring over the past 5 years, perform an analytical estimate of the consequences of hypothetical release scenarios—'off-site consequence analysis (OCA),' and submit a summary report, called a Risk Management Plan (RMP), to the EPA.

The CAA requires EPA to make all RMPs available to both state and local governments as well as the public, although it also restricts access to the off-site consequence analysis portion of the plan. Facilities must update their RMP at least every 5 years, or more frequently when certain changes occur. EPA RMP went into effect in 1999.

## I.6. REGULATORY REQUIREMENTS

The main regulatory requirements affecting the chemical process industry are that all process facilities adhering to regulations must notify their activities and establish a report, a management system, and an internal emergency plan addressing safety issues. There are also obligations on public authorities relating to external emergency plans, land-use planning, public information on safety measures, and accident reporting and inspections, according to each specific situation. For comparison, Table I.3[4] shows the elements that constitute the management systems of all cited Regulations. In this sense, all of them address hazard identification as a required element of the management system, the so-called Process Hazard Analysis (PHA). Hereafter, the following contents are intended to analyze specific regulatory requirements for hazard identification (elements highlighted in bold in Table I.3).

### I.6.1. Seveso Directive

Analyzing the Seveso II Directive contents, there are three statements which address hazard identification: (1) Article 9, (2) Annex II and, (3) Annex III, principles referred to in article 7 and information referred to in article 9 on the management system and the organization of the establishment with a view to the prevention of major accidents. The following contents show most of the essential regulatory requirements related to hazard identification:

- Article 9 (Safety Report), paragraphs 1(a), 1(b), and 2, respectively:

"*Demonstrating that a major-accident prevention policy and a safety management system for implementing it have been put into effect in accordance with the information set out in Annex III*".

"*Demonstrating that major-accident hazards have been identified and that the necessary measures have been taken to prevent such accidents and to limit their consequences for man and the environment*".

"*The safety report shall contain at least the data and information listed in Annex II*".

---

[4] Program 1 only needs to document a worst-case release and coordinate emergency response activities

**Table I.3.** Elements that constitute the management systems of all cited Regulations.

| **OSHA PSM Rule** | **SEVESO SMS** | **EPA RMP (Program 2)** | **EPA RMP (Program 3)** |
|---|---|---|---|
| Employee Participation | Organization and personnel | Safety Information | Process Safety Information |
| Process Safety Information | **Hazard identification and evaluation** | **Hazard Review** | **Process Hazard Analysis** |
| **Process Hazard Analysis** | Operational control | Operating Procedures | Standard Operating Procedures |
| Operating Procedures | Management of change | Training | Training |
| Training | Planning for emergencies | Maintenance | Mechanical Integrity |
| Subcontractor Safety | Monitoring performance | Compliance Audits | Compliance Audits |
| Pre-Startup Safety Review | Audit and review | Incident Investigations | Incident Investigations |
| Mechanical Integrity | | | Management Of Change |
| Non-routine Work Authorizations | | | Pre-Startup Reviews |
| Management of Change | | | Contractors |
| Incident Investigation | | | Employee Participation |
| Emergency Planning and Response | | | Hot Work Permits |
| Compliance Audit | | | |
| Trade Secrets | | | |

- Annex II (“Identification and accidental risks analysis and prevention methods”), paragraphs A, B, and C, respectively:

“*Detailed description of the possible major-accident scenarios and their probability or the conditions under which they occur including a summary of the events which may play a role in triggering each of these scenarios, the causes being internal or external to the installation*”.

“*Assessment of the extent and severity of the consequences of identified major accidents*”.

“*Description of technical parameters and equipment used for the safety of installations*”.

- Annex III (Safety Management Systems), paragraph c(ii):

“*Identification and evaluation of major hazards – Adoption and implementation of procedures for systematically identifying major hazards arising from normal and abnormal operations and the assessment of their likelihood and severity.*

### I.6.2. OSHA PSM Rule

Specific PHA Regulatory Requirements are shown in Table I.4

### I.6.3. EPA RMP Rule

EPA RMP defines three Program levels based on the processes relative potential for public impact and the level of effort needed to prevent accidents. For each Program level, the rule defines requirements that reflect the level of risk and effort associated with the processes at that level. The essential information about these programs is summarized as follows:

**Table I.4.** Specific PHA Regulatory Requirements (CFR Part 1910, 1992).

| | |
|---|---|
| **Employee Participation** | |
| **c(1)** | Employers shall develop a written plan of action |
| **c(2)** | Employers shall consult with employees and their representatives on the conduct and development of PHAs and on the development of the other elements of PSM Rule |
| **c(3)** | Employers shall provide to employees and their representatives access to PHAs and to all other information required to be developed under the PSM Rule |
| **Process Safety Information** | |
| **d(1)** | Information pertaining to the hazards of the highly hazardous chemicals in the process, e.g., Material Safety Data Sheets (MSDS) |
| **d(2)** | Information pertaining to the technology of the process, e.g., process chemistry, Process Flow Diagrams (PFDs) |
| **d(3)(i)** | Information pertaining to the equipment in the process, e.g., Piping and Instrumentation Diagrams (P&IDs) |
| **d(3)(ii)** | The employer shall document that equipment complies with recognized and generally accepted good engineering practices |
| **d(3)(iii)** | For existing equipment designed and constructed in accordance with codes, standards, or practices that are no longer in general use, the employer shall determine and document that the equipment is designed, maintained, inspected, tested, and operating in a safe manner |
| **Process Hazard Analysis** | |
| **e(1)** | The employer shall perform an initial PHA (hazard evaluation) on processes covered by PSM Rule. The PHA shall be appropriate to the complexity of the process and shall identify, evaluate, and control the hazards involved in the process. Employers shall determine and document the priority order for conducting PHAs based on a rationale which includes such considerations as extent of the process hazards, number of potentially affected employees, age of the process, and operating history of the process. The PHA shall be completed prior to process startup |
| **e(2)** | The employer shall use one or more of the following methodologies that are appropriate to determine and evaluate the hazards of the process being analyzed: What-if, Checklist, What-if/Checklist, HAZard & Operability study (HAZOP), Failure Modes and Effects Analysis (FMEA), or an appropriate equivalent methodology |
| **e(3)** | The PHA shall address: The hazards of the process; The identification of any previous incident which had a likely potential for catastrophic consequences in the workplace; Engineering and administrative controls applicable to the hazards and their interrelationships; Consequences of failure of engineering and administrative controls; Facility sitting; Human factors; and, A qualitative evaluation of a range of the possible safety and health effects of failure of controls on employees in the workplace |
| **e(4)** | The PHA shall be performed by a team with expertise in engineering and process operations, and the team shall include at least one employee who has experience and specific knowledge to the process being evaluated. Also, one member of the team must be knowledgeable in the specific PHA being used |
| **e(5)** | The employer shall establish a system to promptly address the team’s findings and recommendations; assure that the recommendations are resolved in a timely manner and that the resolution is documented; document what actions are to be taken; complete actions as soon as possible; develop a written schedule of when these actions are to be completed; communicate the actions to operating, maintenance and other employees whose work assignments are in the process and who may be affected by the recommendations or actions |
| **e(6)** | At least every five (5) years after the completion of the initial PHA, the PHA shall be updated and revalidated by a team meeting the requirements in paragraph (e)(4) of this section, to assure that the PHA is consistent with the current process |
| **e(7)** | Employers shall retain PHA and updates or revalidations for each process covered by this section, as well as the documented resolution of recommendations described in paragraph (e)(5) of this section for the life of the process |

**Program 2:** processes not eligible for Program 1 or subject to Program 3 are placed in Program 2, which imposes stream-lined prevention program requirements, as well as additional hazard assessment, management, and emergency response requirements (EPA, 2004). For each Program 2 process, all the elements of the Program 2 must be implemented, which entails a hazard review. The EPA has stream-lined the PHA requirement of OSHA's PSM standard to create a requirement that will detect process hazards at the simpler processes in Program 2. Specific PHA regulatory requirements related to Program 2 are the following:

"*Hazard Review shall address opportunities for equipment malfunction or human error that could cause a release; safeguards that will control the hazards or prevent the malfunction or error; steps to detect or monitor releases*", and …"*check the equipment to make sure that it is fabricated, installed, and operated properly*".

"*Update the review at least once every five years or whenever there is a major change in the process*", and …"*If major change, resolve problems identified in the new review before startup the changed process*".

**Program 3:** processes not eligible for Program 1, and either subject to OSHA's PSM under federal or state OSHA programs or classified in one of ten specified North American Industrial Classification System (NAICS) codes, are placed in Program 3, which imposes OSHA's PSM as the prevention program as well as additional hazard assessment, management, and emergency response requirements (EPA, 2004). For each Program 3 process, all the elements of the Program 3 must be implemented, which entails a PHA. These specific PHA regulatory requirements are equivalent to those established by PSM Rule, but off-site impacts must be additionally addressed.

## I.7. SPECIFIC CONCLUSIONS

Regulations clearly highlight hazard identification as a key element of any safety management system, and provide technical tools for achieving this goal by using PHA techniques (e.g., What-if, HAZard and OPerability study - HAZOP) during the entire process life-time. However, there is a lack of information on how to treat most of the factors that they address (e.g., facility siting, human factors). The following contents are clarifications of regulations statements related to PHA:

- Employees with a working understanding of chemical processes should serve as informational resources in the development of chemical process accident prevention plans, the performance of PHAs, and the conduct of incident investigations and audits. They are expected to use judgment, on a case-by-case basis, to determine an appropriate methodology for the PHA for each covered process.
- Employers are expected to identify all credible causes and consequences for hazard scenarios, also including causes of previous incidents in the PHA worksheet, and near misses. Additionally, they are expected to identify all safeguards for the process and also their failures as causes. Additionally, they are also expected to address facility siting issues (e.g., spatial relationship between the hazards and the plant personnel); and human failures.
- The PHAs will address off-site impacts when conducted under EPA’s rule, and should identify all failure scenarios that could lead to significant exposure of workers, the public, or the environment.

While regulations state a complete set of factors to be addressed for hazard identification, there is an absence of criteria for conducting PHAs, weaknesses highlighted into regulation contents by using terms which entail subjectivity (e.g., “employers are expected to use judgment”; “PHA leader has to be trained”). Therefore while the chemical industry recognizes which factors have to be addressed, what tools and when these have to be performed, it is not acquainted with how to proceed when identifying potential hazardous scenarios, nor with defining and preparing PHAs up to their being reported.

# CHAPTER II. HAZARD IDENTIFICATION AS THE FOUNDATION OF PROCESS SAFETY

Process Hazard Analyses are mandatory for process facilities that manage hazardous materials, and they are techniques focused on analyzing equipment, instrumentation, utilities, human factors and external events that might impact on the process with the aim of identifying what can go wrong; thus, identifying potential systems interactions and failures that could result in an accident. They are the foundation of all risk and safety analysis and should ensure complete risk evaluations and adequate protection devices. While hazard identification may be the most important stage for risk management, it depends on subjectivity issues (e.g., human observation, good judgment and intuition, creativity, expertise, knowledge) which introduce bias. The following contents introduce the risk management system required to analyze risk from the chemical  process facilities, and then overview the PHA techniques commonly used for hazard identification. At the end, the readers should perceive evidence of two inherent risk analysis aspects: subjectivity and uncertainty.

## II.1. RISK MANAGEMENT

Managing industrial risks requires the systematic application of management policies, procedures, and practices to the tasks of analyzing, assessing, and controlling risk in order to protect employees, the general public, and the environment, as well as company assets. Therefore, several management activities should be addressed for risk analysis, the process of gathering data and synthesizing information in order to develop an understanding of the risk of a particular enterprise. Chemical process facilities have many possible applications for risk analysis, but actual interests are focused on knowing how to allocate resources to minimize the chance of a catastrophic accident by assessing the risk of episodic events. With the understanding from such risk analyses, it is possible to evaluate and select risk management options. Figure II.1 shows the stages to be performed for risk management, and each stage is briefly introduced by highlighting specific tools intended to answer the following questions on the spot:

- What can go wrong?
- How likely is it?
- What are the impacts?
- Is the risk tolerable?

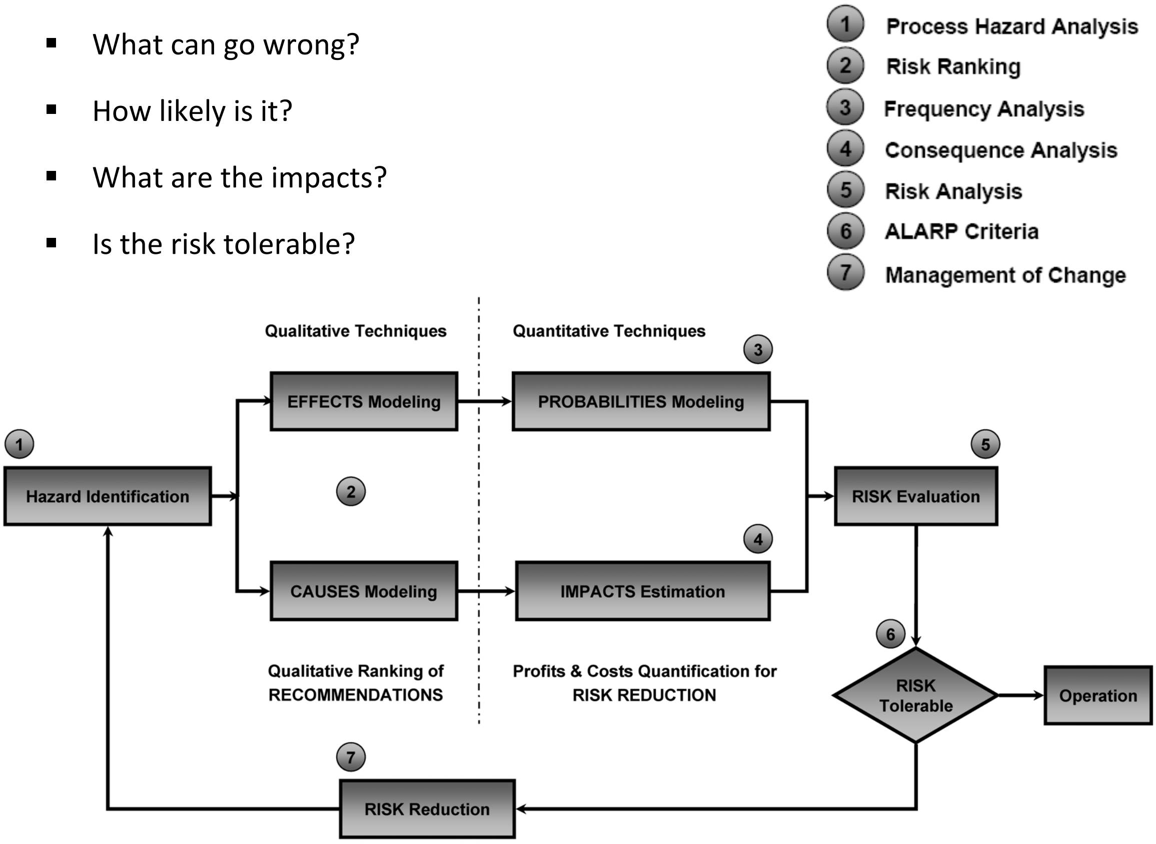

**Figure II.1.** Stages to be performed for risk management.

### II.1.1. Hazard Identification and Evaluation

The purpose of this stage is to identify what can go wrong and lead to hazardous scenarios (the sources of risk). The nature of the hazards depends on the circumstances. Industrial plant hazards might include failures of equipment, human error, and the use of equipment outside its design specification, whereas in the formation of high-level policy they may be the potential causes of impact on society or environmental problems. In any case, the aim of the activity is to maximize the identification of hazards. There are many PHAs for hazard identification, and all depend on human observation, judgment, and creativity. As well as being the key attributes of an effective study, they also introduce subjectivity, and therefore, the potential for bias (Redmill, 2002a). For this reason, hazard identification requires the greatest involvement of plant personnel. For an existing process, only plant personnel know the status of process equipment and the current operating and maintenance practices. Excluding those personnel from the hazard identification step increases the chance of over-looking important potential hazards (Arendt & Lorenzo, 2000).

Endeavors to perform the hazard identification depend on the size of the problem and the specific techniques used. For example, while in some well-understood and simple systems, the use of brainstorming, what-if analysis, or checklist may be adequate; more laborious, time-consuming, and more-structured methods (e.g., HAZOP, Failure Modes and Effects Analysis - FMEA) should be conducted for complex systems (e.g., petroleum-refining industry). Likewise, there is greater confidence in the exhaustiveness of HAZOP and FMEA techniques due to their rigorous approach which helps to ensure a thoroughness which guides the freedom and creative thinking of the experts involved. However, no technique can guarantee that all hazards or potential accidents have been identified.

Risk Ranking is a tool to provide a qualitative evaluation of a range of the possible safety and health effects of failure of controls with the purpose of assisting the PHA team in their decisions for prioritizing the planning for the control of the hazards they have identified. Risk ranking will be accomplished by qualitatively estimating severities and likelihoods; and combining them into risk estimates: risk matrix, grid or table.

Even so, while it is advisable to establish corporate, or at least, site-wide risk ranking schemes with the aim of enforcing consistency to all PHA results, there are no accepted industry standards for risk ranking schemes. In the end, what it is essential for risk ranking is the presence of consistency on assigning values throughout the entire study, a fact that will be supported by expertise.

### II.1.2. Frequency Analysis

Frequency analysis involves estimating the likelihood of occurrence of hazardous scenarios identified via PHA. The estimation can be done through direct comparison with experience or extrapolation from historical accident data. While this method may be of great assistance in determining accident frequencies, most scenarios identified may be inimitable, meaning that frequencies must be synthesized using frequency estimation methods and models. Hereafter, synthesizing the frequencies involves determining combinations of failures and circumstances that can cause the scenarios of interest, developing basic failure data from available industry sources (CCPS, 1989; Denson et al., 1991; IEEE, 1984; INPO, 1983; NCSR, 1984; OREDA, 1997) or throughout process facilities that have considerable equipment operating experience in maintenance files, operating logs, and the minds of operators and maintenance personnel. Additionally, appropriate probabilistic mathematics to determine can be used to determine the frequency estimates, an approach supported by applying specific methodologies. Examples of these techniques are the Event Tree Analysis (ETA), which is used to define all scenarios that could result from a particular initiating event, and the Fault Tree Analysis (FTA), technique used to estimate the frequency or probability of individual events (Haasl et al., 1981). However, results of frequency analysis are estimations featured by uncertainties from a variety of causes. A sensitivity analysis of the models, assumptions, and/or data should provide an idea of the true uncertainty, but for most decisions, parties will have to rely on the best estimates, compensating for any uncertainty with good judgment and intuition.

### II.1.3. Consequence Analysis

Consequences are usually stated in an expected number of injuries or casualties or, in some cases, exposure to certain levels of energy or concentrations of substances. Consequence analysis results are estimates of the statistically-expected exposure of the target population to the hazard of interest and the safety/health effects related to that level of exposure. These estimates customarily use average meteorological conditions and population distribution, and may include mitigating factors, such as evacuation and sheltering. Therefore, considerable empirical database exists on the effects of fires and explosions on structures and equipment.

Meanwhile, sophisticated models and correlations have been developed for consequence analysis (e.g., CFAST, DEGADIS, Breeze, EFFECTS, SuperChems), providing valuable tools for characterizing the source of the release of material or energy associated with the hazard being analyzed, estimating the transport of the material and/or the propagation of the energy in the environment to a target of interest, identifying the effects of the propagation of the energy or material on the target of interest, and finally, quantifying the health, safety, environmental, or economic impacts on the target of interest. But again (e.g., frequency analysis), the consequence estimates can have very large uncertainties. Estimates that vary by orders of magnitude can result from (1) basic uncertainties in chemical/physical properties, (2) differences in average vs. time-dependent meteorological conditions, and/or (3) uncertainties in the release, dispersion, and effects models.

The level of effort required for a consequence analysis will be a function of the number of different accident scenarios being analyzed; the number of effects the accident sequence produces; and the detail with which the release, dispersion, and effects on the targets of interest are estimated. A survey of models available can be found in (Borysiewicz et al., 2006)

### II.1.4. Risk Analysis

Many definitions for the term “risk” exist (see Glossary for several terms related to risk concept); but in the context of assessment of the hazards posed by chemical process facilities, it refers to a function of the likelihood of occurrence (frequency analysis), of possible undesired events (hazard identification) and the magnitude of their associated consequences (consequence analysis) based on engineering evaluation and mathematical techniques. Its estimation will be used to take decisions, usually supported by using graphical devices (e.g., F-N curve, risk profile, risk contour) to show risk and the relationship between frequencies and consequences. In any case, taking into account most of the factors that contribute to the total risk of a process facility, the risk values will highlight the major sources of risk and will give the decision-maker a clear target(s) for re-design or other loss prevention efforts. Techniques to achieve these goals are, for example, the QRA. Valuable information can be found in (Arendt & Lorenzo, 2000; Borysiewicz et al., 2006). Results from the estimated risk will be used to make decisions for reaching risk levels that are “As Low As Reasonably Practicable” (ALARP), also defined as the risk level that is tolerable to the organization.

### II.1.5. ALARP Criteria

A risk is ALARP when it has been demonstrated that the cost of any further risk reduction, where the cost includes the loss of defense capability as well as financial or other resource costs, is grossly disproportionate to the benefit obtained from that risk reduction. The ALARP principle was not formally defined in legislation, but the term has acquired meaning through many interpretations by the courts. In determining what is reasonably practicable, consideration must be given to the benefits of the activity and to the social and economic factors involved (Skelton, 1997). The ALARP principle leads to the classification of risk into three regions according to Figure II.2[5]: (1) a level above which risk is not tolerable (2) a level below which the risk is negligible; (3) a region between mentioned levels, thus being necessary to prove that everything has been done to reduce the risk to as low a level as reasonably practicable.

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[5] Source: H&SE, 1992

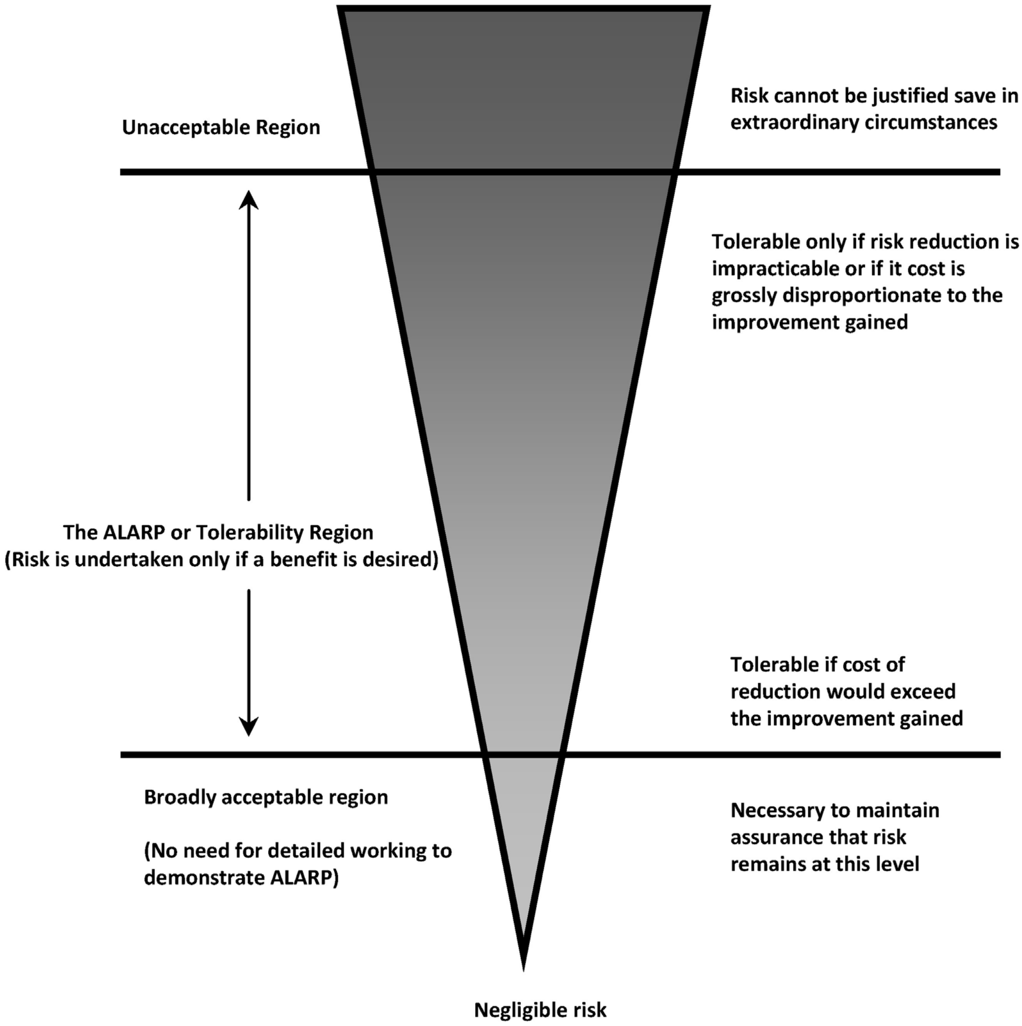

**Figure II.2** “As Low As Reasonably Practicable” (ALARP) criteria.

### II.1.6. Management Of Change

Where the risk from the system is assessed not to be broadly acceptable and ALARP or tolerable and ALARP, as defined by the Tolerability Criteria, it will be necessary to implement a combination of prevention, control and/or mitigation strategies for risk reduction, enabling risk acceptance to be met by tolerability criteria. In this sense, a management of changes is required to identify and review prior to their implementation, and the impact of design, operational, and procedural changes on process safety should be addressed and managed. Here again, a PHA will be conducted for ensuring that hazards are reduced, and ensure that no new hazardous scenarios are being introduced.

After over-viewing the step-by-step risk management program, it is important to highlight the following aspects:

The subjective nature of qualitative results from hazard identification may cause a lack of confidence in some parties using them. These people believe that if quantitative methods are applied to express the significance of a potential scenario, then the limitation of subjectivity will simply vanish. However, focusing on the inherent uncertainty of numerical precision (i.e., frequency analysis, consequence analysis, risk analysis) it is not difficult to confirm the following aspects:

(1) Associated uncertainty with data to be used for risk estimation

(2) A great deal of judgment that influenced the selection of accident models

These thoughts should encourage third parties to have confidence in the PHA team, which is intended to probably conduct the most difficult and critical stage of the risk management decision-making procedure. What is clear, without any judgment or uncertainty, is that if a hazardous scenario is over-looked when carrying out PHAs, this will not be analyzed, and the effectiveness of risk decisions will fall down, instead of using the most sophisticated models and input data for treating the identified ones.

Likewise, the results of a risk analysis depend on the techniques employed, the ways in which they are used, and the consistency with which they are used with respect to each other, all of these factors being subject to human discretion (Redmill, 2002b).

## II.2. PROCESS HAZARD ANALYSIS

Identifying hazards is fundamental for ensuring the safe design and operation of a system in process plants and other facilities. Several techniques are available to identify hazardous situations, all of which require their rigorous, thorough, and systematic application by a multi-disciplinary team of experts. Success rests upon first identifying and subsequently analyzing possible scenarios that can cause accidents with different degrees of severity. Without a structured identification system, hazards can be overlooked, thus entailing incomplete risk-evaluations and potential loss. There is a plethora of references that list PHAs. However, none of these are comprehensive, and many only provide a brief listing of methodologies. In this sense, the most-valued publications reviewing PHAs include a report by the U.K Health and Safety Laboratory (Gould et al., 2005), and two books (Crawley & Brian, 2003; CCPS, 1992) that discuss the purposes, execution methodologies, advantages, and limitations of the most often-used PHA techniques.

PHAs are fundamental for the assessment of the consequences of incidents, for the assessment of the risks involved and for the selection of the most appropriate preventive and protective systems (Crawley & Brian, 2003). Additionally, a PHA can also highlight gaps in the management systems of a process safety program, thus it can be used to investigate the probable causes of an incident that has occurred, as part of a facility's management of change program, and to identify critical safety equipment for special maintenance, testing, or inspection as part of a facility's mechanical integrity program (CCPS, 1992). The first systematic technique of hazard identification to be used within process industries was the HAZOP, formally published by Lawley in 1974, and which is still used extensively today. Since then, a number of other techniques have been developed, some to address specific problems, others to provide more rapid assessments. A total of 40 techniques have been reviewed (Gould et al., 2005). Thus, the broad range of techniques available can make it difficult for a manager or a safety specialist to decide which is the most appropriate and effective technique to use in a particular situation.

The present research is not intended to provide tools for selecting the appropriate PHA technique for a specific process and for precise scopes, purposes and objectives. However, the present section highlights key commitments which should be taken into account when hazard identification has to be performed, such as factors that affect all PHA techniques. For this reason, the following contents summarize essential information about PHA features, summarize PHAs cited in regulations and introduce the specific research topic, the HAZOP study, methodology which will be fully-analyzed. Meanwhile, additional information related to PHA can be found in (Kletz, 1993, 1998, 2001; Lees, 1996; Wells, 1996, and Frank & Whittle, 2001).

The appropriate PHA technique will be chosen according to the following factors: process size and complexity, project life-time, expected impacts of potential hazardous scenarios, and scope, purpose and objectives of the study. Once the methodology has been selected, a step-by-step procedure has to be performed for ensuring that the study has been completely (1) defined and prepared, (2) organized, and (3) executed and documented. The following contents show the minimum and essential steps to perform PHAs. Detailed information is shown in (CCPS, 1992; Crawley & Brian, 2003; Gould et al., 2005).

### II.2.1. PHA Definition and Preparation

The first phase requires to not only explicitly state the purpose, scope, and objectives of the study, but also to appoint a team leader and select an expert team. Hereafter, the preparation of the study will be addressed. The success of all subsequent efforts depends upon this phase.

The responsible party that requests the PHA must clearly define the PHA scope (e.g., physical boundaries of the system, modes of operation to be included), purposes (e.g., compliance with regulations, meeting company policy requirements) and objectives. The appropriate objectives for a PHA depend upon several factors, including what phase of its life-time the project (see Table II.1[6]) is at when the hazard evaluation is performed.

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[6] Adapted from CCPS, 1992

As a project evolves, the types of hazardous situations investigated change from general questions about basic process chemistry to more detailed questions about equipment and procedures. Thus, the required information and the team knowledge also change. After PHA definition, two commitments have to be ensured for its preparation: assembly of process information required for hazard identification, and appointment of the required team (i.e., team leader, and expert team) for ensuring specific knowledge.

**Table II.1.** PHA interests according to the project lifetime.

| **Research and Development** |
|---|
| Identify chemical interactions that could cause runaway reactions, fires, explosions, or toxic gas releases |
| Identify process safety data needs |
| **Conceptual Design** |
| Identify opportunities for inherent safety (see glossary) |
| Compare the hazards of potential sites |
| **Pilot Plant** |
| Identify ways for toxic gas to be released to the environment |
| Identify ways to deactivate the catalyst |
| Identify potentially hazardous operator interfaces |
| Identify ways to minimize hazardous wastes |
| **Detailed Engineering** |
| Identify ways for a flammable mixture to form inside process equipment |
| Identify how a reportable spill might occur |
| Identify which process control malfunctions will cause runaway reactions |
| Identify ways to reduce hazardous material inventories |
| Identify safety-critical equipment that must be regularly tested, inspected, or maintained |
| **Construction and Start-Up** |
| Identify error-likely situations in the start-up and operating procedures |
| Verify that all issues from previous PHAs were resolved satisfactorily and that no new issues were introduced |
| Identify hazards that adjacent units may create for construction and maintenance workers |
| Identify hazards associated with the vessel-cleaning procedure |
| Identify any discrepancies between the as-built equipment and the design drawings |
| **Routine Operation** |
| Identify employee hazards associated with the operating procedures |
| Identify ways an overpressure transient might occur |
| Identify hazards associated with out-of-service equipment |
| **Process Modification or Plant Expansion** |
| Identify whether changing the feedstock composition will create any new hazards or worsen any existing ones |
| Identify hazards associated with new equipment |
| **Decommissioning** |
| Identify how demolition work might affect adjacent units |
| Identify any fire, explosion, or toxic hazards associated with the residues left in the unit after shutdown |

On one hand, the management party will assemble the required information ensuring it is up-to-date, with the exception of technology information that can be created in conjunction with the PHA (e.g., concept stage). Information (see on: le II.2[7]) is based on:

(1) Process chemicals,

(2) Technology and

(3) Equipment

Firstly, the information about hazardous materials should be comprehensive enough for an accurate assessment of any potential hazardous scenario which it could lead to (i.e., fire and explosion characteristics, reactivity hazards, safety and health hazards to the public, and corrosion and erosion effects on process equipment and monitoring tools). Secondly, the information about process technology should show major equipment, main flow streams including valves, and inter-connecting process flow lines, flow rates, stream composition, temperatures, and pressures. Additionally, the points of pressure, level and temperature control. All this information is contained in the Process Flow Diagrams (PFDs). Lastly, the information about process equipment should be based on construction materials, pump capacities, pressure heads, compressor horsepower, and vessel design pressures and temperatures. Major components of control loops are usually shown along with key utilities. Piping and Instrumentation Diagrams (P&IDs), which are required under process equipment information, are appropriate to show some of these details. Finally, all data being used in a PHA must be inspected to ensure they are appropriate, complete and accurate.

On the other hand, the team make-up is an essential element of a successful PHA. It relies on the principle that a team of people working in a brainstorming session will more thoroughly review the process than would be accomplished by each person working individually. Teams can vary in size and in the operational background, but they must have expertise in engineering and process operations, and understand the method being used.

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[7] Adapted from CCPS, 1992

The level and types of skills that personnel must have to participate in PHAs depend on several factors, including the type of process or operation analyzed, the technique selected, and the objective of the analysis. But what is clear, is that one member of the team must be fully-knowledgeable about the implementation of the PHA method (i.e., the team leader) for its management (e.g., preparation for the study, ensuring participants understand the process and their roles, guiding team members through the review, managing the team, supervising the recording of the meetings, ensure the PHA reports are complete and accurate). Hereafter, the ideal PHA team usually consists of five to seven people (e.g., team leader, process engineer, chemist, safety engineer)[8]:

- If too large, the group approach fails because too many people are trying to communicate with one another and are inhibited from working closely.
- If the group is too small, it may lack the breadth of knowledge needed to help assure completeness and the creativity generated by multiple interactions.

Therefore, the team leader must be able to meld them into a cohesive working unit to ensure optimum effectiveness (Frank et al., 1993). The use of a team approach is generally recognized to enhance the productivity and improve the resultant quality of PHAs, a fact that highlights that team member selection is at least as important as technique selection in the success of the analysis. There are many references related to PHA team composition and management (CCPS, 1992, Frank et al., 1993, Dowell III, 1994).

### II.2.2. PHA Organization

Both management party and team leader should set up a meeting schedule that is realistic but as condensed as possible in order to provide a concentrated, focused analysis, and also ensure the full participation of selected team members. Planning the study sequence usually includes the initial selection of study nodes or systems/subsystems, viz., selected process sections to be independently analyzed.

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[8] Titles of job positions may vary with facilities and companies

**Table II.2.** Technology information that can be created in conjunction with the PHA.

Chemical reaction equations and stoichiometry for primary and important secondary or side reactions
Type and nature of catalysts used
Reactive chemical data on all streams, including in-process chemicals
Kinetic data for important process reactions (e.g., order, rate constants, approach to equilibrium)
Kinetic data for undesirable reactions, such as decompositions and auto-polymerizations
Process limits stated (e.g., pressure), along with a description of the consequences of operating beyond these limits
Process Flow Diagrams (PFDs) and a description of the process steps or unit operations involved
Design energy and mass balances
Major material inventories
Description of general control philosophy (i.e., primary control variables and the reasons for their selection)
Special design considerations that are required because of the unique hazards/properties of the chemicals involved
Safety, health, and environmental data for raw materials, intermediates, products, by-products, and wastes
Regulatory limits and/or permit limits
Applicable codes and standards
Plot plans
Vendor drawings and operation and maintenance manuals
Computer control system hardware and software design
Operating procedures (with critical operating parameters)
Instrument loop drawings and logic diagrams
Emergency response plan and procedures
Valve and instrumentation data sheets
Control system and alarm description
Area electrical classification drawings
Building and equipment layouts
Electrical classifications of equipment
Mechanical equipment data sheets
Equipment catalogs
Piping specifications
Utility specifications
Test and inspection reports
Piping and Instrumentation Drawings (P&IDs)
Maintenance procedures
Relief system design basis
Ventilation system design basis
Safety system(s) design basis
Fire protection system(s) design basis
Incident reports
Meteorological data
Population distribution data
Site hydrology data
Previous safety studies
Internal standards and checklists
Corporate safety policies
Relevant industry experience

This division may be made based on the area e basis of area within the facility, type of process, stage in the operation, or some other criterion; and discussed with the expert team before starting study sessions.

The team leader must devote additional time outside team meetings for meeting preparation and documentation. The manpower required to conduct a PHA depends on many factors, including the review method selected, the training and experience of the review team, the extent and complexity of the process, its instrumentation and controls, and whether the process is a procedure-oriented operation (e.g., batch reaction) or a continuous operation (e.g., petroleum refining).

Additionally, because the team may assess the likelihood of causes and the severity of consequences of hazard scenarios identified (Hazard Evaluation), the team leader will define levels and definitions established for severity, likelihood and risk prior to starting sessions (criteria agreed upon by management). Risk ranking allows prioritizing the scenarios to more effectively address the recommendations that may arise.

### II.2.3. PHA Execution and Documentation

A PHA team requires a number of hours to complete a study for a typical process. The team will therefore usually hold several meetings, or working sessions, spread over several days to perform the study. During each session, the expert team records their work on a worksheet. The main objective during PHA sessions is to identify process hazards, inherent chemical or physical characteristics with the energy potential for damaging people, property, and/or environmental. Therefore, the identification of these scenarios requires being aware of the whole sequence of events that define them.

The scenario starts with an initiating event (i.e., equipment failure, human error, external event) that could lead to process deviations (departures from normal operating conditions). Hereafter, if the deviation proceeds uncorrected, loss of control could lead to an accident event. Various protection systems (e.g., alarms, interlocks, emergency relief systems) may be employed to keep the accident event from occurring.

The identification of the complete scenario sequence needs to address the following elements: (1) Identification of process hazards; (2) review of previous incidents; (3) analyze engineering and administrative controls and consequences of control failures; (4) consider facility siting; (5) consider human factors; and (6) evaluate the effects of incidents on the public. After identifying a scenario, the team should determine whether the design and/or operating changes are needed to further protection, These judgments are usually based on qualitative risk evaluation (e.g., risk ranking), and they allow the management to prioritize the immediate efforts of corrective actions (i.e., PHA results) derived from the study. These could alert the management to potential problems that require action, suggest alternatives for safety improvements, or may recommend a specific corrective action if the problem is simple and the team is unanimously in agreement. The proposed action items are presented to the management for review and evaluation, and for determination of what, if any, corrective actions should be taken to eliminate hazards or reduce risks.

On the other hand, recording the results is vital to the study. It is impossible to record manually all that is said, yet it is important to document what the team reviews and the background of any recommendations made. It is also important that the documentation allow for, and facilitate, following up any action items and information needs. The basic documentation produced to facilitate these needs includes a PHA worksheet, some form of action items report, and a final study report. These commitments are easily achievable by using one of the PHA software packages available on the market (PMRC, 2008).

Finally, the PHA report, as a first draft, should be circulated to the team members by providing a cut-off date for comments. This version has to include PHA worksheets, and also how the study was conducted, information about the process, who participated, assumptions made, summary of the results, and copies of reference materials. The aim is to meet the needs of various audiences (e.g., management, technical reviewers, and regulators). Lastly, the final report will be signed-off at least by the team leader and the responsible manager, and it will be distributed to responsible persons for following-up the action items. Thus, the approval of the final report version is a commitment by the management to implement all action items.

## II.3. PHA TECHNIQUES OVERVIEW

PHA techniques could be classified into two groups, according to their formality: flexible and rigorous methods. As far as flexible methods are concerned (e.g., checklist, what-if), there is a lack of formal guidance because of for flexibility in order to allow application in a wide range of circumstances. For this reason, guidance for applying these techniques concentrates on providing a description of the technique rather than setting any standards relating to the quality of its application. Regarding rigorous methods (e.g., HAZOP, FMEA, FTA), there are more structured methods, where a procedure of application is defined due to its necessity for analyzing more complex facilities (e.g., petroleum refining processes).

### II.3.1. Checklist

A checklist can be applied during the whole process life-time, from the initial design to the decommissioning. It is easy-to-use, versatile, cost-effective, and able to identify common and customarily-recognized hazards. It provides the simplest of hazard analyses, a technique which uses a list of prepared questions (normally “yes” or “no” answers) about the design and operation of a facility, and used to identify common hazards.

The methodology works well when the process is very stable and no changes are made, but it is not as effective when the process has undergone extensive change. The checklist may miss the most recent changes and consequently the changes would not be evaluated. Therefore, its use is adequate for well-understood systems. Without extensive past experience, careful observation, and documented fault and hazard logs, a checklist would not be soundly based (Redmill, 2002b). Moreover, its adequacy also depends on the circumstances of its use being the same as those in which it was created; if they differ, the checklist could be out-of-date and dangerously misleading. Checklists, even when appropriate, need to be reviewed periodically.

### II.3.2. What-If

While “What-If” can be applied during the whole process life-time because it is a very flexible technique (used in a wide range of circumstances), it is one of the least structured hazard identification methods available. Its success is therefore highly dependent upon the experience of the analysts. The technique involves personnel brainstorming a series of questions that begin, “What if…”. All questions represent a potential failure or misoperation of the facility.

The response of the process and/or operators is evaluated to determine if a potential hazard can occur. If so, the adequacy of any existing safeguards is weighed against the likelihood and severity of the potential scenario to determine whether modifications to the system should be recommended. Furthermore, the success of a “What-If” analysis is highly dependent upon the thoroughness of the "What If" questions posed, a task which at the same time is dynamic: as one question is asked other questions will occur to the team (Primatech, 2007). These questions should be documented as they occur for later consideration.

The process being analyzed is first broken down into smaller parts (i.e., sub-systems), and for each part, the system drawings and operating procedures are studied and "What If" questions are developed. Hereafter, each sub-system is systematically reviewed, and recommendations are identified, as appropriate, and assignments are made to be followed up.

A “What-If/Checklist” can be applied during the whole process life-time, a technique which combines creative thinking features from the “What-if” portion, but maintains a systematic approach from the Checklist. Although the technique is able to evaluate the significance of accidents at almost any level of detail, it usually focuses on a less detailed level of resolution.

### II.3.3. Failure Modes and Effects Analysis

The Failure Modes and Effects Analysis (FMEA) examines the failure effects of each component of a system. It is a formal technique that identifies and evaluates the significance of the failure, and establishes preliminary recommendations to reduce the likelihood or severity of the failure occurring. As the need for a team is not often emphasized, the method is often carried out by one person. However, an individual lacks the multiple viewpoints required in hazard identification, is subject to the inside view and an 'overconfidence bias', and is unlikely to carry out a thorough investigation. FMEA is also likely to miss hazards that result from the interactions of components rather than from the failure of the components themselves, and hazards are frequent in modern systems, particularly those in which control is provided by software.

### II.3.4. Event Tree Analysis

Event Tree Analysis (ETA) is an inductive methodology which uses a graphical representation for describing (i.e., qualitative and quantitative) all possible consequences (e.g., vapor cloud explosion, pool fire) that could occur once an initiating event is being analyzed (Figure II.3). Thus, the technique is able to identify the scenario sequence from the cause to the consequences according to enabling events (e.g., layers of protection) or conditions. Normally, it is conducted after brainstorming hazard identification techniques (e.g., HAZOP), which have identified a complex potential scenario that requires specific attention.

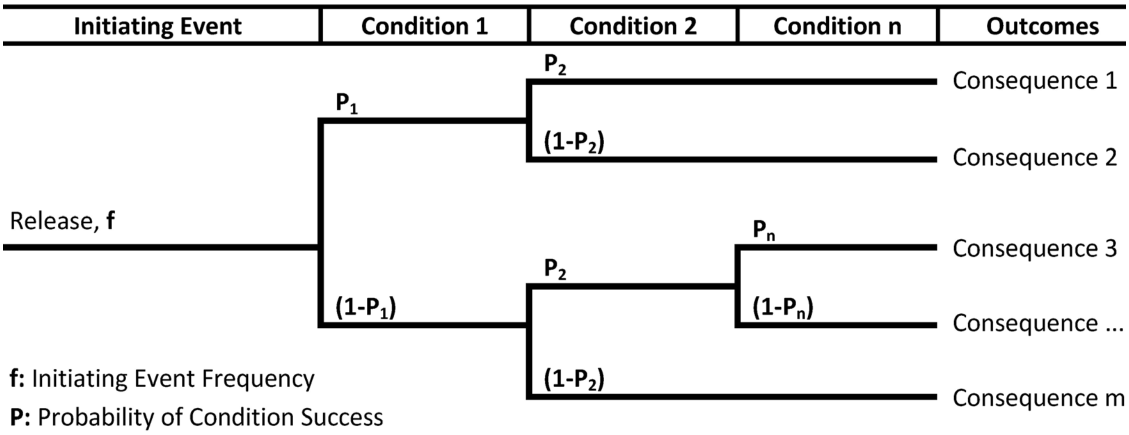

**Figure II.3.** Event Tree Analysis example.

### II.3.5. Fault Tree Analysis

Fault Tree Analysis (FTA) is a deductive methodology which uses a graphical representation of the combination of faults leading to a predefined undesired event, viz., Top Event. The methodology uses Boolean logic gates (i.e., AND, OR) to describe (i.e., qualitatively and quantitatively) how equipment failures and human errors can combine to cause a main system failure. While ETA identifies outcomes from an initiating event (inductive), FTA proceeds in the opposite direction, identifying most of the basic events that could lead to a predetermined outcome (deductive). It allows the hazard analyst to focus preventive or mitigative measures on significant basic causes to reduce the likelihood of an accident. As in ETAs, it is conducted after brainstorming hazard identification techniques, which the results of which may entail further analysis of specific scenarios. Thus, while FTA is useful for identifying the whole set of initiating events that can lead to an undesired outcome (e.g., runaway reaction), it also can provide tools for quantitative data of Top Event probabilities. Figure II.4 shows an example of Fault Tree.

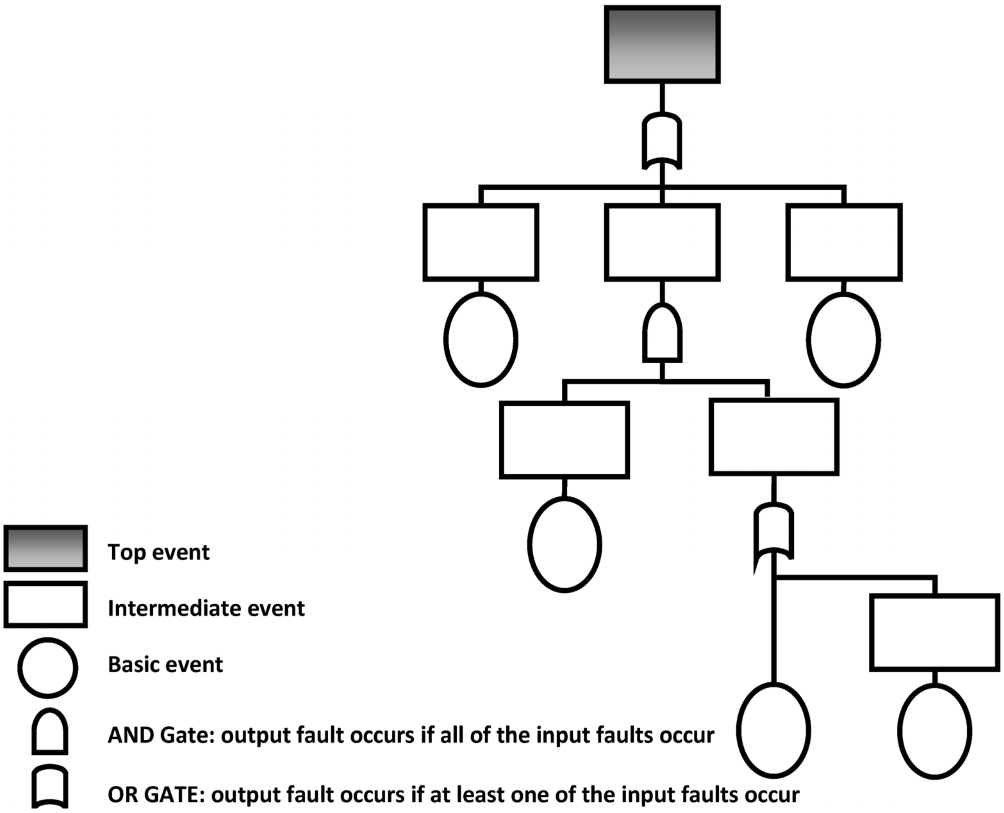

**Figure II.4.** Fault Tree Analysis example.

Finally, once summarized PHA techniques specifically mentioned in regulations, provide valuable information for selecting the appropriate technique according to a particular situation. Table II.3 shows their advantages and disadvantages

### II.3.6. HAZard & OPerability (HAZOP) Study

A HAZOP study is a highly disciplined procedure meant to identify how a process may deviate from its design intent. It is defined as the application of a formal, systematic critical examination of the process and the engineering intentions of new or existing facilities to assess the potential for the malfunctioning of individual pieces of equipment, and the consequential effects on the facility as a whole. Its success lies in the strength of that methodology in following a system's Process Flow Diagrams (PFDs) and Piping and Instrumentation Diagrams (P&IDs), breaking the design into manageable sections with definite boundaries called nodes, thus ensuring the analysis of each piece of equipment in the process. A small multi-disciplinary team, whose members should have sufficient experience and knowledge to answer most questions on the spot, undertakes the analysis. The members are carefully selected, and given the authority to recommend any necessary changes in design.

Executing the method relies on using guidewords (such as, “no”, “more”, “less”) combined with process parameters (e.g., temperature, flow, pressure) that aim to reveal deviations (such as less flow, more temperature) in the process intention or normal operation. This procedure is applied in a particular node, viz., as a part of the system characterized by a nominal intention of the operative parameters. Having determined the deviations, the expert team explores their feasible causes and their possible consequences. For every pair of cause-consequence, safeguards must be identified that could prevent, detect, control, or mitigate the hazardous situation. Finally, if the safeguards are insufficient to solve the problem, offering recommendations must be considered. Table II.4 shows the key HAZOP terminology.

**Table II.3.** PHA advantages and disadvantages.

| Advantages | Disadvantages |
|---|---|
| **Checklist** | |
| It can be customized to the requirements of individual applications and companies | The criterion of a good checklist requires considerable expertise and experience |
| Its use is straightforward, well-structured, easily understood and consistent | The technique can lead to a “blinkered” study that does not fully explore the hazards |
| Useful for standard or repeated operations to ensure no basic problem is overlooked | Use alone, a study can lead to a false sense of security |
| Added-value if added to the list and maintained an open mind during its use | The technique has very limited usefulness for new and novel processes |
| It is much cheaper to apply than other more manpower intensive methods | It is only as good as knowledge of the compilers at the time |
| **What-If** | |
| It can be used at any part of the life cycle changing the list of issues to be discussed | Dependent on the leader skills, discussions, imagination and the intuition of the team |
| It is simple and a study can be conducted relatively quickly | If loosely structured the team may waste time on trivial events or miss important areas |
| It allows the use of imagination and knowledge of the group | Qualitative results and less detailed than other techniques (false sense of security) |
| Useful in the early stages to identify major issues and areas needing further study | The leader has to carry out some initial research to identify the issues |
| **FMEA** | |
| Able to identifying mechanical and electrical equipment failures, reliability problems | Not effective at identifying combinations of failures |
| It is not difficult to apply and the results are easily understood | Concentrates on the equipment and does not address operational errors |
| The analysis can highlight both local and general system failures | The analyst must be familiar with equipment functions and failure modes |
| A semi-quantitative ranking of the hazards can be produced | When applied by a single analyst the technique may miss important interactions |
| **ETA** | |
| Provides a logical graphical description of potential outcomes from initiating event | Limited to the identification of special hazards |
| The technique is structured and methodological, yet relatively simple | The analyst must be well-trained and experienced to ensure an effective study |
| Qualitative and quantitative results obtained ( | The probabilities used in the quantification must be robust and relevant |
| **FTA** | |
| Deductive technique able to identify combination of failures, equipment and human | It is time-consuming and should only be used in the most appropriate circumstances |
| It leads to a logical graphical description of the root causes of a hazard | Each fault tree should refer to a specific problem |
| It identifies key or single point dependencies leading to the hazard using minimum cut set | The analyst needs to be skilled determining the degree of detail to be included |
| It encourages to explore new causes that might contribute to an unforeseen hazard | Its Value will be limited if data are of poor quality and lack robustness or relevance |
| The technique encourages exploration of remote but credible causes of a hazard | Results should, for major events, be conditioned by consequences analysis and risk criteria |
| They can also be useful in estimating and improving plant availability | All results must be treated with care |

**Table II.4.** Key HAZOP Terminology.

| | |
|---|---|
| Design intent | Overall statement of what the process involves |
| Node | Process section within which parameters are investigated for deviations from its design intent |
| Node intention | Defines how the process is expected to be operated, only considering node equipment |
| Specific Parameter | Physical- or chemical-parameters of process materials |
| General Parameter | Other aspects of the design intent complementing specific parameter information |
| Parameter intention | Range of allowable values for the parameter during process operations |
| Guidewords | Simple words or phrases used to qualify or quantify the intention |
| Deviation | Departure from the node’s intention |
| Hazard | Deviation having the potential to cause damage, illness, injury, or other form of loss |
| Causes | Reasons why deviations may occur |
| Scenario | Sequence of situations starting from the initiating event up to consequences |
| Consequence | The effect of the occurrence of a deviation |
| Safeguard | Physical- or procedural-measure that will eliminate or reduce the likelihood of a hazard |
| Recommendation | Suggested actions to prevent, detect, control, or mitigate the scenario identified |

The basics of the study methodology are highlighted as follows:

a. Basic roles of the team leader:

- The team leader works with the project manager in defining the purpose, scope and objectives of the analysis and the election of team members.
- Directs the team members in gathering process safety information on prior to the start of the study.
- Plans the study with the project manager and schedules team meetings.
- Leads the team in the analysis of the selected process keeping team members focused on discovering hazards and/or operability problems associated with the process and directs the team scribe in recording the results of the team findings.
- Ensures that the analysis thoroughly covers the process as it is defined at the start of the study and ensures it is completed in the time allotted during the planning stage.
- Writes a report detailing the study findings and recommendations the group makes and reports the findings and recommendations to the management.
- Fields any follow-up inquiries by project implementation regarding the study recommendations.

b. Basic roles of the Expert Team:

- The engineering experts assigned may include a multi-disciplinary team of experts with the required knowledge to reach the study purpose, scope and objectives.
- The expert team is responsible for providing expertise in their respective discipline as it applies to the hazard analysis of the process being studied.
- The team is responsible for attending the initial hazard analysis meeting.
- They are required to provide documentation of any existing safeguards and procedures.

- 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.

### II.3.6.1. Specific HAZOP Strengths and Weaknesses

Strengths

- The method can identify not only hazards, but also operating problems.
- Highly structured and formal approach.
- A wide range of hazards can be assessed (e.g., chemical, mechanical, control).
- New, novel, and existing processes can be analyzed.
- The team gains a deep understanding of how the process is likely to operate.
- Much better operating procedures can be written after the study.
- Systematically applies guide words and parameters to all process equipment.
- It examines the consequences of the failure, a fact that aids in the production of recommendations for methods to minimize or mitigate the hazard.

Weaknesses

- The high resource requirements, both in manpower and data.
- The method is time-consuming and expensive, especially in continuous chemical processes which involve a large amount of equipment (e.g., petroleum refining processes).
- To fully perform the study the process has to be designed to such a level that P&IDs are available.
- Additional guide words are required for unusual hazards.
- The study requires leader judgment and team expertise to identify all possible causes and consequences of the deviations.
- The results are subject to the analyst’s bias, experience, knowledge, and creativity.
- HAZOP documentation is not always written in a style to ensure easy reading by external members.

## II.4. SPECIFIC CONCLUSIONS

PHA techniques are tools which are intended to help analysts find ways of avoiding or reducing both the causes and consequences of life-threatening occurrences. These tools guide responsible parties to identify what can go wrong, viz., finding causes or operating problems for deciding what actions to take to prevent them. Their ultimate aim is to avoid injuries or death of workers and/or the public, environmental impacts, and also, economic losses.

Hazard identification has as advantage when using PHA techniques defined as a team-based approach. A multi-disciplinary knowledge will ensure a deeper analysis, a fact that confirms the sentence that establishes “two minds are better than one”. The most reliable and structured PHA techniques for analyzing complex process facilities are all team-based, enforcing brainstorming features. However, PHAs are subject to a number of theoretical and practical limitations. Assumptions and limitations from PHA results will be inherited by subsequent analysis for risk management decisions. Thus, while any stage from a risk management program entails subjectivity and uncertainty, the key importance falls on hazard identification, a discipline which “establishes the game rules”, and which can be considered as the foundation of risk management (e.g., if a scenario is overlooked, it will not be evaluated, affecting risk estimation results for realistic decision-making). For these reasons, it is essential to be aware of PHAs inherent limitations, in order to attempt future improvements for their effectiveness. Thus, limitations are listed as follows:

- The PHA team can never be certain that all hazardous situations have been identified, and for those identified, the team can never guarantee all of their possible causes and effects.
- A PHA study analyzes a "snapshot" of the process. Any changes in the design or in the operating and maintenance procedures may have a significant impact on the safety of the facility.
- Results of a PHA study are difficult to duplicate by independent experts, even with the variety of experience-based and predictive methods available.

- Hazard identification is largely dependent on good judgment. The subtle assumptions that hazard analysts and process experts necessarily make while performing PHAs can often be the driving force behind the results.

- PHAs generate a wide range of information which could sometimes be difficult to interpret by responsible parties when following up recommendations. As written in (CCPS, 1992): “Combined with hazards analysts' tendencies to use copious amounts of jargon, reviewers can find themselves wondering what to do with all this information”.

- PHAs are inherently based on the collective wisdom of the PHA team.

However, these three actions require technical development for their establishment according to process chemical facilities and regulations:

- Enforcing the structural features of the PHA technique itself.

- Training leaders and team members on conducting specific PHAs (e.g., HAZOP) by giving them appropriate tools and guidelines to proceed.

# CHAPTER III. RESEARCH PURPOSE, SCOPE AND OBJECTIVES

The aim of this research is to develop a simple methodology for precisely appraising the status and trends of HAZard & OPerability studies, and hereafter providing specific guidelines for responsible parties on defining, preparing, organizing, executing and writing HAZOP studies in the petroleum-refining industry, continuous chemical processes, especially complex, due to the large amount of equipment and instrumentation to be reviewed, all of them related to complicated chemical unit operations.

## III.1. RESEARCH PURPOSE AND SCOPE

The main aim of this work is to provide guidelines for project managers, team leaders and expert team members for managing, conducting, and participating in HAZOPs to be applied in continuous chemical processes. Two aspects have to be analyzed for standardizing criteria: (1) to modify the HAZOP structure itself for reinforcing objectivity, and (2) to analyze processes with similar technology to be ”hazoped” for standardization.

Due to the similar technology of most petroleum refining units, HAZOP is modified and adapted to ensure most of the present hazardous situations will be identified, taking care to reach the optimum equilibrium between criteria for standardization (intended to minimize subjectivity) and freedom for creative thinking (reinforcing brainstorming). In this sense, this work itself could be used as a guideline for responsible parties interested in identifying hazards in continuous process facilities that manage highly hazardous materials.

The present work is not valid for “hazoping” discontinuous processes, batch processes and/or procedures due to their opposite nature versus steady-state processes. While hazoping continuous processes only requires a “snapshot” of the process, and also it is totally focused as an equipment-oriented analysis; in time-depending processes it is necessary to conduct as many HAZOPs as procedures or receipts define the process. This means different criteria has to be taken into account, from process equipment (less complex than units analyzed), but with additional analysis for taking into account each procedure defined (which should be taken as an independent node to be analyzed). In this sense, to conduct HAZOPs in discontinuous processes requires two approaches to be simultaneously conducted: analysis of process equipment in each procedure defined. Additionally, the magnitude of human intervention is significantly higher than steady-state processes, a key factor to be deeply analyzed in depth.

Finally, it is important to highlight that criteria has been carefully implemented to ensure that most of the hazardous scenarios will be identified, and also that US OSHA PSM Rule, EPA RMP, and Seveso Directive requirements will be accomplished.

## III.2. OBJECTIVES

### III.2.1. Establishment of the HAZOP Management System

Petroleum-refining processes are complex to understand. A plethora of unit operations and specific control devices and equipment are carefully linked to achieve the pursued goal. Most of these processes present a great amount of documentation to be reviewed for hazard identification. For example, an individual unit could be defined by tens of P&IDs, and many other sources of information. This inherent complexity requires careful definition of a management system which entails concerted efforts across several phases. Individual tasks to achieve these goals are the following:

1. To define the body of the required management system (HAZOP Management System): (1) definition and preparation; (2) organization; and (3) execution and documentation.
2. To provide detailed criteria to asses each HMS phase.

### III.2.2. Assessments for defining and preparing HAZOP Studies

The main objective of this task is to identify all management steps involved in setting up HAZOP studies, presenting them in a chronological order of application, and providing tools for assessing responsible parties with the aim of ensuring the whole set of factors and variables to take into account of the first HMS phases are achieved and smoothed in order to be connected to the subsequent phases. Individual tasks to achieve these goals are the following:

1. To better understand the preliminary HAZOP tasks.
2. To provide detailed information relating HAZOP studies according to the process lifetime. This aspect will entail a better understanding of “why” and “when” to conduct the study.
3. To define the whole set of specific responsibilities of project managers and team leaders.
4. To develop criteria for defining the purpose, scope, and objectives of the study.

5. To explain the experts' knowledge required to brainstorm sessions, and their required duties in each HAZOP stage.
6. To develop "ready-to-use" tools for checking the necessary key HAZOP information, and also assessing responsible parties for converting it to a suitable form.
7. To establish criteria for defining qualitative ranking, both for severities and likelihoods of scenarios that will be identified during brainstorming sessions.

### III.2.3. Assessments for organizing HAZOP studies

Due to the fact that HAZOP studies conducted in continuous chemical processes are complex, tedious and time-consuming, its organization is a key factor for success. The main objective of this task is to provide detailed criteria to undertake the required procedures to ensure that a HAZOP study will be well-organized; and also, to reinforce a smooth-linking between subsequent HMS phases. Individual tasks to achieve these goals are the following:

1. To develop a new procedure defining how to break designs into manageable sections with well-defined boundaries (nodes).
2. To assess team leaders on selecting process nodes.
3. To define a new global node treatment.
4. To pioneer a new tool for predicting the number of nodes according to the process complexity.
5. To develop a mathematical model able to predict the expected time to conduct the entire study.
6. To provide guidelines on planning the study.

### III.2.4. Assessments for executing and documenting HAZOP studies

After analyzing particular features and specific attributes of several petroleum refining units, the main objective of this task is to provide tools for ensuring effective brainstorming during HAZOP sessions, and also guide responsible parties how to correctly record information on the HAZOP worksheets to assure that is appropriately placed and understandable. Individual tasks to achieve these goals are the following:

1. To encourage questioning all factors specified both in OSHA PSM and the Seveso Directive for addressing hazard identification.
2. To develop a structural hierarchy for defining the minimum set of deviations in order to ensure the identification of key hazardous scenarios.
3. To define the order of application of these deviations, avoiding repetitive analysis, and strengthening the structure of HAZOP itself.
4. To guide team leaders in structuring brainstorming sessions and logically recording HAZOP worksheets.

# CHAPTER IV. HAZOP, STATE OF THE ART AND TRAINING

Regarding the specific objectives to be reached, it was necessary to analyze the HAZOP state-of-the-art, and also to carry out real HAZOP studies participating in different roles. These roles started from the preparation stage of the study, its execution, and its outputs. I had the opportunity to participate in several HAZOPs developed in refining units. Atmospheric distillation, alkylation, Ethyl-Tert-Butyl-Ether (ETBE) production, hydro-desulfurization, etc, are examples of these sessions. From this work, very valuable research documentation was obtained for the development of this study. Likewise, it was also necessary to understand the detailed information which describes these processes. Documentation such as PFDs, P&IDs and the process description were theoretically analyzed, outside the framework of the HAZOP features and requirements. This work allowed the development of the nodes selection procedure. Finally, the participation in a prestigious training course focused on team leader skills gave me the opportunity to share experience and opinions with other process safety consultants, and establish current weaknesses to be assisted. .

## IV.1. HAZOP STATE-OF-THE-ART

One of the main purposes of the study is to review the state-of-the-art of the HAZOP methodology. The intention is to gather HAZOP-related literature from books, guidelines, standards, major journals, and conference proceedings, with the purpose of classifying the research conducted over the years in order to examine potential requirements, and application limitations. This work also entails identifying new trends and research needs for enhancing HAZOP studies in process facilities that manage highly hazardous materials.

### IV.1.1. HAZOP Evolution

The concept of a 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 (Chudleigh, 1994), road-safety measures (Jagtman et al., 2003), and hazard analysis in photovoltaic facilities (Fthenakis & Trammell, 2003), among others. This diversity of usage shows how HAZOP has become considered as a powerful technique to improve many kinds of systems. In this sense, it is necessary to limit the scope of the review to considering the evolution of HAZOP research from its starting point to the present day on issues about chemical processes, accounting for the OSHA PSM Rule, (1992); and the SEVESO Directive (2003).

HAZOP studies evolved from the Imperial Chemical Industries' "Critical Examination" technique formulated in the mid 1960s. One decade later, HAZOP was published formally as a disciplined procedure to identify deviations from the design intent. Lawley (1974) defined and delineated the principles needed to carry out operability studies and Hazard Analysis due to the increasing complexity of new processes that could not be examined thoroughly using the then-conventional approaches based on equipment-oriented practices.

Indeed, the requirement for having process-oriented methods of examination was the reason for the creation of HAZOP. Lawley's paper defines the planning, execution, and treatment of the operability study. Two years later (Lawley, 1976), he specified the technical – and managerial – principles underlying HAZOP studies, and detailed the factors that had to be taken into account to develop the HAZOP successfully. The planning of the study, the skills of the leader, the study procedure, the evaluation of potential problems, and the process of considering the changes proposed in the analyzed units were set out carefully. Moreover, he gave new examples of the study to show how HAZOP worked. Just one year later, the Chemical Industries Association in the UK published the first guideline to HAZOP, as a technique used in the process industries for identifying hazards and planning safety measures (CIA, 1977).

Over the last 30 years, numerous other guidelines and books have appeared. Among the important contributions on adapting the technology for the processing industry are those of Knowlton (1981), Nolan (1994), Kletz (1993, 1998, 1999, 2001), Lees (1996), Wells (1996), EPSC (2000), and Macdonald (2004). This plethora of publications shows the evolution of HAZOP as a vital technique applied worldwide that is recognized by legislation, and has demonstrated its effectiveness in identifying environmental, safety, and health-hazards. Knowlton (1981) was the first author to develop a book focused only on HAZOP applications, giving valuable information on the creative process to generate deviations; Nolan (1994) shared his practical experience discussing specific topics both for HAZOP and "What If" techniques. Both methodologies are fully described. The book also introduces tools for HAZOP time and costs estimation. The document was intended as a typical guideline and reference book to be applied at petroleum, petrochemical and chemical facilities by describing the nature, responsibilities, methods and documentation required in the performance of such reviews. Kletz (1993, 1998, 1999, 2001), considered one of the most influential authors on several process-safety topics, wrote an excellent book defining in technical terms HAZOP and, at the same time, sharing his experience and thoughts with a characteristic entertaining personal style. Lees (1996) and Wells (1996) contributed their concepts of HAZOP development, and extended their focus to a wide-range of aspects of hazard identification and loss prevention.

In 2000, EPSC (2000) formulated new HAZOP guidelines adapting the methodology to the emergence of new technologies and sharing their considerable experience in using the technique most effectively.

Finally, a British Standard (2001), established and defined new requirements for carrying out a HAZOP, thereby clearly pointing to its continuing importance as the most widely-used technique in process plants and other types of facilities.

Recently, Macdonald (2004) updated the field in his book with the latest data on the characteristics of HAZOP, documenting how to carry out a HAZOP and connecting it with future studies focused on Safety Integrity Level (SIL) assignments. The document concentrates on the application of hazard study methods and the actions that follow from them for providing protection against hazards. Additionally, the book provides training in three basic steps (i.e., identifying hazards, evaluating risks, and specifying risk reduction measures) that form part of the overall risk management framework for process facilities.

Table IV.1. lists the most notable books and guidelines on HAZOP, highlighting the most essential and broadly used documentation needed for understanding its underlying concept and its evolution. Hereafter, I consider the papers that were published over the years, according to their research area, and the evolution of process technology, and HAZOP methodology.

### IV.1.2. Published Literature

The review starts by summarizing the main ideas in about 200 published studies, classifying the publications in several groups, and expanding their particular features independently in the next section. Thereafter, there is a discussion of the collected information, and conclusions have been established after highlighting present-day weaknesses in the preparation, execution, and documentation stages of HAZOP studies, so as to avoid them in future research.

**Table IV.1.** Key HAZOP References.

| Year | Author / Institution | Title | Paper | Guideline | Book | Standard |
|---|---|---|---|---|---|---|
| 1974 | Lawley | Operability Studies And Hazard Analysis | ■ | | | |
| 1977 | CIA | A Guide to Hazard and Operability Studies | | ■ | | |
| 1981 | Knowlton | Hazards and Operability Studies, The Guideword Approach | | | ■ | |
| 1983 | Kletz | “HAZOP & HAZAN”. Identifying and Assessing process Industry Hazards (first edition) | | | ■ | |
| 1986 | Kletz | “HAZOP & HAZAN”. Identifying and Assessing process Industry Hazards (second edition) | | | ■ | |
| 1996 | Lees | Loss Prevention in Process Industries hazard identification, assessment and control | | | ■ | |
| 1991 | HSE | Guidance on HAZOP procedures for computer-controlled plants | | ■ | | |
| 1992 | Kletz | “HAZOP & HAZAN”. Identifying and Assessing process Industry Hazards (third edition) | | | ■ | |
| 1992 | CCPS | Guidelines for Hazard Evaluation Procedures | | | ■ | |
| 1994 | Nolan | Application of HAZOP and What-if Safety Reviews to the Petroleum, Petrochemical and Chemical industries | | | ■ | |
| 1996 | Wells | Hazard Identification and Risk Assessment | | | ■ | |
| 1999 | Kletz | “HAZOP & HAZAN”. Identifying and Assessing process Industry Hazards (fourth edition) | | | ■ | |
| 1999 | Redmill | System Safety: HAZOP and Software HAZOP | | | ■ | |
| 2000 | EPSC | HAZOP: Guide to best practice. Guidelines to best practice for the process and chemical Industries | | | ■ | |
| 2001 | BS IEC 61882 | Hazard and Operability studies (HAZOP studies) – Application Guide | | | | ■ |
| 2004 | McDonald | Practical HAZOPs, Trips and Alarms | | | ■ | |

HAZOP is the focus of much research aimed at improving the safety of chemical plants that increasingly operate at higher temperatures and pressures, and encompass more complex, sophisticated processes. The information has been mainly collected from publications in major journals and conference proceedings, but also from books, guidelines, and standards. Tables IV.2 and IV.3 show the sources of the most published papers and conference proceedings, respectively.

**Table IV.2.** Sources of the Most Published Papers.

| Sources of Most Published Papers |
|---|
| Computers & Chemical Engineering |
| Journal of Loss Prevention in Process Industries |
| Reliability Engineering & System Safety |
| Process Safety Progress |
| Chemical Engineering Progress |
| IEEE Transactions on Reliability |
| Professional Safety |
| AIChE Journal |
| Hydrocarbon Processing |
| ISA Transactions |
| Journal of Hazardous Materials |
| Plant/Operations Progress |
| Safety Science |
| Industrial and Engineering Chemistry Research |
| Nuclear Engineering and Design |
| Accident Analysis & Prevention |
| AIChE Symposium Series |
| Chemical Engineering Science |
| Computer methods and Programs in Biomedicine |
| Environmental Modeling & Software |
| Expert Systems with Applications |
| Gas Separation & Purification |
| IEE Colloquium on Hazards Analysis |
| International Journal Hydrogen Energy |
| Korean Journal of Chemical Engineering |
| Quality and reliability engineering international |
| Tsinghua Science and Technology |

The period covered is from its starting point in 1974 with the first publication of work carried out by Lawley (1974), up to the present. The number of published studies gradually rose over the years from 1974 until 1997-1998, the period with the maximum number of publications. Over the three decades of HAZOP improvements, 60% of the research occurred from 1990-2000 (Figure IV.1); further, most of this work concerns the development of expert systems intended to automate HAZOP (Figure IV.2).

**Table IV.3. S**ources of Conference Proceedings**.**

| **Conference Proceedings Sources** |
|---|
| International Conference on Human Factors in Control Rooms |
| Annual Conference into the Major Safety, Reliability and Risk Analysis - ESREL |
| Annual Conference of the Society of Maintenance and Reliability Professionals |
| Annual Conference on Systems Integrity, Software Safety and Process Security |
| Conference and Workshop on Reliability and Risk Management |
| IEE Colloquium on Hazards Analysis |
| IEE Colloquium on Model Building Aids for Dynamics System Simulation |
| IEEE International Conference on Computational Cybernetics |
| International Conference on Systems, Man and Cybernetics |
| International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems |
| International Conference on Probabilistic Safety Assessment and Management - PSAM |
| International Process Plants Reliability Conference and Exhibition |
| International Symposium Loss Prevention and Safety Promotion in the process Industries Loss Prevention |
| International Workshop on Artificial Intelligence for Industrial Applications |
| Risk Management And Critical Protective Systems: Proceedings of SARSS |
| Safety Critical Systems Symposium |

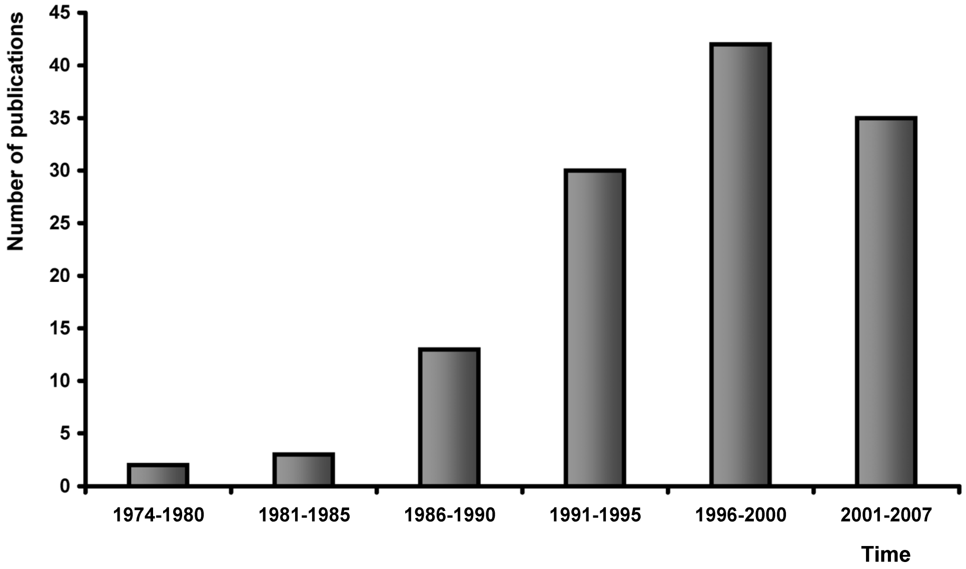

**Figure IV.1.** Trend of related-HAZOP publications.

Many different viewpoints have been advanced on improvements in HAZOP, from extending its execution in several technological fields, to its automation by developing expert systems. As shown in Table IV.4, it has aggregated the reviewed literature into six research topics that I deemed a sufficiently detailed classification for undertaking a global view of HAZOP. However, other particular topics within each main research line may easily be expanded, as will be shown in the next section. I found it instructive and interesting to specify the starting point of the HAZOP and its continuous progress over the years to the present, highlighting its success and consolidation as the most systematic, rigorous, thorough, and universally used hazard-identification technique.

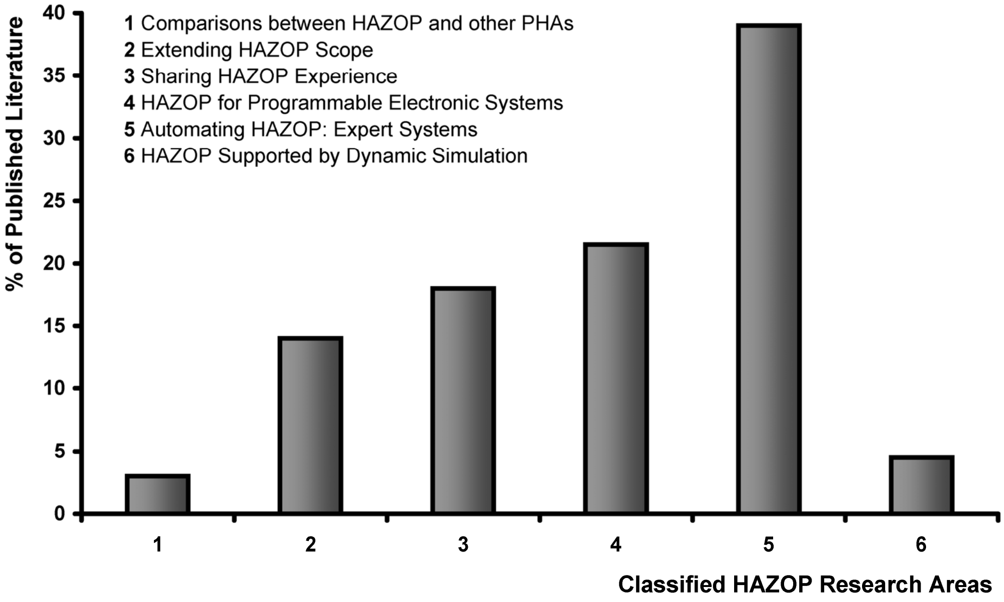

**Figure IV.2.** HAZOP research lines proportion.

**Table IV.4.** Classification of Literature According to Research Areas.

| Research Topics | Percentage of Papers (%) |
|---|---|
| **1. Comparing HAZOP with other PHAs** | 5 |
| **2. Extending HAZOP Scope** | |
| 2.1. Extending the Hazard Identification Scope | 5 |
| 2.2. Considering Quantification | 4 |
| 2.3. Considering Human Factors | 5 |
| 2.4. Considering Specific HAZOP Modifications | 2 |
| **3. Sharing HAZOP Experience** | 24 |
| **4. HAZOP for Programmable Electronic Systems** | |
| 4.1. Software Safety Assessment | 11 |
| 4.2. Assigning a Target Safety Integrity Level | 8 |
| **5. Automating HAZOP: Expert Systems** | 32 |
| **6. HAZOP Supported by Dynamic Simulation** | 4 |

### IV.1.3. HAZOP Research Areas

#### IV.1.3.1. Comparing HAZOP with other PHAs

This section shows research focusing on the analysis of HAZOP and compares it with similar safety-analysis systems. Generally, the emphasis in this section is on defining the intended coverage of a HAZOP study, and identifying other PHA techniques that complement its application.

After defining the starting point of a safety analysis and considering the differences between safety analysis and safety management, Suokas (1988) evaluated the scope of four different methods: HAZOP; Action Error Analysis (AEA); Work Safety Analysis (WSA); and, Management Oversight and Risk Tree (MORT). His aim was to identify and assess the coverage of the search procedures employed in these different methods for identifying accident contributors. He showed that research on the scope of HAZOP concentrated mainly on deviations in the physical sub-system, and in a lesser way, on those in the human sub-system, while lacking a description of a management sub-system. This shortcoming affected the value of HAZOP results. In a later paper, Suokas & Rouhiainen (1989) reviewed the potential for quality evaluation, using results from several comparable investigations. They re-affirmed that HAZOP covered hazards induced by process deviations and human errors in manual operations, but organizational factors remained outside the scope of the methodology. They called for more research on management matters to incorporate them as a standardized element in safety and risk analyses, especially HAZOP.

Hoepffner (1989) compared HAZOP's features with two other PHA techniques, viz., Fault Tree Analysis (FTA), and Failure Modes and Effects Analysis (FMEA). The author defined HAZOP as being midway between them. HAZOP started according to the deductive approach (downward) postulating top events (deviations), and then followed the inductive method (upward) by asking what would happen to the system. This definition revealed the reason for the success of HAZOP and underscored its widespread usage compared to other well-known analysis systems.

Montague (1990) considered what single method or combinations of them should be used for process risk evaluations. He explored the values of three common ones; HAZOP, Facility Risk Review (FRR), and Quantitative Risk Analysis (QRA), illustrating their effectiveness in producing useful recommendations for improving safety. He concluded that selecting the right method is not a trivial task, and managers can make objective decisions only by seeing the types of results from various approaches.

### IV.1.3.2. Extending HAZOP Scope

Some efforts were made to extend the scope of HAZOP. Its application in specific systems and the intention to analyze the particular features of these systems generated the need to consider possible combinations between HAZOP and other PHA techniques, or modifications. This field has accounted for the analyses of several systems and particularities, centering on human factors, new technologies such as Programmable Electronic Systems (PES), renewable energy systems, batch systems, and management factors. This section details this research work, excluding PES HAZOP that will be discussed in a separate section because of its wide applicability. Additionally, there has been considerable work on applying the HAZOP to batch processes than is discussed herein; and much of it will be explored when I discuss research on automating HAZOP and considering human factors.

#### Extending Hazard 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, by focusing on their identification of hazards, operability problems, and reliability.

Post (2000) 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. Other authors discussed the same matter (Hendershot et al., 1998; King et al., 1997; Alley et al., 1998).

Trammel & Davis (2001) 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 up-time in semi-conductor manufacturing process.

Later, Trammel et al. (2004) extended the utility of this hybrid method by adding Layer Of Protection Analysis (LOPA) to evaluate and apply effective controls. They concluded that the HAZOP portion of this combination eased the selection of system limits and hazard identification, while the FMEA portion effectively estimated and evaluated risk. Incorporating LOPA to specifically evaluate and quantify existing or proposed Independent Protection Layers (IPLs) ensures the identification of the appropriate controls.

Burgazzi (2004) 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 analysis 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.

Considering Quantification

Many authors attempted to extend the HAZOP application from identifying hazards to evaluating their impacts.

Bendixen & O'Neill (1984) considered HAZOP and FTA as the best combination of 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?

(3) Which criterion was to be applied in consequence modeling estimation?

Ozog and co-workers (1995, 1987) 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. (2002) 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. Recently, Cozzani et al. (2007) developed a specific methodological approach to analyze comprehensively the risk from hazardous materials in marshalling yards. They considered the HAZOP analysis of railway wagons, using a set of possible deviations of the process variables from the design values; thereafter, they evaluated the expected occurrence frequencies of the TEs by carrying out an FTA. Shafaghi et al. (1988) 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 recognition of preliminarily hazards, HAZOP successfully identified many types of risks, sources of non-optimum system reliability, and also improvements in the design of the heat pumps.

Considering Human Factors

In this section, work is cited 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 to 90 percent of operational risk is attributable to human error (Baybutt, 2002).

Schurman and Fleger (1994) 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”, “mis-timed”) 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 (2002) new approach for delineating human-failures and human-factor issues, which 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 in combination (Person - Facility Aspect - Failure Type) producing the looked-for deviations, (i.e., specific human failures).

Aspinall (2006) also focused on addressing human factors in HAZOPs, and then re-stated the basic principles of HAZOPs in order to show how the established Guide Word-driven method could be used for human-factor issues. The author showed how to proceed in any stage of a process lifetime and strongly advocated the importance of a clear design intention (or activity intention) for defining additional deviations for human factors investigation.

Rasmussen & Whetton (1997) 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 analysis.

Managerial vulnerabilities and organizational failures significantly contribute to causing accidents. Kennedy & Kirwan (1998) 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 procedures for study, 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, Pátkai (2006) 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. Currently, many commercial software packages are available, developed specifically to ease the data management of a hazard-identification analysis. They are listed in (Website, 2008).

Batch processes entail major human involvement, and its inherent technology must be treated differently from continuous processes. Automated batch processes allow some flexibility for change that must be considered in identifying hazards. Mushtaq & Chung (2000) offered a formalized approach for applying HAZOP methodology to batch processes, suggesting examining a typical batch plant by dividing it into three operational phases: charge and discharge steps that are analyzed as a continuous process, and, reaction, reviewed by separating it into its different operations, such as mixing, and heating.

They listed and interpreted new guide words for this discontinuous process, extending its application to the safe design of processes in pipeless plants. Justifying the time-consuming feature of the methodology, the authors highlighted the need to have a computer-support tool to guide and document the study. I further discuss this work in session 3.5, automating HAZOP. An essential reference is Kletz's book (Kletz, 2001), a valuable comprehensive assessment of human errors in chemical engineering. In this book, the author shares his expertise and views on human errors as a cause of accidents, and shows several accidents that have occurred, mainly in the oil and chemical industries (e.g., accidents due to a lack of physical or mental ability, accidents due to wrong decisions, accidents due to management errors).

### Considering Specific HAZOP Modifications

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 (2003) discussed the requirement for a specific PHA technique that directly and exclusively addressed major process accidents. HAZOP can be time-consuming as it aims at identifying operability problems in many nodes. Major Hazard Analysis (MHA) begins by considering the first sub-system, 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 & Fromm (1991) 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 was already 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, resulting from the amount of information and cause-consequence pairs highly related to abnormal situations in process facilities, Suzuki et al. (2004) developed a HAZOP based operator decision support system (implemented by using Microsoft Access) with the aim of predicting possible hazards. This tool could support operators to take corrective action against abnormalities. The authors extended the HAZOP features by adding a data base with valuable information to be used for maintenance personal and operators.

#### IV.1.3.3. Sharing HAZOP Experience

In this section, much of the information in the open literature that is based on professional experience is reviewed. Due to the inherent subjectivity in any PHA, it is important to share professional experiences about HAZOPs. Even though HAZOP is structured and systematic, it depends on human observation, judgment, and creativity. I do not intend for this review to be a destructive dissection, because a major benefit of hazard identification is its subjectivity (Redmill, 2002) (its requirement for thought). Clearly, a most valuable way to learn and acquire expertise is sharing knowledge with others. Likewise, the extensive literature, described below, discusses experiences and applications based on executing HAZOP assessments.

Qureshi (1988) explored the stages required to carry out a HAZOP, emphasizing the importance of the leader's experience and the team members' skills. Contrary to common belief, he concluded that HAZOP did not take any longer than reviews based on a checklist, provided these considerations were taken into account. Many authors have defined parameters to improve the effectiveness of the HAZOP study. Thus, Mckelvey (1988) suggested key elements that make HAZOP powerful and effective in identifying chemical-process hazards. He depicts eight basic steps to explain its success, from defining the scope of the study to the following-up procedure ensuring that all recommendations from the study were addressed. In contrast, he uses six key problems to show why HAZOP sometimes failed, the first of which was lack of experience. He concluded that it was important to have the best possible input, the most experienced team, and enlightened, cooperative management to ensure success.

Similarly, Jones (1992) exposed HAZOP's benefits and pitfalls, concluding that the critical factor in success was the manner in which management responded to recommendations. In a re-arrangement of Kletz's thoughts, Gujar (1996) revealed some of the HAZOP lacunas. Several authors shared their experiences on HAZOP by defining stages of the study and considering particularities to improve them: the examples they gave included planning for HAZOP, HAZOP preparation, HAZOP team composition, hazard specialists' responsibilities, and timing (Goyal, 1993; Sweeney, 1993; Kelly, 1991; Swann & Preston, 1995; Wong et al., 2004; Laul et al., 2006).

Focusing on the documentation stage of a HAZOP study, Freeman (1991) established a detailed HAZOP report content and detailed basic rules for developing one. Pully (1993) described the manner in which HAZOP was performed for petroleum-refinery units, the types of results obtained, and the benefits from it. George (1997) emphasized the process information required and its relevance to other PHAs, while Bullock et al. (1991) exposed the unwitting abuse of HAZOP. Their article indicated that the quality of human input can be improved and abbreviated variants of the traditional HAZOP which might be viewed with suspicion. Recently, Dunjó et al. (2008) analyzed the evolution of HAZOP studies and highlighted the importance of developing a standardized methodology for selecting nodes in complex facilities such as the petroleum-refining industry.

Over the years, HAZOP has been applied to a wide range of industries and activities, and to specific situations. Robinson (1995) described how HAZOP was applied successfully and cost-effectively in existing operating plants, mechanical systems, electrical systems, computer systems, transport systems, and the like, highlighting the importance of developing a suitable model to represent these particular systems; several authors gave practical examples by applying HAZOP to a liquid-hydrogen petrol station (Jones, 1984), steelworks (Swuste, 1997), hydrogen plant (Brown & Buchier, 1999), and large gasholders (Bernatik & Libisova, 2004).

Kletz (1991, 2006) validated the success of the HAZOP for incident investigation, explaining four accidents that might have been prevented. From the reverse point of view, Mahnken (2001) described how case histories could help HAZOP, so demonstrating the connection between HAZOP guidewords and real-world accidents. The strength and validation of HAZOP is well-founded. Thus, from its first publication it has changed remarkably little, although it has been modified for specialized applications, such as batch processes, laboratory operations, mechanical operations, and even for identifying possible hazards in genetic engineering (Kletz, 1997). However, the industry was slow to recognize the need for incorporating additional HAZOP parameters for computer-controlled systems. Nevertheless, the several changes proposed for the HAZOP procedure would make it suitable for the PES. This work is covered in the next section.

### IV.1.3.4. HAZOP for Programmable Electronic Systems

The speed and flexibility of computers has fostered the increasing use of software in industry to control or manage safety-critical systems. Indeed, as systems become more and more complex, and faster and faster response time is required, the only feasible approach is to use a computer and software. However, while incorporating a computer to control, protect, and monitor the operation of a chemical plant has improved efficiency, at the same time it has introduced new routes for failure and potential risks. Because of the successful widespread use of HAZOP in the process industry, researchers and engineers are suggesting ways of adapting HAZOP (CHAZOP and PES HAZOP) to safety-critical systems (Kletz, 1995). This section describes the research aimed at adapting the traditional HAZOP to computer-controlled plants.

#### Software Safety Assessment

Andow (1991) developed the first guideline on HAZOP procedures for computer-controlled plants, recommending using a framework similar to that of the conventional HAZOP. Chung & Broomfield (Kletz, 1995) assembled wide-ranging information about the state-of-the-art of HAZOP studies undertaken in PES plants that focused on the current situation, identifying much research accomplished, although no agreed format for HAZOP was established. After describing four different CHAZOP schemes, the authors concluded that a total system view was required, and offered a systematic approach for developing a hazard identification methodology to assess the system’s safety, and improve its overall quality.

McDermid & Pumfrey (1994) justified the HAZOP as the most appropriate study for assessing all stages of the design and implementation life-cycle because its inductive and deductive safety features support safety assessment. They propounded the essential principles of a software safety-analysis based on applying a set of guidewords to suggest hypothetical failures. Lawrence & Gallagher (1997) proposed undertaking software hazard analysis by focusing on the early stages of its life-cycle.

Subsequently, McDermid et al. (1995) shared their experience using HAZOP in software systems, offering four examples using additional techniques, such as Software Hazard Analysis & Resolution in Design (SHARD), that they considered had useful, widespread applicability for investigating the safety properties of a range of computer-based systems. Earthy (1992) highlighted the special benefit of HAZOP for software analysis in identifying the effects of interactions between software, its computer environment, and the real world in which it is used.

Nimmo (1994) described the new skills needed to identify and correct new hazards consequently introduced by the growth in the numbers of computer-controlled plants. He described how to add CHAZOP to the traditional HAZOP to improve the safety integrity of the plant by dividing the entire analysis into two phases. The first phase encompasses the traditional HAZOP; the second looks specifically at the PES and its interactions with the process and operators. Collins (1995) defined the new adaptations required for applying HAZOP to control systems, including the new information needed, its management, the required new skills of the leader and expert team, and modifications to the traditional HAZOP. Redmill et al. (1997) revealed common difficulties in preparing guidelines on applying HAZOP to PES, and gave suggestions on how to overcome them, listing them as actions and premises that must be accounted for. Two years later, they published a book elaborating on the technical – and managerial – requirements for executing HAZOPs on software systems (Redmill, 1999).

After summarizing the research into software HAZOP, Fenelon & Hebbron (1994) evolved some recommendations and drew together the common threads of the work. They proposed three different models of HAZOP: a formal model, an algorithmic one, and a causal one.

The following year, they expounded on the potential value of integrating these three models: HAZOP, Ward & Mellor, and Calculus of Communication Systems (Fencott & Hebbron, 1995). There was much more such work on modifying the traditional HAZOP; the aspects treated included a new set of guidewords, management criteria, and new documentation (Schubach, 1997; Freeman, 2001; Burns & Pitblado, 1993; Love, 2001).

Yang & Chung (1998) formulated a novel modeling representation for identifying hazards related to computer-controlled processes. Called the Process Control Event Diagram (PCED), it expresses the control logic and its effects on the process, and complements P&IDs information and the combined features from Signed Directed Graph (SDG) and Event Time Diagram (ETD). Subsequently, Chung and Edwards (1999) applied the same criteria to both batch and continuous computer-controlled plants.

### Assigning a Target Safety Integrity Level

Because of the rapid evolution in automating the process industry, the industrial community has drawn up procedures to assess new requirements for assigning a target SIL for all Safety Integrity Systems (SIS) applications. Standards (ANSI/ISA-S84.01, 1996; IEC 61508, 1998, IEC 61511, 2003) describe them. The SIS consists of the instrumentation or controls installed for mitigating the hazard or bringing the process to a safe state in the event of a process upset. A SIS is used for any process in which the PHA has determined the insufficiency of the mechanical integrity of the process equipment, the process control, and other protective equipment to mitigate the potential hazard (Summers, 1998).

The features of a HAZOP study and the need to assign SIL for SIS revealed that the information obtained from HAZOP made it a serious candidate to use for linking its results with the input data required to start analysis for the SIL assignment; this situation now is being studied comprehensively. Particularly the HAZOP final stage, during which the team identifies safeguards used to mitigate the hazardous events, affords valuable information for considering SIL assignments.

Additionally, HAZOP has been combined with, and made consistent with Logic Trees (Fault & Event Trees), which are written and solved numerically in any complete risk analysis. When combined with Logic Trees, HAZOP becomes a powerful tool for plant design, allowing the designer to define the SIL in accordance with the appropriate event tree.

Summers (1998) examined the six most common PHAs utilized throughout the process industries, highlighting the HAZOP study as the most interesting technique for functional safety requirements because it provided a prioritized basis for implementing risk-mitigation strategies. Five years later, she suggested that the features of LOPA offer a powerful, analytical tool for assessing the adequacy of protection layers to mitigate process risk (Summers, 2003); again, HAZOP was deemed important in developing LOPA. The same point of view was considered in a study published in (Calixto, 2007). Dowell III (1998) followed the same direction, first describing the modified features of HAZOP for qualitatively assigning the required SIL, and then considering LOPA as a semi-quantitative technique for categorizing an event's severity, numerically estimating the initiating event's frequency, and obtaining numerical values of Probability of Failure on Demand (PFD) for each layer of protection. He concluded LOPA could be undertaken after HAZOP to calculate the needed SIL for most of SIS functions, and considering FTA for specific complex systems. Later, he illustrated specific criteria for generating scenarios automatically from HAZOP data to be employed in LOPA based on lesson-learned during HAZOP meetings and LOPA preparation (Dowell III &Williams, 2005).

Stavrianidis & Bhimavarapu (1998, 2000) discussed the requirements established for the two functional safety standards discussed above. They outlined the steps required to assign target SIL considering the scope of HAZOP, from identifying process hazards to developing accident scenarios for every initiating event. Thereafter, depending on the specific system, the application of several semi-quantitative or quantitative techniques will finalize the SIL procedure.

Finally, detailed information about LOPA features and application is contained in (Dowell III, 1997; CCPS, 2001; Marszal & Scharpf, 2002), sources that introduce the LOPA as a technique to be used between HAZOP (as a qualitative hazard identification technique) and Fault Tree Analysis (as a quantitative tool). Likewise, LOPA starts from the HAZOP results and semi-quantitatively accounts for the risk reduction of each safeguard by comparing risk values from the corporation's criteria for unacceptable risk. Moreover, if further detailed analysis is required, FTA can be applied.

### IV.1.3.5. Automating HAZOP: Expert Systems

The development of expert systems for automating HAZOP was undoubtedly 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. This section discusses the global efforts made towards this goal, arranging the studies under specific topics and authors. In discussing the authors, papers are taken chronologically. I especially note a 1996 review of the older work on PHA automation (Venkatasubramanian & Preston, 1996).

Parmar and Lees (1987a, 1987b) 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 (1976). One year later, Heino et al. (1988) 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. Other expert-system prototypes based on classical knowledge bases are proposed in (Weatherill & Cameron, 1989; Wang et al., 1991; Zerkani & Rushton, 1993; Heeyeop et al., 1994).

Weatherill & Cameron (1989) developed a prototype based on a PC version of Prolog, a language considered excellent for expressing logic and performing symbol manipulation. A basic inference engine was enhanced and tailored to become user-friendly, showing the potential use of HAZOP expert system in both educational and industrial environments. Wang et al., (1991) developed a 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 (Zerkani & Rushton, 1993) was developed, a 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. (1994) 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, and rule networks for consequences reasoning which used both forward and backward chaining. Readers interested in further information related to expert systems based on classical knowledge bases should address (Tait, 1994; Leone, 1996; Shimada et al., 1996; Miller et al., 1997).

One important factor to consider in managing HAZOP studies is the time required to execute the entire analysis. Freeman et al. (1992) 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 complexity of the system, and the experience of the HAZOP team leader. Five years later, Khan and Abbasi (1997) 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 the function of three parameters: number of P&IDs, complexity of P&IDs and the skills of the team leader. Chung (1993) developed a qualitative analysis of the behavior of a process plant. The system, termed QUalitative Effects ENgine (QUEEN), takes the topology of a plant as input and generates the complete SDG from a library of models describing individual units in the plants. Additionally, Chung introduced the first steps from the Artificial Intelligence research community focusing on automating the qualitative hazard-identification procedure. Later, Jefferson et al. (1995) used QUEEN as an engine to emulate various forms of hazard identification, particularly describing its employment as the basis of an automated hazard-identification tool, emulating conventional HAZOP studies.

Kang et al. (1999) formulated and developed the Automatic Hazard Analyzer (AHA) using the expert system shell G2 composed of three knowledge bases, viz., a unit, an organization, and a material. The first modeled a process unit in different terms of variable and function, the organizational knowledge base gave information about the spatial arrangement of process units and streams, and finally, the material – knowledge base considered the properties of the material according to the National Fire Protection Association's (NFPA's) code. The system also had three hazard-analysis algorithms: the deviation analysis, the malfunction analysis, and the accident analysis. This paper was the origin of future research by the same authors (Kang et al., 2001), a work that described and applied the model to olefin dimerization plants. The results showed that more possible accidents could be identified and that the development methodology had the ability to capture process hazards in terms of both functional failure and unexpected variable deviations, thereby improving the quality of the hazard analysis.

Galluzzo et al. (1998) described their methodology for HAZOP automation on continuous systems; it included both cause – and consequence – models. The former contained the data needed to propagate the deviations of variables from the unit backwards to the previous one to find the causes of deviations, including operative faults and failures. Nevertheless, several differences precluded the method's applicability to batch or semi-continuous systems due to its time-dependent nature.

For a batch plant, the procedural phases must be considered as nodes, in addition to the equipment unit. Accordingly, the authors developed software support, based on their previous work, by adding models to accommodate phases of the operational procedure and the equipment units (Galluzzo et al., 1999; Bartolozzi et al., 2000). Furthermore, Cocchiara et al. (2001) integrated a method for analyzing single interlock systems, starting from the output of the plant's HAZOP analysis.

Venkatasubramanian and his colleagues published numerous papers within the framework of automating HAZOP. First, Venkatasubramanian & Vaidhyanathan (1994) 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 & Venkatasubramanian (1995) 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 (Vaidhyanathan & Venkatasubramanian, 1996). For batch procedures, Srinivasan & Venkatasubramanian (1996) 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 (Srinivasan et al., 1997; 1998, Srinivasan & Venkatasubramanian, 1998a; 1998b, 1998; Venkatasubramanian et al., 2000; Viswanathan et al., 2000, 2002; Dash & Venkatasubramanian, 2003). Srinivasan et al (1997, 1998) integrated knowledge-based and mathematical programming approaches for process safety verification; an approach capable of performing exact analysis when required and thus overcoming qualitative ambiguity. Srinivasan & Venkatasubramanian (1998a, 1998b) 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 (Srinivasan & Venkatasubramanian, 1998c) expanded the scope of PHA automation, not only for hazard identification, but also for covering the entire PHA process. They proposed an integrated framework and a knowledge-based system, called PHAzer.

The system used 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. Further detailed information can be found in (Venkatasubramanian, M. L. Preston, 1996; Venkatasubramanian et al., 2000; Vaidhyanathan, V. Venkatasubramanian, 1996), references that afford a perspective on an intelligent system for PHA.

Khan and Abbasi also published much work on automating HAZOP. Their first paper (Khan and Abbasi, 1997a) 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 on 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 a new knowledge-based software tool, termed TOPHAZOP to speed up the OptHAZOP (Khan and Abbasi, 1997b). 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: Knowledge-base, inference engine, and user interface (Khan and Abbasi, 2000).

Further work to improve specific features of this system and other applications are reported in (Khan and Abbasi, 1998; Khan et al., 2001; Khan, 2005). In (Khan and Abbasi, 1998), the readers will find the state-of-art-review of the available techniques and methodologies for carrying out risk analysis in chemical process industries. Additionally, the paper presents a set of methodologies developed by Khan & Abbasi to conduct risks analysis. The same authors present a risk analysis methodology, called ORA (Optimal Risk Analysis) based on a set of tools and techniques developed previously by themselves (Khan et al., 2001).

Finally, Khan (2005) proposed a knowledge-based expert system for automating HAZOPs for offshore process facilities. The framework was aimed to enable HAZOPs at significantly lesser costs and with better accuracy than conventional HAZOPs. The framework associated an extensive and dynamic knowledge-base with the software which incorporated details of all typical process units and works out numerous modes of failure for given input operational conditions.

Similarly, the STOPHAZ project represents the major efforts made in Europe. The development of this project, financed by the European Commission, took important steps towards applying knowledge-based systems to safety analysis of chemical plants (Jefferson et al., 1995). The focus of the STOPHAZ project was to provide a software tool able to reduce the overall time taken to complete the safety study on a developed process design. Other work includes the development of a Qualitative Hazard Identifier (QHI) (Catino & Ungar, 1995), a system that used a set of qualitative equations derived from a quantitative description of the plant behavior. The set of equations was steady-state-simulated so that conclusions could be drawn from the resulting qualitative values of process quantities. The HAZOPTool (Karvonen, 1990) considered only one deviation in a single process unit at one time and offered its user the possibility of evaluating the generated candidate event chains after each step of this kind. Thus, the user had a major influence on which deviations and process units were studied more thoroughly and which of the considered event chains would be stored as part of the final HAZOP report. Finally, the COMHAZOP (Rootsaert & Harrington, 1992), as an aid for hazard and operability studies in process plant. Graf & Schmidt-Traub (2000, 2001) introduced a new model-based approach for identifying hazards creating qualitative equipment models, and implementing them with the state-chart language – state-transition diagrams facilitating the modeling of hierarchy and modularity, extremely helpful to chemical plants.

Recently, Bragatto et al. (2007) integrated Product Lifecycle Management (PLM) systems to support HAZOP analysis throughout the lifecycle of a process plant with a prototype software tool called IRIS. The tool usefully enriches and adapts the knowledge gained by analysis, and integrates the different documents managed by PLM systems.

Additionally, PLM systems aimed at an overall management of the plant's digital models, such as drawings, diagrams and 3D models, which represent the plant from different points of view, offer capabilities of automating the design process and linking the data produced during the various phases of project development. Ning LÜ & Xiong (2007) applied signed directed graphs to computer-aided HAZOP studies together with fault diagnosis that automatically finds all possible abnormal causes or adverse consequences. However, some problems remain, such as eliminating redundant consistent paths, and overcoming inherent qualitative ambiguities by combining SDG with quantitative information. Other recent work is described in references (Guimarães & Lapa, 2006; Trucco & Leva, 2007). Guimarães & Lapa (2006) developed a methodology which uses risk priority number to scale any parameter characteristics of the system and a fuzzy inference system for estimating risk from expert opinion about the quantification of the linguistic variables, named FuzzyHAZOP_rpn. Finally, Trucco & Leva (2007) developed a simulator for approaching human errors in complex operational frameworks (e.g., plant commissioning). The authors integrated the quantification capabilities of human reliability assessment (HRA) methods with a cognitive evaluation of the operator. The probabilistic cognitive simulator (PROCOS) directly evaluated how a corrective action influenced the probability of success or failure of a critical activity.

#### IV.1.3.6. 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. The purpose of this methodology is to determine risk from operational disturbances, and to develop the means for effective risk reductions (Ramzan et al., 2007a). Svandova et al. (2005) recently suggested complementing HAZOP studies with simulations. Eizenberg et al. (2006) introduced HAZOP into process-safety education, both for educational purposes and training operators. Combining HAZOP with dynamic simulation could offer students the means of 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. (2007a) 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 shown in a separate paper (Ramzan et al., 2007b). Labovský et al. (2007a, 2007b) integrated a mathematical-model approach with HAZOP analysis. They initially applied the methodology of a chemical reactor, highlighting the combination as a useful tool of equipment in all steps of its design, not only during its operational stage. The mathematical-model revealed deviations from normal operating conditions, and analyzed the response of the device. Later, the methodology was applied in a MTBE production unit to show 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.

### IV.1.4. Specific HAZOP Review Conclusions

HAZard & OPerability (HAZOP) methodology is a Process Hazard Analysis (PHA) technique used worldwide for studying not only the hazards of a system, but also its operability problems, by exploring the effects of any deviations from design conditions. This work is intended to gather HAZOP-related literature from books, guidelines, standards, major journals, and conference proceedings, with the purpose of classifying the research conducted over the years and define the HAZOP state-of-the-art on studies carried out in chemical process facilities. Likewise, this research not only reviews, but also categorizes the publications collected, and it should facilitate further access to information for those researching and practicing HAZOP. About 200 papers have been reviewed, covering a period from 1974, the year when the first formal HAZOP paper published, to the present. Over these thirty-five years, many authors have focused on improving specific HAZOP aspects, but most papers were published over the last fifteen years. The first and only HAZOP Standard was published in 2001.

The literature has been classified into six main areas, considering specific aspects for improving HAZOP and these areas have been organized chronologically to make the follow-up of the evolution of HAZOP research easer.

It has been found that early authors focused primarily on detecting the features of HAZOP (e.g., the contributions that could be analyzed). Later, authors conducted research aimed at extending theses features, and, as process facilities were evolving, they turned to exploring new deviations and control options. Independently, efforts began on automating HAZOP by developing expert systems; this is the most wide-ranging area of HAZOP research. Recently, authors have been displaying interest in merging HAZOP features with dynamic simulation, mainly for teaching purposes.

Based on the reviewed documents, the following contents highlight key conclusions that support efforts carried out and tendencies that have been under study:

The 80% of the total publications are related to three main areas: (1) Sharing HAZOP experience (18%), (2) HAZOP for Programmable Electronic Systems (22%), and, (3) Expert systems for automating HAZOPs (40%). Sharing professional expertise (e.g., providing valuable information on how to treat specific situations, new applications and approaches), is considered to be a key feature in training team leaders, HAZOP managers, and team members. On the other hand, HAZOP for Programmable Electronic Systems (e.g., research focused on adapting HAZOP features for reviewing new technologies) is considered fundamental for keeping HAZOP up-to-date.

HAZOP is the foundation of process safety – and risk – management programs. It is the most studied PHA method; indeed, abundant research has centered on re-adapting HAZOP as process systems evolved. However, the first and only HAZOP Standard needs to be enhanced (e.g., it does not include guidance on how to break a process into nodes). It is noted that valuable advances have been made by developing expert systems for HAZOP automation. These findings do much to illuminate specific processes, their aspects and particularities, but most HAZOPs in the process industry are still being conducted by human expert teams.

Considering the HAZOP state-of-the-art and engineering judgment on conducting hazard identification analysis, it has been identified that more research is needed in addressing the following issues:

a) HAZOPs conducted by human beings are subject to the analyst's bias, experience, knowledge, and creativity. One should attempt to gain knowledge from the experience of parties involved, but also it could be valuable to standardize the HAZOP structure for processes that present equivalent technology (e.g., petroleum-refining processes).

b) A related human-factor issue appears when hazard identification is focused, not only on analyzing typical process deviations, but also initiating events led by human errors. These events normally present higher frequencies of occurrence than others (e.g., a control failure). While endeavors have been focused on improving the expert team motivation for finding these types of causes, their integration into the HAZOP structure still remains incomplete.

c) Identifying causes and hazardous scenarios from programmable electronic systems (PES). Improvements could be made when looking for potential causes of control device failures. When linking the HAZOP results to other techniques intended for gathering Safety Integrity Level (SIL) values of Safety Instrumented Systems (SIS) to be implemented, the list of initiating events that could lead to the hazardous scenario may not be complete (e.g., why the Level Control Valve is not closing when analyzing a higher level?). This deviation could be caused by an error in the sensor, due either to the logic solver or the actuator (for many causes). Including a detailed failure mode for PES would more easily facilitate the subsequent analysis for SIL needs of risk reduction.

d) Most endeavors for standardizing HAZOP studies have been made with the aim of automating its execution. Expert Systems development is the most powerful tendency in the evolution of HAZOP, and disciplines, such as process engineering and artificial intelligence, have been merged. Knowledge bases, petri-nets, signed digraphs and other principles have contributed to better understand the 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 is needed to effectively apply them in hazard identification and loss prevention.

According to the HAZOP limitations identified, the following research needs should be addressed for improving HAZOP applications:

1. Development of a node-selection methodology for guiding team leaders through the process documentation – Process Description, PFDs, P&IDs, Plot Plan – with the aim of detecting specific design intents, and defining their boundaries.

2. Improvement of HAZOP time-estimation models thereby simplifying the current cumbersome models.

3. Development of a structural hierarchy for defining a set of deviations namely (1) define the minimum set of deviations for ensuring that key hazardous scenarios are identified, and, (2) define their order of application, avoiding repetitive analysis and strengthening the HAZOP structure itself. These properties will better guide team leaders and will favor standardization.

4. Development of guidelines on how to fulfill a HAZOP worksheet, defining what information has to be placed in each column, and how to report that information to ensure the maximum level of understanding, not only for HAZOP members, but also for external concerned parties.

Finally, it is important to mention that most of the contents of this specific work have been published in a recognized scientific journal (Dunjó et al., 2010):

Jordi Dunjó, Vasilis Fthenakis, Juan A. Vílchez' and Josep Arnaldos, (2010). Hazard and operability (HAZOP) analysis. A literature review. Journal of Hazardous Materials 173 (1-3), pp. 19-32.

After highlighting the HAZOP state-of-the-art, the research needs that should be addressed, and also the main legislation gaps related to hazard identification (Introduction of the document), the following contents of the manuscript are intended to show what has been studied, how it has been analyzed, and finally, the results reached. The following stages were necessary to finally achieve the research purpose: (1) HAZOP Training, (2) Conducting HAZOPs (i.e., field work and data analysis), and (3) Methodology, results, and conclusions.

## IV.2. HAZOP TRAINING

### IV.2.1. HAZOP Training Course

It was necessary to acquire knowledge on the HAZOP methodology itself prior to starting the analysis of continuous chemical processes. While one of the key aspects for conducting HAZOPs is based on the experience and skills of the team leader, it was considered essential to participate on a recognized training course, a fact that provided knowledge not only on the HAZOP features, but also on many other issues totally related to process safety and hazard identification. Furthermore, OSHA expects that PHA team leaders be qualified to lead PHAs, either by experience prior to the establishing of the PSM standard (1992), or through training.

Through a recognized US Process Safety Consultancy, I had the opportunity to attend a world recognized training course related to HAZOP studies for team leaders. The course helped prepare team leaders for facilitating PHA study teams. In addition to receiving expert instruction on the technical and managerial procedures involved in leading a PHA team, I had the opportunity to form a study team with other participants and take turns leading the team. The workshops were overseen by an instructor who gave feedback on performance. This fact was useful to discover the tactics and success factors that help ensure a successful study. The benefits of attending the mentioned training course favored the following facets:

- To acquire detailed guidelines for facilitating HAZOP studies.
- To receive guidance and instruction that has been drawn from experience in actual facilities.
- To share experience with other participants and the instructor.
- To better understand both the regulatory requirements and the best practices for promoting safer and more secure processes.
- To be aware of present weaknesses in the methodology.
- To be familiar with complex P&IDs.
- To acquire experience and criteria for developing the present work.

### IV.2.2. Conducting HAZOPs

At this point, the required training for understanding both petroleum-refining process complexity and HAZOP features is based on the following tasks:

(1) Review of the most relevant research related to HAZOP development, a task which helped to better understand HAZOP evolution and present weaknesses.

(2) Analysis of accurate drawings related to petroleum-refining processes, a task which provided the ability to read and understand these processes for the assessment of safety, environmental and regulatory compliance issues such as HAZOP studies.

(3) Participation in a HAZOP training course, a task which provided the industry's practical point of view thereby sharing knowledge and experience with other process safety consultants. Additionally, it was possible to act as a team leader in a planned HAZOP study.

The present section presents the last required task needed for establishing criteria on conducting HAZOPs in petroleum-refining processes: (4) the participation in real HAZOPs.

It was possible to attend 8 different HAZOP studies of petroleum-refining processes, participating in several roles with the aim of being aware of the most relevant factors that influence both quality and results: (1) as a listener, taking the required time to decide how experimental data should be acquired, (2) as a team member, trying to understand and participating in the brainstorming sessions, (3) as a scribe, a fact that allowed me to become aware of how documentation should be written.

While the first three HAZOPs have taken into account the preliminary studies for detailed definition as to which variables and factors had to be recorded and be the focus of improvement, the last 5 studies were applied and continuously improved. The final methodology, considered to be the most appropriate to follow, has been illustrated in *Chapter VI - Methodology*.

Several factors were changed during the HAZOP studies conducted with the aim of emphasizing their importance and finally deciding the best potential combinations between them: number of team members, team members' roles, team leaders, scribes, HAZOP meeting rooms, HAZOP tables' layout, size of nodes selected, etc. All of these factors have been the basis for defining the following aspects and steps of HAZOP studies conducted in continuous chemical processes:

- Why and when to apply a HAZOP study.
- Definition of specific project manager responsibilities.
- How to define the purpose, scope and objectives of a HAZOP study.
- Definition of the "mandatory" team members.
- Definition of the minimum HAZOP information and how to convert it to a suitable form.
- Establishing the "game rules" of the study – Risk ranking criteria.
- Development of a node selection procedure.
- Definition of a new global node concept for extending hazard identification features.
- Development of a mathematical model for HAZOP time estimation.
- Definition of criteria for planning the study and arranging meetings.
- How to generate the appropriate deviations by combining guidewords and parameters.
- Development of a Deviation Structural Hierarchy (DSH) both for specific and general parameters.
- How to structure the brainstorming sessions.
- How to fill out HAZOP worksheets.

The 5 petroleum refining processes hazoped are the following: (1) Atmospheric distillation (including Desalting); (2) Gas Separation; (3) Alkylation (hydrofluoric acid process); (4) Hydrodesulfurization; and (5) ETBE production. *Chapter V - Field Work and Data Analysis* analyzes data acquired from these five HAZOPs, numerical data which has been shown in *Annex III* of the present manuscript (Experimental Data).

# CHAPTER V. FIELD WORK AND DATA ANALYSIS

The aim of this chapter is to analyze the data collected while preparing, organizing, executing and writing HAZOPs in five petroleum-refining processes. A statistical analysis of the different variables considered may help and provide guidance on taking decisions and conclusions on how to proceed in all HAZOP-related phases. The full set of data collected can be found in *Annex III* of the present manuscript, and the proposed methodology to carry out HAZOPs based on this analysis is fully described in *Chapter VI - Methodology*. However, graphical resources such as PFDs, P&IDs, and other key information used when reviewing the mentioned processes are not shown due to confidentiality issues.

## V.1. DATA ANALYSIS

### V.1.1. Key variables considered

Petroleum-refining processes are complex to understand. A plethora of unit operations and specific control devices and equipment are carefully linked to achieve the pursued goal. Additionally, the analysis of the most relevant aspects of HAZOP studies performance requires taking into account several key variables. For these reasons, the whole package of considered variables has been classified according to the HAZOP phase to which they apply. Likewise, after conducting the mentioned HAZOPs and deciding which is the most appropriate way to treat the collected variables, it became clear to classify them into independent groups for numerical analysis. Hereafter, the following contents define the four groups considered, their intention, as well as the related variables that have to be analyzed:

- Main data that describes both HAZOP dimension and the process analyzed: the variables are intended to develop a HAZOP time-estimation model able to predict the expected time for conducting the study.

The list of variables is:

- ✓ Number of process description pages (PDescription)
- ✓ Number of Process Flow Diagrams (PFDs)
- ✓ Number of Piping & Instrumentation Diagrams (P&IDs)
- ✓ Number of pieces of Major Equipment (ME)
- ✓ Number of Nodes (Nd)
- ✓ Total time required to prepare and organize the study ($T_P$)
- ✓ Total time required to execute the study ($T_S$)
- ✓ Total time required to write the draft report ($T_W$)

- Specific data that describes nodes selection methodology applied: variables are intended to extract valuable information on the time required to decided and highlight the extension and features of nodes that will be reviewed during brainstorming.

The list of variables is:

- ✓ Number of Principal Sections (PS)
- ✓ Time to select Principal Sections on PFDs ($T_{PS}$)
- ✓ Number of nodes per Principal Section (Nd/PS)
- ✓ Time to select Nodes on PFDs ($T_{NdPFD}$)
- ✓ Time to transfer Nodes from PFDs to P&IDs ($T_{NdP\&ID}$)

- Specific data that describes the structure of selected nodes: variables are intended to define the "structural" features of nodes selected. This information takes into account which process equipment is part of the selected node and should be valuable in order to analyze nodes sizing coherence.

The list of variables is:

- ✓ Number of pieces of Major Equipment (ME)
- ✓ Number of Flow Control Valves (FCVs)
- ✓ Number of Level Control Valves (LCVs)
- ✓ Number of Pressure Control Valves (PCVs)
- ✓ Number of Temperature Control Valves (TCVs)
- ✓ Number of Pumps (Pumps)
- ✓ Number of Exchangers (Exchangers)

- Key data that describes brainstorming sessions: during brainstorming sessions not only was data recorded for considering the time required to analyze each node, but also other factors that directly affect the HAZOP success.

The list of variables is:

- ✓ Time required to brainstorm a node ($T_{BTNd}$)
- ✓ Number of sessions where the node has been brainstormed (N)
- ✓ Number of expert members present in the session (Members)

### V.1.2. Numerical Analysis

The numerical analysis is basically intended to assess and compare sample distributions for each variable or groups of variables collected, to examine their shape and spread, and also, if possible, to find a relationship between variables. The most common and most-used tools to develop this work are the following (Minitab, 2004):

a. Individual Value Plot: a tool used to assess and compare sample distributions by plotting individual values for each variable or group of variables, making it easy to spot outliers and see the distribution shape.

b. Histogram: a tool used to examine the shape and spread of the sample data. Histograms divide sample values into many intervals called “bins”. Bars represent the number of observations falling within each “bin” (its frequency).

**c. Residual Plots:**

c.1. Histogram of residuals: an exploratory tool to show general characteristics of the data, including typical values, spread or variation, shape and unusual values in the data.

c.2. Normal plot of residuals: the points in this plot should generally form a straight line if the residuals are distributed normally. If the points on the plot depart from a straight line, the assumption of normality may be invalidated.

c.3. Residuals versus fitted Values: a tool intended to show a random pattern of residuals on both sides of 0. If a point lies far from the majority of points, it may be an outlier. Also, there should not be any recognizable patterns in the residual plot.

c.4. Residuals versus order: This is a plot of all residuals in the order that the data was collected and can be used to find non-random error, especially of time-related effects. While a positive correlation is indicated by a clustering of residuals with the same sign, a negative correlation is indicated by rapid changes in the signs of consecutive residuals.

d. ScatterPlot: a tool used to show the relationship between two variables by plotting one against the other.

e. Fitted Line Plot: a procedure that performs regression and plots a regression line through the data. Polynomial regression is one method for modeling curvature in the relationship between a response variable (Y), and a predictor variable (X) by extending the simple linear regression model to include $X^2$ and $X^3$ as predictors.

f. Boxplot: a tool also called “box-and-whisker plot” to assess and compare sample distributions.

g. Chart Bars: a tool used to compare some measure of data categories. It has been used to show the measurement of the mean.

h. Graphical Summary of Basic Statistics: a tool used to produce a graphical summary of basic statistics of the measured data. This includes the histogram of data with an overlaid normal curve, boxplot, 95% confidence intervals for the mean, and 95% confidence intervals for the median. These graphs have been shown at the end of *Annex III – Experimental Data*.

### V.1.2.1. Analyzing the HAZOP dimension and process complexity

Part of the analysis of the main data that describes both HAZOP dimension and process complexity has been included in *Chapter VI – Methodology* of the manuscript. This fact is due to the fact that results obtained from this analysis are ready-to-use by interested parties that desire to apply the methodology directly. However, although only a basic analysis has been carried out here, the main conclusions leading from it will be illustrated later. Therefore, the main conclusions attempt to show a mathematical model that predicts the required time to conduct a HAZOP study from its preparation and organization to the first draft of the HAZOP report. This includes the following tasks:

- To collect and organize the key data needed to performance a HAZOP
- Time to execute the HAZOP brainstorming sessions
- Time to prepare the first draft of the HAZOP report

These three factors have been analyzed to find relationships between factors that inherently define the complexity of the process to be “hazoped” (i.e., number of pieces of major equipment, number of P&IDs, number of PFDs, total amount of “minor” equipment – e.g., FCVs, Pumps - present in the process). After many combinations, all of them studied both from the point of view of mathematics and process safety matters, it was possible to establish well-suited regression between the total time expected to complete a HAZOP study in continuous chemical processes (first response) and the expected number of nodes to be selected (second response) by considering the following variables (predictors):

- ME: Number of pieces of major equipment present in the process
- P&IDs: Number of P&IDs required to define the process

Thus, the total time required to conduct a HAZOP study is defined as follows:

$$\mathbf{T_H = T_P + T_S + T_W} \qquad \textbf{(V.1)}$$

- $T_H$: total time to perform the HAZOP study, in hours (h)
- $T_P$: time to define, prepare and organize the study, in hours (h)
- $T_S$: time to execute the study via brainstorming sessions, in hours (h)
- $T_W$: time to write the first draft of the HAZOP report, in hours (h)

The key data used to develop these models are shown in table V.1.

**Table V.1**. Key data required for modeling.

| HAZOP | P&IDS | ME | Nd | $T_P$ (h) | $T_S$ (h) | $T_W$ (h) | $T_H$ (h) |
|---|---|---|---|---|---|---|---|
| A | 14 | 20 | 14 | 16 | 40 | 6 | 62 |
| B | 15 | 21 | 15 | 18 | 48 | 5 | 71 |
| C | 22 | 19 | 16 | 20 | 54 | 8 | 82 |
| D | 24 | 23 | 18 | 25 | 60 | 9 | 94 |
| E | 25 | 30 | 19 | 30 | 65 | 13 | 108 |

A simple regression using least squares has been performed. Apart from fitting general least squares models, also the following tasks have been conducted: (1) storage of the regression statistics, (2) examination of the residual diagnostics, and (3) generation of prediction (PI) and confidence (CI) intervals. The $T_P$ model is shown in Figure V.1.

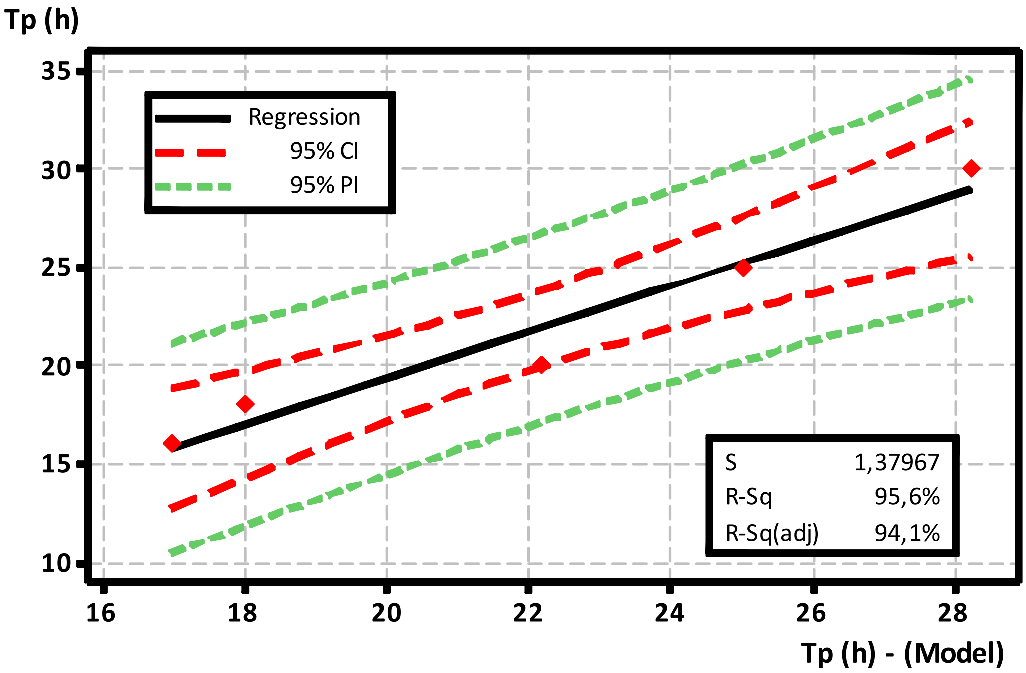

**Figure V.1.** Fitted Line Plot - Actual $T_p$ versus $T_p$ model.

The resulting equation to determine the time to define, prepare and organize the study, is:

$$T_P\ (h) = 0.698 \cdot P\&IDs + 0.359 \cdot ME \qquad (V.2)$$

The normal probability plot of the residuals, the residuals versus the fitted values, the histogram of the residuals and the residuals versus the order of the data are shown in Figure V.2.

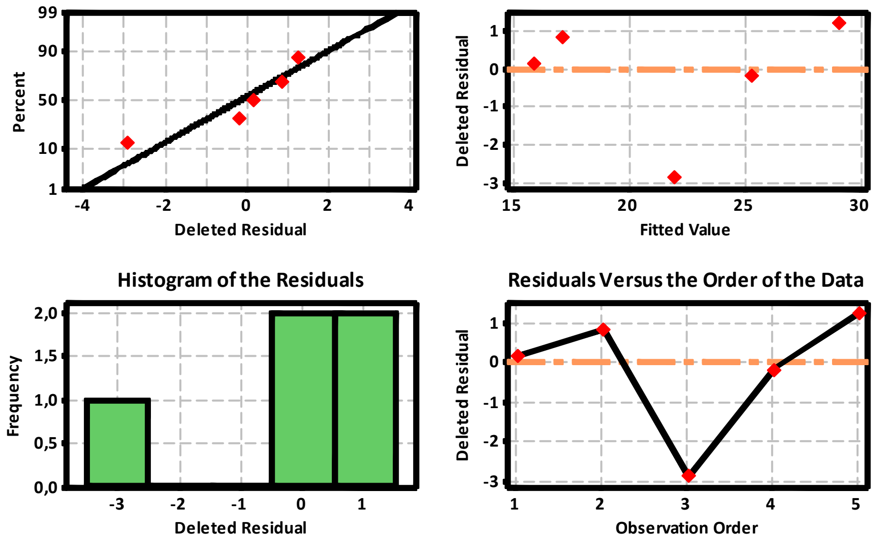

**Figure V.2.** Residual Plot for $T_P$.

Additionally, a regression using least squares has been conducted with the aim of predicting the expected number of nodes to be selected. The predictors used for this purpose are the same for $T_p$ modeling: ME and P&IDs. The results of the regression are shown in Figure V.3.

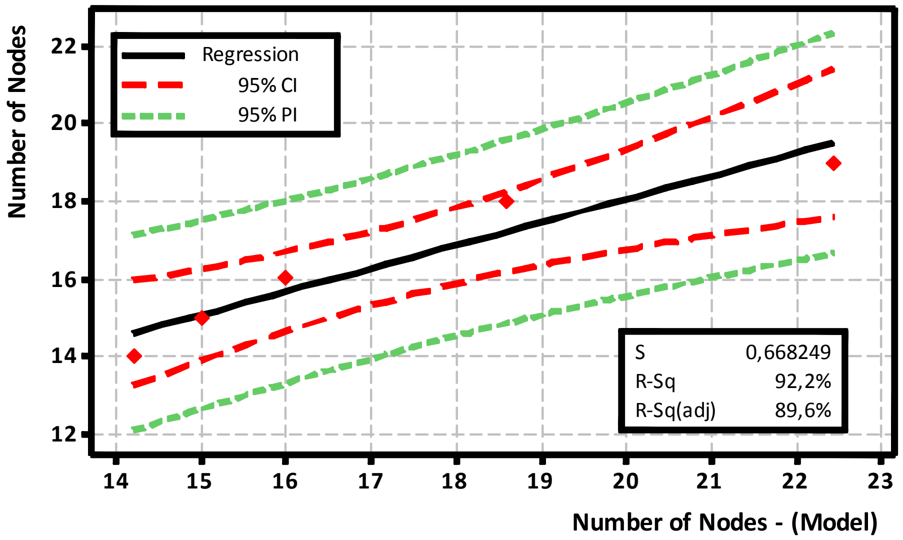

**Figure V.3.** Fitted Line Plot - Actual Nd versus Nd model.

The resulting equation to determine the number of nodes to be selected is:

$$\mathbf{Nd = 0.288 \cdot P\&IDs + 0.508 \cdot ME} \qquad \textbf{(V.3)}$$

Again, the normal probability plot of the residuals, the residuals versus the fitted values, the histogram of the residuals and the residuals versus the order of the data are shown in Figure V.4.

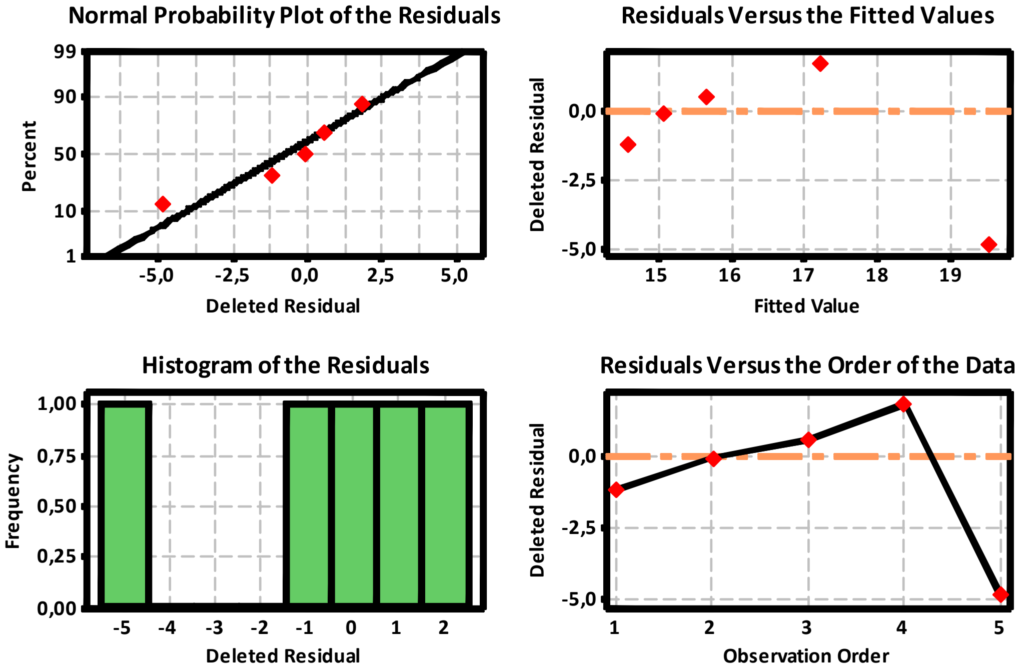

**Figure V.4.** Residual Plots for Nd.

Regarding the $T_s$ factor, it is necessary to separate the treatment of the first node (which takes more time than the others due to additional aspects conducted during the first HAZOP session), from the rest of them. This fact is fully explained and justified later in this Chapter, and also in *Chapter VI - Methodology*. For this reason, the following contents only provide the procedure followed to obtain the $T_S$ prediction model:

- Time to brainstorm the first node: the mean value equals 5.52 hours, and after conducting a t-test, it is possible to ensure, with a 95% confidence, that the time required to brainstorm them will take between 4.98 and 6.05 hours. A conservative rule of thumb to take into consideration is that the review of a first node will take 6 hours.

- Time to brainstorm process nodes: the mean value equals 3.01 hours, and after conducting a t-test, it is possible to ensure, with a 95% confidence, that the time required to brainstorm the first node will take between 2.91 and 3.11 hours. According to this close interval, a realistic rule of thumb to take into consideration is that the review of the process nodes will take 3 hours. (Here global nodes have been identified as process nodes).

By taking into account these two assumptions, the $T_s$ can be modeled as follows:

$$T_S\ (h) = 3 \cdot (1 + Nd) \qquad \text{(V.4)}$$

Finally, the time for documenting the HAZOP study ($T_W$) has been modeled as a function of $T_P$ according to previous work (Freeman et al., 1992; Khan & Abbasi, 1997) (Equation V.5); it accounts for the time required for revising the information generated during brainstorming, the HAZOP first draft.

$$T_W\ (h) = 0.40 \cdot T_P \qquad \text{(V.5)}$$

Therefore, the final expression for the total expected time to conduct a HAZOP study is the following:

$$T_H\ (h) = 3 + 1.841 \cdot P\&IDs + 2.027 \cdot ME \qquad \text{(V.6)}$$

Figure V.5 compares the actual values of the total time required to perform a HAZOP study and the proposed model.

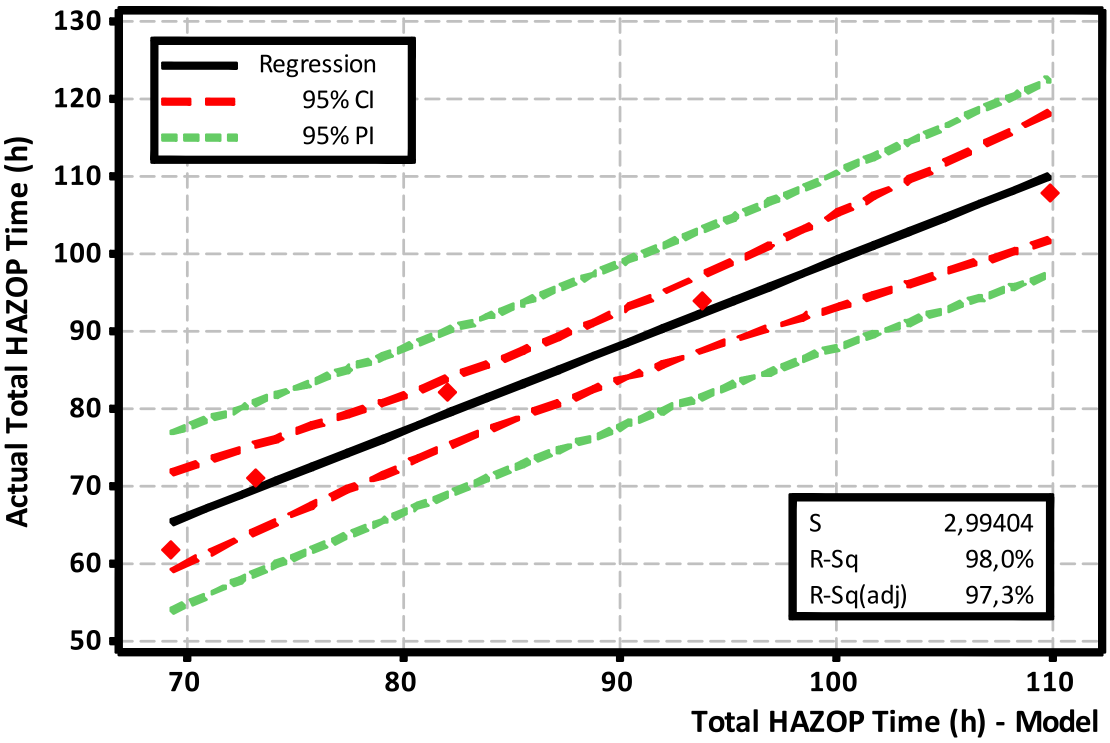

**Figure V.5.** Fitted Line Plot – Actual $T_H$ versus $T_H$ Model.

Figure V.6 shows the residual plots for the total HAZOP time.

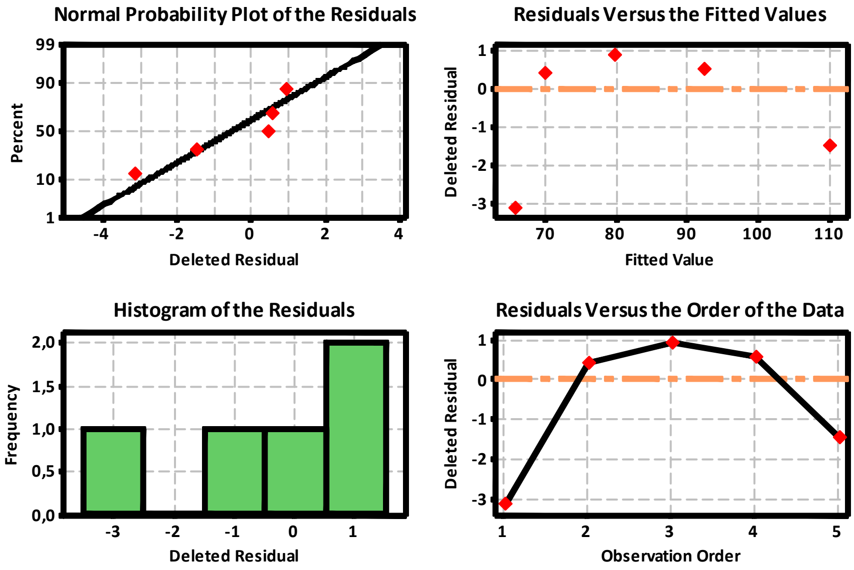

**Figure V.6.** Residual Plots for the Total HAZOP Time – (Eq. V.6).

Finally, and only so as to know the order of magnitude of a HAZOP that has to be performed, a team leader could apply the following easy-to-use and easy-to-remember expression (Equation V.7) for predicting the total HAZOP time. This expression also complies with the 95% CI shown in Figure V.5.

$$\mathbf{T_H\ (h) = 3 + 2\cdot(P\&IDs + ME)} \qquad \mathbf{(V.7)}$$

The residual plots for the total HAZOP time predicted by using equation V.7 (see Figure V.7) are practicably equivalent of which have been shown in Figure V.6.

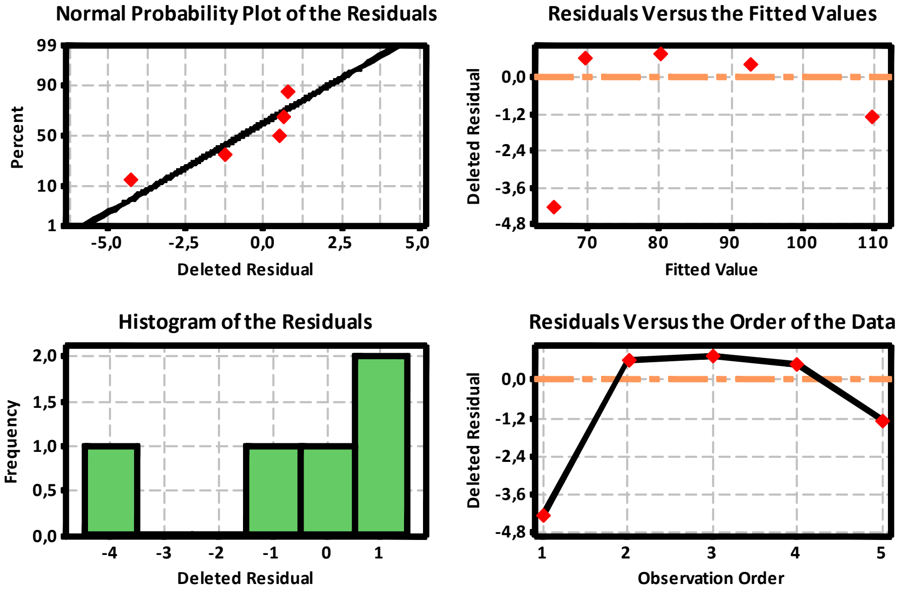

**Figure V.7.** Residual Plots for the Total HAZOP Time – (Eq. V.7).

### V.1.2.2. Analyzing data that describes the nodes selection methodology

Time to select the Principal Sections on PFDs

The following contents review data collected from the time required to decide and select the Principal Sections (PS) on PFDs. Figure V.8 shows the individual value of the time to select Ps on PFDs:

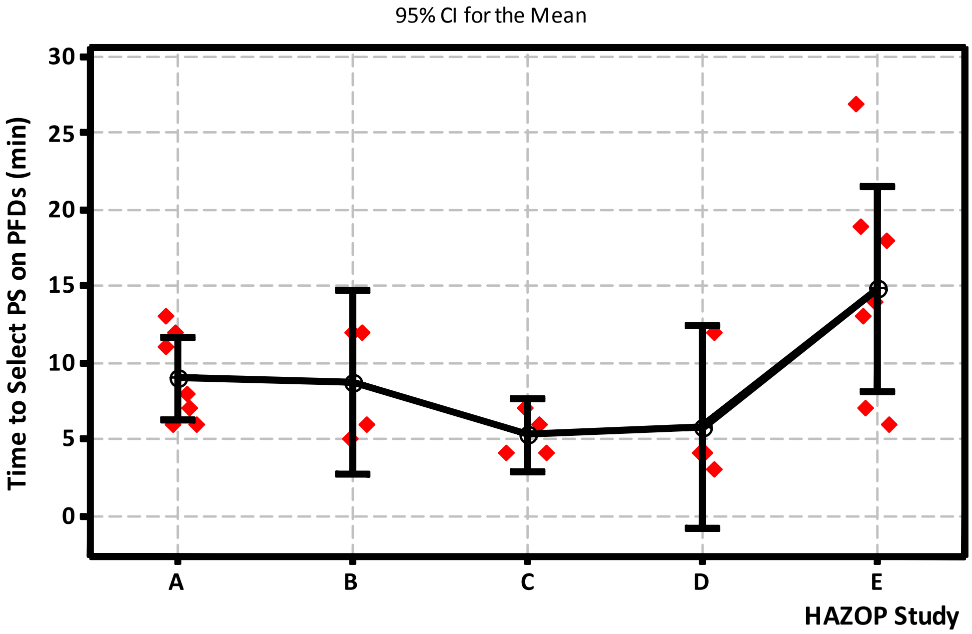

**Figure V.8.** Individual Value of the Time to select PS on PFDs versus HAZOP.

Basic statistics of the time required to select PS on PFDs are shown in Figure V.9.

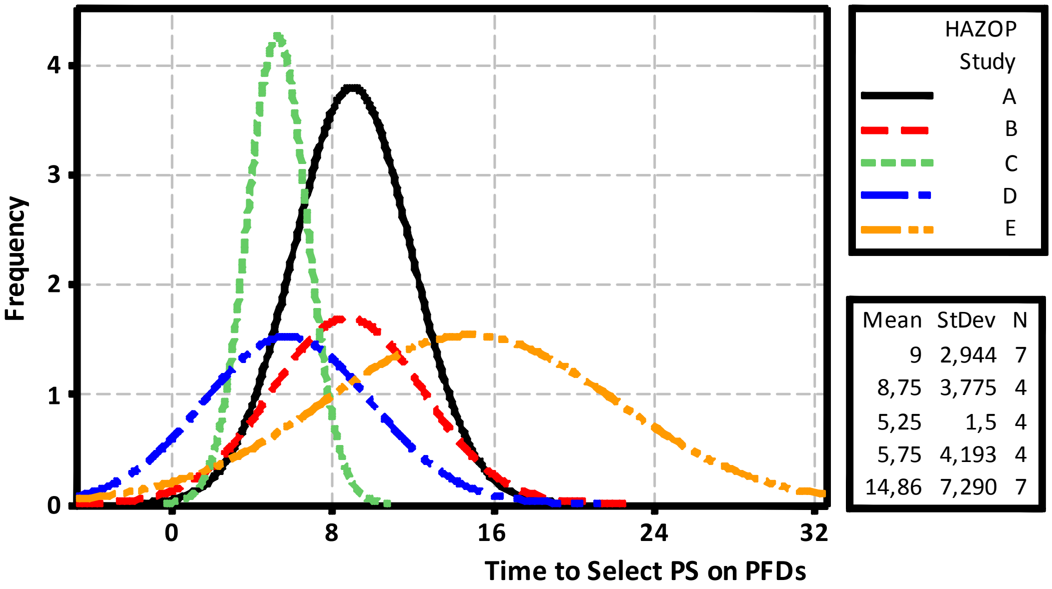

**Figure V.9.** Histogram of the Time to select PS on PFDs.

Figure V.10 shows the residual plots for the time to select PS on PFDs.

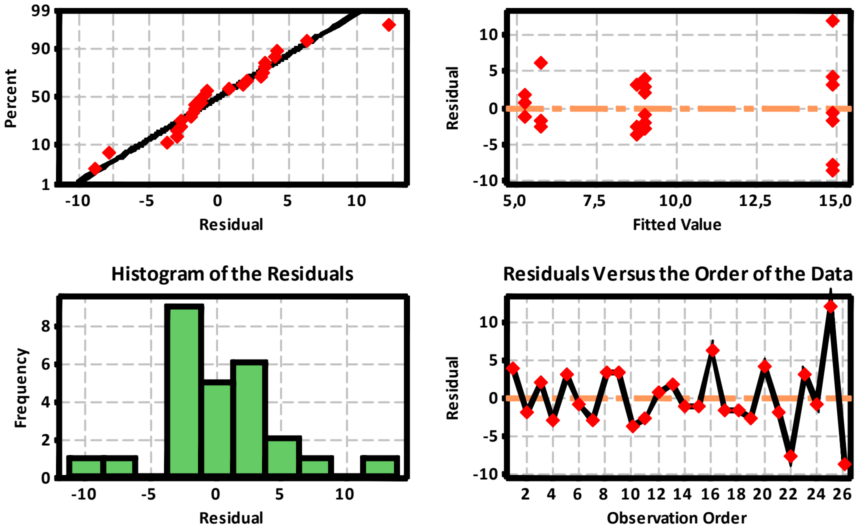

**Figure V.10.** Residual Plots for the Time to select PS on PFDs.

The key documentation that supports the PS selection is: the process description contents (which can be more or less detailed), and the PFDs (which can be more or less congested from the point of view of the number of pieces of equipment present in a specific PFD). Thus, the ratio between number of pages used to describe the process (the level of detail), and the number of PFDs (a measurement of diagrams congestion) should influence on the required time to select the PS (most evidence should be depicted if involved a team leader without experience). The following chart (Figure V.11) shows the ratio of the following two variables as a function of the HAZOP study reviewed: number of pages used to describe the process features, and the number of PFD used to represent the main process equipment connections.

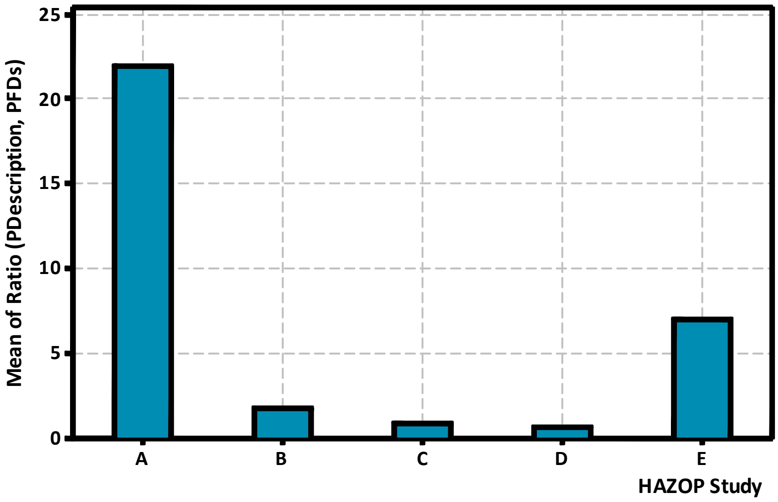

**Figure V.11.** Mean Ratio of [PDescription/PFDs] versus HAZOP.

Comparing the time required to select PS and the PDescription/PFDs ratio, it is assumable that IF the ratio drops, the time to select PS will also be lower. This fact is confirmed focusing on HAZOPs B, C and D. Additionally, and comparing HAZOPs A and E, studies that present an equivalent number of pages to describe the process (22 and 21 pages, respectively), it can be stated that HAZOP A requires less time to select the PS. Thus, the only variable that can explain these differences is the number of PFDs. While HAZOP A presents only one PFD, the HAZOP E takes three diagrams to describe the process. The ratio is less in HAZOP E rather than HAZOP A, but the time required to select principal sections is greater in HAZOP E. This is explained by introducing a new variable in the present analysis: the number of P&IDs, which are 14 for the HAZOP A; and 25 for the HAZOP E. The number of P&IDs is valuable information that takes into consideration the process complexity, and confirms that more time is required to understand the process analyzed via HAZOP E, i.e. more time to select PS.

The process description (i.e. number of pages that describe the process features, the number of PFDs and P&IDs) affect the time required to select nodes. That means it is important to take into account these variables when developing the basic engineering of a process (e.g., equipment congestion in diagrams, description of the level of detail of process characteristics). The decision on how to describe a process (with the point of view of optimizing a HAZOP performance) is out of the scope of the present research. Furthermore, all these factors were studied with the aim of establishing a relationship between them and the time required to select the principal sections, but no coherent correlation has been found. Subjective factors such as: team leader experience, clarity in process description contents, and also the availability to understand PFDs and P&IDs, directly affect it. However, and after considering the whole set of HAZOPs analyzed, a t-test performance states that, with a 95% of confidence, the time required to select an individual PS will take between 7.17 and 11.76 minutes. A conservative rule of thumb could be to consider 10 minutes per PS, obviously, only for guidance and not as a strict rule. This should help inexperienced team leaders to have an idea about time requirement.

Finally, and focusing on the number of PS selected, it could be possible to establish guidance from it. It is not possible to standardize the number of PS to be selected as a function of basic process data. The following reasoning can be followed:

- A t-test focused on the number of nodes present per PS states a 95 % confidence interval of (2.36-3.56), i.e., mean = 2.96 (see *Annex III* for further information).
- A t-test focused on the number of major equipment present per node states a 95% confidence interval of (1.30-1.63), i.e., mean = 1.47 see *Annex III* for further information).

Taking as 3 the mean number of nodes present in a PS, and 1.5 the mean number of major equipment per node, the team leader should size PS with a number of major equipment no more than 6, and no less than 3. As an optimum number, also validated via engineering judgment, well-sized PS will take 4 or 5 major equipment.

Time to select nodes from Principal Sections on PFDs

The following contents review data collected from the time required to decide and select the preliminary nodes on PFDs.

Figure V.12 shows the individual value of the time to select nodes on PFDs for HAZOP studies conducted.

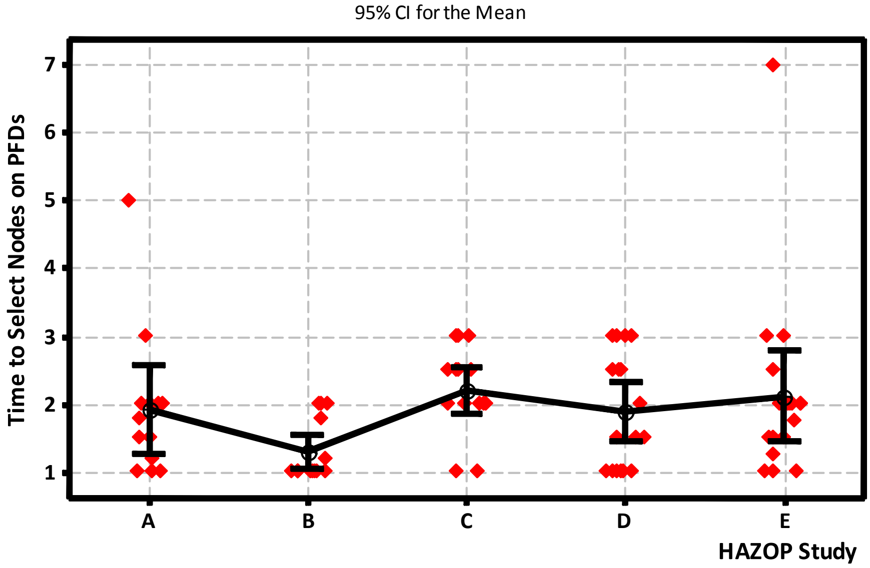

**Figure V.12.** Individual Value of the Time to select Nd on PFDs versus HAZOP.

Basic statistics of preliminary nodes timing are shown in Figures V.13 and V.14.

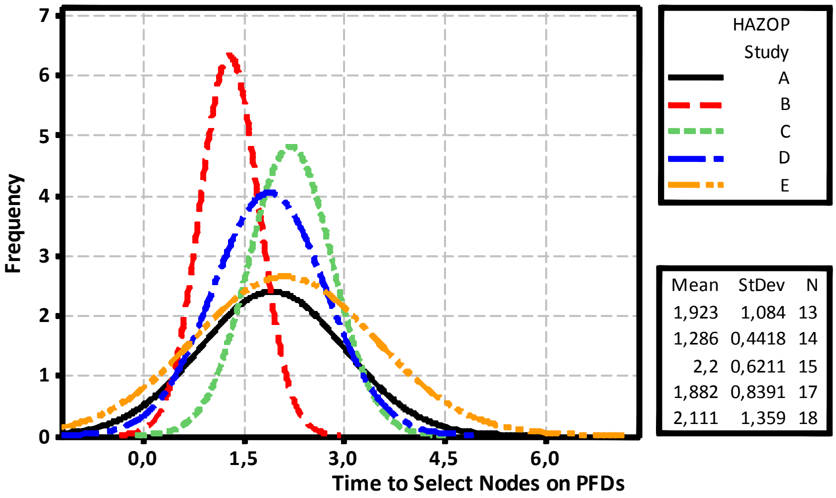

**Figure V.13.** Histogram of the Time to select Nd on PFDs.

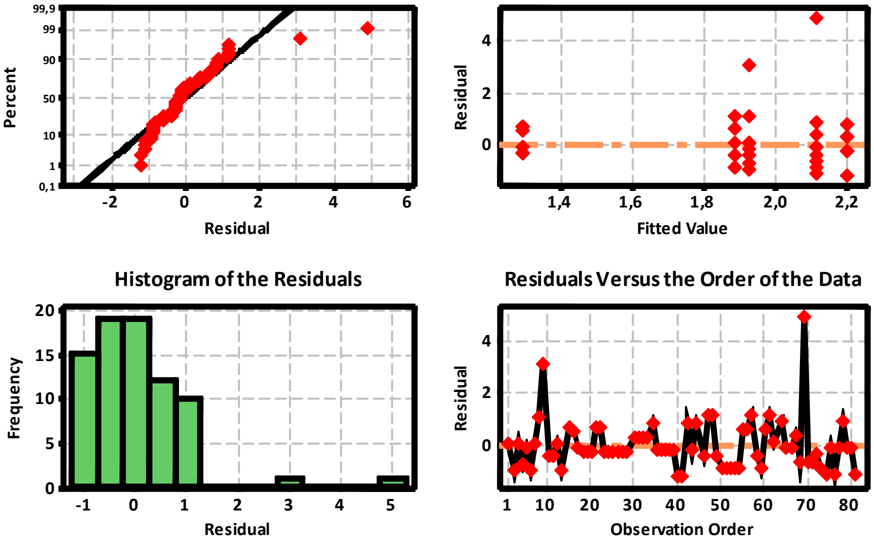

**Figure V.14.** Residual Plots for the Time to select Nd on PFDs.

Basic statistics highlight that two points could be considered as outlier points, and thus, take them off of the analysis. The first point (HAZOP A) is a node that takes 5 minutes to be selected. It is present in a PS that contains two nodes, and the number of pieces of major equipment that defines itself as 3. According to the previous analysis, this node complies with “normal” featured nodes, and, it has been decided, does not consider it as an outlier point. However, the second point (HAZOP E) takes 7 minutes for its selection and its main features are the following: (1) it comes from a PS that only contains the mentioned node; (2) it takes 4 major piece of equipment for its definition.

These characteristics present divergence to the rest of nodes selected, and for this reason will be not considered for further analysis. Also the reasoning established in the present paragraph confirms coherence when considering the optimum node and PS sizing in relation to the time needed to define them. Hereafter, a t-test applied to the time required to select preliminary nodes establish a 95% confidence interval of 1.67 and 2.12 minutes, where the mean equals to 1.90. But after excluding the outliner point, this interval closes to 1.63 and 1.95 minutes. Finally, and taking into account the minimum time required to select preliminary nodes, a rule of thumb could state that a node will take 2 minutes to be selected, and additionally: (1) it comes from a PS that contains 2 or 3 nodes, (2) the amount of major equipment present in the node will be 1 or 2. While no individual values are possible to exactly define these studied features, small intervals depicted (CI) not only help to understand the methodology, but also confirm the optimum size and time both for PS and nodes.

Time required to transfer nodes from PFDs to P&IDs

The following contents review data collected from the time required to decide and select the detailed nodes on P&IDs.

Figure V.15 shows the individual value of the time to select nodes on P&IDs for HAZOP studies conducted.

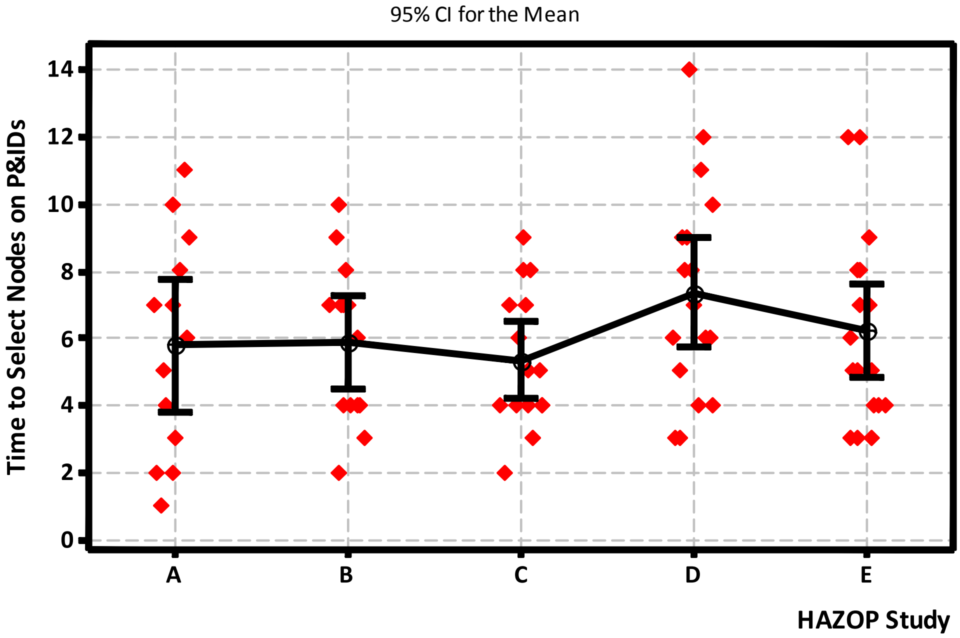

**Figure V.15.** Individual Value of the Time to select Nd on P&IDs versus HAZOP.

Basic statistics of detailed nodes timing are shown in Figures V.16 and V.17.

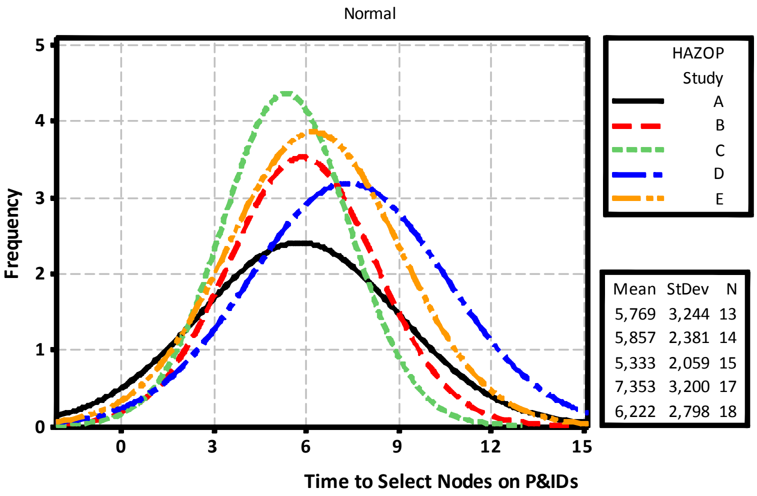

**Figure V.16.** Histogram of the Time to Select Nd on P&IDs.

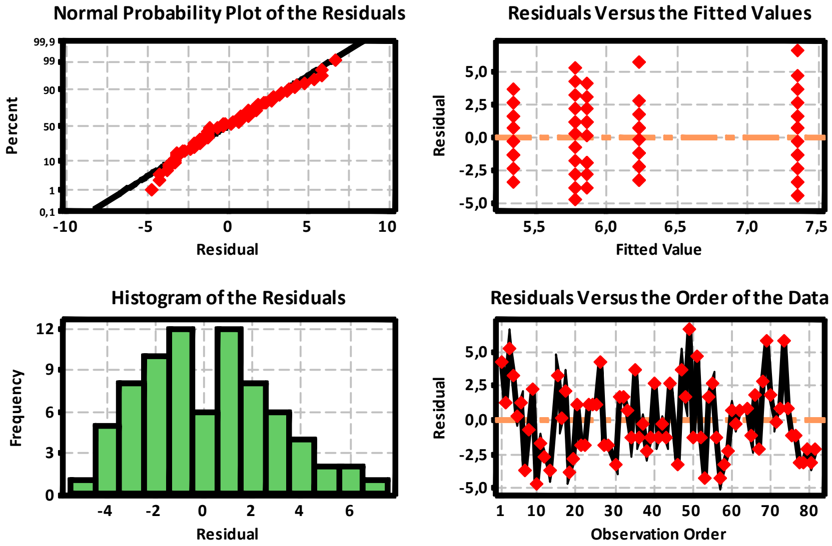

**Figure V.17.** Residual Plots for the Time to Select Nd on P&IDs.

A t-test focused on the time required to select detailed nodes states a 95% confidence interval of (5.52-6.79), i.e., mean = 6.16 (see *Annex III – Experimental Data* for further information). However, these values are susceptible to being dropped. Focusing on the individual value of time required to select detailed nodes on P&IDs, it is evident that HAZOP D takes more time that others. After analyzing the number of nodes that come from the same PS, it is confirmed that HAZOP D presents the highest value in relation to the other (Nd/PS ratio). Figure V.18 not also shows this reasoning, but also depicts that with a number of more than 3 nodes per PS it directly increases the time to select detailed nodes.

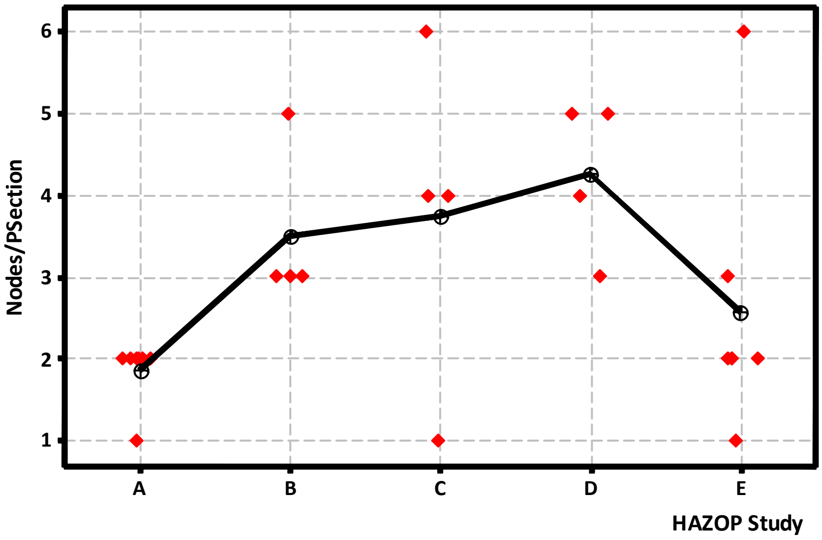

**Figure V.18.** Individual Value of [Nd/PS] versus HAZOP.

Therefore, and only for illustrative purposes, once extracted nodes that come from PS defined with more than 3 nodes, the new t-test analysis states the following results: (1) 95% confidence interval: (5.09, 7.10) minutes, and (2) Mean: 6.09 minutes. Further information is shown via the individual value of the time to select detailed nodes for only those that come from PS conformed for no more than 3 nodes (Figure V.19).

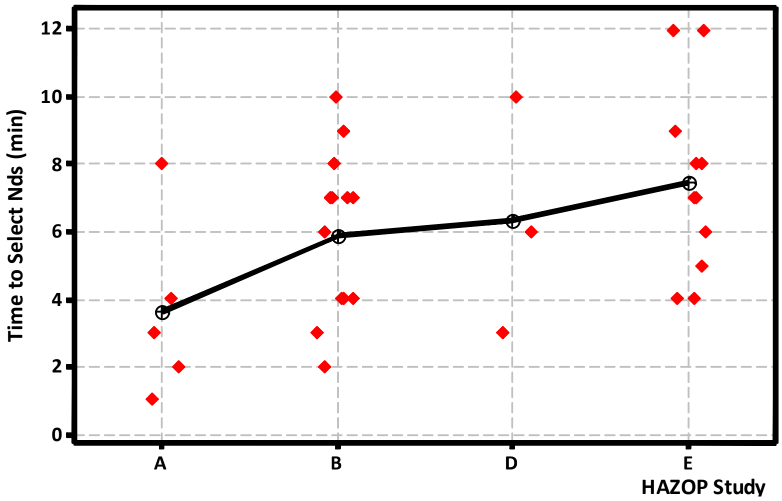

**Figure V.19.** Individual Value of the Time to Select Nd versus HAZOP.

Once individual factors of the selection methodology have been analyzed (i.e., PS, preliminary nodes, and detailed nodes), it is appropriate to consider the total time required for node selection. The intention is to fit the total time with basic variables that are inherent from the process and easily taken into account just before starting the organization of a HAZOP study.

The relationship between the time required to select detailed nodes and the number of ME present in the process analyzed is shown in Figure V.20.

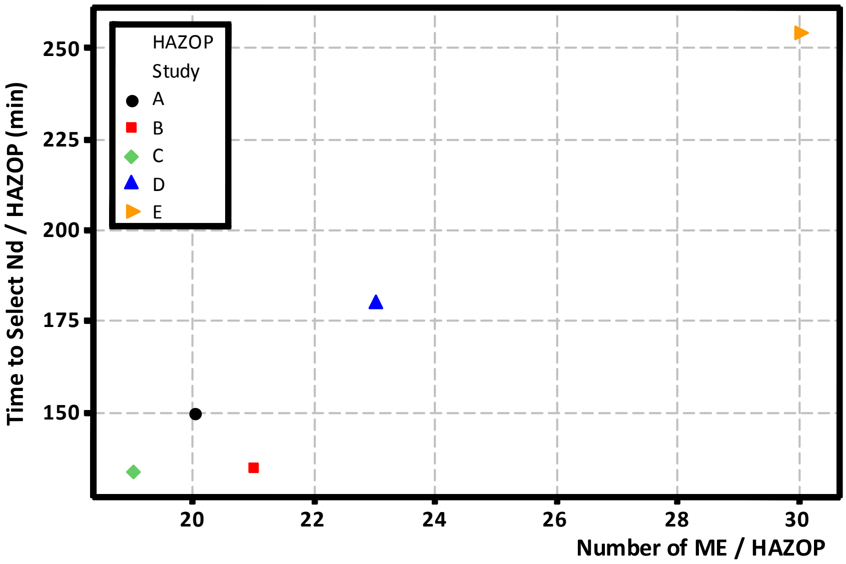

**Figure V.20.** Time to Select Nd versus ME.

PS features of the HAZOP C do not comply with the fact that they should be constituted by no more than 4 nodes. This is the only point that causes divergence when the total time required to select nodes is plotted versus the number of major equipment present in the process to be "hazoped". According to previous contents, it has been decided to exclude and consider it as an outliner. For modeling purposes this will improve the fitted line (Figure V.21).

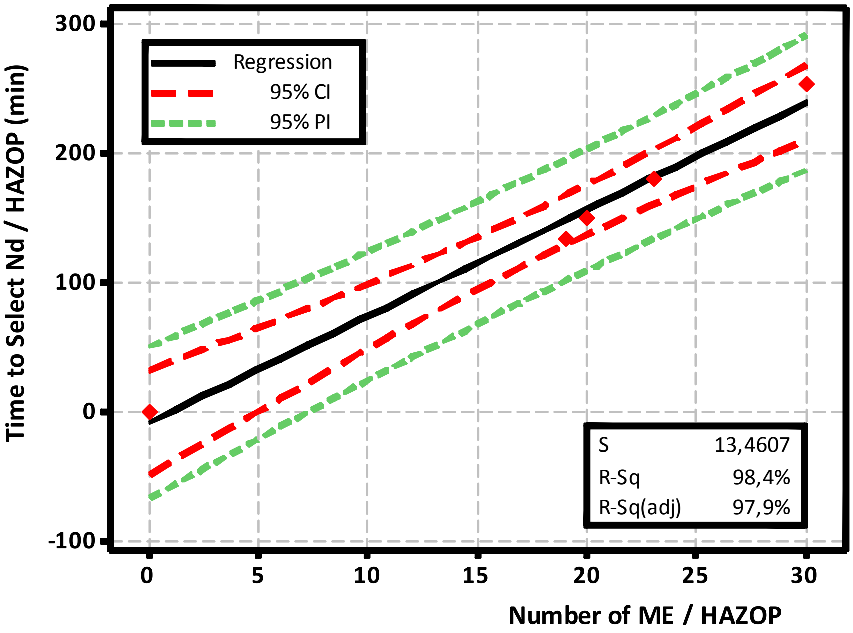

**Figure V.21.** Fitted Line Plot – Time to Select Nd versus ME.

Figure V.22 shows the basic statistics of the previous fitted line (Figure V.21).

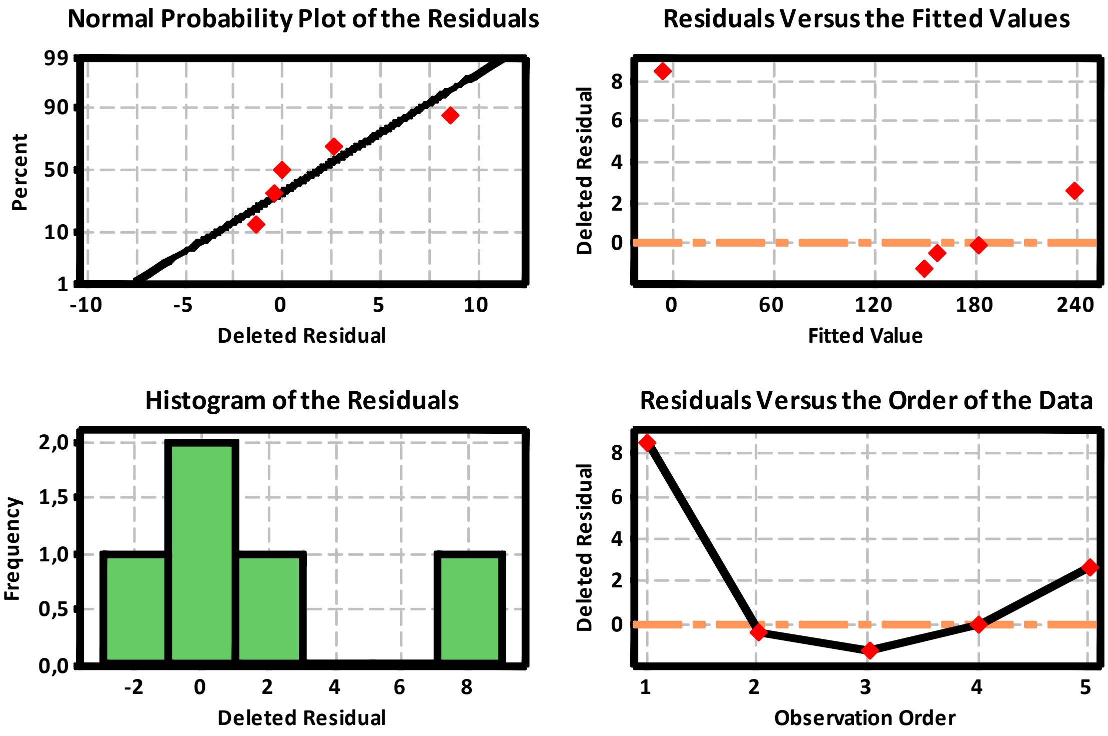

**Figure V.22.** Residual Plots for Time to Select Nd per HAZOP.

Therefore, as a rule of thumb, the expected time to select nodes by following the methodology is:

**$T_{Nd}$ (min) = 8 ME** **(V.6)**

Where:

- $T_{Nd}$ = Total time required to select nodes, in minutes
- ME = Total amount of major equipment present in the process

It has also to be noticed that further analysis has been carried out to find other interesting relationships between the required time to select detailed nodes and other types of equipment (i.e. FCVs, LCVs, PCVs, TCVs, Pumps, Exchangers), and has not been possible to find any other practicable and coherent relationship between these variables (Figure V.23). In relation to this fact, here it is important to mention that equipment present in node boundaries (e.g., FCVs, Pumps) has been considered twice when collecting data by taking into account in the two nodes that share their “structure”.

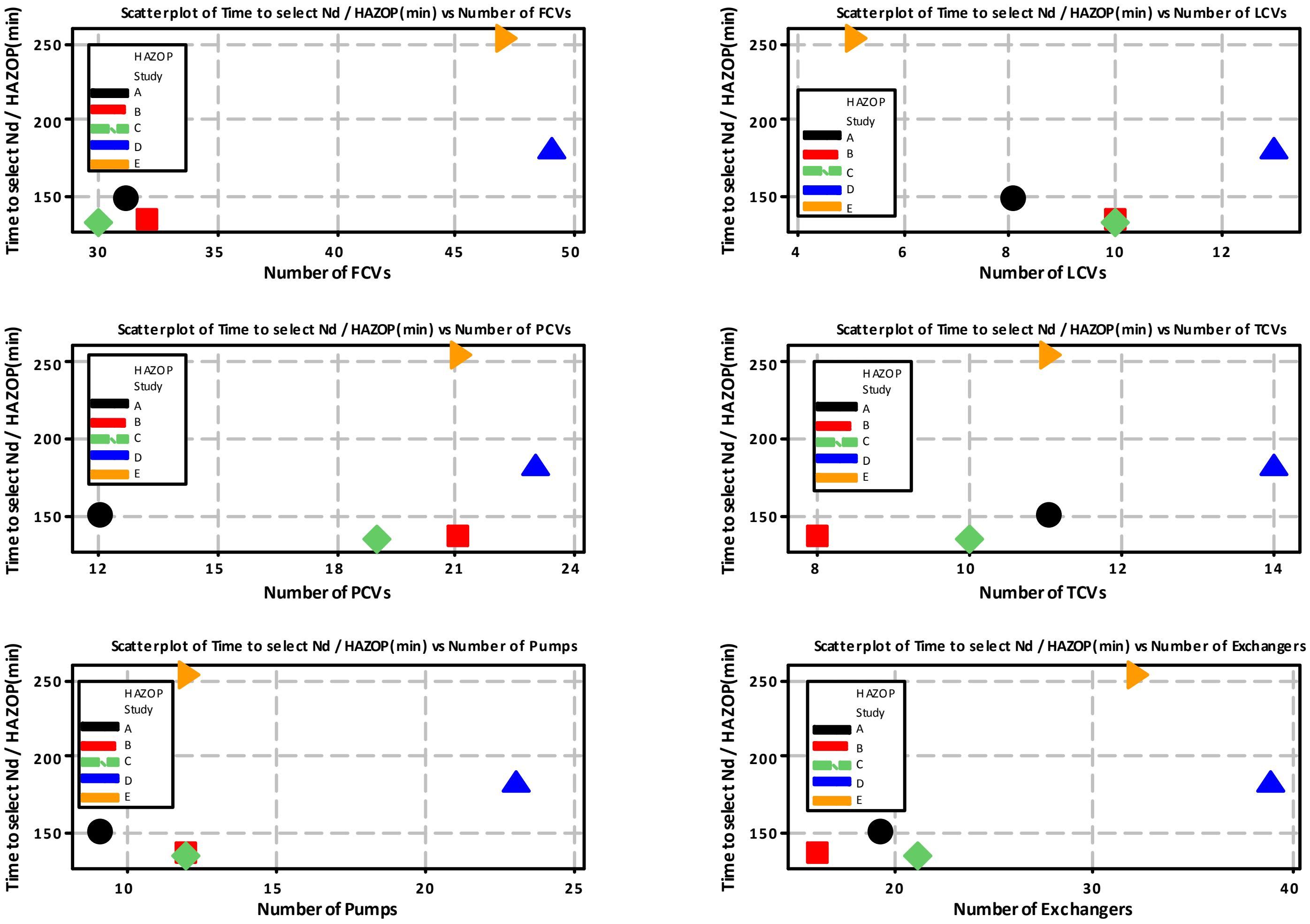

**Figure V.23.** Analysis of Time to Select Nd versus Equipment.

**Table V.2.** Mean and 95 % CI of equipment present in Nodes.

| | **HAZOP A** | | **HAZOP B** | | **HAZOP C** | | **HAZOP D** | | **HAZOP E** | | **ALL HAZOPs** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Mean** | **95% CI** | **Mean** | **95% CI** | **Mean** | **95% CI** | **Mean** | **95% CI** | **Mean** | **95% CI** | **Mean** | **95% CI** |
| **MEs** | 1.54 | (1.07- 2.00) | 1.50 | (1.12-1.88) | 1.27 | (1.01-1.52) | 1.35 | (0.99-1.71) | 1.67 | (1.18-2.15) | 1.47 | (1.30-1.63) |
| **FCVs** | 2.38 | (1.41-3.36) | 2.29 | (1.06-3.51) | 2.00 | (1.09-2.91) | 2.88 | (1.73-4.03) | 2.61 | (1.44-3.78) | 2.45 | (2.00-2.91) |
| **LCVs** | 0.62 | (0.03-1.20) | 0.71 | (0.06-1.37) | 0.67 | (0.21-1.12) | 0.76 | (0.15-1.38) | 0.28 | (0.05-0.51) | 0.60 | (0.39-0.81) |
| **PCVs** | 0.92 | (0.54-1.31) | 1.50 | (0.57-2.43) | 1.27 | (0.62-1.91) | 1.35 | (0.60-2.10) | 1.17 | (0.65-1.69) | 1.25 | (0.97-1.52) |
| **TCVs** | 0.85 | (-0.33-2.03) | 0.57 | (-0.17-1.31) | 0.67 | (0.016-1.32) | 0.82 | (-0.090-1.74) | 0.61 | (0.19-1.03) | 0.70 | (0.38-1.02) |
| **Pumps** | 0.69 | (0.18-1.21) | 0.86 | (0.22-1.49) | 0.80 | (0.43-1.17) | 1.35 | (0.81-1.90) | 0.67 | (0.37-0.96) | 0.88 | (0.68-1.08) |
| **Exchangers** | 1.46 | (0.70-2.23) | 1.14 | (0.27-2.02) | 1.40 | (0.68-2.12) | 2.30 | (1.34-3.25) | 1.78 | (1.15-2.41) | 1.65 | (1.31-1.99) |

### V.1.2.3. Analyzing specific data that describes the structure of selected nodes

The analysis of the structure of selected nodes has the intention of highlighting the mean and the 95% confidence interval of the equipment considered (Table V.2). This will give an idea of the equipment present in nodes selected following the proposed methodology (see *Chapter VI – Methodology*). A t-test has been conducted for each variable per HAZOP, and finally, the global results by considering the whole set of HAZOPs together give an idea about the dimension and structure of nodes selected. Further basic statistics of these variables can be found in *Annex III – Experimental Data*.

Figure V.24 shows the mean value of equipment present per node and per HAZOP. All HAZOPs present an equivalent mean number of pieces of total equipment per node, a total number which fits between 8 and 8.5. Only the HAZOP D, which previously has been criticized on how nodes had been selected, shows a greater value than 10. While the specific equipment that constitutes a node will be different depending on the process analyzed, the mean of the total amount of equipment that constitutes a node is coherent with regarding to the five HAZOPs analyzed, and also gives an idea about the node sizing. Additionally, the results obtained also confirm that the equipment selected to be analyzed is representative.

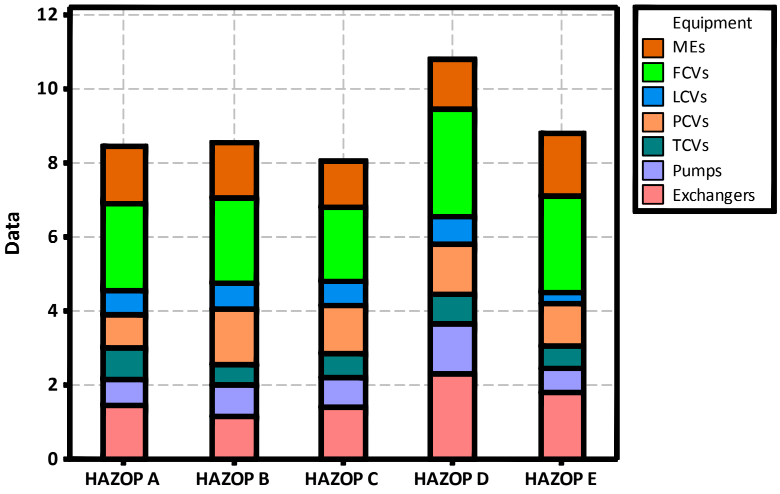

**Figure V.24.** Mean Value of Equipment present per Nd and per HAZOP.

Therefore, and only as a rule of thumb, it is possible to state a margin of the equipment that should be present in a specific node. Data is summarized in Table V.3 (e.g., a node with less than 5 equipments and with more than 12 should be revised).

**Table V.3.** Expected number of equipment in process nodes.

| **Number of Equipment** | Mean | 95 % CI | Expected Equipment |
|---|---|---|---|
| **MEs** | 1.47 | (1.30-1.63) | 1 to 2 |
| **FCVs** | 2.45 | (2.00-2.91) | 2 to 3 |
| **LCVs** | 0.60 | (0.39-0.81) | 0 to 1 |
| **PCVs** | 1.25 | (0.97-1.52) | 1 to 2 |
| **TCVs** | 0.70 | (0.38-1.02) | 0 to 1 |
| **Pumps** | 0.88 | (0.68-1.08) | 0 to 1 |
| **Exchangers** | 1.65 | (1.31-1.99) | 1 to 2 |
| **TOTAL Equipment** | | | 5 to 12 |

#### V.1.2.4. Analyzing key data that describes brainstorming sessions

Time required to brainstorm nodes

The following contents review data collected from the time required to brainstorm nodes selected, and also analyze how factors such as the number of session and number of members present during the brainstorming affect it.

Figure V.25 shows the individual value of the time to brainstorm nodes for HAZOP studies conducted. Focusing on Figure V.25, there are five values (one per HAZOP) that are clearly significantly higher than the rest. A Boxplot diagram will highlight this aspect (Figure V.26).

The five points that do not follow the pattern are the first node analyzed in each HAZOP considered. Due to the special treatment of the first node, the time to brainstorm these is practically twice compared with the subsequent. This fact can be explained because the timing recorded for the first node analysis not only includes the node review itself, but also the following tasks (see *Chapter VI – Methodology* for detailed information):

- Introduction to the team members
- Explanation of what is a HAZOP study and how will be conducted
- Drawing proposal of nodes selected and discussion of its appropriateness

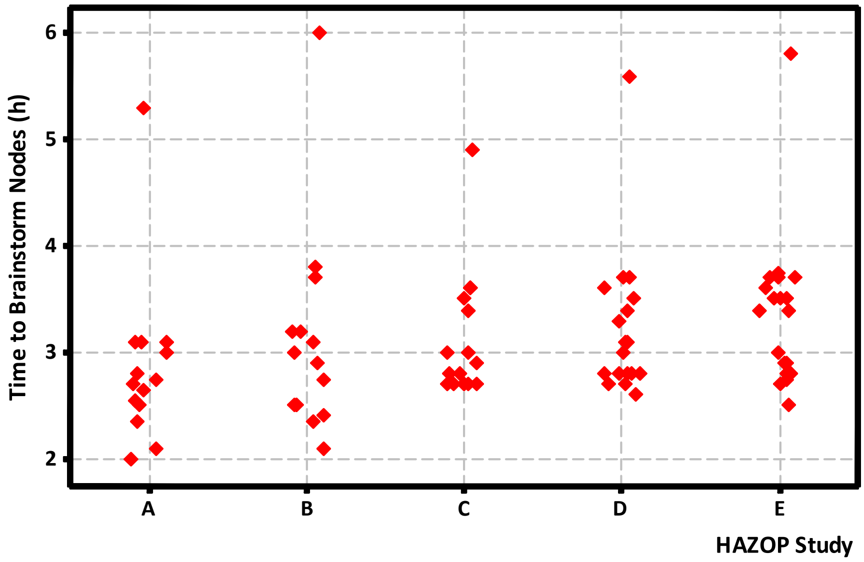

**Figure V.25.** Individual Value of the Time to Brainstorm Nd versus HAZOP.

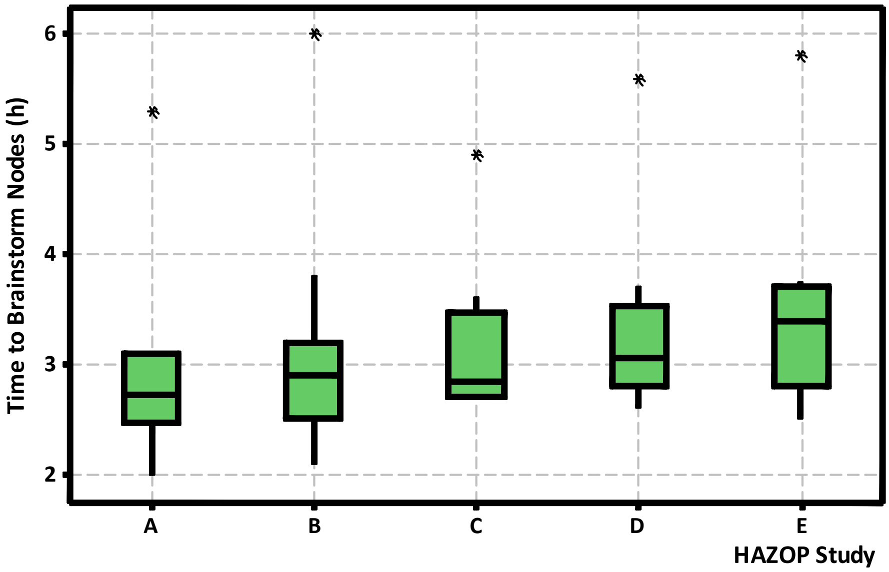

**Figure V.26.** Boxplot of Time to Brainstorm Nd.

All these factors together create a longer period of time for brainstorming the first node, if they are included in that task. For this reason, the first nodes of HAZOPs analyzed will be independently treated. Figure V.27 shows the time required to brainstorm the five first nodes of HAZOPs under study.

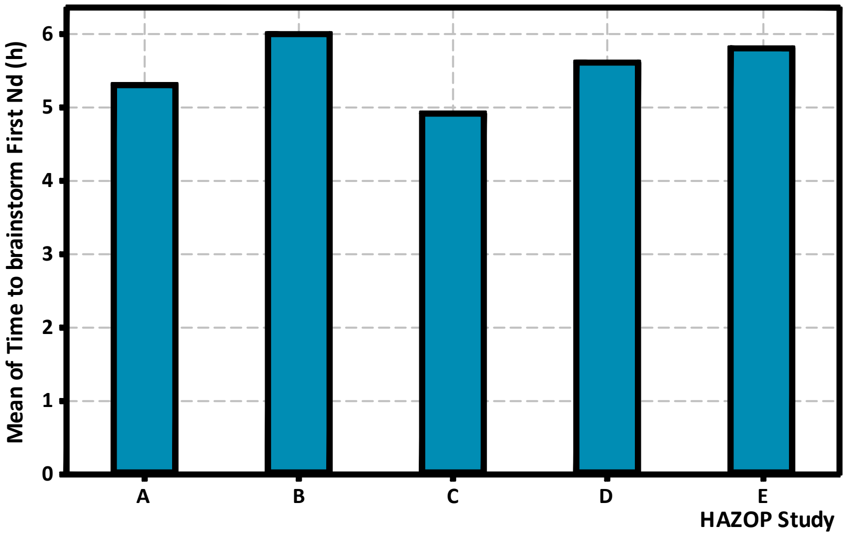

**Figure V.27.** Mean Time to Brainstorm first Nd versus HAZOP.

The mean value equals 5.52 hours, and after conducting a t-test, it is possible to ensure, with a 95% confidence, that the time required to brainstorm the first node of a HAZOP will remain between 4.98 and 6.05 hours. Basic statistics can be consulted in *Annex III – Experimental Data*.

Additionally, and even data analysis does not highlight significant differences between process nodes (first nodes already excluded) and global nodes, it is preferable to treat independently them. Both the selection procedure and brainstorming conducted in the process and the global node are significantly different. Focusing on the global node features, the following contents highlight their most important aspects. Figure V.28 shows the time required to brainstorm the global nodes of HAZOPs under study.

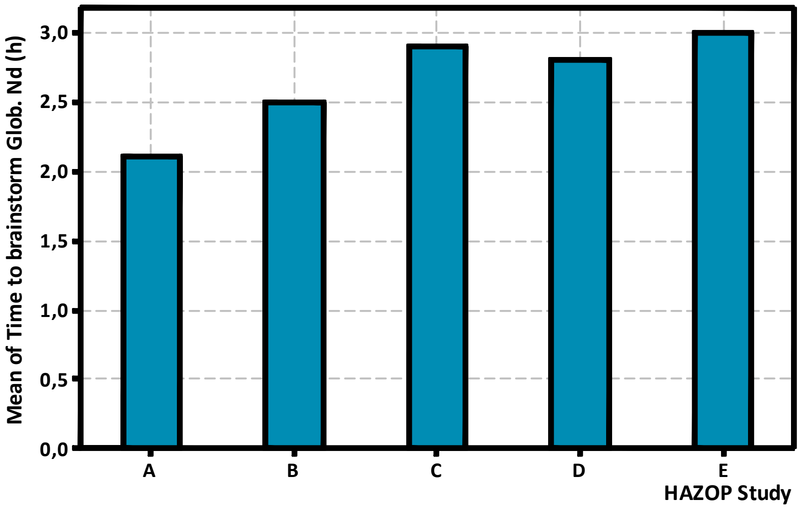

**Figure V.28.** Mean Time to Brainstorm Global Nd versus HAZOP.

The mean value equals 2.66 hours, and after conducting a t-test, it is possible to ensure, with a 95% confidence, that the time required to brainstorm a global node will take between 2.21 and 3.11 hours. Further basic statistics can be found in *Annex III – Experimental Data*. What is interesting to mention is that the time coherently increases as a function of the total amount of equipment that defines the process. Once excluding both first and global nodes from the present data analysis, the following contents apply to the process nodes of the five HAZOPs analyzed. The first action taken into account is to focus on the individual value of the time required to brainstorm process nodes versus the HAZOP study (Figure V.29).

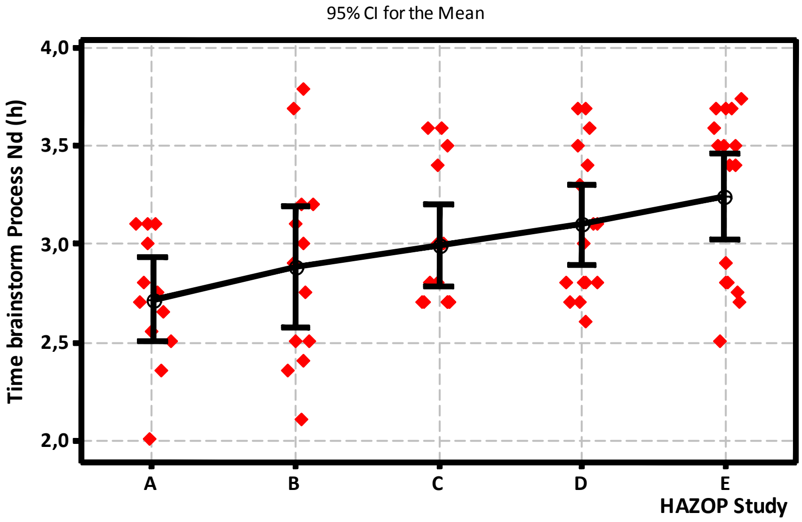

**Figure V.29.** Individual Value of the Time to Brainstorm Process Nd versus HAZOP.

Table V.4 shows the t-test conducted with the aim of acquiring both the mean and the mean-95%-confidence interval for the five HAZOPs analyzed.

**Table V.4.** Mean and 95% CI for the time to brainstorm process nodes.

| HAZOP Study | Variable | Value |
|---|---|---|
| **HAZOP A** | **Mean**<br>**95% CI** | 2.72<br>(2.50-2.93)) |
| **HAZOP B** | **Mean**<br>**95% CI** | 2.88<br>(2.57-3.20) |
| **HAZOP C** | **Mean**<br>**95% CI** | 2.99<br>(2.78-3.20) |
| **HAZOP D** | **Mean**<br>**95% CI** | 3.10<br>(2.90-3.30) |
| **HAZOP E** | **Mean**<br>**95% CI** | 3.24<br>(3.02-3.46) |
| **ALL HAZOPs** | **Mean**<br>**95% CI** | 3.01<br>(2.91-3.11) |

Focusing on the process nodes results it is possible to state that the time required to brainstorm a specific process node is influenced by the total number of nodes that have to be reviewed during the HAZOP study. This fact takes into account the complexity of the process (number of nodes), and also the HAZOP methodology (time required to brainstorm a node). Both factors are fitted as shown in Figure V.30.

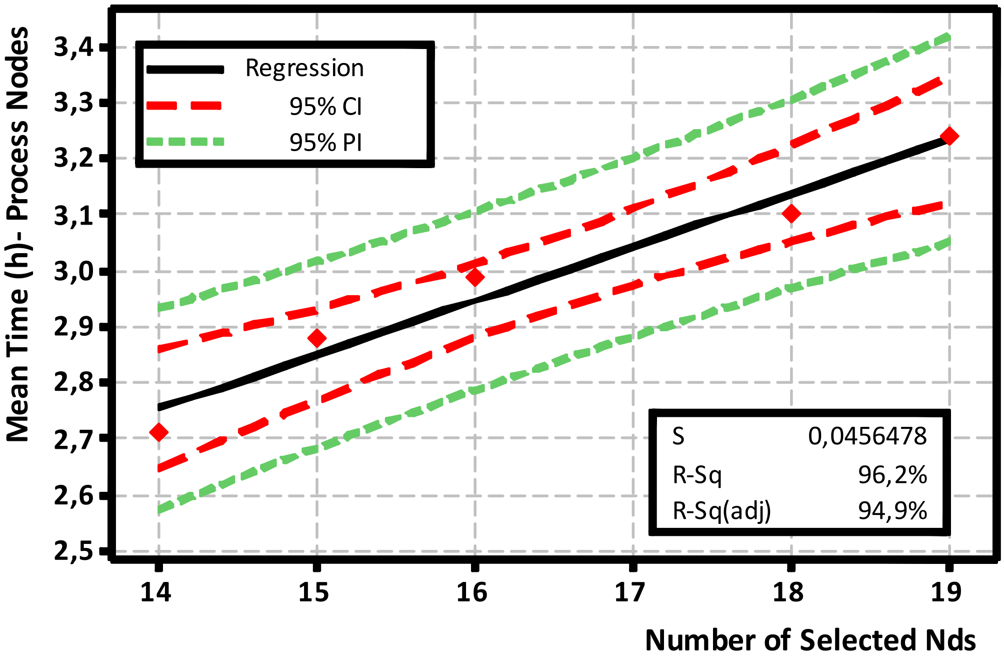

**Figure V.30.** Fitted Line Plot – Mean Time to Brainstorm Process Nd versus Nd.

Thus, a rule of thumb could state that it is possible to establish a relationship between the number of selected nodes and the expected mean-time for process nodes brainstorming:

$$\mathbf{T_{BTNds}\,(h) = 1.41 + 0.01 \cdot Nd} \qquad \mathbf{(V.7)}$$

Where,

- $T_{BTNds}$ = Time required to brainstorm process nodes, in hours
- Nd = Number of selected nodes

The basic statistics of the fitted line plot are the following:

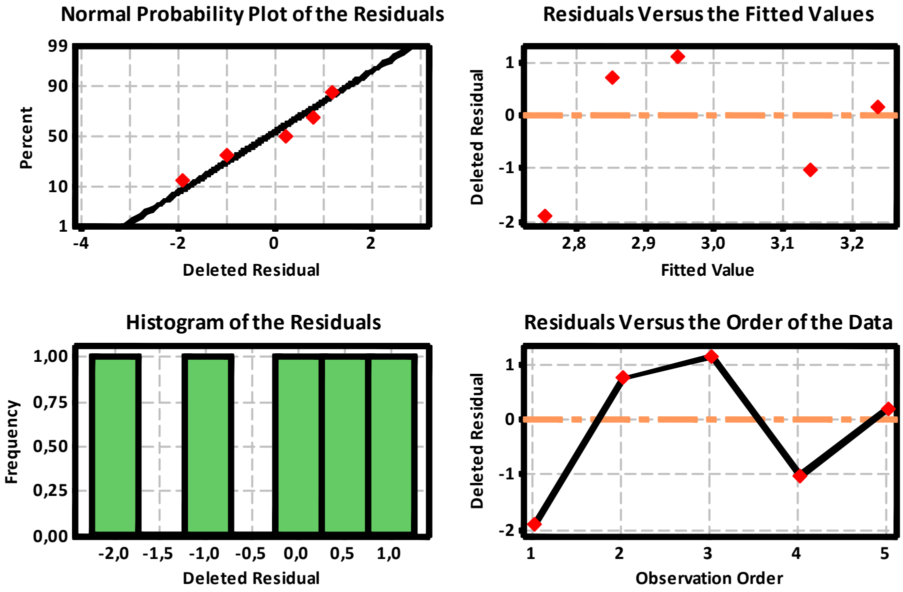

**Figure V.31.** Residual Plots for Mean Time to Brainstorm Process Nd.

Finally, and comparing the required time to brainstorm global and process nodes, it is clear that more time is needed to brainstorm process nodes (mean time equals to 3.01 rather than 2.66 hours), a fact that can be explained by considering the number of deviations that are reviewed in each type of node, and their specific purposes as well (according to the approach developed in *Chapter VI – Methodology*).

The following contents are intended to analyze how the session number and the number of members present during sessions affect the time required to brainstorm a specific process node.

Analyzing the Number of sessions

According to Figure V.32, the mean-value equals 5.6 sessions per HAZOP, and after conducting a t-test, it is possible to ensure, with a 95% confidence, that the expected number of sessions will remain between 4.49 and 6.71 hours. Further basic statistics can be found in *Annex III – Experimental Data*. However, these results have to be interpreted as follows: depending on the course of the HAZOP analysis, the number of hours dedicated per session may vary, and will also directly vary with the number of nodes. Additionally, deciding how many sessions should a HAZOP take, not only should take into consideration the process complexity, but also management aspects. This fact will be solved in *Chapter VI – Methodology*.

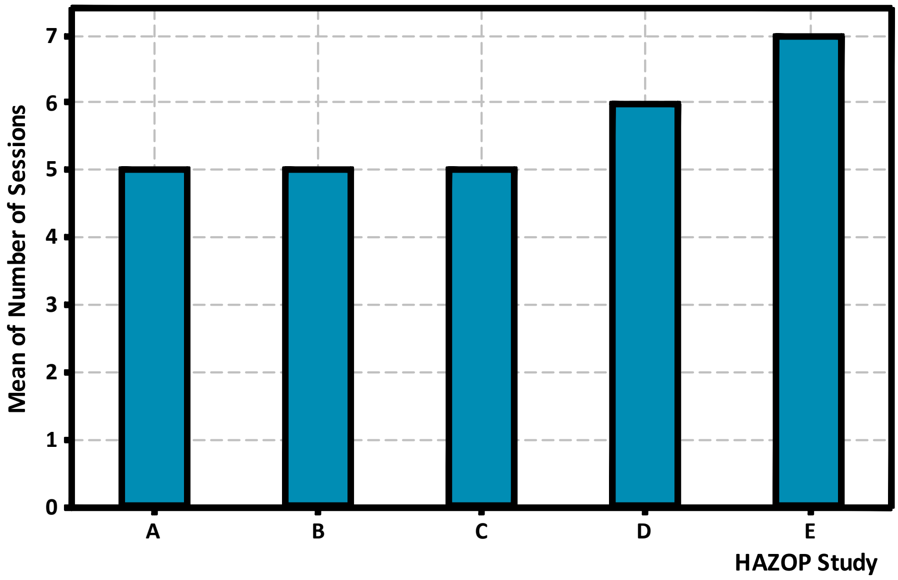

**Figure V.32.** Mean-number of Sessions versus HAZOP.

Another factor to consider is to study how the mean-time to brainstorm process nodes varies as a function of the number of sessions. Comparing results depicted in Figure V.32 and Figure V.33, it is clear that the number of sessions increases with the number of nodes to be reviewed, as well as the mean-time to brainstorm them.

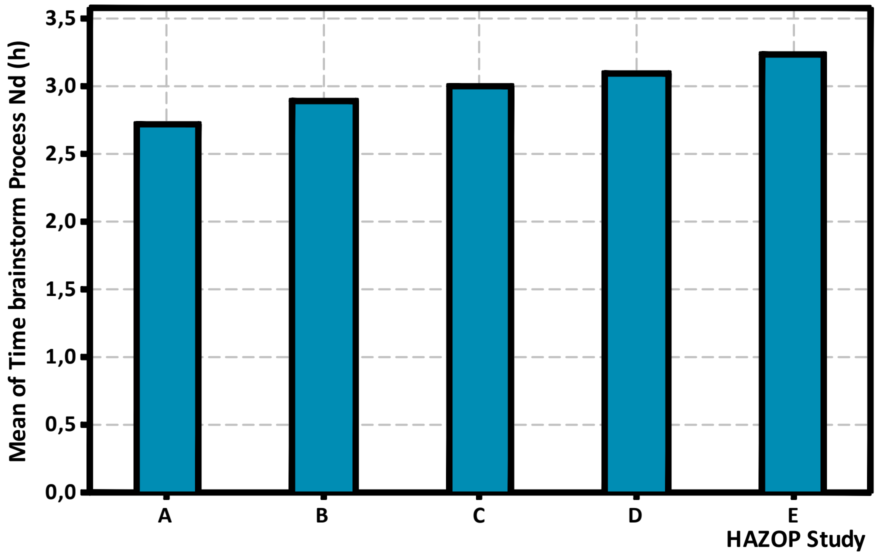

**Figure V.33.** Mean-time to Brainstorm Process Nd versus HAZOP.

However, the individual of the time to brainstorm process nodes versus the number of sessions (see Figure V.34) practically demonstrates no variance between time and sessions.

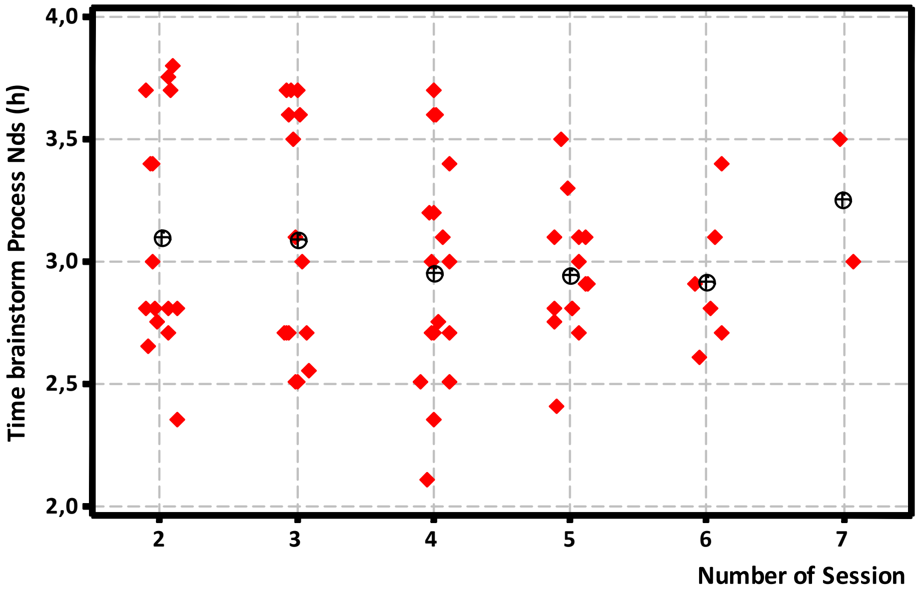

**Figure V.34.** Individual Value of the Time to Brainstorm Process Nd vs. Session Number

Finally, it could be interesting to depict the expected number of sessions as a function of the number of selected nodes. This fact is shown in Figure V.35.

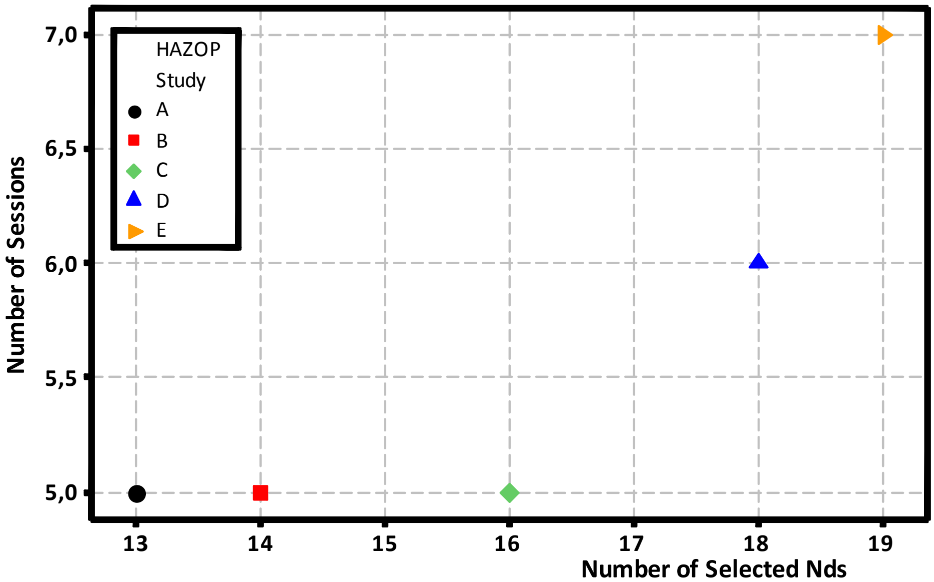

**Figure V.35.** Number of Sessions versus Number of Selected Nd.

While the number of sessions remains constant from 13 to 16 nodes, it starts to increase from this value. Trying to model the required number of sessions as a function of the number of nodes could be interesting, but directly depends on the number of hours per session. Likewise, *Chapter VI – Methodology*; gives criteria on the best procedure to follow focused on the distribution of the sessions when conducting a HAZOP.

Analyzing the number of members

According to Figure V.36, it is important to mention that the recorded number of members exclude the role of both the team leader and the scribe, and only considers the number of experts with different knowledge and background who are there to give support during brainstorming.

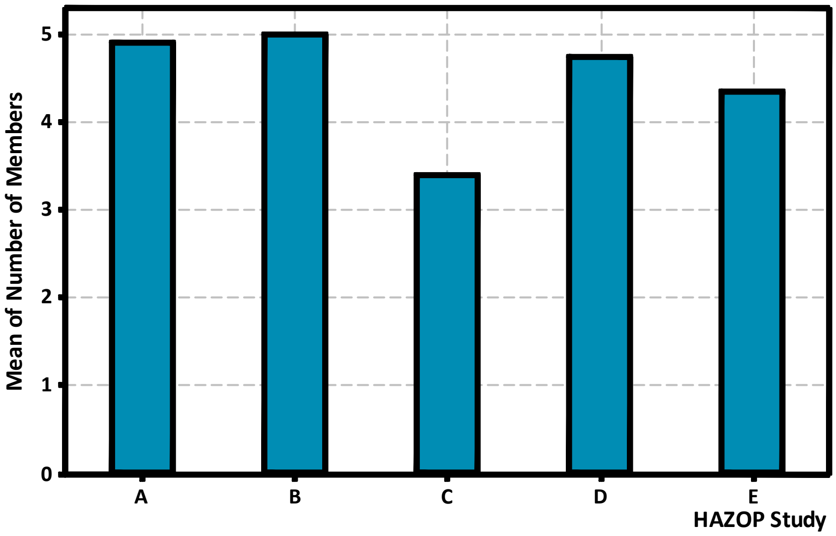

**Figure V.36.** Mean Number of Members versus HAZOP.

The mean value equals 4.44 members, and after conducting a t-test, it is possible to ensure, with a 95% confidence, that the time required to brainstorm a global node will remain between 4.20 and 4.68 members. Further basic statistics can be found in *Annex III – Experimental Data*. The individual value of time to brainstorm process nodes versus the number of members is shown in Figure V.37.

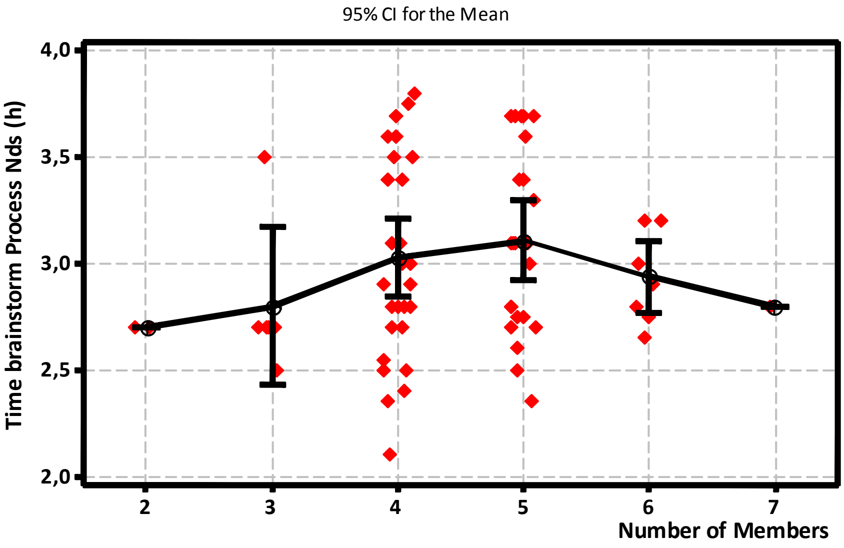

**Figure V.37.** Individual Value of the Time to Brainstorm versus Number of Members

According to Figure V.37, a number of 4 and 5 members cause a higher period of time to brainstorm the selected node. However, experience on participating in the five HAZOPs under review confirms that sometimes there is a wide number of members present during brainstorming, but really only a few of them are actively participating. Thus, it is clear that when the number of members increases, the difficulty to guide them also increases (from the point of view of the team leader) and consequently, the time to brainstorm as well. This fact is demonstrated by considering the number of members from two to five. Additionally, it could be stated that when the number of members is greater than six, the real number of active members participating decreases, and thus, also the questions on the spot that can be brainstormed. Therefore, despite considering the number of members present during the brainstorming, it is not possible to establish strict criteria on what the optimum size of the number of team members should be due to leadership behaviors between them. However, *Chapter VI – Methodology* establishes guidance about the minimum expert team knowledge required to ensure effective brainstorming sessions.

## V.2. SPECIFIC CONCLUSIONS

The whole package of variables considered have been classified according to the HAZOP phase that they apply to. The groups considered and their specific conclusions are the following:

### Main data that describes both HAZOP dimension and the process analyzed

A mathematical model able to predict the time required to perform a HAZOP study has been developed. This model is based on two predictors that are easy to acquire and which define the complexity of the process to be hazoped: (1) the number of P&IDs, and (2) the number of major equipment. Additionally, another model has been developed for predicting the expected number of nodes to be selected. The same predictors have been used for this ultimate purpose. Detailed information related to these two models is shown in *Chapter VI - Methodology*.

### Specific data that describes nodes-selection methodology applied

According to basic statistics applied to the related data, it is possible to take as 3 the mean number of nodes present in a principal section, and 1.5 the mean-number of pieces of major equipment per node. Thus, the team leader should size principal sections with a number of pieces of major equipment to no more than 6, and no less than 3. As an optimum number, also validated via engineering judgment, well-sized principal sections should take between 4 and 5 pieces of major equipment.

After conducting a t-test applied to the time required to select preliminary nodes, results confirm a 95% confidence interval of 1.67 and 2.12 minutes, where the mean equals 1.90. A rule of thumb could state that a node will take 2 minutes to be selected on PFDs, and additionally: (1) it should come from a principal section that contains 2 or 3 nodes, (2) the number of pieces of major equipment present in the node will be 1 or 2. While no individual values are possible to exactly define these studied features, the small intervals provided (confidence intervals – CI) not only help to understand the methodology, but also tackle the optimum size and time both for principal sections and nodes.

Additionally, once extracted, nodes that come from principal sections defined with more than 3 nodes, a t-test analysis states the following results about the time required to select nodes on P&IDs: (1) 95% confidence interval: (5.09, 7.10) minutes, and (2) Mean: 6.09 minutes. Thus, defining principal sections with no more than 3 nodes, as well as defining nodes with no more than 2 major pieces of equipments, are the two factors than ensure the minimum time required to select nodes (i.e., principal sections, preliminary nodes, and detailed nodes). Finally, and only for guidance purposes, a model has been developed to predict the time that a node selection will take. The response is the function of the number of pieces of major equipment that constitutes the process to be hazoped.

### Specific data that describes the structure of selected nodes

It has been checked, and validated, that the mean value of equipment present per node and per HAZOP is statistically equivalent. This number ranges between 8 and 8.5. Only the HAZOP D, which previously has been criticized on how nodes had been selected, shows a greater value than 10. While the specific equipment that constitutes a node will be different, depending on the process analyzed, the mean of the total number of pieces of equipment that constitutes a node is coherent regarding the five HAZOPs analyzed, and also gives an idea about the node sizing. Furthermore, the results obtained also confirm that the equipment selected (i.e., FCVs, LCVs, PCVs, TCVs, Pumps, and Exchangers) to be analyzed is representative according to the nature of the processes.

### Key data that describes brainstorming sessions

The mean-value to brainstorm first nodes are clearly higher than the rest of nodes (i.e., process and global nodes) and equals 5.52 hours, and after conducting a t-test, it is possible to ensure, with a 95% confidence, that the time required to brainstorm the first node of a HAZOP will take between 4.98 and 6.05 hours. A rule of thumb for timing-prediction purposes is to consider that the first node will take 6 hours (conservative criteria).

Regarding the time required to brainstorm global nodes, the mean value obtained equals 2.66 hours, and after conducting a t-test, it is possible to ensure, with a 95% confidence, that the time required to brainstorm a global node will take between 2.21 and 3.11 hours. However, there is no significant statistical difference between global and process nodes, and this is the reason why the workable values have been taken from the last ones. A process node presents the following results: mean value equals 3.01, with a 95% confidence-interval of 2.91 and 3.11 hours. The close confidence interval obtained not only confirms a practically constant time to brainstorm them, but also an equivalent nodes size. Furthermore, the methodology to brainstorm them also influences these results (deviations and guidewords to be used for hazard identification purposes will be shown in *Chapter VI – Methodology*). Finally, and due to the close interval acquired, a rule of thumb could be used for considering as 3 hours the time required to brainstorm process and global nodes.

Number of Sessions and Members

Both the number of sessions and the number of members have been analyzed. However, no definitive results have been found. Both variables require not only technical criteria, but also management duties, and this could be the reasonable explanation of the results obtained. Despite of these outcomes, *Chapter VI – Methodology* addresses criteria related to them by taking into consideration experience gained throughout the performance of the five HAZOPs reviewed.

# CHAPTER VI. METHODOLOGY

Based on the previous contents of the manuscript, the present chapter establishes criteria to effectively conduct HAZOP studies. Here are listed, structured and defined the whole set of actions that have to be taken into account when performing the study. Both technical and management aspects are addressed. The challenge is to provide the key information that ensures that after reading it, an inexperienced interested party would be able to perform a HAZOP study by following these guidelines, or in case of an experienced team leader, improve some aspects from their own criterion. Thus, the following contents should not only be considered as a theoretical resource of information, but also as a dynamic document to be used during field work.

## VI.1. INTRODUCTION – THE HAZOP MANAGEMENT SYSTEM

How to conduct successful HAZard & OPerability (HAZOP) studies requires the product of concerted efforts throughout a management system constituted of three phases:

(1) Definition and Preparation

(2) Organization

(3) Execution and Documentation

The first phase requires not only detailed definition of the purpose, scope, and objectives of the study, but also appointing a team leader and selecting an expert team. Hereafter, the preparation of the study will be addressed. The success of all subsequent efforts depends on this phase. The second phase should address two key commitments:

(1) To divide the process into manageable parts for immediate reviewing

(2) To plan the study for arranging meetings

Finally, the third phase requires identifying and documenting which hazardous scenarios could arise from the process design intent, and assist which recommendations should be considered.

Analyzing the information acquired by reviewing the HAZOP state-of-the-art, and also studying and conducting HAZOP studies in the petroleum refining industry, requires an effort necessary for reinforcing the HAZOP structure itself. A detailed management system for HAZOPs has to be defined for conducting well-suited HAZOPs in continuous chemical process facilities.

Thus, the HAZOP Management System (HMS) will guide team leaders and will favor standardization on the following aspects:

(1) Guidance on which sequential steps have to be considered for setting-up HAZOPs

(2) Development of a node-selection methodology for detecting specific design intents

(3) Development of a model able to predict the expected number of nodes to be selected as a function of basic variables easy to acquire

(3) Development of a new HAZOP time-estimation model, thereby simplifying the current cumbersome models

(4) Development of a deviations-structural hierarchy for ensuring that key hazardous scenarios will be identified, and also for avoiding repetitive analysis and strengthening the HAZOP structure itself

(5) Guidance on how to fulfill HAZOP worksheets to ensure the maximum level of understanding

The aim of the HMS is to define and structure the whole set of actions which have to be conducted, both for project managers and team leaders, for defining and preparing HAZOPs, thereby connecting and ensuring the success of all subsequent HMS phases. The following contents are intended to give criteria to responsible parties for setting-up HAZOPs. Consistently, two sub-aims have been carefully pursued. On one hand, care of contents has been taken into account to be used directly as a guideline-aid (the figures and checklist depicted are “ready-to-use” for accomplishing this goal. See also *Annex I*). On the other hand, the contents confirm the necessary smoothing connection between HMS phases.

The full sequence of actions affecting HAZOP performance is shown in Table VI.1.

**Note:** The full set of actions that define the HMS were defined according to the experience gained after acquiring knowledge on both continuous chemical processes and HAZOP studies according to the analysis developed in *Chapter V – Field Work and Data Analysis*. From this point, each main HMS phase will be described.

**Table VI.1.** HAZOP Management System.

**HAZOP Management System**

| | |
|---|---|
| **First Phase. HAZOP Definition & Preparation** | |
| 1 | Deciding why & when to conduct a HAZOP study |
| 2 | Ensuring a well-matched Safety Management System – (Information) |
| 3 | Establishing the PHA software-aid to be used |
| 4 | Ensuring the minimum HAZOP meeting room attributes |
| 5 | Sending project specifications to team leader candidates |
| 6 | Appointing the team leader |
| 7 | Defining detailed purpose, scope and objectives of the study |
| 8 | Selecting the appropriate HAZOP team by ensuring attendance |
| 9 | Assembling and reorganizing the necessary information for conducting the study |
| 10 | Establishing Risk Ranking Criteria |
| **Second Phase: HAZOP Organization** | |
| 1 | Diving the process into manageable sections with defined design intents |
| 2 | Planning the study for arranging meetings |
| **Third Phase. HAZOP Execution & Documentation** | |
| 1 | Generating deviations – Guidewords & Parameters |
| 2 | Brainstorming sessions – identifying hazardous scenarios & managing the team |
| 3 | Reporting the study results |
| 4 | Following-up recommendations confirming their scheduled implementation |

## VI.2. HAZOP DEFINITION AND PREPARATION

Detailed assistance is needed for defining the first HAZOP steps (Figure VI.1), covering actions because company interests confirm a HAZOP has to be conducted until a well-suited input-data for carrying out the next study phase is ensured in its organization. Therefore, the scope of the present contents takes into account the following factors:

(1) “Why”, “when”, “how”, and “where” HAZOPs have to be conducted

(2) “Who” has to be involved. Thus, sharing know-how on conducting HAZOPs, criteria will be shown, both for the study itself (HAZOP) and also the processes to be studied (Continuous chemical processes)

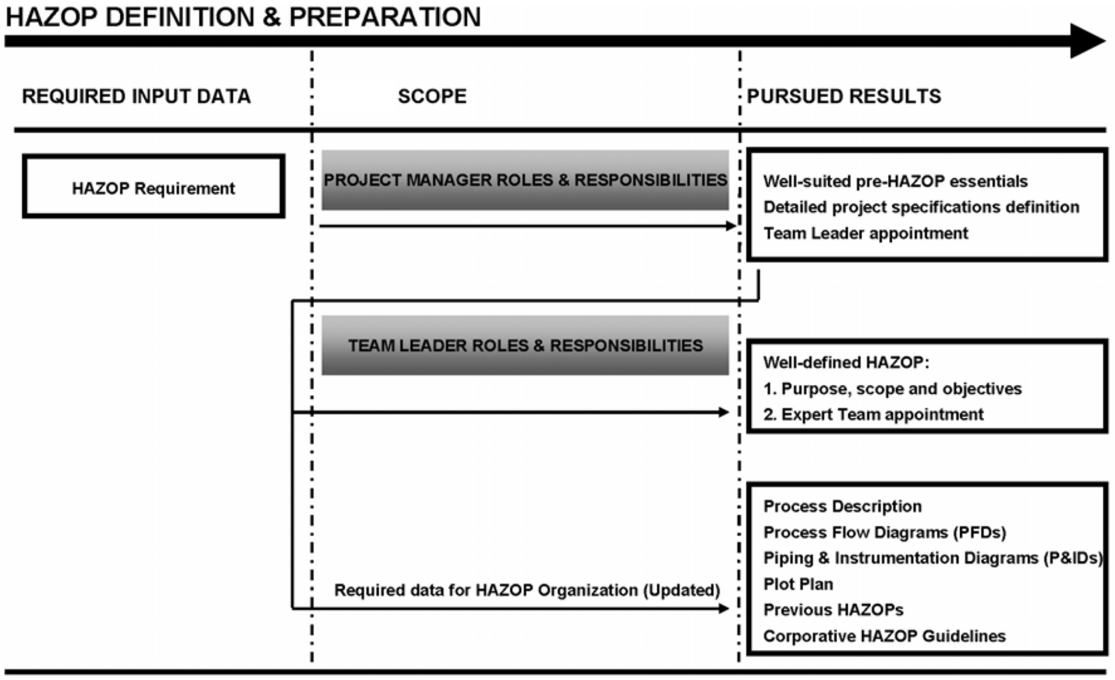

**Figure VI.1.**Scope of the first HMS phase.

### VI.2.1. Why and When to Apply a HAZOP Study?

HAZOP studies are carried out for several reasons: to observe good engineering practices, to meet regulatory requirements, to comply with the recommendations of internal audits, to investigate accidents, or to determine safety management system recommendations.

The project manager is responsible for deciding why and when to carry out the study, both in new and existing process facilities. In the case of new facilities, the study will only be considered once the basic engineering documentation, including the initial versions of the P&IDs, has been completed. The exact configuration of the HAZOP study may have to be updated during the project. For existing facilities, any change in the process carried out requires the HAZOP study to be updated (e.g., importance of Management Of Change; MOC) Therefore, it is necessary to determine whether the changes introduced require a new hazard identification analysis. In any case, the validation procedure will have to be implemented. Consequently, the decisions on why and when to apply a HAZOP study directly depend on the process lifetime, and the purpose, scope and objectives should be defined accordingly. The information presented below highlights the relationship between the process lifetime and the relevance of the HAZOP study.

HAZOP cannot be applied during the conceptual stage of a project because there are no detailed P&IDs at this point. A hazard review should be carried out to identify potential breaches of the process and evaluate the severity of possible hazards. This review should be conducted as early as possible so that there is enough time to make fundamental modifications to the design concept, following principles of inherently safe design. The P&IDs available during the design stage are reasonably accurate and the design concept is totally defined. The HAZOP study is most effective at this stage because there is sufficient detail to provide satisfactory answers to many of the questions generated during the hazard review. In addition, if the results of the study indicate that the design concept needs to be modified, it is much more cost-effective to incorporate changes at the design stage rather than later in the project. Furthermore, if the study is conducted at the design stage, it is not usually necessary to carry out an additional analysis at the pre-start-up stage. However, if modifications to the design are made after the detailed study, the original HAZOP team should be re-convened to review all of the changes. Operating procedures are generally finalized at the pre-start-up stage. Consequently, a detailed review of the operating procedures should be completed prior to commissioning the plant, and many companies have found HAZOP to be a useful tool for performing this task.

HAZOP was originally considered suitable for new plants only, but it quickly became recognized as a useful tool for existing facilities due to greater awareness in industry of its benefits and the introduction of new regulatory requirements. The potential hazards in an existing plant can change dramatically over a period of years due to the dynamic nature of process facilities, and many of the modifications made to older facilities may not have undergone a thorough hazard analysis. Accordingly, any changes carried out could compromise the safety of the original plant design. Process facilities must remain dynamic, so occasional modifications are essential. Possible modifications include adding vessels or pumps, changing venting schemes to reduce pollution potentials, and altering processes to improve yields, conserve energy, or reduce costs. Although it would not be cost-effective to convene a HAZOP meeting for every proposed change, many accidents in the process industry have occurred as a result of unforeseen consequences of “small” modifications. Consequently, companies must determine whether the planned changes will entail risks to health, safety and/or the environment. If this is found to be the case, the existing HAZOP study will have to be up-dated. In addition, when a process unit is scheduled to be tested and integrated, a thorough hazard analysis must be carried out prior to shut-down. The HAZOP study will help to identify potential hazards that may not be present during normal operations. Although many companies implement standard maintenance preparation procedures and use checklists to isolate equipment and minimize personnel exposure, these systems may not be sufficiently thorough for extensive or complex processes such as those used in the petroleum refining industry. HAZOP studies conducted in existing plants immediately before a major overhaul have two objectives: to identify new or overlooked hazards, and to support maintenance preparation, particularly if adjacent process equipment is to remain in service.

Ideally, both the number of changes and their magnitude should be considered. In this case, three types of re-validation procedures can be carried out. Tables VI.2 and VI.3 show the types and advantages of revalidations, respectively. Detailed information on PHA re-validation is available in (Frank & Whittle, 2001), which presents a common-sense, tested approach for resource-effective PHA re-validation.

This approach is designed to provide plant managers, operating personnel, engineering groups and safety professionals with supplementary information and methods for conducting effective re-validations as a result of changes in the process or the equipment used, the existence of gaps and deficiencies in previous HAZOP studies, the availability of new knowledge because each new re-validation provides the opportunity to reconsider past conclusions in the light of current knowledge, unresolved recommendations, regulatory requirements, and requirement changes.

**Table VI.2.** Types of HAZOP Revalidation.

| | |
|---|---|
| Endorsement | The existent study is complete<br>No changes have been implemented from its execution<br>No new criteria has been appeared |
| Revision | New improvements have been introduced<br>The unit has to be analyzed for considering partial or complete revision |
| Replacement | A wide number of improvements have to be implemented<br>The new information is unmanageable considering the existing study |

**Table VI.3.** Reasons and Benefits for Revalidation.

| |
|---|
| The process safety information (updated) is complete and precise |
| The operating procedures are updated |
| The recommendations of the previous HAZOP have been implemented |
| The lessons learned from recent incidents have been taken into account and applied |
| The new quality requirements appeared from the last HAZOP have been included |
| The last and more recent legal requirements have been had into consideration |

### VI.2.2. Specific Project Manager Responsibilities

Before a HAZOP study is implemented, the project manager must ensure that: (1) the safety management system (SMS) contains a suitable information management system for storing the results of previous studies and current process data for subsequent analysis; (2) PHA software is available for conducting the study, as this will ensure the consistency and integrity of the analysis and save time; (3) the HAZOP meeting room has an appropriate layout; and (4) a suitable team leader has been appointed.

Companies should develop a management system for organizing and documenting the knowledge acquired during the process lifetime. This information includes diagrams, operating procedures, company standards, guidelines and checklists, which should all be reviewed periodically when the process is modified.

For hazard identification, the system should include a MOC program to ensure that all modifications are properly reviewed, drawings and procedures are kept up-to-date, and all previous HAZOPs have been taken into account. Appropriate documentation is crucial in setting up HAZOP studies due to the fact that analyzing obsolete documentation may lead to hazards being overlooked and even create new hazards. Consequently, HAZOP studies must not be carried out if the key input data are not fully reliable. Project managers should perform a "spot field-check" to determine whether at least the diagrams are adequate. Once the HAZOP study has been completed, managers should ensure that the system operation incorporates the results and that all approved corrective actions are implemented as scheduled.

PHA software must be used to manage, store and document information generated by PHAs. HAZOP studies cannot be performed without the appropriate hardware and software, which provide easy and fast access to previous PHA data, ensure that data are stored and displayed using a consistent format, automatically generate specific knowledge bases, facilitate possible inspections procedures, and ensure the overall coherence of the study. The key benefits of using PHA software are shown in Table VI.4. Hyatt (1996) and Hyatt et al. (1996) provide concise and valuable information on the pros and cons of different PHA software applications.

**Table VI.4.** Benefits on using PHA Software.

| |
|---|
| Past studies can be reused to retain valuable corporate knowledge and intellectual property |
| To build on previous studies avoiding wasting time and resources |
| To customize templates to the company's specific guidelines and organizational needs |
| To ensure consistency of the studies to the corporate standards |
| To assure uniformity of risk studies, since steps are not allowed to be forgotten or skipped |
| To allow data linking features reducing the amount of time and effort required to finish a study |
| To filter reports according to specified requirements |
| To allow to share the information in a variety of formats for easy and controlled access |

HAZOP brainstorming sessions should be conducted in a meeting room with specific features and items. Past experience reveals that the attributes of the room directly affect the results of a HAZOP study, so members must be comfortable and have easy access to documentation. It may be preferable to use a meeting room outside the process facility, so that brainstorming sessions are not disrupted by team members who need to leave to carry out daily tasks.

However, this is not always possible, and studies for new designs are being carried out at contractor's offices. Current HAZOP studies are usually performed at the facility in question. Table VI.5 shows the basic items that the meeting room must contain to ensure that the study is carried out effectively, and Figure V.2 shows the ideal layout.

**Table VI.5.**Minimum Project Specifications Contents.

| **Project Information** | **Comments** |
|---|---|
| Company name, Facility, Process and Location | Identification of the process to be analyzed |
| Project manager identification | HAZOP responsible person |
| Preliminary purpose, scope and objectives of the study | Study requirements definition – first consideration before leader assistance |
| **Attached Documentation** | Minimum – "Critical" – documentation for HAZOP organization |
| 1. Process Description | Detailed written description of process principal sections |
| 2. Process Flow Diagrams (PFDs) | Relationship between major equipment of a plant facility |
| 3. Piping & Instrumentation Diagrams (P&IDs) | Relationship between process equipment and control instrumentation |
| 4. Plot Plan, layout diagrams | Schematic description of the equipment layout |
| 5. Previous HAZOPs | Previous HAZOPs conducted on the same process |
| 6. Corporative HAZOP guidelines – if developed | Criteria for conducting HAZOPs |

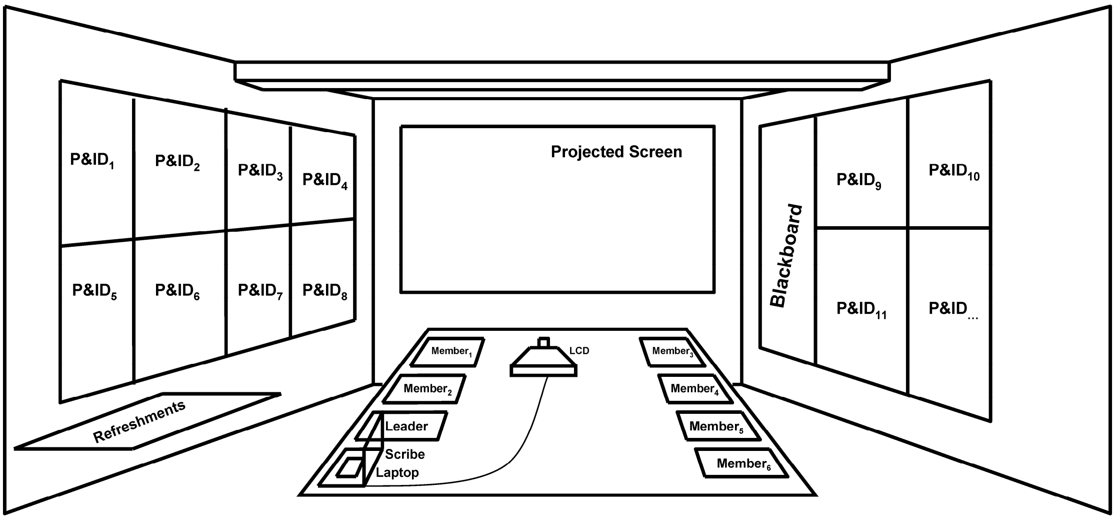

**Figure VI.2.**HAZOP Meeting Room Layout.

Although companies will make their own decisions, it is recommended to appoint an external team leader, as this ensures that the assessment will be independent and objective. A team leader who has no connections with the company will be able to provide assistance in specific situations without favoring any of the parties involved (no in-house influence) and share experience that is useful in solving problems identified in previous studies (expertise). The literature contains extensive information on the desired attributes and abilities of team leaders. The project manager compiles critical HAZOP input data (Table VI.5) so that the project specifications may be sent to candidate team leaders.

They should analyze the specifications and return their proposals[9] (Table VI.6). This strategy is intended to identify the most suitable team leader for a specific HAZOP study. Once the team leader has been appointed, he/she will begin to work with the project manager.

**Table VI.6.** Team Leader Proposal Contents.

| **Consultant identification** |
|---|
| Company name (Consulting) |
| Team leader identification – including experience on leading HAZOPs |
| Scribe identification - including experience on reporting HAZOPs |
| **Nodes Selection** |
| List and description of nodes selected |
| Nodes description should include the following information: |
| 1. Design intent |
| 2. Boundaries |
| 3. Process conditions |
| 4. Related equipment |
| 5. PFDs and P&IDs involved |
| **HAZOP Time Estimation** |
| Expected number of sessions |
| Criteria for planning the study – including meeting arrangement: |
| 1. Hours per session |
| 2. Sessions per day |
| 3. Days per week |
| Proposed HAZOP elapsed time (weeks) |

### VI.2.3. Defining the Study

The definition of the study has a strong influence on the contents and emphasis of the analysis and establishes the criteria for selecting the most appropriate team of experts. The project manager and team leader work closely to define the two key aspects of the study: the details of its purpose, scope and objectives; and the most suitable HAZOP team for achieving the objectives.

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[9] The proposals made by the team leader should include preliminary information for organizing HAZOP studies (HMS second phase). This preliminary information should establish how to divide the process design into manageable sections and provide a general study plan so that initial HAZOP meetings can be arranged.

### VI.2.3.1. Details of the Purpose, Scope and Objectives of the Study

A HAZOP study is defined by three aspects: the reason for the study (purpose); the area covered by the analysis (scope); and the goals pursued (objectives).

First, the purpose should include the process name and the chemicals involved, and will be defined according to the process lifetime, the process type, and several additional factors such as regulatory requirements and company policies; the purpose affects the way in which the study will be performed and defines the desired outcomes. Second, the scope will include all equipment and tools involved in the process. Third, the objectives should always include the identification of hazards (environmental, safety and health hazards) that could arise on- and off-site, and the potential operating problems, depending on each specific case. Table VI.7 contains simple and concise guidelines for defining HAZOP studies.

**Table VI.7.** Guidelines for defining HAZOP studies.

| **Guidelines for defining HAZOP studies** | |
|---|---|
| **PURPOSE** – why the study is performed | |
| | Meet regulatory requirements |
| | Meet industry requirements |
| | Company requirements |
| | Comply with good engineering practices |
| | Reduce legal liabilities |
| | Part of a post-incident investigation |
| | Comply with insurance company requirements |
| | Meet contractual requirements with customers or vendors |
| **SCOPE** – what is included in the study | |
| 1. Process boundaries | Limits of the process properly determined |
| 2. Equipment | Equipment involved that manage covered chemicals |
| 3. Utilities/Services | List of the utilities serving the process |
| 4. Modes of Operation | Modes of operation included |
| 5. External events | List of external events considered credible for the process |
| 6. Level of detail | Level of detail – partly determined by the study purpose |
| 7. Level of causality | Treatment of the causes |
| 8. Design intent | Method of defining parameters to be considered |
| 9. Exclusions | Identification of items excluded |
| **OBJECTIVES** – what is to be considered | |
| | HAZOP covers only major hazards associated with covered chemicals |
| | HAZOP includes other types of hazards from covered chemicals |
| | HAZOP includes hazards from non-covered chemicals |
| | HAZOP includes hazards from other process materials/equipments |
| | HAZOP focus only on regulatory issues |
| | HAZOP includes other issues of importance to the plant |

Table VI.8 provides additional information on possible hazards in process facilities that manage highly hazardous materials, and is intended to help identify the hazards that should be included in the objectives of a specific HAZOP study.

**Table VI.8.** Assessment of possible hazards to be identified.

| **Assessment of possible hazards in process facilities that manage highly hazardous materials** |
|---|
| **A. COVERING REGULATORY ISSUES (MAJOR ACCIDENTS)** |
| **TOXIC RELEASE** |
| Attending acute exposure and serious effects. Also asphyxiants |
| **FIRE** |
| 1. Pool fires |
| 2. Jet fires |
| 3. Flash fires |
| 4. Fireballs |
| 5. Warehouse fires |
| **EXPLOSION** |
| **1. Physical explosions** |
| 1.1. Pressure burst |
| 1.2. Rapid phase transition |
| **2. Chemical explosions** |
| 2.1. Condensed phase explosion |
| 2.2. Vapor / gas phase explosion |
| **REACTIVITY** |
| Uncontrolled decomposition, rearrangement or polymerization of a single instable compound |
| Loss of control of reactions |
| Chemical interactions from inadvertent mixing of two or more chemicals leading to an uncontrolled chemicals reaction |
| **B. COVERING OTHER TYPES OF HAZARDS FROM COVERED CHEMICALS** |
| 1. Corrosives |
| 2. Skin irritants |
| 3. Lachrymators, etc |
| **C. COVERING HAZARDS FROM NON-COVERED CHEMICALS** |
| 1. Raw materials |
| 2. Intermediates |
| 3. Products and by-products |
| 4. Additives |
| 5. Catalysts |
| 6. Waste streams, etc. |
| **D. COVERING HAZARDS FROM OTHER PROCESS MATERIALS / EQUIPMENTS** |
| 1. Nitrogen asphyxiation |
| 2. Scalding from steam or hot oil |
| 3. Hot surfaces / materials |
| 4. Cryogenic materials |
| 5. Pinch points |
| 6. High pressures, |
| 7. High kinetic energy |
| 8. Vacuum |
| 9. High voltage /current, etc. |

### VI.2.3.2. Selecting the Appropriate Team of Experts

The team of experts consists of professionals from different backgrounds who bring a variety of viewpoints to the process and work together to produce a more thorough review than would be possible if they worked individually. The types and level of skills that HAZOP team members must possess depend upon several factors, including the type of process or operation analyzed, and also the specific purpose, scope and objectives of the study. However, experience of HAZOP studies for continuous chemical processes suggests that there is an optimum team size, and that members must attend all HAZOP sessions:

- A team with more than seven members is not productive, because all members try to communicate with each other at the same time and are prevented from working closely and coherently.
- A team with fewer than five members does not possess the knowledge to guarantee a sufficient degree of creativity through interaction. Therefore, the optimum size is between five and seven members.

Table VI.9 shows the minimum collective knowledge required for multi-disciplinary brainstorming sessions.

**Table VI.9.** Minimum HAZOP Team Knowledge.

| Expert knowledge | Features |
|---|---|
| Design Engineering | knowledge of how the process is intended to operate<br>knowledge of applicable standards, codes, specifications, etc. |
| Process Engineering | Understanding of the process science and technology<br>Ability to judge the adequacy of existing safeguards |
| Operations & Maintenance | "Hands on" operating<br>Maintenance experience |
| Safety | Knowledge of process hazards<br>knowledge of safety systems |
| Other | Specialty areas |

The project manager should make sure that none of the original group members is substituted, as this causes a distraction and delays the planning process because brainstorming sessions tend to repeat previous discussions to take into account the criteria of new members. Useful information on how to manage a PHA team, including identifying weaknesses so that discussions are not dominated by members with stronger personalities, can be found in Frank et al. (1993) and Dowell III (1994).

Table VI.10 shows the responsibilities of team members during each phase of the study according to the HMS. This template is suitable for distribution to team members and is intended to foster greater motivation and interest in the process.

### VI.2.4. Preparing the Study

To ensure that the HAZOP study is prepared correctly, the project manager and team leader must compile the appropriate information for conducting the analysis, ensure that all information is accurate, comprehensive and up-to-date, and establish criteria for prioritizing recommendations.

#### VI.2.4.1. HAZOP Information – Conversion to a Suitable Form

The examination must not be carried out until a complete and accurate representation of the system under study has been drawn up. The value of a HAZOP study depends on the completeness, appropriateness and accuracy of the representation of the design, including the intention of the design. Consequently, the information package should be prepared as carefully as possible. The information management system is a key component of the infrastructure used to support a HAZOP study.

The information required for a HAZOP study must include a complete and accurate description of the process carried out in the facility, as it will be used to perform PHAs, establish hazard communication requirements, and document the design configuration of each process.

Table VI.11 is provided to be used to classify information according to its priority (points defined as “critical” make up the minimum documentation for drafting team leader proposals), to check the types of information required for a specific HAZOP study, and to monitor information status. If the representation of the design is flawed or incomplete, it should be corrected before the study begins.

**Table VI.10.** HAZOP Members Roles and Responsibilities.

| ROLE | HAZOP MANAGEMENT STAGE | HAZOP EXECUTION STAGE | HAZOP DOCUMENTATION STAGE |
|---|---|---|---|
| HAZOP manager has to assure all study stages are carried out with success, having into account both company and legal requirements | | | |
| **MANAGER** | To define the purpose, scope and objectives of the study | To assure the attainment of the study requirements. | To assure the final documentation quality |
| | To select the team leader | | |
| | To select the expert team, with experience and faculty | | |
| | To provide the needed documentation | To assure the responsibilities assignment | To follow-up the recommendations |
| | To communicate the study plan | | |
| | To guarantee the required HAZOP meeting room | | |
| Site Coordinator is an optional role intended to support the HAZOP manager for assuring well-suited sitting facilities, locations, equipment, etc. | | | |
| **COORDINATOR** | Liaison between team and HAZOP meeting room | To manage the team inside the work place | |
| | | To facilitate any required photocopy, etc. | |
| | | To manage the lunch logistic, refreshments, etc. | |
| Team leader' role is based on guiding the whole HAZOP. It is recommended his was not directly related on the company to assure objectivity | | | |
| **LEADER** | To analyze the required HAZOP documentation | To define the study to the team | To carry out the final study report |
| | To subdivide the system into nodes | To explain the HAZOP technique to the team | |
| | To plan the sequence of work sessions | To guide the team on using HAZOP (sessions) | |
| | To know legal requisites | To assure the effective work of the team | |
| | To assure the documentation quality, quantity and deadline | To maintain the control of the sessions schedule | |
| Scribe is an optional role intended to support the team leader on all HAZOP stages and document the information generated during HAZOP sessions | | | |
| **SCRIBE** | To provide technical support to the team leader | To document the generated information | To provide technical support to the leader |
| Expert team is a multidisciplinary group of professionals with different background for assuring a thoroughly review of the process | | | |
| **TEAM** | | To be involved on the hazard identification stage | |
| | To claim the documentation with sufficient prior notice | To identify causes and consequences of scenarios | To check the final documentation |
| | To analyze in detail the documentation received | To identify process safeguards | To evaluate the labor of the team leader |
| | To have knowledge of the process has to be analyzed | To propose recommendations | To focus on solving the recommendations |

**Table VI.11.** Assessment of Required HAZOP Information.

| **Assessment of required HAZOP information** |
|---|
| **Information on hazards of highly hazardous chemicals in the process** |
| Material Safety Data Sheets |
| **Information on the technology of the process** |
| Process Description and Plant Operation |
| Process Flow Diagrams (PFDs) |
| Instrumentation and controls |
| Maximum intended inventory |
| Safe upper and lower limits for several process parameters |
| Consequence evaluation of process parameters deviations |
| Critical action list |
| Diagrams describing operation modes |
| **Information on the equipment in the process** |
| Materials of construction |
| Piping and Instrumentation Diagrams (P&IDs) |
| Electrical classification |
| Relief system design |
| Material energy balances |
| Safety systems (interlocks, detection, etc.) |
| Critical equipment list |
| **Other useful information** |
| Corporative HAZOP guidelines |
| Plot Plan – Layout diagrams |
| Information on previous incidents |
| Information on services and utilities |
| Relevant codes, standards and guidelines |
| Skills of operating and maintenance personnel |
| Cause and effects diagrams |

Once the team leader has confirmed the validity of the information, he/she will draw up the initial organizational approach (defined in the team leader proposal) and arrange the first HAZOP session, subject to the agreement of the project manager. Details of the documentation and organizational approach will be sent to team members for review at least one week before the first session.

### VI.2.4.2. Risk Ranking Criteria

Risk ranking is a management tool for prioritizing recommendation follow-up. Companies are advised to develop corporate risk ranking schemes to ensure that the results of the HAZOP study are as consistent as possible. Risk ranking is accomplished by calculating qualitative estimates of the severities and likelihoods of hazardous scenarios and combining them to create general risk estimates in matrix, grid or table form. There are several qualitative ranking methods, which form the basis of semi-quantitative or quantitative techniques such as LOPA, FTA, or QRA. HAZOP studies only need to be conducted for hazard identification, and HAZOP is considered the best PHA technique for generating data for a subsequent LOPA, which examines the hazardous scenarios identified by HAZOP to determine whether SIFs (Safety Instrumented Functions) are required and, if so, the required SIL of each one. The cause frequency and consequence severity are defined to comply with IEC 61511 (2003), and take into account the simplest likelihoods-severities combination (risk matrix) (Figure VI.3). The current criteria reflect the belief that risk ranking performed during HAZOP studies should only be used to determine qualitative properties for recommendations priority. Importantly, the criteria stipulate that the severity and likelihood values should be assigned consistently throughout the study, and that risk ranking should be used only to prioritize recommendations, and not for quantification.

| **Consequence Severity Levels (S)** | |
|---|---|
| Minor (**$S_M$**) | Impact initially limited to local area of event with potential for broader consequence, if corrective action not taken |
| Serious (**$S_S$**) | Impact event could cause serious injury or fatality on site or off site |
| Extensive (**$S_E$**) | Impact event that is five or more times severe than a serious event |

| **Cause Frequency Levels (L)** | |
|---|---|
| Low (**$L_L$**) | A failure or series of failure with a very low probability of occurrence within the expected lifetime of the plant |
| Medium (**$L_M$**) | A failure or series of failure with a low probability of occurrence within the expected lifetime of the plant |
| High (**$L_H$**) | A failure can reasonably be expected to occur within the expected lifetime of the plant |

| **Risk Matrix (R)** | | | |
|---|---|---|---|
| | **$S_M$** | **$S_S$** | **$S_E$** |
| **$L_L$** | $R_6$ | $R_5$ | $R_3$ |
| **$L_M$** | $R_5$ | $R_4$ | $R_2$ |
| **$L_H$** | $R_3$ | $R_2$ | $R_1$ |

**Figure VI.3.** Risk Ranking Criteria.

## VI.3. HAZOP ORGANIZATION

The HAZard & OPerability (HAZOP) study is a structured method of examining hazard and operability by exploring the effects of various deviations from design conditions. However, despite its structured features, the method is complex, tedious, and time-consuming. Its organization is a key factor for success. A well-organized study requires detailed criteria to undertake two essential procedures:

(1) How to break designs into manageable sections with well-defined boundaries.

(2) How to readily predict the expected time to conduct the entire study.

This work offers guidance to team leaders on selecting process nodes, introduces a new global node treatment, and pioneers news tools, not only to predict the expected number of nodes to be selected, but also for estimating time. The information is taken from several HAZOP studies conducted in continuous chemical process (see *Chapter V – Field Work and Data Analysis*). The node-selection depicts a new nodes-sizing mode that ensures HAZOP outcomes meet regulatory requirements; the time-estimation model, easier and faster to apply than those previously proposed, highlights shortening brainstorming sessions. Additionally, a new deviations management for brainstorming nodes will be illustrated, thereby confirming the prediction of the time studies.

Therefore, with the aim of enforcing specific HMS deficiencies, the present contents offer tools for ensuring well-organized studies. The study discusses:

(1) How to select nodes.

(2) What the desired size of nodes is.

(3) How to plan the study for the arrangement of the sessions.

Figure VI.4 highlights which documentation is imperative for the organization task, and also the desired results.

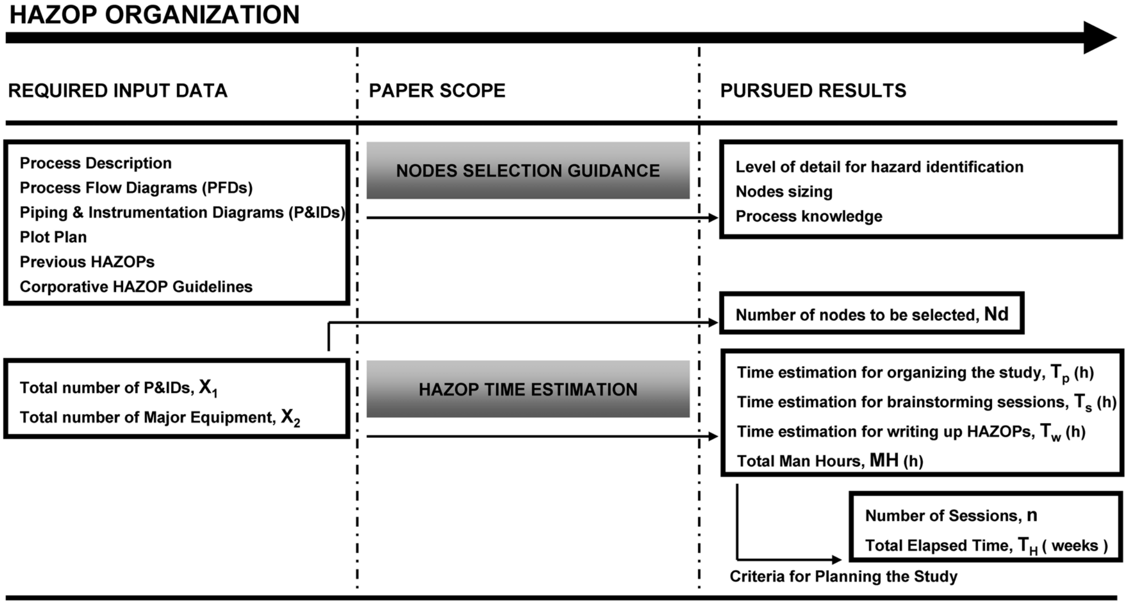
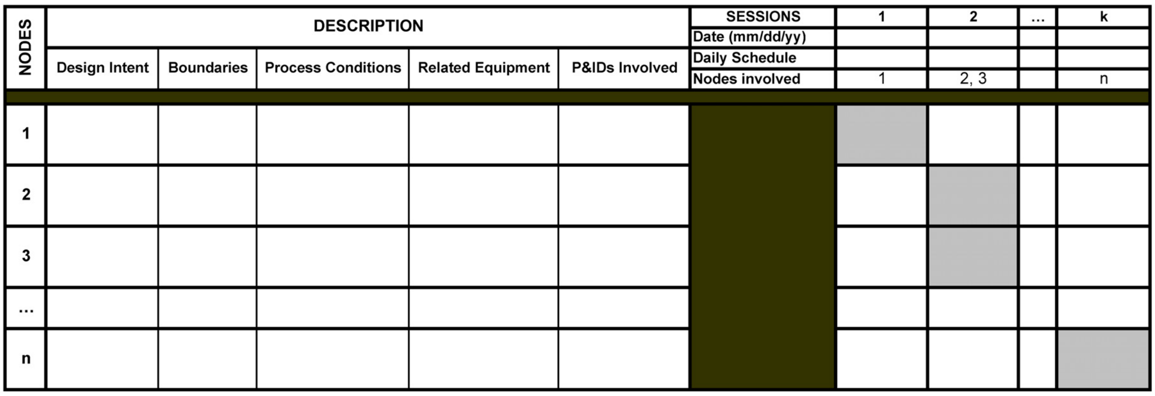


**Figure VI.4.** Scope of the organization task.

Figure VI.5 gives an example of how team leaders should send these results to project managers and team members according to Table VI.5.



| NODES | DESCRIPTION | | | | | SESSIONS | 1 | 2 | … | k |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Date (mm/dd/yy) | | | | |
| | | | | | | Daily Schedule | | | | |
| | Design Intent | Boundaries | Process Conditions | Related Equipment | P&IDs Involved | Nodes involved | 1 | 2, 3 | | n |
| 1 | | | | | | | ▨ | | | |
| 2 | | | | | | | | ▨ | | |
| 3 | | | | | | | | ▨ | | |
| … | | | | | | | | | | |
| n | | | | | | | | | | ▨ |

**Figure VI.5.** HAZOP Organization Results: Sample Worksheet.

### VI.3.1. Breaking the Process into Manageable Sections

It is impracticable to brainstorm all the information contained in P&IDs because doing so would overlook most of the potentially hazardous scenarios. Conversely, by breaking the process into very small parts, the study would become repetitive and extremely time-consuming; furthermore, the general picture of the process would be harder to comprehend. Thus, the process has to be broken into nodes, or manageable sections, by optimizing the time allotted for their review, and ensuring identification of most of the potential hazardous scenarios. Despite its importance, no research has assisted nodes management (Dunjó et al, 2008), and the practice currently is considered partly as an art, based on the leader's judgment.

Continuous chemical processes involve a wide range of equipment, instrumentation, utilities, and further devices, all interconnected via complex schemes thereby assuring fulfillment of the main design intent (e.g., petroleum-refining processes). However, this intent is susceptible to disruption by grouping specific equipment that share a same sub-aim or intention (e.g., equipment for distilling a mixture of products, equipment for pre-heating feed before starting to operate a specific unit operation). The following discussion will guide team leaders on distinguishing the sub-aim intentions from the main process-design intent up to the desired nodes size by ensuring the following two aspects (assuring both will favor the effectiveness of brainstorming):

(1) The equipment conforming section must share the same intention.

(2) The sections are equal in size.

Even though brainstorming, and thus nodes, are based on logical representations that show relationships between process components without scale, viz., P&IDs, a complementary physical representation showing the process layout, the Plot Plan, must be formulated to ensure complete hazard identification. Accordingly, both representations entail two nodes categories.

On one hand, process nodes are process sections that share design intent and are constituted by a set of lines and equipment, and additional items (e.g., instrumentation, utilities) based on P&IDs. They focus on what could happen “inside the line” and so traditional deviations apply (e.g., no flow, less pressure, more temperature). On the other hand, the global node[10] is a single section based on plot plan and focuses on what could happen “outside the line”. It is intended as a “bird’s-eye view” perspective for identifying hazards. Hence, complementary deviations apply (e.g., loss of containment, as well as human factors) in assisting the designation of the following hazardous issues:

(1) Initiating events that affect more than one node (e.g., flooding, electric power).

(2) Conditions that affect more than one node (e.g. facility siting, human factors, piping configuration).

(3) The need to view hazards from the position of the overall process (e.g. multiple failure scenarios that may encompass causes originating from more than one node).

#### VI.3.1.1. Selecting Process Nodes

While traditional HAZOPs base brainstorming on reviewing the process “line-by-line”, the actual selection of nodes attempts to identify a group of lines and equipment suitable to review together because they share the same design intent. Thus, considering a well-grouped set of process items as a node, brainstorming will be faster without losing the desired level of detail for identifying hazards. Nevertheless, identifying changes in design intents requires process knowledge. In this sense, the following contents describe the sequential steps that team leaders must follow to progressively acquire process knowledge that will finally ensure well-selected nodes, starting from the aim of the main process up to the specific intentions of the nodes.

---

[10] Global node applies to the last brainstorming session; it avoids the situation wherein the expert team is disinclined to review process nodes with required attention, thereby overlooking potential scenarios.

The following are the minimum sources of information that should be used:

(1) Process description (PDescription)

(2) Process Flow Diagrams (PFDs)

(3) Piping & Instrumentation Diagrams (P&IDs)

These data will support leaders in identifying firstly the Principal Sections of the processes (PS), secondly the intentions of the nodes via PFDs (Preliminary nodes), and lastly, the definitive nodes via P&IDs (Detailed nodes). Figure VI.6 shows the nodes-selection flux diagram.

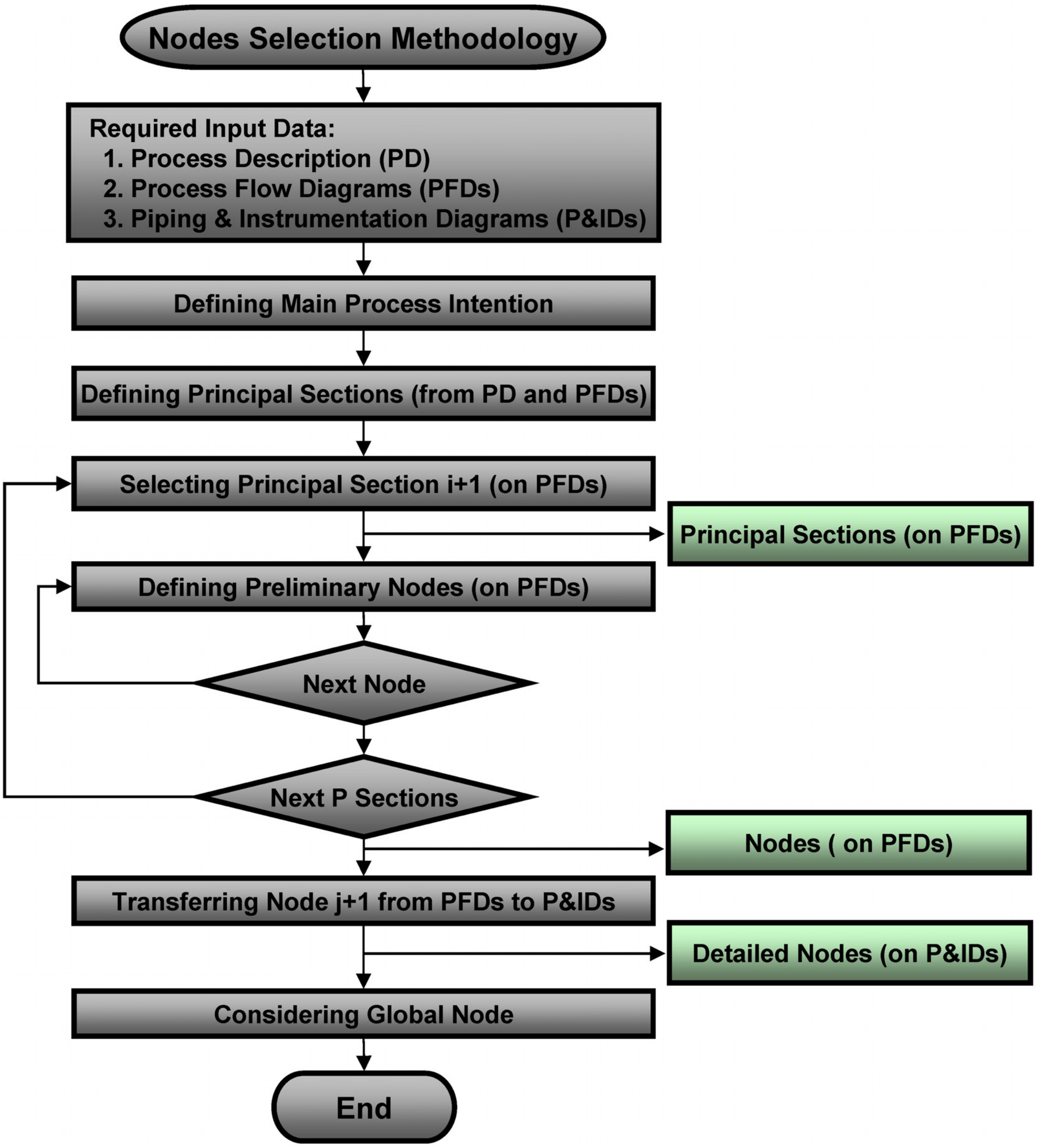


**Figure VI.6.** Nodes Selection Methodology: Flux Diagram.

The typical designs of chemical processes are intended to economically produce added-value products from a variety of raw materials through a succession of treatments. Raw materials undergo several physical-treatment steps, reading them for chemical reactions. Thereafter, they pass through the reactor and then undergo further physical treatment (e.g., separations, purifications) for generating the final desired product.

This explanation highlights the scope of the principal sections, easily found by reading the description of the process. The principal sections are addressed as encompassing a wide variety and large number of equipment that are involved in achieving a sub-aim, so contributing to the overall design intention of the process. Therefore, these principal sections will be marked on PFDs, diagrams that graphically provide the following details:

(1) How the principal sections are connected; it is important to be aware of which equipment shares the principal section's boundaries (e.g., control valves, pumps).

(2) Which major equipment is involved. In this sense, the principal sections represent the first process subdivision.

Figure VI.7 shows principal sections, their desired sizing, and highlights specific points for defining its boundaries in a standard petroleum-refining process. Further information related to specific PS features can be found in *Chapter V – Field Work and Data Analysis.*

Not all equipment contained into a principal section shares the same design intent. Team leaders will focus individually on each principal section, and will break them into smaller ones according to changes in the design intent, thereby defining the size of the final nodes. Because PFDs are easier to understand than P&IDs, and are intended to describe the entire route of the fluid system by highlighting changes in process conditions, i.e., the key points for considering boundaries of the nodes, it is appropriate to base the choice of preliminary nodes upon them. Major equipment, pipelines, pumps and control valves likewise are selected for defining a node.

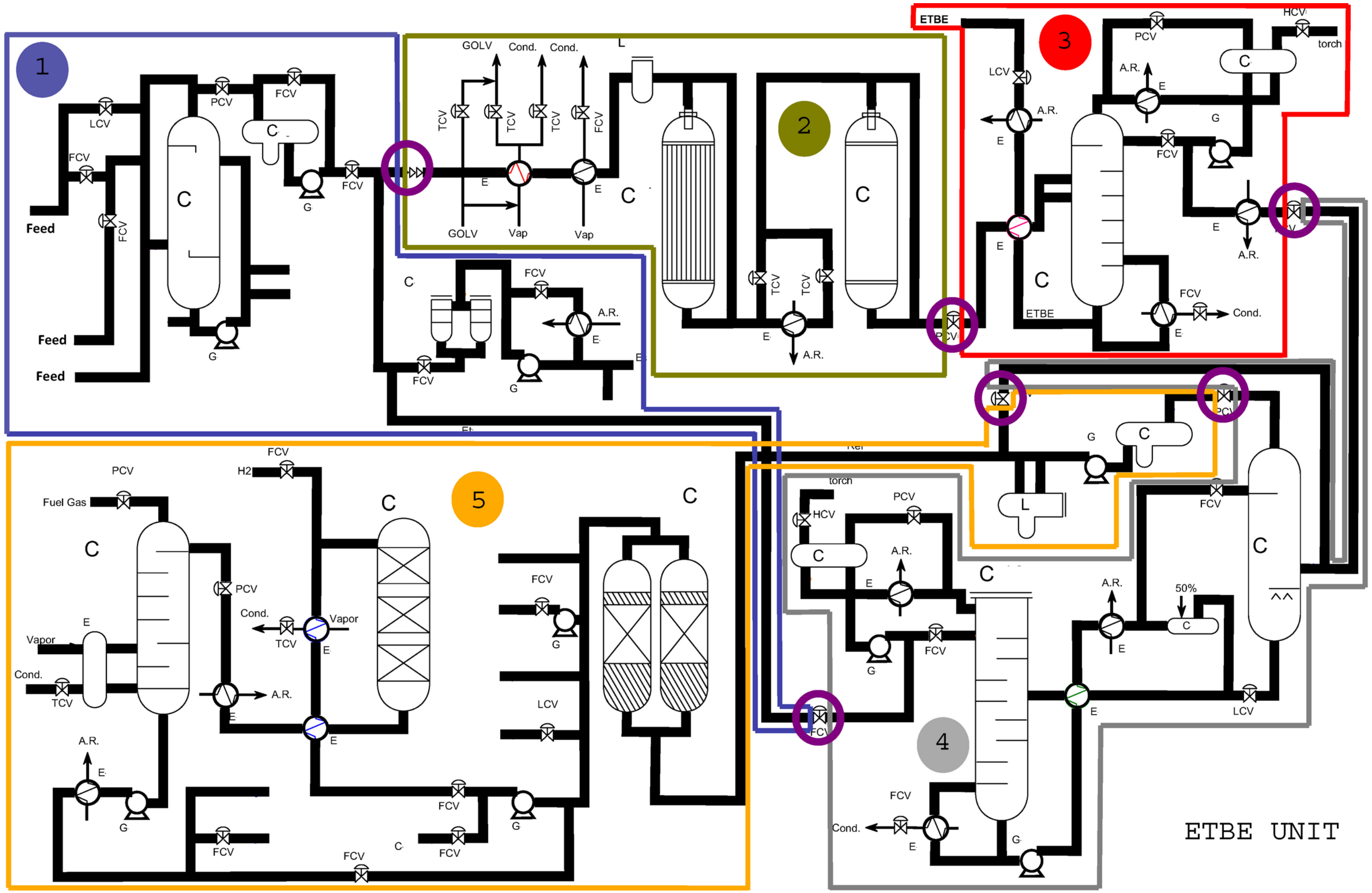


**Figure VI.7.** Principal Sections: Example

A principal section will contain two, three, four, and rarely five nodes, viz., design intent changes (according to *Chapter V – Field Work and Data Analysis* results). How to instruct leaders in identifying design-intent changes is not an easy task (less for standardization) because any process facility presents its own specific features and particularities. Hence, illustrating real selected nodes is the best procedure for assuring the acquisition of knowledge because members have visual documentation of nodes sizing and their key boundary points. Thus, it has been decided to show two refining units in order to give the scope of the full range of typical design intentions present in continuous chemical processes (see Figures VI.8 and VI.9). Nodes have been numbered and marked, and boundary points highlighted on PFDs. Thirty nodes are depicted, a sufficient number for instruction.

Brainstorming sessions entail reviewing P&IDs. The last step to follow for acquiring definite nodes is to transfer the preliminary nodes from PFDs to P&IDs. Thus, team leaders will select a preliminary node, detect its boundary items, and look for them on P&IDs. Hereafter, they will mark the whole set of equipment between boundaries according to preliminary node equipment involved; the same procedure will be repeated iteratively to the last preliminary node considered. Although PFDs only show the relationships between major equipment, P&IDs detail all process equipment and its relationship with control instrumentation, and utilities. Consequently, additional equipment and control loops will be involved during the transfer procedure. It will be necessary to evaluate three possibilities: (1) Including them as part of the actual node, (2) including them as part of the contiguous node, or, (3) should sufficient entities be generated because of their size, independent intention, and/or potential hazardous scenarios, and whether to consider the additional equipment as a new node. In cases of doubt, leaders will find support by using Process description. Once nodes have been selected, the results are highlighted in three different formats:

(1) Listings, specifying the nodes' design intent, boundaries, related equipment, process conditions, and stating which P&IDs are involved in each one.

(2) Graphics illustrating the nodes' scope on PFDs using color markers.

(3) Illustrating them on P&IDs employing the same color criteria.

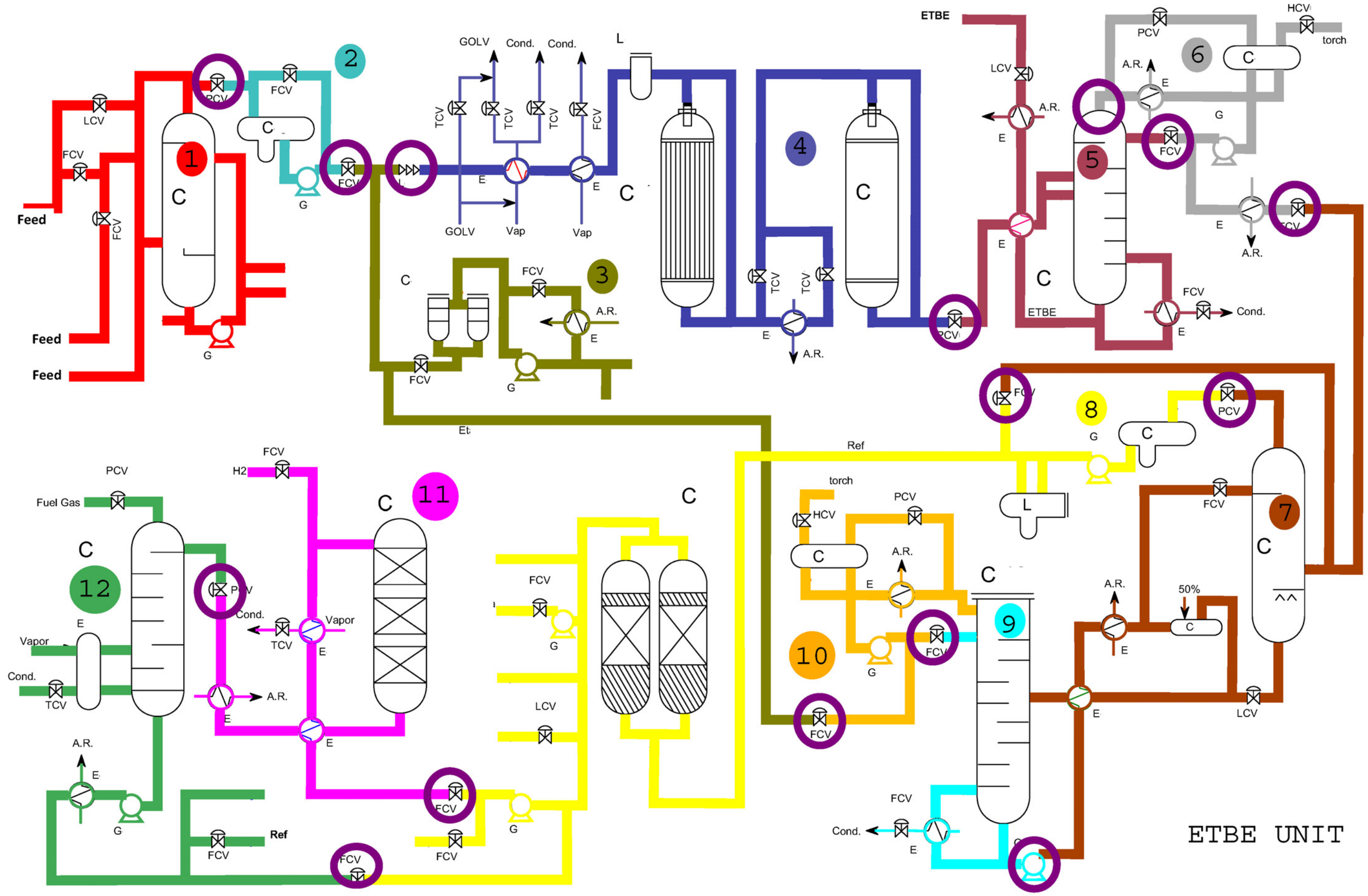


**Figure VI.8.** Preliminary Nodes Selection; Example

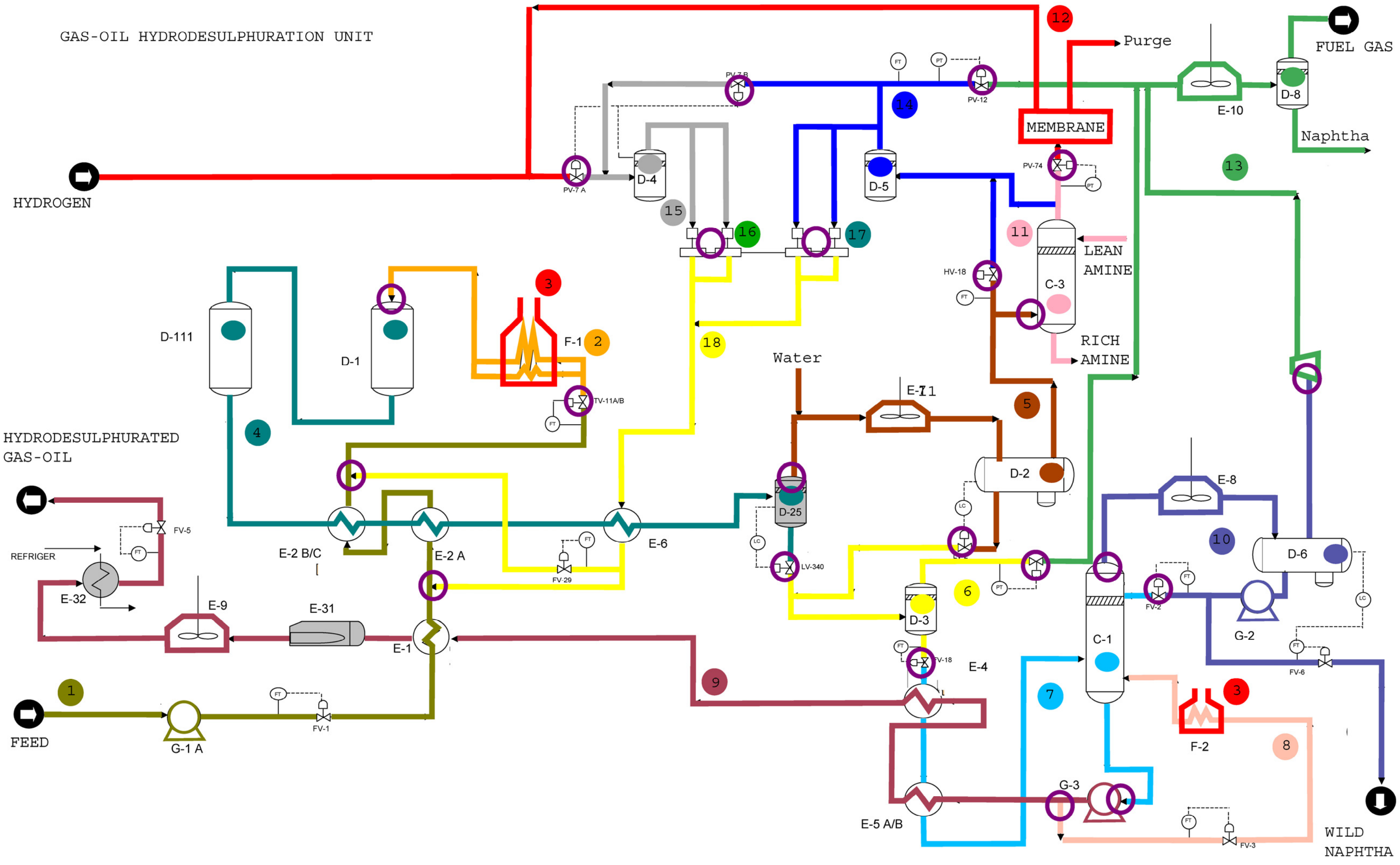


**Figure VI.9.** Preliminary Nodes Selection: Example

### VI.3.2. Estimating HAZOP Time

Efforts have been focused on providing tools for estimating HAZOP time by developing a new model that considers the following criteria:

(1) Studies defined and prepared.

(2) Nodes sized according to the descriptions in this work.

(3) Brainstorming sessions conducted following the criteria discussed in the next HMS phase treatment (see section HAZOP Execution and Documentation).

All these criteria are intended to minimize the team leader's judgment, and thus, to avoid the introduction of subjective factors into the model (e.g., the team leader's experience). The experimental data has been assembled from five HAZOPs conducted in continuous chemical processes. The total hours required for completing each HMS phase were recorded (Table V.1), along with the time required for a deeper analysis of each node reviewed, on how to plan a tentative HAZOP-meeting schedule. The total hours ($T_H$) that predict the model are the sum of all HMS phases (Equation V.1, see *Chapter V – Field Work and Data Analysis*).

The model has been conceived as the simplest possible for estimating HAZOP time, by searching for the minimum set of predictors that would produce the best fitting data. In a first attempt, some potential predictor candidates for modeling have been considered(e.g., number of P&IDs, number of PFDs, number of pieces of major equipment, equipment and lines per P&ID, number of control valves).

After conducting the best subsets regression, the model chosen was based on the following two predictors: The number of P&IDs (P&IDs), and the number of pieces of major equipment (ME), that is, information easy to extract from PFDs. The following reasons justify this decision. Firstly, these two predictors are acquired and managed extremely simply. Secondly, together they define precisely the complexity of the process. The number of P&IDs highlights the initial idea of process extension, and the number of pieces of major equipment details whether P&IDs are congested or not, thereby providing valuable information on the complexity of the diagrams.

Lastly, the model delivers accurate results that have been fitted to actual data using regression analysis, i.e., the least squares method. Additionally, a new concept account has been considered because of its relevance in planning the study. The total number of nodes (Nd) to be selected was modeled by using these same predictors (Equation V.3, see *Chapter V – Field Work and Data Analysis*). Table VI.12 shows the model's input and output data. Finally, additional predictors could be added to refine the model, although this widened the model's complexity. Thus, it was aimed for optimum criterion between accuracy and simplicity.

**Table VI.12.** Input Data and Model Results.

| **Factors considered** | **Symbol** | **Input Data** | **Output Data** |
|---|---|---|---|
| Number of P&IDs | P&IDs | ■ | |
| Number of Major Equipment | ME | ■ | |
| Number of Nodes | Nd | | ■ |
| Required Preparation Time (h) | $T_P$ | | ■ |
| Required Sessions Time (h) | $T_S$ | | ■ |
| Required Writing Time (h) | $T_W$ | | ■ |
| Number of sessions | N | | ■ |
| Total Man Hours | MH | | ■ |
| Total Elapsed Time (weeks) | $T_H$ | | ■ |

Equation V.2 (see *Chapter V – Field Work and Data Analysis*) gives the time predicted for defining, preparing, and organizing HAZOP studies ($T_P$). Additionally, the time for its documentation has been modeled ($T_W$) as a function of $T_P$ according to previous work (Freeman et al., 1992; Khan & Abbasi, 1997) (Equation V.5, see *Chapter V – Field Work and Data Analysis*); it accounts for the time required for revising the information generated during brainstorming, the HAZOP first draft. Further actions up to the final HAZOP report are not covered (out of the model scope) because they are not totally dependent on the team leader's decisions.

The time required for HAZOP sessions ($T_S$) was analyzed in detail; the data collected highlighted the necessity to treat separately the first HAZOP sessions and the subsequent ones. On one hand, the first sessions require further actions rather than just brainstorming the first node (Table VI.13).

**Table VI.13.** Actions to Carry Out during the First Session**.**

| |
|---|
| Introduce the team members themselves |
| Record attendance |
| Define the scheduling particularities, such as break times, daily timetable, and lunch time |
| Explain the HAZOP methodology to be used during the sessions |
| Detail features of the software that will be used |
| Review the purpose, scope, and objectives of the study |
| Review the process to be analyzed |
| Check the available documentation |
| Mark and confirm the node subdivision |
| Consider the first node selected |

Also, reviewing the first node requires more time than subsequent ones because the expert team needs some training before they are familiar with identifying hazards. For these reasons, and for modeling purposes, it was assumed that first nodes include both their own review and all these other mentioned actions.

The mean-time for completing the five first session/node was 5.52 hours. A Student's *t* test was applied to analyze data dispersion, and the resulting 95% confidence interval verified that the first session/node takes between 4.98 and 6.05 hours. Hereafter, a reasonable rule of thumb is assuming 6 hours per first session/node as a conservative criterion (see Figure VI.10).

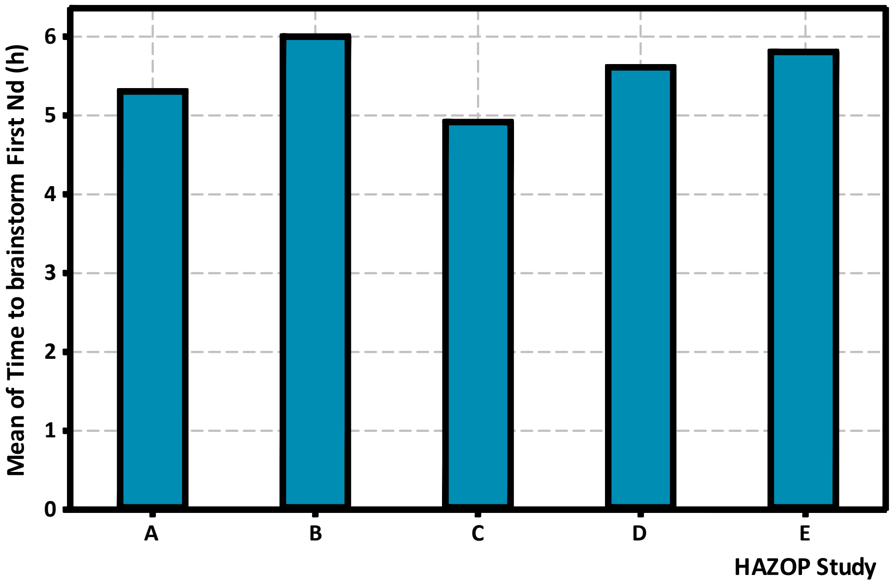


**Figure VI.10.** Analysis of the time required for the five first session/node.

On the other hand, a tendency to randomness was noted after timing 77 nodes during subsequent sessions (Figure VI.11).

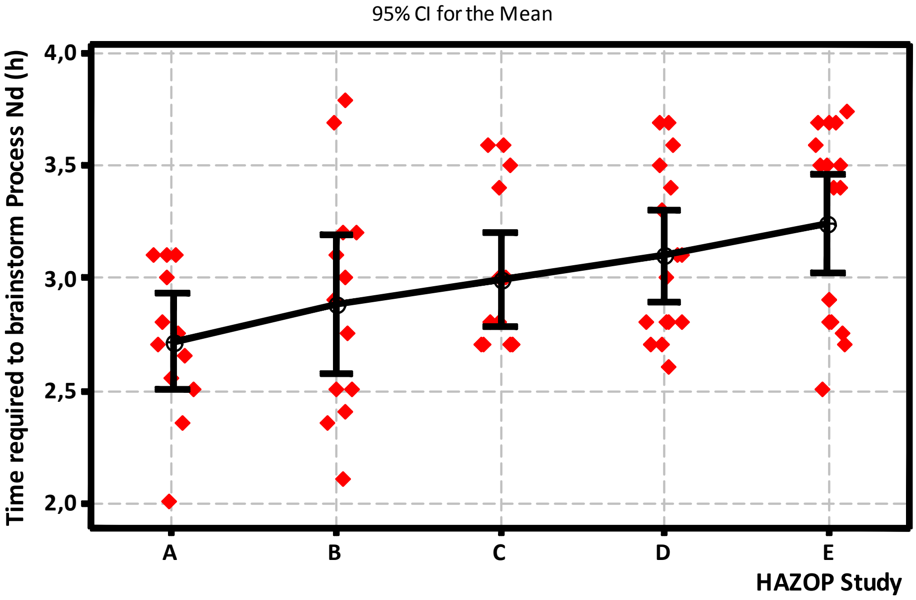


**Figure VI.11.** Analysis of Node Reviewing Time/HAZOP.

An analysis confirmed this random tendency, but also highlighted a slight interval of time that covers all nodes. The basic statistics derived depict the following information:

- Focusing on each HAZOP analyzed, the mean-time of the nodes increases according to the complexity of the process, that is, more "troubles" must be managed when more P&IDs and major equipment have to be analyzed; and,
- The 95% of mean-confidence interval verifies that each node takes between 2.91- and 3.11-hours.

This limited period confirms two of the important goals pursued: Uniformity when considering the proposed nodes sizing, and consistency in brainstorming following the criteria shown in the following section (HAZOP Execution and Documentation). Finally, $T_S$ was expressed according to the number of nodes predicted, thereby creating a more intuitive model (Equation V.4, see *Chapter V – Field Work and Data Analysis*)).

The actual model has been applied to estimate the required time for executing a HAZOP study according to the example shown in Figure VI.8; the findings appear in Table VI.14.

**Table VI.14.** HAZOP Time Estimation Model Application **–** Example

| **Parameters** | **Symbol** | **Input** | **Output** | **Assumptions** |
|---|---|---|---|---|
| Number of P&IDs | P&IDs | 13 | | Total number of P&IDs to be analyzed |
| Number of Major Equipment | ME | 18 | | Total number of major equipment depicted on PFDs |
| Number of Nodes, | Nd | | 13 | Number of nodes to review, including the global node |
| Required Preparation Time (h) | $T_P$ | | 15.6 | Required time for defining, preparing and organizing the study |
| Required Sessions Time (h) | $T_S$ | | 42 | Total number of hours for reviewing nodes |
| Required Writing Time (h) | $T_W$ | | 6.4 | Required time for writing and sending the first HAZOP draft |
| Required HAZOP Time (h) | $T_H$ | | 64 | Total number of hours for finishing HAZOP |
| Total Man Hours (h) | MH | | 448 | Man hours taking into account 7 HAZOP members participation |
| Number of sessions | S | | 7 | First session: first node reviewing. Following sessions: 2 nodes / session |
| Total Elapsed Time (weeks) | $T_{HAZOP}$ | | 3.14 | Criteria established in Table VI.15 |

### VI.3.2.1. Planning the Study for Arranging Meetings

HAZOP scheduling should not be viewed as a rigid assignment, but rather as serving to keep management aware of the required commitment for the study, and to assist team members in planning their external professional duties. Table VI.15 has guidelines on distributing the total hours required for conducting HAZOPs.

**Table VI.15.** Planning the Study. Criteria for arranging meetings.

| Time (hours) | Time (weeks) | Considerations |
|---|---|---|
| $T_P$ (h) | $T_P$ (w) = 1/16 $T_P$ (h) | 4 hours per day; 4 days per week |
| $T_S$ (h) | $T_S$ (w) = 1/24 $T_S$ (h) if $Nd > 9$<br>$T_S$ (w) = 1/30 $T_S$ (h) if $Nd \leq 9$ | 6 hours per session; 4 sessions per week<br>6 hours per session; 5 sessions per week |
| $T_W$ (h) | $T_W$ (w) = 1/16 $T_W$ (h) | 4 hours per day; 4 days per week |
| $T_H$ (h) | $T_H = T_P + T_S + T_W$ | Sum of the total time predicted |

For HAZOP management and reporting stages, it is considered that half of the daily workable hours are dedicated to the study, thereby allowing time for other daily professional duties, while the execution of the study will require members to attend brainstorming sessions for the entire working day. Thus, while planning prioritizes the HAZOP requirements, it also offers some flexibility. Thus, consecutively conducting sessions assures that team members become familiar with the methodology and the brainstorming procedure. Re-starting the HAZOP several days after the last node reviewed necessitates guiding the professional participants again. The following are the key commitments for scheduling brainstorming sessions:

- Schedule well in advance to minimize conflicts with the other commitments of team members.
- Avoid large gaps between meetings, and
- If convenient, schedule three-hour-sessions per day during the morning.

Further, for studies estimated to require one week or less, arrange consecutive sessions, and for multiple-week studies, plan four sessions to allow the continuation of regular work activities. Management should be informed if significant changes in the schedule become necessary.

### VI.3.2.2. Assessing Model's Results and Comparing them with Previous Models

The results have been compared with actual data, and calculated accuracy per HAZOP (respectively, Figure VI.12 and Figure VI.13).

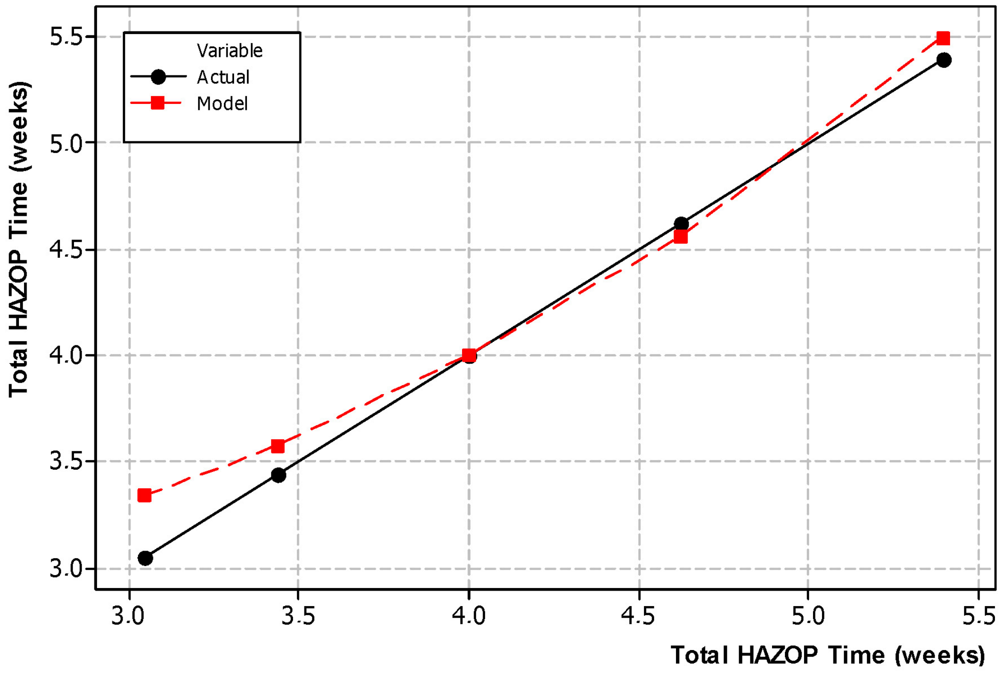


**Figure VI.12.** Comparison between Model Results and Actual Data.

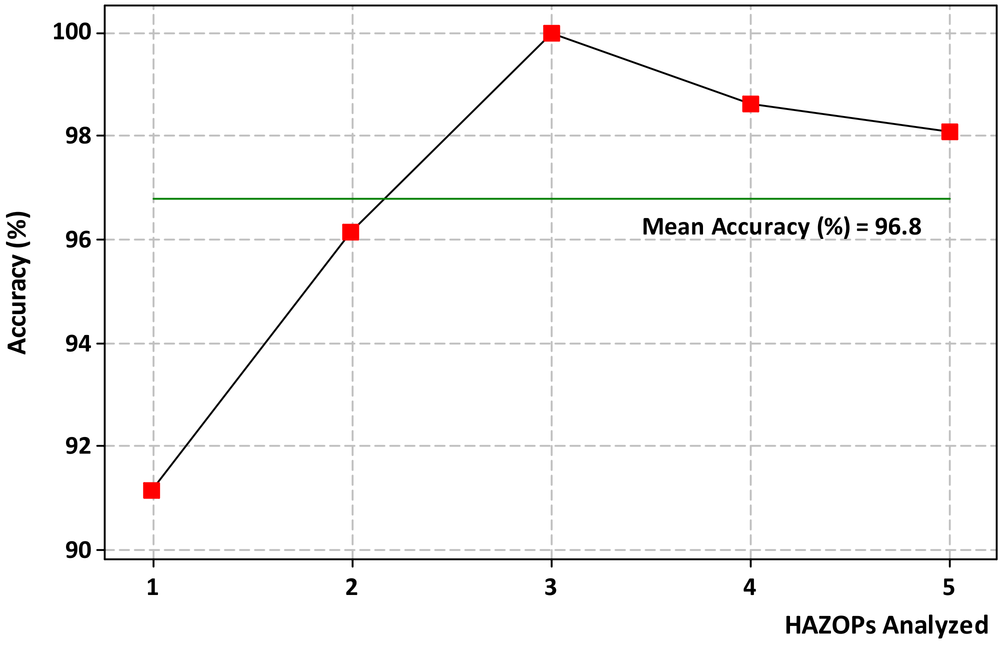


**Figure VI.13.** Model Accuracy per HAZOP Analyzed.

The model fits actual data with an accuracy of between 90-100% (96.8% mean accuracy). Analyzing results per each HAZOP highlighted that accuracy depends on the difference between P&IDs and the major equipment. The greater the difference, more complex P&IDs have to be managed, involving more congested P&IDs; thus, further potential issues could appear during the whole HMS (e.g., additional difficulties for nodes sizing, greater difficulty for identifying hazards). This aspect explains the first two modeled HAZOPs.

Conversely, smoother and more consistent HAZOPs are applied if P&IDs and major equipment tend to be the same. Hence, accuracy rises during the third- and fourth-HAZOP due to absence of additional issues.

Finally, should the HAZOP have to review a wide number of P&IDs, then independently of the difference between them and the major equipment, the process complexity also increases, and again, additional issues could appear. This is the reason why accuracy is falling in the fifth HAZOP analyzed.

The actual model was compared with the data developed in Khan & Abbasi's most recent work (1997). Since the models are based on different predictors (Table VI.16), and different processes which were used for modeling, it was necessary to establish criteria for this comparison thereby assuring the equivalence of the studies.

Only one factor is able to ensure such balance; the number of major equipment for reviewing. While the current model uses this factor, it was necessary to estimate it from Khan & Abbasi's work, who based time-estimations on the number of P&IDs and their complexity, to the number of equipment, considering both major equipment (e.g., vessels, distillation columns) and secondary equipment (e.g., pumps, exchangers), along with the number of pipelines. After considering the P&IDs employed for modeling, they were classified as these authors proposed; simple, standard, complex, and very complex. Then, the total number of ME per P&ID has been extracted, and finally, the mean number of pieces of major equipment per category has been considered as follows: 1, 2, 3, and 4 number of pieces of major equipment per category, respectively. Consequently, it was possible to compare one case study (Table VI.17).

**Table VI.16.** Comparison between HAZOP time-estimation models.

| **MODEL** | **Freeman et al. (1992)**<br>$T_H = T_P + T_S + T_W$ | **Khan & Abbasi (1997)**<br>$T_H = T_P + T_S + T_W + T_D$ | **Proposed Model**<br>$T_H = T_P + T_S + T_W$ |
|---|---|---|---|
| **Preparation Time Estimation ( $T_P$ )** | | | |
| Description | $T_P$ depends on the number of P&IDs and its complexity (simple, standard, complex, very complex) by counting number of equipments, pipelines and interlocks per P&ID | $T_P$ depends on the number of P&IDs and its complexity (simple, standard, complex, very complex) by counting number of equipments and pipelines per P&ID | $T_P$ depends on the number of P&IDs (P&IDs), total number of major equipment (ME), and requires to follow the proposed node selection approach |
| Input Data | Number of P&IDs, and complexity | Number of P&IDs, and complexity | $X_1$ , $X_2$ , and **Node Selection Approach** |
| Output Data | $T_P$ | $T_P$ | $T_P$ and number of nodes ( $Nd$ ) |
| **Sessions Time Estimation ( $T_S$ )** | | | |
| Description | $T_S$ depends on the leader skills (novice, average or experienced; which relies on the number of previous HAZOPs carried out), number of P&IDs and its complexity | $T_S$ depends on the leader skills (novice, moderately experienced, experienced and highly experienced; which relies on the number of previous HAZOPs carried out), number of P&IDs and its complexity | $T_S$ depends on the number of $Nd$ (P&IDs, ME), and requires to follow the proposed HAZOP execution approach |
| Input Data | Number of P&ID, complexity, leader skills | Number of P&IDs, complexity, leader skills | $Nd$ , **HAZOP Execution Approach** |
| Output Data | $T_S$ | $T_S$ | $T_S$ |
| **Writing Time Estimation ( $T_W$ )** | | | |
| Description | $T_W$ depends on $T_P$ | $T_W$ depends on $T_P$ | $T_W$ depends on $T_P$ |
| Input Data | $T_P$ | $T_P$ | $T_P$ |
| Output Data | $T_W$ | $T_W$ | $T_W$ |
| **Delay Time Estimation ( $T_D$ )** | | | |
| Description | Not considered | $T_D$ includes time lapsed due to non-availability of members, documents, or any other essential items, and individuals responding time | Not considered |
| Input Data | | $T_P$ , $T_W$ | |
| Output Data | | $T_D$ | |

**Table VI.17.** Comparison between Equivalent Studies.

| 1. Input Data | Khan &Abbasi Study | | Current Study | |
|---|---|---|---|---|
| Number of Major Equipment, ME | 20 | | 19 | |
| 2. Output Data | Model | Actual | Model | Actual |
| Time for defining, preparing and organizing the study, $T_P$ (h) | 30 | - | 22 | 20 |
| Number of nodes to be selected, Nd | - | - | 16 | 16 |
| Time for executing the study, $T_S$ (h) | 42 | - | 54 | 51 |
| Time for documenting the study, $T_W$ (h) | 13.9 | - | 8 | 8 |
| Time lapsed due to several issues, $T_{Delay}$ (h) | 7.9 | - | - | - |
| Time for conducting the whole study, $T_H$ (h) | 93.8 | 95 | 84 | 79 |

Before discussing this comparison, it is noted that 70% of the analyzed diagrams were classified as simple and standard P&IDs, a fact that is revealed by focusing attention on the difference between the total number of P&IDs to review when comparing input data between studies. The explanation is that over the years, P&IDs have evolved to be depicted as less equipment-congested, thereby generating more diagrams. However, and what is imperative for comparison, is that the total number of pieces of major equipment is equivalent. Finally, analyzing the case study, the following is the most important aspect: 17% less time is required for “hazoping” equivalent processes when the studies are defined and prepared according to the first phase of the HMS defined, and executed and documented adhering to the contents of this document. Additionally, accuracy is higher, and the results conform to regulatory requirements.

More details that support criteria established in the present section can be found in *Chapter V – Field Work and Data Analysis.*

## VI.4. HAZOP EXECUTION AND DOCUMENTATION

The aim of this work is to provide tools for ensuring effective brainstorming. A structural hierarchy has been proposed, for defining the minimum set of deviations to ensure the identification of key hazardous scenarios, and defining their order of application, avoiding repetitive analyses, and strengthening the structure of HAZOP itself. In addition, it is demonstrated how to properly record information in the HAZOP worksheets to assure that it is appropriately placed and understandable. This work would guide team leaders in structuring and expediting HAZOP sessions, assisting the compliance with the Occupational Safety and Health Administration (OSHA) Process Safety Management Rule (PSM), and the Seveso Directive legislation.

After organizing a HAZard & OPerability (HAZOP), the execution stage follows. Enacting the method relies on using guidewords (e.g., “no”, “more”, “less”) combined with various parameters (e.g., temperature, flow, pressure) that aim to reveal deviations (e.g., less flow, more temperature) of the process intention or normal operation. This procedure is applied in a particular node, viz., as a part of the system characterized by a nominal intention of the operative parameters. Having determined the deviations, the expert team explores their feasible causes and possible consequences. For every pair of cause-consequence (scenario), safeguards must be identified that could prevent, detect, control, or mitigate the hazardous situation. Finally, if the safeguards are insufficient to resolve the problem, the team should offer recommendations.

HAZOP studies evolved from the Imperial Chemical Industries’ “Critical Examination” technique formulated in the mid 1960s, and a plethora of publications appeared with important contributions for adapting HAZOP’s features according to the evolution of chemical-process facilities (see *Chapter IV – HAZOP, State of the Art and Training*). Nevertheless, even today, there remain entities to be improved (e.g., nodes selection, brainstorming), corresponding to modern technology. The present work covers each step for reinforcing brainstorming and completing the HAZOP tables. Its scope covers tasks using data obtained after organizing the study (i.e., nodes, session schedule) up to the first HAZOP draft (Figure VI.14).

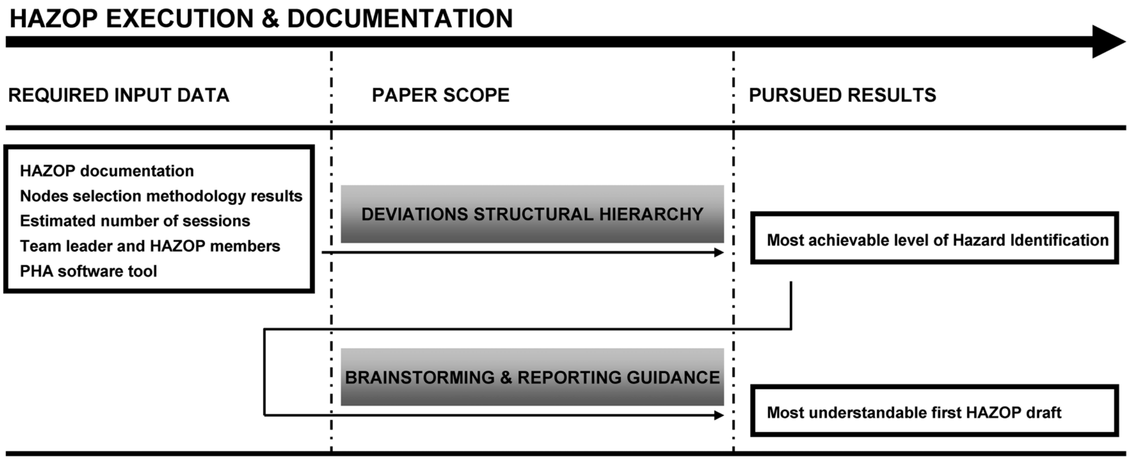


**Figure VI.14.** Scope of the HAZOP execution and documentation phase.

Furthermore, criteria established in the present work follow several suggestions discussed by Palmer (2004). They encompass the development of a structural hierarchy defining the following:

- The minimum set of deviations to be brainstormed.
- Their order of application.
- Content of HAZOP worksheets (i.e., layout of the worksheet, what must be recorded in each worksheet column, and how to do so).

It is noted that the proposed structure does not reduce the freedom of creative thinking required for brainstorming; on the contrary, the proposed structure encourages team members on brainstorming interactions between the mechanical, electrical and human systems addressing the guidelines for hazard identification in the Occupational Safety & Health Administration (OSHA) PSM Rule (1992) and the Seveso Directive (2003):

- OSHA PSM Rule: paragraphs (c), (d), and (e)
- Seveso Directive: Article 9, paragraphs 1(a), 1(b), and 2; Annex II, paragraphs A, B, and C; Annex III, paragraph c(ii)

### VI.4.1. Generating Deviations – Guide Words and Parameters

HAZOP systematically questions every selected node to identify qualitatively how deviations from normal operation could occur, and whether further protective measures, altered operating procedures, or design changes are required. The questioning is focused sequentially around a number of guidewords derived from HAZOP methodology. An ordinary guideword list (Table VI.18) is used for process facilities; others are available to guarantee specific HAZOP purposes and objectives.

While these guidewords have no meaning if treated solely, their combination with process- and general-parameters (Table VI.19) identifies deviations from design intentions.

In this sense, there are two approaches for recognizing deviations (Figure VI.15).

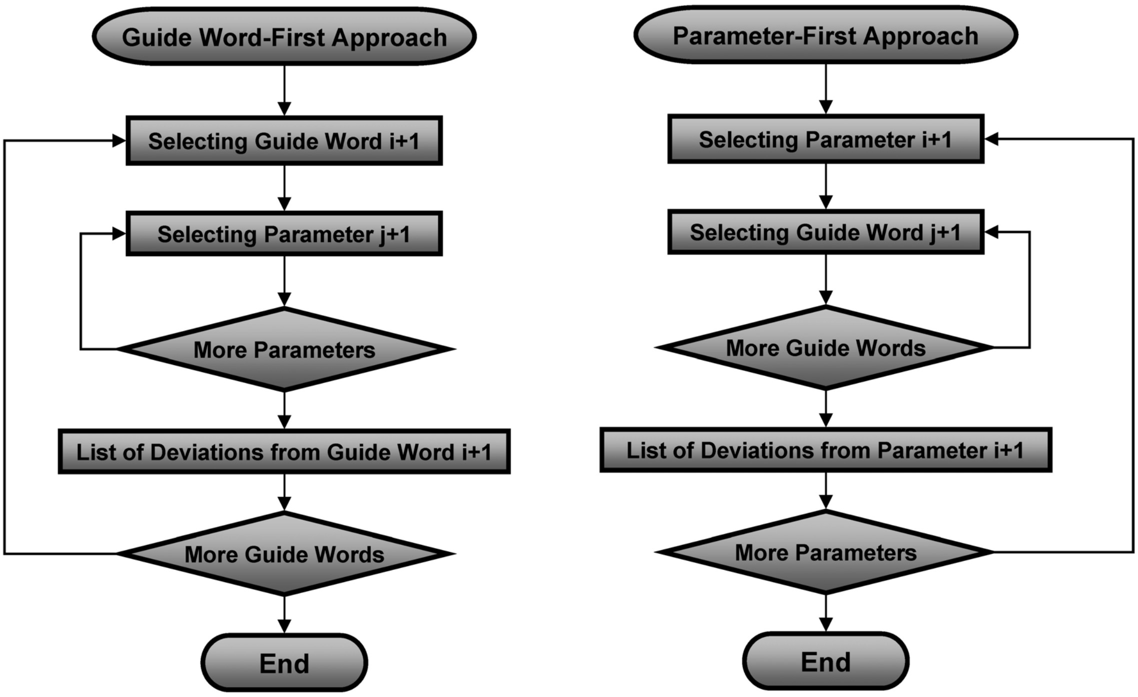


**Figure VI.15.** The Two Approaches for Generating Deviations.

**Table VI.18.** Standard Guide Words for Continuous Chemical Processes.

| Guide Word | Meaning | Explanation |
|---|---|---|
| No | Negation of design intent | No part of the intention is achieved but nothing else happens |
| More | Quantitative increase | The intention occurs in a way that is quantitatively greater |
| Less | Quantitative decrease | The intention occurs in a way that is quantitatively lesser |
| As Well As | Qualitative increase | All of the intention is achieved, together with something else |
| Part Of | Qualitative decrease | Some of the intention is achieved but some is not |
| Reverse | Logical opposite of intent | The opposite of the intention happens |
| Other Than | Complete substitution | No part of the intention is achieved and something quite different happens |

**Table VI.19.** List of Specific- and General-Parameters**.**

| Specific | General | | | | | |
|---|---|---|---|---|---|---|
| Flow | pH | Sequence | Stirring | Time | Operation | Instrumentation |
| Temperature | Addition | Implantation | Separation | Measure | Emergency | External Event |
| Phase | Testing | Viscosity | Speed | Control | Spare Equipment | Blow down |
| Level | Static | Particle Size | Signal | Utilities | Maintenance | Corrosion /Erosion |
| Pressure | Sampling | Transfer | Stop / Start | Relief | Reaction | Purging / Inerting |
| Composition | Safety | Mixing | Communication | Evacuation | Containment | Human Factor |

On the one hand, the “guideword-first approach” starts with a guideword, testing the same type of deviation on all possible parameters before moving to the next guideword. The European Process Safety Center’s (EPSC) Guide (2000) confirms that this approach encourages a creative thinking by the study team. On the other hand, the “parameter-first approach” allows the team to concentrate on all the possible deviations of one parameter before considering the next one. The EPSC affirms that this approach affords more convenience and consistency, but also demands greater understanding and more precise application by the team leader and members. Thus, efforts are centered on providing tools for satisfying this required “understanding and application.” In this sense, while the guideword-first approach is intended to stimulate creativity about which set of deviations should be considered (it does not consider structuring the brainstorming itself), the parameter-first approach entails a less creative methodology for deciding upon deviations, but enforces uniformity in brainstorming, the main aim of the research. For this, a Deviations Structural Hierarchy (DSH) was developed that covers a complete set of deviations (it must guarantee that most departures from process conditions are analyzed). The DSH has to be supported by a comprehensive node description, with a clear definition of the intention of the parameter. This requirement entails classifying the parameters into two categories:

> (1) Specific parameters, viz., variables affecting physical- or chemical-aspects that can be measured or detected. Their departures from design conditions might cause hazardous scenarios in the absence of safeguards (e.g., flow, temperature, level).
>
> (2) General parameters, viz., group of situations that, if absent or qualitatively modified, could generate a hazardous condition (e.g., addition, containment). While they rigorously cause specific parameter deviations, their independent analysis conveniently ensures complete hazard identification.

Table VI.20 depicts consistent deviations with process parameters in chemical-process facilities.

**Table VI.20.** Guidewords and Parameters: Compatibilities**.**

| | **No** | **More** | **Less** | **As Well As** | **Part Of** | **Reverse** | **Other Than** |
|---|---|---|---|---|---|---|---|
| **Temperature** | | ■ | ■ | | | | |
| **Flow** | ■ | ■ | ■ | ■ | | ■ | |
| **Pressure** | | ■ | ■ | | | | |
| **Level** | | ■ | ■ | | | | |
| **Phase** | | | | ■ | ■ | | ■ |
| **Composition** | | | | ■ | ■ | | ■ |
| **Utilities** | ■ | | | ■ | ■ | | |
| **Operation** | | | | ■ | ■ | | ■ |
| **Containment** | ■ | | | | | | |
| **Implantation** | | | | ■ | ■ | | |
| **Human factor** | | | | ■ | | | |
| **External event** | | | | ■ | | | |

Focusing on reviewing deviations in a process node that involves a set of equipment sharing a design intent, it is necessary to denote which point or equipment is examined once a deviation is under revision. For example, in heat exchangers, tubes and shell containing different fluids should be analyzed separately because independent causes and consequences could be generated. Meanwhile, if several points of reference were identified, they should be reviewed independently; this procedure is repeated for the affected deviation as many times as the number of points of reference identified. Although several deviations may not involve more than one point of reference, it is important to introduce this concept for ensuring that most process items will be analyzed.

### VI.4.2. Deviations Structural Hierarchy

The Deviations Structural Hierarchy (DSH) covers deviations from process nodes and also takes into account the global node; thus, it is invaluable for completing hazard identification of potential scenarios that might be overlooked in applying only the former. On the one hand, applying the DSH to process nodes covers all specific parameters that are normally highlighted on PFDs and P&IDs (i.e., pressure, level, phase, temperature, flow, and composition), and also key general parameters that directly affect process intentions (i.e., human factors, operation, utilities, and containment).

Thus, a set of ten parameters will encompass changes in the design intent of the process nodes, and, combined with six standard guidewords, will generate sixteen deviations.

On the other hand, applying DSH to the global node incorporates general parameters, which, combined with guidewords, stimulates the diagnosis of scenarios that could simultaneously scope several process nodes. After conducting the five HAZOPs via DSH, all interested parties (i.e., managers, team leaders, and expert teams) confirmed that a set of six deviations will thoroughly cover the global-node analysis. A total of 22 deviations (16 from process nodes, and 6 from the global node) cover all factors that should be addressed for complying with regulation requirements. HAZOP team members should recognize the need for additional treatments according to the HAZOP's scope, purposes, and objectives.

The order of executing selected deviations is described in the following section. This order is decided by considering sequentially three levels of detail:

(1) Categories of parameters.

(2) Parameters within each category.

(3) Deviations generated per parameter.

### VI.4.2.1. Deviations from Specific Parameters

Deviations from specific parameters could entail similar hazardous scenarios. For example, "more flow" could be related to "more level", both leading to overflow, and "more temperature" with "more pressure" leading to a run-away reaction. Therefore, three pairs of parameters should be reviewed sequentially to encourage uniformity in brainstorming: (1) "Level-flow", (2) "pressure-temperature", and, (3) "composition-phase". Hence, more related situations will appear, for example, when sequentially brainstorming both "level" and "flow" parameters rather than considering "level" and "composition". Thus, the main aim is to avoid suddenly changing the focus of brainstorming.

The last arrangement is based on the following criteria: (1) The first priority is for following fluid routes according to a continuous chemical-processes entity (“level-flow”), and furthermore, the first priority should be assigned to “level” rather than “flow” because nearly all their potential “causes” should be similar or comparable when reviewing departures from “flow”; (2) the second priority is following key changes in the properties of fluids (“pressure-temperature”), and furthermore, here giving precedence to “pressure” rather than “temperature” because the outcome will be more consistent by linking “flow” (the previous deviation) with “pressure” rather than with “temperature” (e.g., especially if gases or vapors are involved); and, (3) the last priority is for “composition” and “phase” parameters, the review of which will be aided by knowledge acquired via previous deviations analysis.

While “composition” and “phase” only consider a single guideword combination (i.e., “other than composition”, and “other than phase”), the rest of specific parameters reveal more than one (e.g., “more level”, “less level”) Therefore, a definite hierarchy should be established by putting the deviations in order of importance. DSH specifically was established for reviewing, as soon as possible, those deviations entailing the strongest departures from design intents: (1) “Level”; more hazardous scenarios could arise from “more level” than “less level” due to possible loss of containment, (2) “flow”; in continuous chemical processes the more severe departure from design intent would be “no flow”, and secondly “less flow”. Hereafter, the opposite situation is considered, “more flow”, and finally, “reverse flow”; and, (3) “pressure” and “temperature”, both of which follow the same criterion, and match up with “level” assumptions by first applying “more” rather than “less” (e.g., high temperature or pressure should be foremost as they may lead to runaway reactions, and failures of mechanical integrity).

#### VI.4.2.2. Deviations from General Parameters

With the aim of maintaining the consistency of brainstorming, the first priority is given to general parameters more closely “coupled” to process engineering equipment (i.e., “utilities” and “operation”), thereby linking categories of parameters.

Finally, in ranking “containment”, “external events”, “human factors”, and “implantation”, the following criteria has been considered: (1) First, “containment” because many worst case scenarios depend on this, (2) “human factors” was placed in the last position to take advantage of all the acquired knowledge on nodes (causes from “human factors” deviation are probably the most difficult to identify because of their unpredictability), and, (3) “external events” were placed just before “human factors” because they impact the process from outside the facility (less predictable). Thus, “implantation” was placed between “containment” and “external events”.

Eventually, it is necessary to note general parameters that must be considered twice:

(1) Addressing what could happen “inside the pipeline” when applying DSH to process nodes.

(2) Addressing hazardous scenarios from a “bird’s-eye-view” when reviewing the global node.

Tables VI.21 and VI.22 show the formulation of the DSH.

### VI.4.2.3. Deviations Management

While the meaning of deviations generated from specific parameters can be followed from PFDs and P&IDs, there is less data when considering those from general parameters. Thus, while both the OSHA PSM Rule, and the Seveso Directive regulations establish the requirement to deal with general issues (e.g., facility siting, utilities, human factors) when developing a PHA, there is no detailed information on how to proceed. The following discussion offers advice for applying them.

1. The failures of utilities are treated in HAZOPs as causes of deviations, such as “no flow” (e.g., failure of electric power to a pump). Therefore, if a deviation is thoroughly brainstormed, several causes will appear as a utility failure. However, in emphasizing the importance of utilities connected to continuous chemical processes (e.g., cooling water, electric power, instruments air, steam, fuel-oil, nitrogen), and also in considering that more than one node could have affected them, this is justified as a candidate HAZOP parameter. The team leader will list the whole set of utilities that might impact on a specific node, and treat each of them as a point of reference.

**Table VI.21.** Deviations Structural Hierarchy – Process Nodes.

| Parameter | Guideword | Deviation | Meaning |
|---|---|---|---|
| **LEVEL** | More | More Level | High level with possible overflow. Flooding of pipes with inappropriate design for liquid phase fluid entries |
| | Less | Less Level | Low level with possible cavitations' phenomena of pump systems connected after vessels. Additionally, the vessel could be totally emptied and remain without liquid, producing problems with equipment designed for drying conditions |
| **FLOW** | No | No Flow | No flow in locations where it was expected flow circulation |
| | Less | Less Flow | Restriction of the fluid flow. Often it is analyzed jointly with the "No Flow" deviation |
| | More | More Flow | Excessive flow in fluid transport piping systems than the expected |
| | Reverse | Reverse Flow | The fluid circulates in the wrong direction than the expected |
| **PRESSURE** | More | More Pressure | High pressure with possible hazards on the mechanical integrity of the node equipment if design pressure is exceeded |
| | Less | Less Pressure | Hazardous scenarios due to piping cavitation, blockage in vessels, etc. Risk of vessel implosions for equipment not designed for these conditions |
| **TEMPERATURE** | More | More Temperature | High temperature with possible thermal damage risk in construction materials or possibility of activating undesirable reactions |
| | Less | Less Temperature | Low temperature with possible risk of fluid freezing, construction materials brittleness or undesirable crystallizations |
| **COMPOSITION** | Other than | Other than Composition | Presence of undesirable chemical substances by contamination or wrong addition (another product or impurities), by services access (water, oil, steam) and undesirable atmospheres generation (air) |
| **PHASE** | Other than | Other than Phase | Presence of a phase state (solid, liquid or gaseous) for which has not intended the operation |
| **UTILITIES** | No | No Utilities | Unexpected services failure. Experience highlights considering services analysis as a specific deviation allows identifying hazardous scenarios not identified in previous deviations |
| **OPERATION** | As well as | As well as Operation | Analysis of other modes of operation than normal (start-up, shutdown, etc.). Valuable to treat carrying out Procedural HAZOPs for operations subjected under written instructions |
| **CONTAINMENT** | No | No Containment | Identification of any operative condition able to cause the emission of hazardous materials off-site: opening valves connected directly to the atmosphere as well as leaks through joints, or breakable mechanical elements |
| **HUMAN FACTOR** | As well as | As well as Human Factor | Determination whether all significant human failures have been identified by considering all the people who are involved, the various functions they may perform, the different types of mistakes they may make |

**Table VI.22.** Deviations Structural Hierarchy – Global Node.

| Parameter | Guideword | Deviation | Meaning |
|---|---|---|---|
| **UTILITIES** | No | No Utilities | Utilities failure considering the whole unit. Experience highlights this analysis allows identifying hazardous scenarios not identified in previous deviations |
| **OPERATION** | As well as | As well as Operation | Intended to identify modes of operation able to cause new hazardous scenarios overlooked in previous parameters. Valuable to treat carrying out Procedural HAZOPs for operations subjected under written instructions |
| **CONTAINMENT** | NO | No Containment | Identification of any operative condition able to cause the emission of hazardous materials off-site focusing the analysis as a “bird’s eye view”. Identification of direct ignition sources and specific locations where toxics leaks are possible |
| **IMPLANTATION** | As well as | As well as Implementation | Analysis of aspects affecting facility sitting: accessibility, get away routes, congestion equipment, vehicle impacts, drainage systems, slope, fire protection devices, facility location, process units spacing, spacing between equipment and potential ignition sources, domino effects, emergency response issues, hazardous area classifications |
| **EXTERNAL EVENT** | As well as | As well As External Event | Analysis of aspects away from process hazards which can cause hazardous scenarios regarding operational safety. Consider as minimum: lightning, flooding, deep cold, external fire and domino effect |
| **HUMAN FACTOR** | As well as | As well As Human Factor | Analysis of aspects focused on health and safety deficiencies of plant personnel as well as regarding the occurrence of major accidents caused for human failures in critical operations. Consider problems limiting personnel activities and emergency procedures |

2. Other process states than normal operation must be explored for identifying hazards. At least the start-up and shut-down modes should be considered (according to the scope of the study). A specific deviation to address this fact is proposed, “as well as operation”. This is a formal attempt to consider other modes, which will be treated as points of reference.

3. Although specific parameters address loss of containment scenarios, a specific deviation has been introduced (“no containment”) for handling those scenarios potentially resulting in fires, explosions, and toxic releases (key scenarios that could engender major accidents). These scenarios might also be used directly as input data for more detailed studies, such as QRAs.

4. The global node includes a specific deviation (“as well as implementation”) to motivate HAZOP members to examine aspects of the layout of processes (e.g., the location of safety systems, such as firewater headers, hydrants, extinguishers, and flammable- and toxic- gas monitors and alarm systems). The team leader also should guide the team to identify the locations of people and significant inventories of hazardous materials, and determine if their proximity creates potential problems (Primatech, 2007).

5. Events originated outside the process that might adversely affect it must be scrutinized. “As well as external event” highlights the importance of visiting this kind of initiating event, both in reviewing process- and global-nodes (e.g., flooding, earthquakes, vehicular impacts, and fires or explosions in adjacent facilities).

6. “As well as human factor” necessitates brainstorming on how human factors might interface with the engineered process. While there is guidance for treating the deviations discussed, here there is none. Regulations demonstrate the necessity to address human factors, but there is a dearth of information on how to proceed. However, this parameter is crucial when applying PHAs (e.g., between 50 to 90% of operational risk is attributable to human error (Baybutt, 2002)).

Therefore, criteria for guiding team leaders have been proposed in two facets of the problem

(1) Which human failures may cause hazardous scenarios?

(2) Which factors impact on human performance?

Table VI.23 classifies some human failures that might be evaluated.

**Table VI.23.** Human Failures Assistance.

| **1. Employee** |
|---|
| Difficulties with clarity and manageability on controls and indicators |
| Accessibility inadequate |
| Task overloading |
| Inappropriate operators for assigned specific tasks |
| Lack of operators’ knowledge (e.g., little specific training, low language skills) |
| Excessive confidence |
| Operator’s physical features (e.g., height, heftiness, vision, hearing) |
| **2. Operational procedures** |
| Absence of knowledge of established procedures |
| Procedure much too simple or complex |
| Poor written procedures |
| Inadequate accessibility to procedures |
| **3. Equipment** |
| Inappropriate equipment identification |
| Poor location of control and switch panel location |
| Difficult calibrations for instruments |
| SCD screen difficult to understand |
| Different SCD screens comparing P&IDs |
| **4. Work Environment** |
| Inadequate temperature and humidity for working |
| Excessively comfortable working conditions |
| Inadequate illumination |
| Excessive noise level |
| Distractions (abnormal trade) |
| **5. Management System** |
| Insufficient human resources |
| Insufficient number of people for attending to time-dependent actions |

### VI.4.3. Structuring Brainstorming

The outcome of brainstorming sessions depends on the collective experiences of the group, which may be incomplete, lacking critical knowledge, or a competency skill set. Two different groups may reach dissimilar conclusions on the cause of an incident. Thus, endeavors have focused on structuring brainstorming, but not reducing rational enquiry and speculation, while enforcing HAZOP's inherent features. Two features improve the effectiveness of brainstorming:

(1) A team leader with well-honed skills

(2) The availability of PHA software tools

Table VI.24 establishes the team leaders' key roles and responsibilities, but gives no detailed information on how to manage a PHA team. For this particularity, valuable information is given by Dowell III (1994) and Frank et al. (1993). Meanwhile, it would be unthinkable to conduct HAZOP sessions without using computer tools. Over the years, PHA software tools and electronic templates have been continually improved and adapted speeding up, and better managing, the information generated during HAZOP sessions.

**Table VI.24.** Team leaders' key roles and responsibilities.

| |
|---|
| Address all key issues according to study's scope, purposes, and objectives |
| Complete the study is completed within the expected time, according to time-estimation model |
| Put optimum pressure on the team, keeping team members involved and energized |
| Understand HAZOPs particularities and be able to explain them |
| Assure proper format of worksheets (banner, columns and columns titles) |
| Ensure worksheet entries are accurate, complete, and concise |
| Treat all realistic- and significant-deviations according to Deviations Structural Hierarchy |
| Guide the team in determining the credibility of a cause, consequence, or safeguards |
| Lead the team in assigning risk rankings consistently |
| Meet and document HAZOP regulatory requirements in completing worksheets |
| Direct the team in properly formulating recommendations |
| Avoid legal- and implementation-problems by recording entries appropriately |

Taking that these two requirements are met, how DSH is brainstormed is discussed (Figure VI.16).

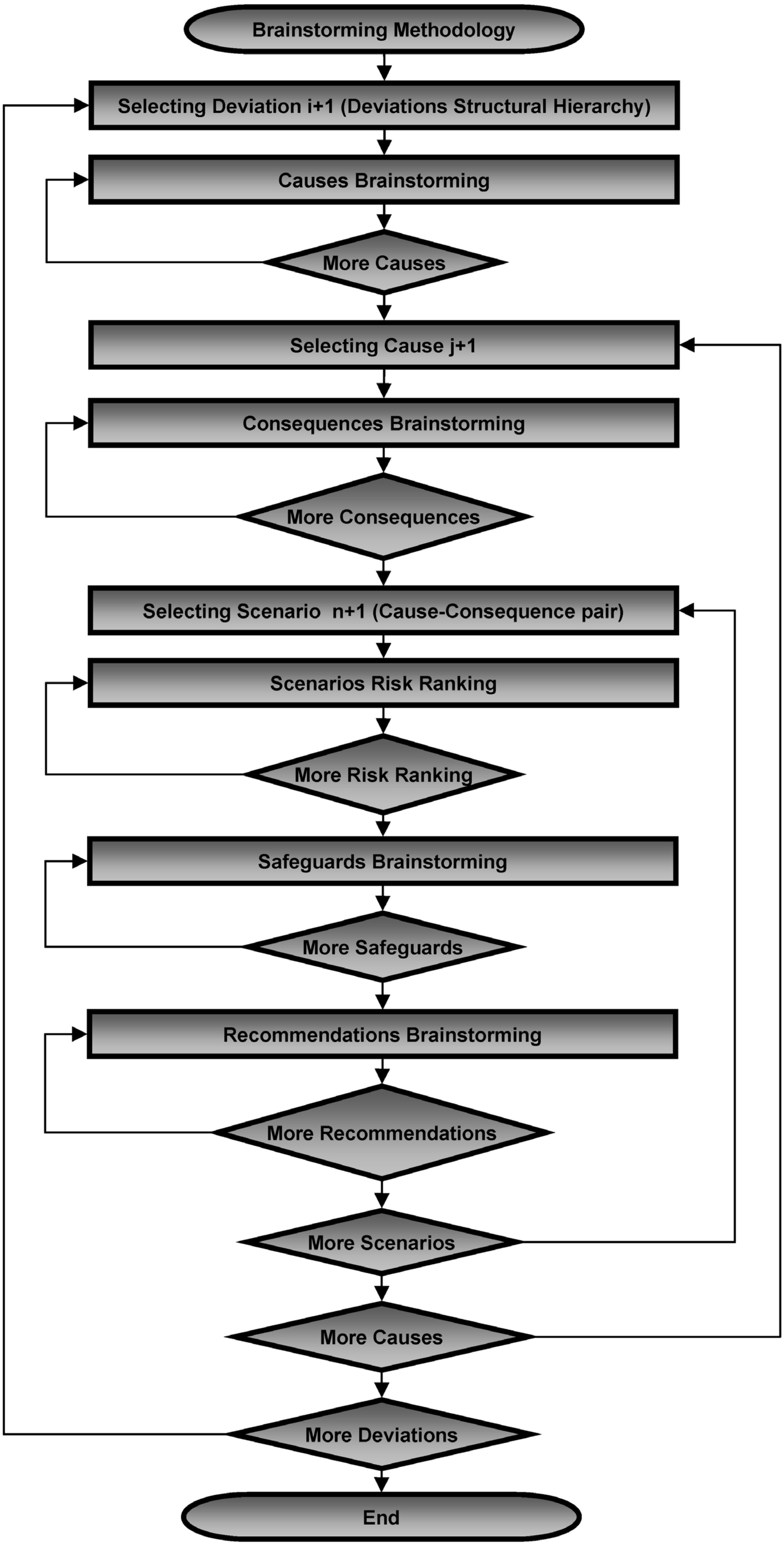


**Figure VI.16.** Brainstorming Flowchart.

While several alternatives exist on how to brainstorm deviations, the first advice is to clarify how it must not be conducted. It is important not to jump between columns in the HAZOP worksheet until the experts unanimously agree that no more information can be extracted from a given factor. Thus, after identifying the first cause of a deviation, moving forward to succeeding columns is strongly discouraged (such as identifying its first consequence, and then jumping to its risk ranking). Filling out HAZOP worksheets line- by-line fractures the smooth flow of brainstorming, and is the main reason for disregarding hazardous scenarios.

The most creative thinking is required for identifying causes, a task that requires unrestrained thought until all HAZOP members agree that all credible situations have been debated. Thereafter, the same procedure will be repeated for each new column under examination. For example, once the causes are listed, the team will focus on the first one, and identify all possible consequences. .After listing all of them for the first cause, the team will focus on the second one, and then repeat the same procedure up to the last cause. This approach will facilitate the brainstorming:

- Team members will rapidly become familiar on how to think intensively and creatively.
- The process will be consistent without reducing innovative thinking.
- Managing the team of experts will be easier.

### VI.4.4. Filling Out HAZOP Worksheets

Because HAZOP brainstorming can be tedious, convoluted, and lengthy, recording is essential. Minimizing the required time for introducing the information generated will maintain the speed of brainstorming (by avoiding disturbances). Thus, it is important to guide the designated scribe on which information to record and how to do so concisely and in detail during sessions. The scribe must be conversant with the previous results from DSH methodology in order to identify issues that could be related (e.g., some causes identified when analyzing “more flow” might previously have been explored when analyzing “more level”).

For example, if an identified cause of “more level” – with numbering 1.1 – appears again when reviewing “more flow”, it will be written as “same as 1.1”, and subsequent columns will remain empty, signifying that for the new information its “consequences”, “risk ranking”, “safeguards”, and “recommendations” are exactly the same in considering the reference “cause”. If the relationship is in doubt, a full description should be given. Likewise, because different causes can entail the same consequence, indexing criteria should be applied not only for “causes”, but also to “consequences” and the rest of the factors. The indexing practice will favor brainstorming by structuring the worksheets, and also in reducing the length of sessions and speeding them up. Even so, special care should be taken not to generate overfilled, concentrated indexed worksheets that are cumbersome to understand, Hence, HAZOP members have to ensure two aspects of the original (not indexed) information:

- It is placed in the right column.
- It is descriptive.

Finally, it is important to mention that filling out HAZOP worksheets is a chain procedure and the quality of the content of subsequent columns is affected by previous ones (e.g., detailed “causes” will make it easier to define “consequences”, and, in turn, comprehensive “consequences” will make it easer to establish “risk ranking”). In the following, the structure for recording information in each HAZOP column is shown (Figure VI.17).

**COMPANY:** name of the company
**FACILITY / UNIT:** name and location of the facility / name of the unit is being reviewed
**HAZOP SESSION (n) & REVISION (n):** number and date of the current session and revision
**NODE (n):** number and boundaries node description
**NODE INTENTION:** description on how the process is expected to be operated only considering node equipment
**DIAGRAMS:** list of P&IDs, PFDs and plot plants involved in the current node
**PARAMETER:** specific or general parameter is being analyzed

| **Structural Hierarchy** | | **Scenarios** | | **Risk Ranking** | | | **Protections** | **Recommendations & Actions** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Guideword** | **Deviation** | **Causes** | **Consequences** | ***S** | ***L** | ***R** | **Safeguards** | **Recommendations** | ****Ref** | ****By** |
| | | | | | | | | | | |

***:** S (consequences severity levels); L (cause frequency level); R (risk)
****:** Ref (recommendation references); By (recommendations responsibilities)

**Figure VI.17.** HAZOP Worksheet Sample.

It is essential to thoroughly list all credible causes of deviations (see Figure VI.18), and to address all types of initiating events (i.e., equipment, human failures, and external events).

Furthermore, the following guidance for assessing the credibility of multiple failures is offered:

- Two concurrent human failures are credible.
- A single equipment failure coupled with a single human failure is credible.
- The simultaneous failure of two or more independent pieces of equipment may not be credible.

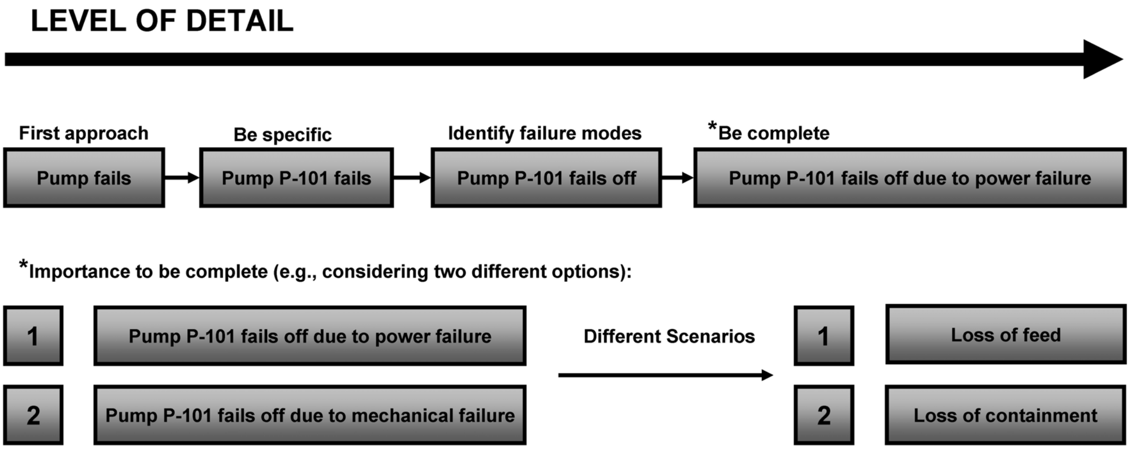


**Figure VI.18.** Example of Recording "Causes".

Conversely, in treating causes, the consequences are easy to identify but their appropriate recording is more complex. It should include all sequential steps from causes up to final impacts, with the following information:

- Identification of the initiating event, without including data on deviation or cause.
- How it happens (defining intermediate events and enablers).
- Where it happens.
- Which hazards could arise (e.g., fire, toxic release, reactivity incident).

When operability is included, the scenario should end with a description of the operability issue, if required, with defining potential impacts (e.g., employee and/or public- health effects, environmental impacts). All listed consequences are considered without the benefit of any safeguards (worst-case scenarios); thus, the imperative form of verbs should not be used. Descriptions should be introduced with conditional clauses since the consequences are hypothetical; thus, “potential release of hexane through the relief valve into the tank’s dike; fire hazard affecting a large area if not contained). Furthermore, consequences that have effects outside the boundaries of a particular node require special attention; presently, there is not a clear treatment. While some leaders do not consider the consequence inside the actual node (e.g., recording a sentence such as “consequences out of the actual scope of the node”), others only specify which node is affected for future analysis. The last option should be addressed, but note that further review is required when brainstorming the global node, a tool intended to address these particular situations.

It is better to ignore existing safeguards until the likelihood of a cause and severity of its consequence (scenario evaluation) is qualitatively ranked. This fact will make it easy to assign safety integrity requirements should studies that are more detailed be needed (e.g., LOPA, QRA). In brainstorming sessions, risk ranking has only been seen as a tool for qualitatively establishing the priorities of the recommendations (e.g., combining identification and quantification breaks the harmony of hazard identification). Tables VI.25 and VI.26 offer guidance for assessing safeguards and recommendations, respectively.

**Table VI.25.** Goals for treating Safeguards.

| |
|---|
| Do not brainstorm if safeguards are present or not (if doubtful , add a recommendation) |
| If adequacy of safeguards is suspect, do l not record it, but make a recommendation |
| Be specific and complete (see Figure 8) about causes (e.g., using names, tag numbers, or other identifiers) |
| Be careful of taking credit for, or relying on human safeguards (e.g., procedures, experience, training) |
| Include all safeguards for the scenario whether within the node or not |
| When possible, record set-points (e.g., pressure relief devices, interlocks, alarms) |
| Consider safeguards organization according the categories (prevention, detection, and mitigation) |

**Table VI.26.** Goals for treating Recommendations**.**

| |
|---|
| Record an action if there is a breach of standards or the team unanimously agreed on a solution |
| Recommend a follow-up investigation if it is not obvious (not spend significant time) |
| Recommend further study of issues (e.g., more detailed risk analysis, conduct research) |
| Clearly define recommendations and unambiguously record them (e.g., third-parties understanding) |
| Consider qualifying recommendations with words such as "consider", "verify", "evaluate", "review", "study", "investigate" |
| Ensure risk-reduction measures are practical and not introduce new hazards |
| Debate the value of a hierarchy of risk-reduction measures: Elimination, prevention over mitigation, and passive over active |
| Favor administrative- and procedural- controls before engineered safeguards |
| Identify the person or department responsible ("By" Column) for each recommendation |
| Avoid worksheet entries that combine more than one recommendation |
| Address changes that result from recommendations in the next HAZOP re-validation |

After the last session, the team leader will revise the information in the worksheets, and then circulate a first draft to team members with a cut-off date for comments. This version must include the HAZOP worksheets, along with details on how the study was conducted, information about the process, who participated, assumptions made, summary of the results, and copies of reference materials. The aim is to meet the needs of various audiences (e.g., management, technical reviewers, and regulators). Lastly, the team leader and the responsible manager must review and sign the final report before its distribution to persons accountable for following-up action items, whose duties are detailed in (Goyal, 1993; Sweeney, 1993; Kelly, 1991; Swann & Preston, 1995; Jones, 1992; Freeman, 1991; Pully, 1993; Hendershot, 1992).

## VI.5. SPECIFIC CONCLUSIONS

According to the review of the HAZOP State-of-the-art, and also with the gaps that were highlighted during the performance of the five HAZOPs that the present manuscript aims at, both main HAZOP limitations and research needs were defined. The present chapter addresses these weaknesses and establishes criteria to effectively conduct studies that have to analyze continuous chemical processes.

### HAZOP Definition and Preparation

Detailed criteria for setting-up HAZOP studies for continuous chemical processes have been established. The criteria cover all of the aspects to be considered from the time a company's interests confirm that a HAZOP study is required to the compilation of suitable input data with which to organize the study, and highlight the issues that will determine whether the study is carried out and documented successfully.

This work is intended to help project managers and team leaders reduce the degree of subjective judgment used in HAZOP planning and to control the inevitable influence of natural factors on study management.

The content of this section has been carefully researched and assembled to achieve two sub-aims. First, all of the technical and management steps involved in setting up HAZOP studies has been identified and presented in the chronological order of application. Instructions are given on how to implement each step. Second, a series of guidelines for project managers and team leaders have been provided. A set of figures, and tables have been assembled to assist interested parties in determining the following information: the most appropriate layout of the HAZOP meeting room; the minimum project specifications to be sent to team leader candidates; the key content of team leader proposals; the essential issues in producing a well-defined HAZOP study; the hazard classification, for defining more accurate HAZOP objectives; the roles of the HAZOP team member, according to the HMS; the required HAZOP information; and the risk ranking criteria for classifying recommendations and connecting the HAZOP study to subsequent semi-quantitative or quantitative studies.

Additionally, this section shows how to ensure a smooth transition between the following phases: gathering suitable input data for breaking down the process into manageable sections – first task, node-selection methodology; making a HAZOP time-estimate – second task, HAZOP time-estimation model; and providing sufficient technical details and administrative information for successful brainstorming and documentation analysis – third and fourth tasks, deviations-structural hierarchy and guidelines for completing HAZOP worksheets.

HAZOP Organization

Two tasks for organizing HAZOP studies carried out in continuous chemical processes have been developed. The first task assists nodes management by offering guidance on how to select nodes, and which is the optimum size for brainstorming, according to design intent changes. The second task develops a new HAZOP time-estimation model, an essential factor for planning the study, and thereby, arranging brainstorming sessions.

The selection of nodes and their sizing was developed by ensuring two features. First, the desired level of detail for identifying most potential hazardous scenarios has been established. This goal is supported by generating process knowledge via analyzing key process- information, and adding a new use of the global node for attending especially to issues that encompass more than one node (e.g., flooding, electric power, facility siting, human factors, and piping configuration). Secondly, the minimum required time for HAZOP sessions due to new nodes sizing has been explored, smoothing brainstorming and making sense by applying a new deviations management. About 30 selected nodes on PFDs have been graphically shown, providing the following valuable information: (1) Nodes sizing; (2) candidate boundary points; and (3) design intent changes.

The new HAZOP time-estimation model simplifies the current cumbersome ones. .It is based on the number of P&IDs and the number of pieces of major equipment. The predictors were justified because they are acquired and managed extremely simply, they precisely define the process' complexity, and accurate results were obtained.

Finally, a simple model has been explored, developed in parallel, for predicting the number of nodes to be selected, a new concept that clearly helps assessing how to plan the study for arranging meetings. The new sizing of the nodes and their brainstorming assessed via a deviations structural hierarchy (described in the section: HAZOP execution and documentation) confirm less time is required for conducting equivalent studies; further, they ensure that results obey regulatory requirements and company policies.

### HAZOP Execution and Documentation

Two tasks for executing HAZOP studies carried out in continuous chemical processes have been developed, both of which confirm the estimation of required HAZOP time presented in the previous section (HAZOP organization).

The first task addresses managing deviations and illustrating a new procedure for brainstorming them (i.e., a Deviations Structural Hierarchy – DSH). Its application ensures two enhancements. First, two sets of deviations (one for reviewing process nodes and the other for analyzing the global node) encourage team members to brainstorm for any specific departure from the design intent. Second, DSH establishes the order of application for deviations to avoid repetitive analysis, yet structure hazard identification without losing freedom for creative thinking. DSH is conformed by 22 deviations that encourage questioning all factors specified both in OSHA PSM and the Seveso Directive for addressing hazard identification.

The second task guides team leaders in structuring brainstorming sessions and logically recording HAZOP worksheets. These guidelines ensure the following enhancements:

(1) Team members rapidly become familiar on how to brainstorm.

(2) The structural features of HAZOP increase.

(3) Leaders more easily manage the team of experts.

(4) The information recorded can be extracted effectively for further studies (e.g., Layer Of Protection Analysis, Quantitative Risk Analysis).

“Ready-to-use” tools for project managers, team leaders and experts have been developed for managing, conducting and attending HAZOP studies in continuous chemical process according to criteria established in the present work. *Annex I* presents a set of figures, tables and checklists totally intended to help HAZOP responsible parties.

# CHAPTER VII. CONCLUSIONS

During the reading of the present manuscript, interested parties should be aware of gaps related to hazard identification which are present in the three mandatory documents considered (i.e., OSHA PSM Rule and EPA RMP, and the Seveso Directive). Additionally, they should be aware of the HAZOP state-of-the-art, current key limitations of the methodology, and finally, which research needs should be addressed for the HAZOP improvement. The contents of this chapter summarize all these factors, from the analysis of the contents of related legislation up to the final methodology proposed. Specific and detailed conclusions can be found at the end of each chapter that comprises this work.

Three key legislations related to process safety in chemical process facilities have been reviewed: the US OSHA PSM Rule, the US EPA RMP, and the Seveso Directive. Regulations clearly highlight hazard identification as a key element of any safety management system, and provide technical tools for achieving this goal by using PHA techniques during the entire process lifetime. However, there is a lack of information on how to treat most of the factors that they address (e.g., facility siting, human factors). While regulations state a complete set of factors to be addressed for hazard identification, there is absence of criteria for conducting PHAs, weaknesses highlighted into regulations contents by using terms which entail subjectivity (e.g., “employers are expected to use judgment”; “PHA leader has to be trained”). Therefore, the chemical industry recognize which factors have to be addressed, what tools and when these have to be performed; but it is not acquainted with how to proceed when identifying potential hazardous scenarios.

PHA techniques are tools intended to help analysts find ways to avoid or reduce both the causes and consequences of life-threatening occurrences. Their ultimate aim is to avoid injuries or deaths of workers and the public, environmental impacts, and also, economic losses. However, PHAs are subject to a number of theoretical and practical limitations. Thus, it is essential to be aware of PHAs inherent limitations, in order to improving their effectiveness.

Specific HAZOP limitations and research needs have been highlighted after carrying out a review of most of the HAZOP-related literature published. Over the thirty-five years of HAZOP history, many authors have focused upon improving specific HAZOP aspects, but most papers were published in the last fifteen years. However, the first and only HAZOP Standard was published in 2001, and it needs to be enhanced (e.g., it does not include guidance on how to break a process into nodes).

Accordingly, it has been identified that more research is needed in addressing the following issues:

- HAZOPs conducted by human beings are subject to the analyst's bias, experience, knowledge, and creativity. One should attempt to gain knowledge from the experience of parties involved, but also it could be valuable to standardize the HAZOP structure for processes that present equivalent technology (e.g., petroleum-refining processes).
- A related human factor issue appears when hazard identification is focused not only on analyzing typical process deviations but also initiating events caused by human errors.
- Identifying causes and hazardous scenarios from programmable electronic systems (PES). Improvements could be made when looking for potential causes of control device failures. When linking the HAZOP results to other techniques intended to gather Safety Integrity Level (SIL) values of Safety Instrumented Systems (SIS) to be implemented, the list of initiating events that could lead to the hazardous scenario may not be complete.
- Most endeavors for standardizing HAZOP studies have been done with the aim of automating its execution. Expert Systems development is the most powerful tendency in the evolution of HAZOP. A considerable amount of work has been conducted in this challenging field; yet more research and application and verification of expert systems is needed to effectively apply them in hazard identification and loss prevention.

According to the HAZOP limitations identified, the following research needs should be addressed for improving HAZOP applications:

- Development of a node-selection methodology for guiding team leaders through the process. It would be valuable to provide a simple tool for predicting the number of nodes to be selected according to the process complexity.
- Improvement of HAZOP time-estimation models, thereby simplifying the current cumbersome models.

- Development of a structural hierarchy for defining a set of deviations namely (1) define the minimum set of deviations for ensuring that key hazardous scenarios are identified, and, (2) define their order of application, avoiding repetitive analysis and strengthening the HAZOP structure itself. These properties will better guide team leaders and will favor standardization.
- Development of guidelines on how to fulfill a HAZOP worksheet, defining which information has to be placed in each column, and how to report that information to ensure the maximum level of understanding, not only for HAZOP members, but also for external concerned parties.

For attending these limitations, field work and data analysis have been carried out, and the following tools and statements have been released:

- A model able to predict the time required to perform HAZOP studies. The new HAZOP time-estimation model simplifies the current cumbersome ones. It is based on the number of P&IDs and the amount of major equipment. The predictors were justified because they are acquired and managed extremely simply, they precisely define the complexity of the process, and accurate results were obtained.
- A model able to predict the expected number of nodes to be selected by using the same predictors of the previous one. This is a new concept that helps assessing how to plan the study for arranging meetings.
- A model able to predict the time that the node selection stage will take. The response is the function of the amount of major equipment that constitutes the process to be hazoped.
- Defining principal sections with no more than 3 nodes, as well as defining nodes with no more than 2 major equipments, are the two factors than ensure the minimum time required to select nodes.

Finally, a methodology for conducting HAZOP studies in continuous chemical processes has been developed. It provides criteria and tools for effectively performing the hazard identification with the aim of ensuring that most of the potential hazards will be identified by minimizing the time of performance. Additionally, it attempts to reduce the subjectivity of the different HAZOP parties by carefully reinforcing the study structure itself, without losing the freedom for creative thinking. The main conclusions of the methodology are summarized:

- Detailed criteria for setting-up HAZOP studies have been established for continuous chemical processes. The criteria cover all of the aspects to be considered from the time a company's interests confirm that a HAZOP study is required to the compilation of suitable input data with which to organize the study, and highlight the issues that will determine whether the study is carried out and documented successfully.

- A methodology for the selection of nodes has been developed and graphical evidence has been provided to recognize the appropriate node constitution: (1) Node sizing; (2) candidate boundary points; and (3) design intent changes. Additionally, the global node concept has been introduced and assessed.

- A Deviations Structural Hierarchy (DSH) has been proposed for managing deviations and brainstorming them. Its application ensures two enhancements. First, two sets of deviations (one for reviewing process nodes and the other for analyzing the global node) encourage team members to brainstorm for any specific departure from the design intent. Second, DSH establishes the order of application for deviations to avoid repetitive analysis, yet structure hazard identification without losing freedom for creative thinking. DSH is conformed by 22 deviations that encourage questioning all factors specified both in OSHA PSM and the Seveso Directive, for addressing hazard identification.

- Guidance on how to brainstorm deviations and how to record their results has been provided. These guidelines ensure the following enhancements: (1) team members rapidly become familiar on how to brainstorm, (2) the structural features of HAZOP increase, (3) leaders manage the team of experts more easily, and (4) the information recorded can be effectively extracted for further studies.

The contents of the proposed methodology have been summarized by using tables, figures and "ready-to-use" checklists for project managers, team leaders and experts for managing, conducting and attending HAZOP studies in continuous chemical process according to criteria established in the present work. These specific contents are intended to be a reference book for helping HAZOP responsible parties

# ANNEX I. READY-TO-USE TOOLS FOR CONDUCTING HAZOPS

This annex collects and summarizes key tables, figures and checklists that have been developed over the manuscript. These have been placed in chronological order according to the sequential phases that define the HAZOP Management System (HMS). These strategic illustrations, as well as their layout provide the key "ready-to-use" tools that should be able to guide interested parties that have the intention to lead HAZOP studies in continuous chemical processes. The final aim of *Annex I* is to provide concise and structured documentation to be used as a "guideline" when conducting real HAZOPs.

The following contents have been put in order as shown below:

- HAZOP Management System Definition.
- Tools & Guidelines for Defining & Preparing HAZOP Studies.
- Tools & Guidelines for Organizing HAZOP Studies.
- Tools & Guidelines for Executing & Documenting HAZOP Studies.

## Preliminaries. HAZOP key documentation:

**Table A.I.1.** Key HAZOP Terminology

| | |
|---|---|
| Design intent | Overall statement of what the process involves |
| Node | Process section within which parameters are investigated for deviations from its design intent |
| Node intention | Defines how the process is expected to be operated, only considering node equipment |
| Specific Parameter | Physical- or chemical-parameters of process materials |
| General Parameter | Other aspects of the design intent complementing specific parameter information |
| Parameter intention | Range of allowable values for the parameter during process operations |
| Guidewords | Simple words or phrases used to qualify or quantify the intention |
| Deviation | Departure from the node's intention |
| Hazard | Deviation having the potential to cause damage, illness, injury, or other form of loss |
| Causes | Reasons why deviations may occur |
| Scenario | Sequence of situations starting from the initiating event up to consequences |
| Consequence | The effect of the occurrence of a deviation |
| Safeguard | Physical- or procedural-measure that will eliminate or reduce the likelihood of a hazard |
| Recommendation | Suggested actions to prevent, detect, control, or mitigate the scenario identified |

## HAZOP MANAGEMENT SYSTEM

### Definition of the whole duties for conducting HAZOP studies:

**Table A.I.2.** HAZOP Management System

| **HAZOP Management System** | **Manager** | **Leader** | ✓ | ✗ | **Comments** |
|---|---|---|---|---|---|
| **First Phase. HAZOP Definition & Preparation** | | | | | |
| 1 Deciding why & when to conduct a HAZOP study | ■ | | | | |
| 2 Ensuring a well-matched Safety Management System – (Information) | ■ | | | | |
| 3 Establishing the PHA software-aid to be used | ■ | | | | |
| 4 Ensuring the minimum HAZOP meeting room attributes | ■ | | | | |
| 5 Sending project specifications to team leader candidates | ■ | | | | |
| 6 Appointing the team leader | ■ | | | | |
| 7 Defining detailed purpose, scope and objectives of the study | ■ | ■ | | | |
| 8 Selecting the appropriate HAZOP team by ensuring attendance | ■ | ■ | | | |
| 9 Assembling and reorganizing the necessary information for conducting the study | ■ | ■ | | | |
| 10 Establishing Risk Ranking Criteria | ■ | ■ | | | |
| **Second Phase: HAZOP Organization** | | | | | |
| 1 Diving the process into manageable sections with defined design intents | | ■ | | | |
| 2 Planning the study for arranging meetings | ■ | ■ | | | |
| **Third Phase. HAZOP Execution & Documentation** | | | | | |
| 1 Generating deviations – Guidewords & Parameters | | ■ | | | |
| 2 Brainstorming sessions – identifying hazardous scenarios & managing the team | | ■ | | | |
| 3 Reporting the study results | | ■ | | | |
| 4 Following-up recommendations confirming their scheduled implementation | ■ | ■ | | | |

## Team leaders’ Roles and Responsibilities during the whole HMS:

**Table A.I.3.** Main Team leaders’ key roles and responsibilities

| |
|---|
| Address all key issues according to study’s scope, purposes, and objectives |
| Complete the study is completed within the expected time, according to time-estimation model |
| Put optimum pressure on the team, keeping team members involved and energized |
| Understand HAZOPs particularities and be able to explain them |
| Assure proper format of worksheets (banner, columns and columns titles) |
| Ensure worksheet entries are accurate, complete, and concise |
| Treat all realistic- and significant-deviations according to Deviations Structural Hierarchy |
| Guide the team in determining the credibility of a cause, consequence, or safeguards |
| Lead the team in assigning risk rankings consistently |
| Meet and document HAZOP regulatory requirements in completing worksheets |
| Direct the team in properly formulating recommendations |
| Avoid legal- and implementation-problems by recording entries appropriately |

## Appropriate HAZOP Meeting Room Layout:

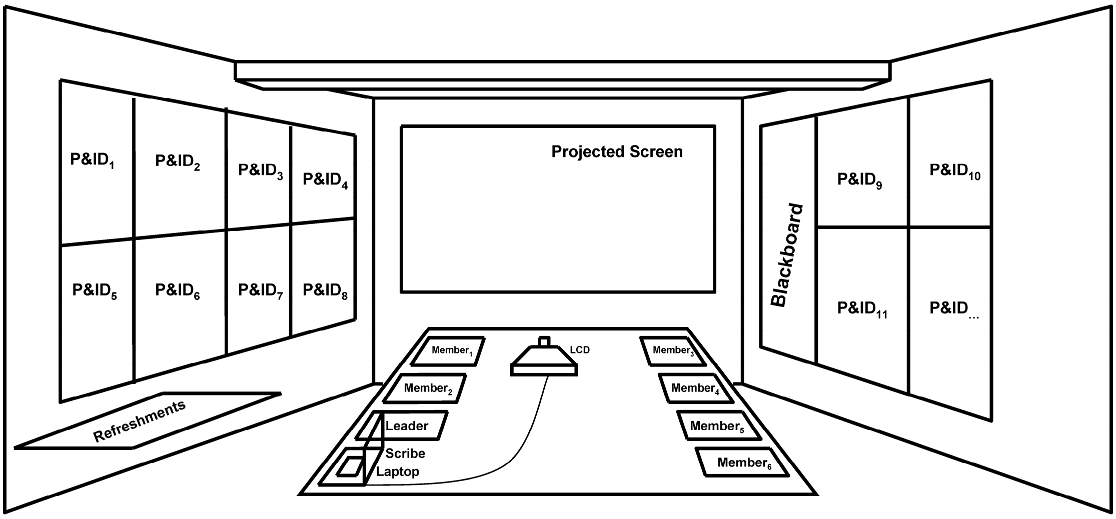


Figure A.I.1. HAZOP Meeting Room Layout

## TOOLS & GUIDELINES FOR DEFINING & PREPARING HAZOP STUDIES

### Minimum Set of Specifications from Project Managers:

**Table A.I.4.** Minimum Project Specifications Contents.

| **Project Information** | **Comments** |
|---|---|
| Company name, Facility, Process and Location | Identification of the process to be analyzed |
| Project manager identification | HAZOP responsible person |
| Preliminary purpose, scope and objectives of the study | Study requirements definition – first consideration before leader assistance |
| **Attached Documentation** | Minimum – “Critical” – documentation for HAZOP organization |
| 1. Process Description | Detailed written description of process principal sections |
| 2. Process Flow Diagrams (PFDs) | Relationship between major equipment of a plant facility |
| 3. Piping & Instrumentation Diagrams (P&IDs) | Relationship between process equipment and control instrumentation |
| 4. Plot Plan, layout diagrams | Schematic description of the equipment layout |
| 5. Previous HAZOPs | Previous HAZOPs conducted on the same process |
| 6. Corporative HAZOP guidelines – if developed | Criteria for conducting HAZOPs |

### Minimum Team Leaders’ Proposal Contents:

**Table A.I.5.** Team Leader Proposal Contents

| **Consultant identification** |
|---|
| Company name (Consulting) |
| Team leader identification – including experience on leading HAZOPs |
| Scribe identification - including experience on reporting HAZOPs |
| **Nodes Selection** |
| List and description of nodes selected |
| Nodes description should include the following information:<br>1. Design intent<br>2. Boundaries<br>3. Process conditions<br>4. Related equipment<br>5. PFDs and P&IDs involved |
| **HAZOP Time Estimation** |
| Expected number of sessions |
| Criteria for planning the study – including meeting arrangement:<br>1. Hours per session<br>2. Sessions per day<br>3. Days per week |
| Proposed HAZOP elapsed time (weeks) |

## Guidelines for defining HAZOP studies:

**Table A.I.6.** Guidelines for defining HAZOP studies.

| **Guidelines for defining HAZOP studies** | | ✓ | ✗ | **Comments** |
|---|---|---|---|---|
| **PURPOSE** – why the study is performed | | | | |
| | Meet regulatory requirements | | | |
| | Meet industry requirements | | | |
| | Company requirements | | | |
| | Comply with good engineering practices | | | |
| | Reduce legal liabilities | | | |
| | Part of a post-incident investigation | | | |
| | Comply with insurance company requirements | | | |
| | Meet contractual requirements with customers or vendors | | | |
| **SCOPE** – what is included in the study | | | | |
| 1. Process boundaries | Limits of the process properly determined | | | |
| 2. Equipment | Equipment involved that manage covered chemicals | | | |
| 3. Utilities/Services | List of the utilities serving the process | | | |
| 4. Modes of Operation | Modes of operation included | | | |
| 5. External events | List of external events considered credible for the process | | | |
| 6. Level of detail | Level of detail – partly determined by the study purpose | | | |
| 7. Level of causality | Treatment of the causes | | | |
| 8. Design intent | Method of defining parameters to be considered | | | |
| 9. Exclusions | Identification of items excluded | | | |
| **OBJECTIVES** – what is to be considered | | | | |
| | HAZOP covers only major hazards associated with covered chemicals | | | |
| | HAZOP includes other types of hazards from covered chemicals | | | |
| | HAZOP includes hazards from non-covered chemicals | | | |
| | HAZOP includes hazards from other process materials/equipments | | | |
| | HAZOP focus only on regulatory issues | | | |
| | HAZOP includes other issues of importance to the plant | | | |

## Assessment of hazards for defining HAZOP objectives:

**Table A.I.7.** Assessment of possible hazards in facilities that manage HazMat

| **Assessment of possible hazards in process facilities that manage highly hazardous materials** | ✓ | ✗ | **Comments** |
|---|---|---|---|
| **A. COVERING REGULATORY ISSUES (MAJOR ACCIDENTS)** | | | |
| **TOXIC RELEASE** | | | |
| Attending acute exposure and serious effects. Also asphyxiants | | | |
| **FIRE** | | | |
| 1. Pool fires | | | |
| 2. Jet fires | | | |
| 3. Flash fires | | | |
| 4. Fireballs | | | |
| 5. Warehouse fires | | | |
| **EXPLOSION** | | | |
| **1. Physical explosions** | | | |
| 1.1. Pressure burst | | | |
| 1.2. Rapid phase transition | | | |
| **2. Chemical explosions** | | | |
| 2.1. Condensed phase explosion | | | |
| 2.2. Vapor / gas phase explosion | | | |
| **REACTIVITY** | | | |
| Uncontrolled decomposition, rearrangement or polymerization of a single instable compound | | | |
| Loss of control of reactions | | | |
| Chemical interactions from inadvertent mixing of two or more chemicals leading to an uncontrolled chemicals reaction | | | |
| **B. COVERING OTHER TYPES OF HAZARDS FROM COVERED CHEMICALS** | | | |
| 1. Corrosives | | | |
| 2. Skin irritants | | | |
| 3. Lachrymators, etc | | | |
| **C. COVERING HAZARDS FROM NON-COVERED CHEMICALS** | | | |
| 1. Raw materials | | | |
| 2. Intermediates | | | |
| 3. Products and by-products | | | |
| 4. Additives | | | |
| 5. Catalysts | | | |
| 6. Waste streams, etc. | | | |
| **D. COVERING HAZARDS FROM OTHER PROCESS MATERIALS / EQUIPMENTS** | | | |
| 1. Nitrogen asphyxiation | | | |
| 2. Scalding from steam or hot oil | | | |
| 3. Hot surfaces / materials | | | |
| 4. Cryogenic materials | | | |
| 5. Pinch points | | | |
| 6. High pressures, | | | |
| 7. High kinetic energy | | | |
| 8. Vacuum | | | |
| 9. High voltage /current, etc. | | | |

## Minimum HAZOP Team knowledge:

**Table A.I.8.** Minimum HAZOP Team Knowledge

| Expert knowledge | Features |
|---|---|
| Design Engineering | knowledge of how the process is intended to operate<br>knowledge of applicable standards, codes, specifications, etc. |
| Process Engineering | Understanding of the process science and technology<br>Ability to judge the adequacy of existing safeguards |
| Operations & Maintenance | “Hands on” operating<br>Maintenance experience |
| Safety | Knowledge of process hazards<br>knowledge of safety systems |
| Other | Specialty areas |

## Summary of HAZOP members' roles and responsibilities:

**Table A.I.9.** HAZOP Members Roles and Responsibilities.

| ROLE | HAZOP MANAGEMENT STAGE | HAZOP EXECUTION STAGE | HAZOP DOCUMENTATION STAGE |
|---|---|---|---|
| HAZOP manager has to assure all study stages are carried out with success, having into account both company and legal requirements | | | |
| **MANAGER** | To define the purpose, scope and objectives of the study<br>To select the team leader<br>To select the expert team, with experience and faculty<br>To provide the needed documentation<br>To communicate the study plan<br>To guarantee the required HAZOP meeting room | To assure the attainment of the study requirements.<br>To assure the responsibilities assignment | To assure the final documentation quality<br>To follow-up the recommendations |
| Site Coordinator is an optional role intended to support the HAZOP manager for assuring well-suited sitting facilities, locations, equipment, etc. | | | |
| **COORDINATOR** | Liaison between team and HAZOP meeting room | To manage the team inside the work place<br>To facilitate any required photocopy, etc.<br>To manage the lunch logistic, refreshments, etc. | |
| Team leader' role is based on guiding the whole HAZOP. It is recommended his was not directly related on the company to assure objectivity | | | |
| **LEADER** | To analyze the required HAZOP documentation<br>To subdivide the system into nodes<br>To plan the sequence of work sessions<br>To know legal requisites<br>To assure the documentation quality, quantity and deadline | To define the study to the team<br>To explain the HAZOP technique to the team<br>To guide the team on using HAZOP (sessions)<br>To assure the effective work of the team<br>To maintain the control of the sessions schedule | To carry out the final study report |
| Scribe is an optional role intended to support the team leader on all HAZOP stages and document the information generated during HAZOP sessions | | | |
| **SCRIBE** | To provide technical support to the team leader | To document the generated information | To provide technical support to the leader |
| Expert team is a multidisciplinary group of professionals with different background for assuring a thoroughly review of the process | | | |
| **TEAM** | To claim the documentation with sufficient prior notice<br>To analyze in detail the documentation received<br>To have knowledge of the process has to be analyzed | To be involved on the hazard identification stage<br>To identify causes and consequences of scenarios<br>To identify process safeguards<br>To propose recommendations | To check the final documentation<br>To evaluate the labor of the team leader<br>To focus on solving the recommendations |

## Assessment of required HAZOP information:

**Table A.I.10.** Assessment of Required HAZOP Information.

| **Assessment of required HAZOP information** | **Critical** | **Detailed** | **Useful** | ✓ | ✗ | **Comments** |
|---|---|---|---|---|---|---|
| **Information on hazards of highly hazardous chemicals in the process** | | | | | | |
| Material Safety Data Sheets | | ■ | | | | |
| **Information on the technology of the process** | | | | | | |
| Process Description and Plant Operation | ■ | | | | | |
| Process Flow Diagrams (PFDs) | ■ | | | | | |
| Instrumentation and controls | | ■ | | | | |
| Maximum intended inventory | | ■ | | | | |
| Safe upper and lower limits for several process parameters | | ■ | | | | |
| Consequence evaluation of process parameters deviations | | ■ | | | | |
| Critical action list | | ■ | | | | |
| Diagrams describing operation modes | | ■ | | | | |
| **Information on the equipment in the process** | | | | | | |
| Materials of construction | | ■ | | | | |
| Piping and Instrumentation Diagrams (P&IDs) | ■ | | | | | |
| Electrical classification | | ■ | | | | |
| Relief system design | | | | | | |
| Material energy balances | | ■ | | | | |
| Safety systems (interlocks, detection, etc.) | | ■ | | | | |
| Critical equipment list | | | ■ | | | |
| **Other useful information** | | | | | | |
| Corporative HAZOP guidelines | ■ | | | | | |
| Plot Plan – Layout diagrams | ■ | | | | | |
| Information on previous incidents | | | ■ | | | |
| Information on services and utilities | | ■ | | | | |
| Relevant codes, standards and guidelines | | ■ | | | | |
| Skills of operating and maintenance personnel | | | ■ | | | |
| Cause and effects diagrams | | | ■ | | | |

## Ranking for recommendations following-up priorities:

**Table A.I.11.** Risk Ranking Criteria

| **Consequence Severity Levels (S)** | |
|---|---|
| Minor ($\mathbf{S_M}$) | Impact initially limited to local area of event with potential for broader consequence, if corrective action not taken |
| Serious ($\mathbf{S_S}$) | Impact event could cause serious injury or fatality on site or off site |
| Extensive ($\mathbf{S_E}$) | Impact event that is five or more times severe than a serious event |

| **Cause Frequency Levels (L)** | |
|---|---|
| Low ($\mathbf{L_L}$) | A failure or series of failure with a very low probability of occurrence within the expected lifetime of the plant |
| Medium ($\mathbf{L_M}$) | A failure or series of failure with a low probability of occurrence within the expected lifetime of the plant |
| High ($\mathbf{L_H}$) | A failure can reasonably be expected to occur within the expected lifetime of the plant |

**Risk Matrix (R)**

| | $\mathbf{S_M}$ | $\mathbf{S_S}$ | $\mathbf{S_E}$ |
|---|---|---|---|
| $\mathbf{L_L}$ | $R_6$ | $R_5$ | $R_3$ |
| $\mathbf{L_M}$ | $R_5$ | $R_4$ | $R_2$ |
| $\mathbf{L_H}$ | $R_3$ | $R_2$ | $R_1$ |

## ALARP (As Low As Reasonable Practicable) Criteria:

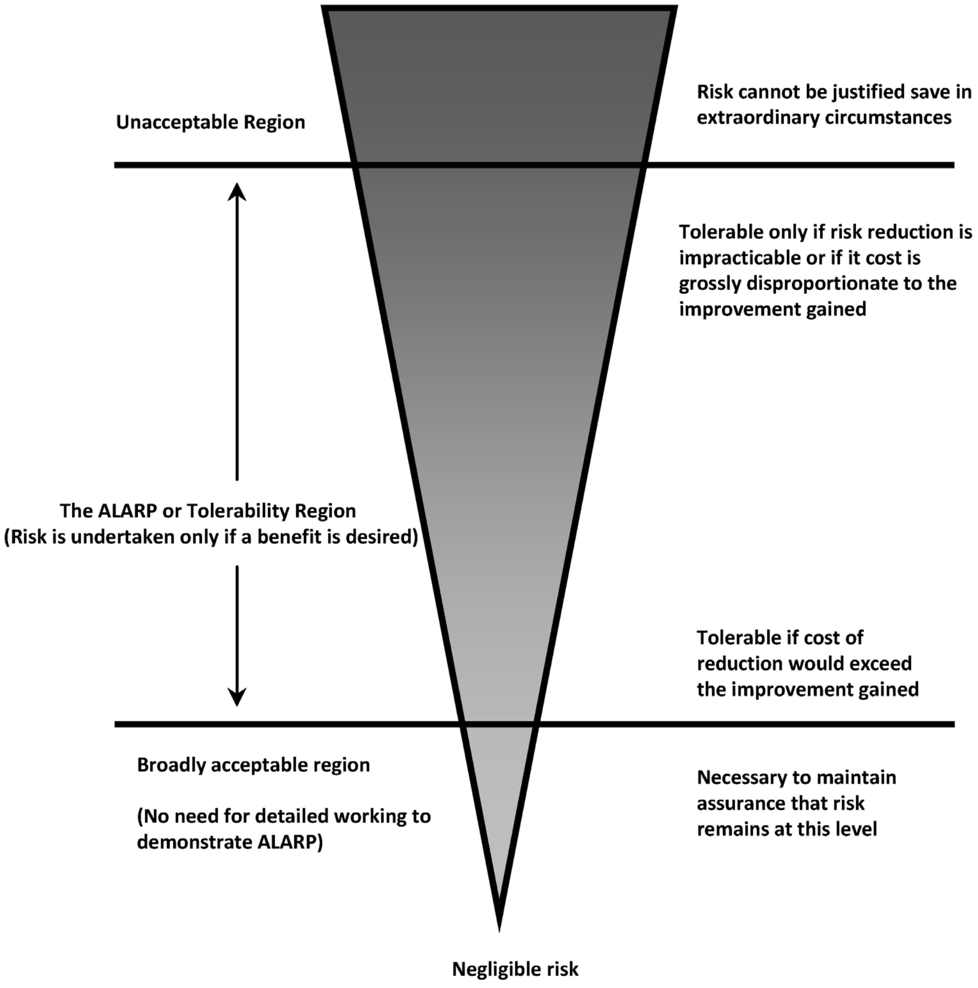


**Figure A.I.2.** ALARP criteria.

## TOOLS AND GUIDELINES FOR ORGANIZING HAZOP STUDIES

### Process nodes and global node definition:

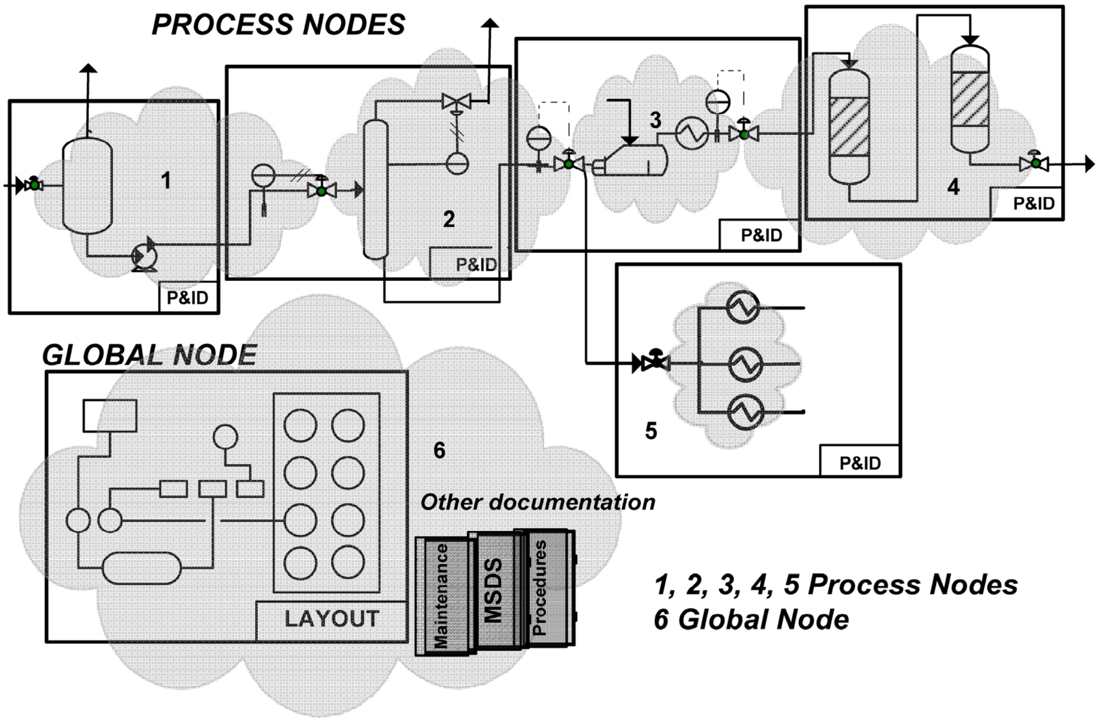


**Figure A.I.3.** Process and Global Nodes Example

### Key HAZOP documentation for node selection:

**Table A.I.12.** Minimum Information Package for HAZOP Organization

| Documentation | Description |
|---|---|
| Process Description | Detailed written description of process principal sections |
| PFDs | Relationship between major equipment of a plant facility |
| P&IDs | Relationship between process equipment and control instrumentation |
| Plot Plan | Schematic description of the equipment layout |
| Previous HAZOPs | Consideration of previous HAZOPs carried out on the same process |
| *Internal HAZOP procedure | Corporative HAZOP guidelines to follow |

*Not all companies have developed their own guidelines

**Methodology for selecting Nodes:**

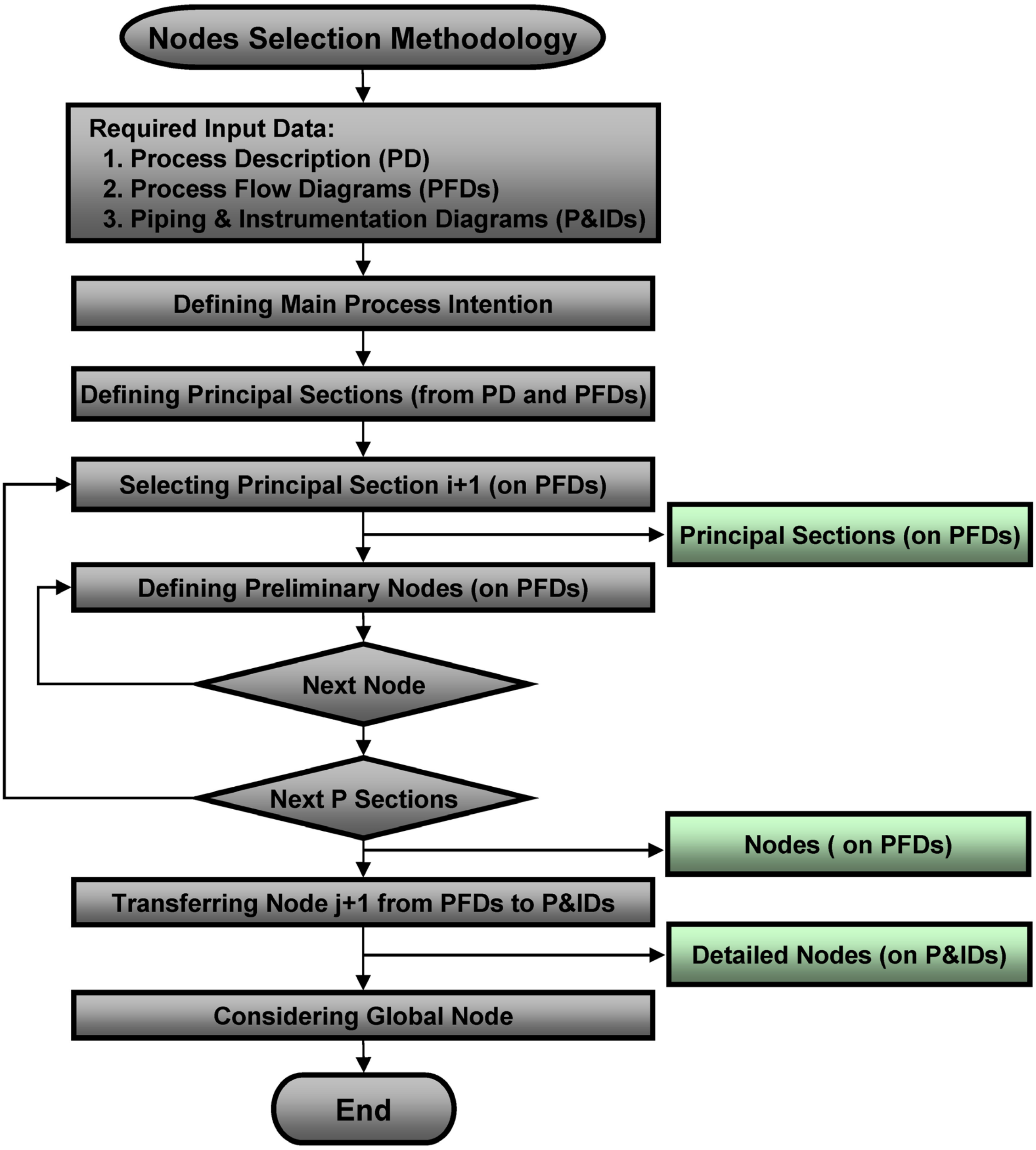


**Figure A.I.4.** Nodes Selection Methodology: Flux Diagram.

## Example of selected principal sections:

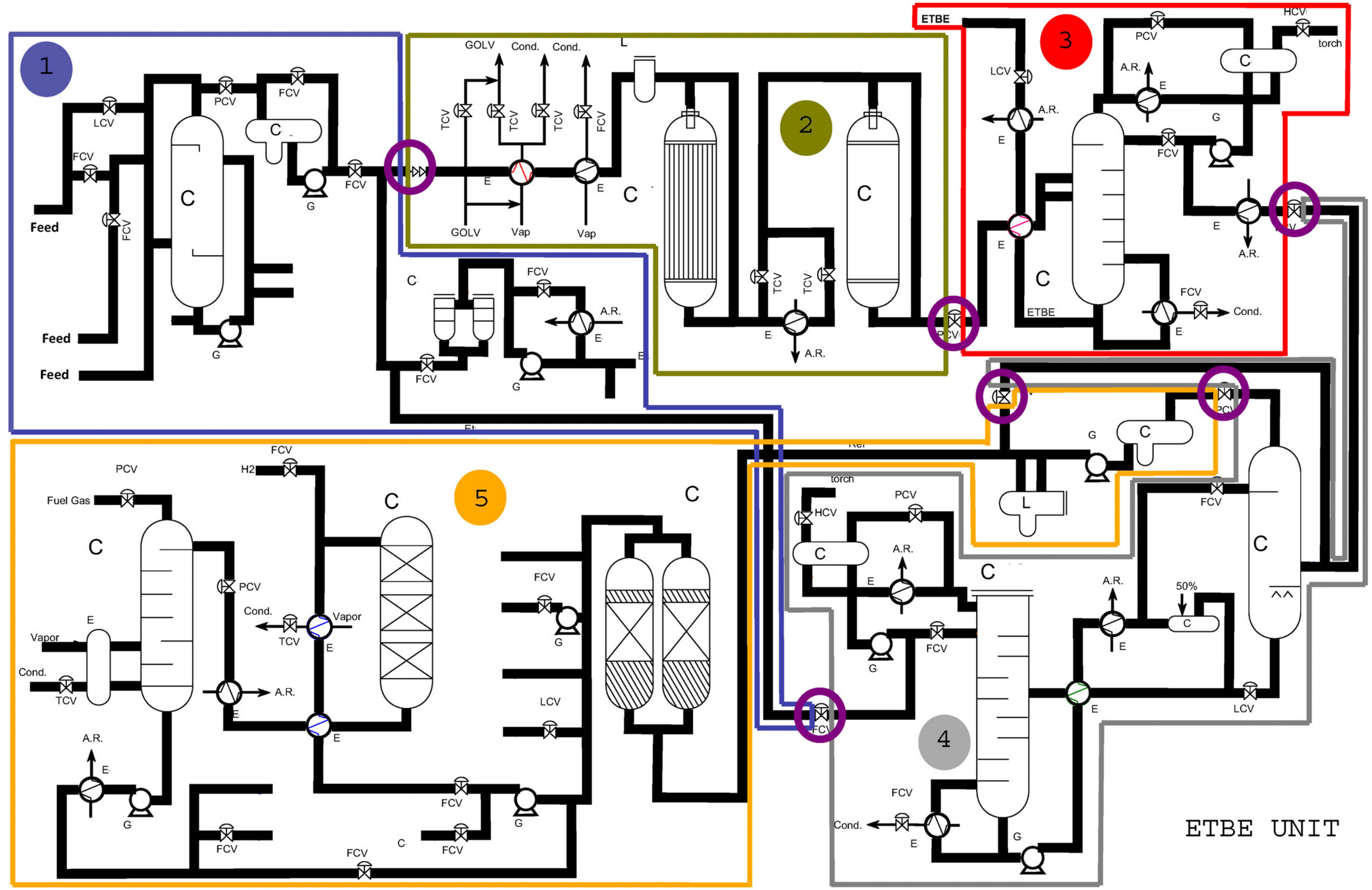


**Figure A.I.5.** Principal Sections: Example (ETBE Production Unit).

## Example of selected process nodes:

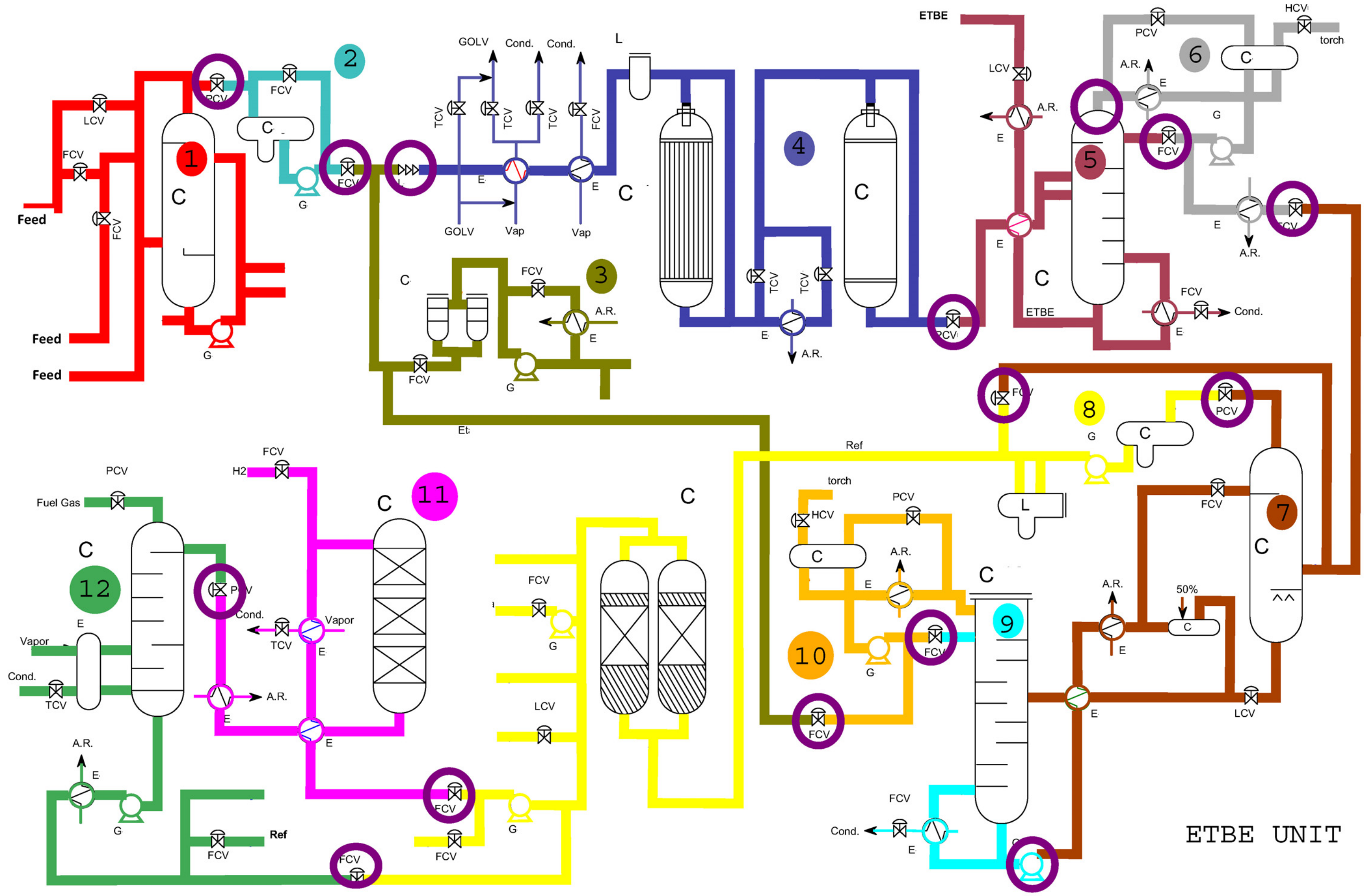
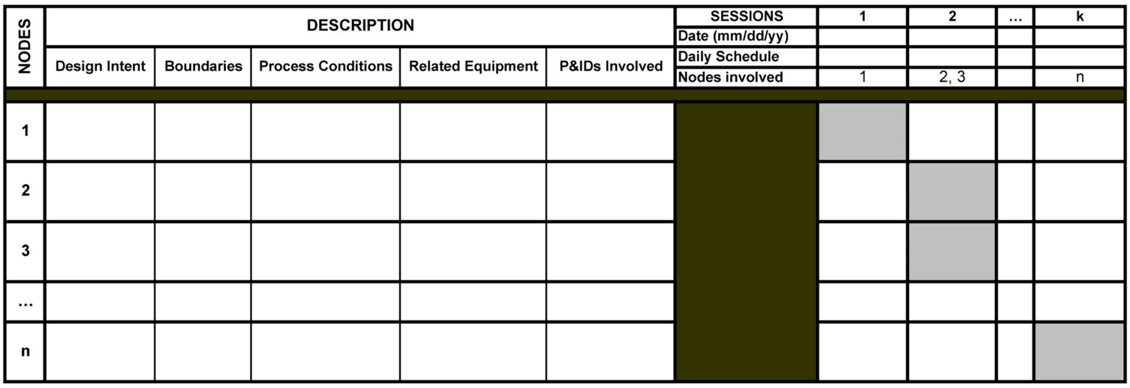


**Figure A.I.6.** Preliminary Nodes Selection Example

## Sample Worksheet for HAZOP Organization Results:



| NODES | DESCRIPTION | | | | | SESSIONS | 1 | 2 | … | k |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Date (mm/dd/yy) | | | | |
| | Design Intent | Boundaries | Process Conditions | Related Equipment | P&IDs Involved | Daily Schedule | | | | |
| | | | | | | Nodes involved | 1 | 2, 3 | | n |
| 1 | | | | | | | ▨ | | | |
| 2 | | | | | | | | ▨ | | |
| 3 | | | | | | | | ▨ | | |
| … | | | | | | | | | | |
| n | | | | | | | | | | ▨ |

**Figure A.I.7.** HAZOP Organization Results: Sample Worksheet.

## Mathematical model for HAZOP time estimation

- **Required input data and model results:**

**Table A.I.13.** Input Data and Model Results.

| Factors considered | Symbol | Input Data | Output Data |
|---|---|---|---|
| Number of P&IDs | $x_1$ | ■ | |
| Number of Major Equipment | $x_2$ | ■ | |
| Number of Nodes | Nd | | ■ |
| Required Preparation Time (h) | $T_P$ | | ■ |
| Required Sessions Time (h) | $T_S$ | | ■ |
| Required Writing Time (h) | $T_W$ | | ■ |
| Number of sessions | N | | ■ |
| Total Man Hours | MH | | ■ |
| Total Elapsed Time (weeks) | $T_H$ | | ■ |

- **Model description:**

**Table A.I.4.** HAZOP Time Estimation Model Example

| **HMS actions included** | **Input Data** | **Model** | **Ouput Data** |
|---|---|---|---|
| **HAZOP definition, preparation and organization ($T_P$)** | | | |
| Defining the purpose, scope and objectives of the study<br>Selecting the appropriate HAZOP team<br>Assembling and reorganizing HAZOP information<br>Establishing risk ranking criteria<br>Dividing the process into nodes<br>Planning the study for arranging meetings | Number of P&IDs ($x_1$)<br>Number of Major Equipment ($x_2$)<br>Node selection criteria | $T_P = 0.698X_1 + 0.359X_2$ | **$T_P$** |
| **Number of Nodes, (Nd)** | | | |
| Estimation of the number of nodes to be selected | Number of P&IDs ($x_1$)<br>Number of Major Equipment ($x_2$)<br>Node selection criteria | $Nd = 0.288X_1 + 0.508X_2$ | **Nd** |
| **HAZOP execution ($T_s$)** | | | |
| Generating deviations – Guidewords & Parameters<br>Brainstorming sessions | Number of nodes; Nd($x_1$, $x_2$) | $T_S = 3(1+Nd)$ | **$T_S$** |
| **HAZOP documentation ($T_W$)** | | | |
| Reporting the study results | **$T_P$** | $T_W = 0.40T_P$ | **$T_W$** |
| **HAZOP study time estimation ($T_H$)** | | | |
| | $T_P$, $T_S$, $T_W$ | $T_H = T_P + T_S + T_W$ | **$T_H$** |

**Criteria for arranging HAZOP sessions:**

**Table A.I.15.** Planning the Study. Criteria for arranging meetings.

| **Time (hours)** | **Time (weeks)** | **Considerations** |
|---|---|---|
| $T_P$ (h) | $T_P$ (w) = 1/16 $T_P$ (h) | 4 hours per day; 4 days per week |
| $T_S$ (h) | $T_S$ (w) = 1/24 $T_S$ (h) if $Nd > 9$ | 6 hours per session; 4 sessions per week |
| | $T_S$ (w) = 1/30 $T_S$ (h) if $Nd \leq 9$ | 6 hours per session; 5 sessions per week |
| $T_W$ (h) | $T_W$ (w) = 1/16 $T_W$ (h) | 4 hours per day; 4 days per week |
| $T_H$ (h) | $T_H = T_P + T_S + T_W$ | Sum of the total time predicted |

## TOOLS AND GUIDELINES FOR EXECUTING AND DOCUMENTING HAZOP STUDIES

### Brainstorming methodology Flowchart:

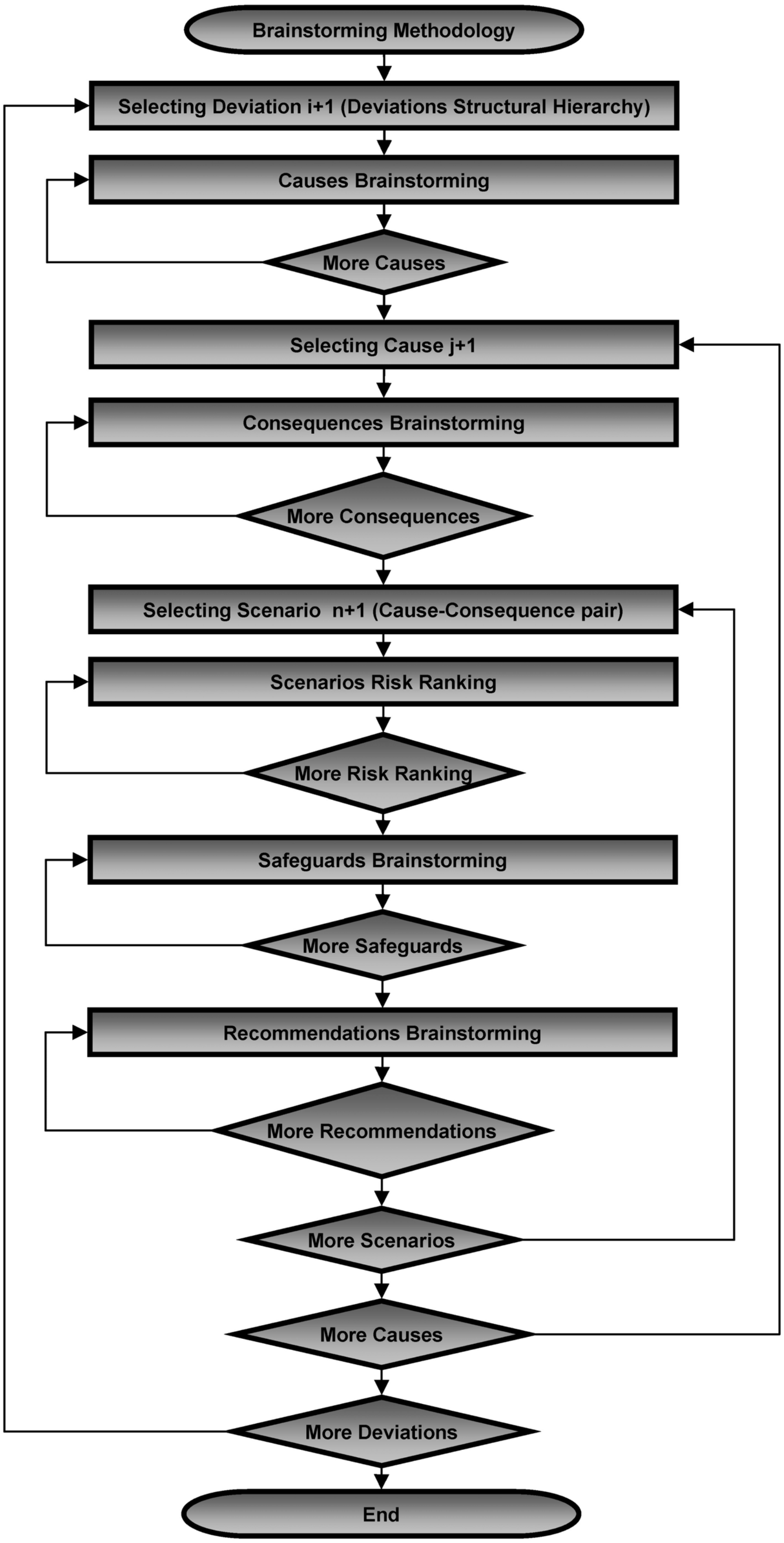


**Figure A.I.8.** Brainstorming Flowchart.

**First brainstorming session duties:**

**Table A.I.16.** Actions to Carry Out during the First Session.

| |
|---|
| Introduce the team members themselves |
| Record attendance |
| Define the scheduling particularities, such as break times, daily timetable, and lunch time |
| Explain the HAZOP methodology to be used during the sessions |
| Detail features of the software that will be used |
| Review the purpose, scope, and objectives of the study |
| Review the process to be analyzed |
| Check the available documentation |
| Mark and confirm the node subdivision |
| Consider the first node selected |

## Deviations structural hierarchy for process nodes:

**Table A.I.17.** Deviations Structural Hierarchy – Process Nodes.

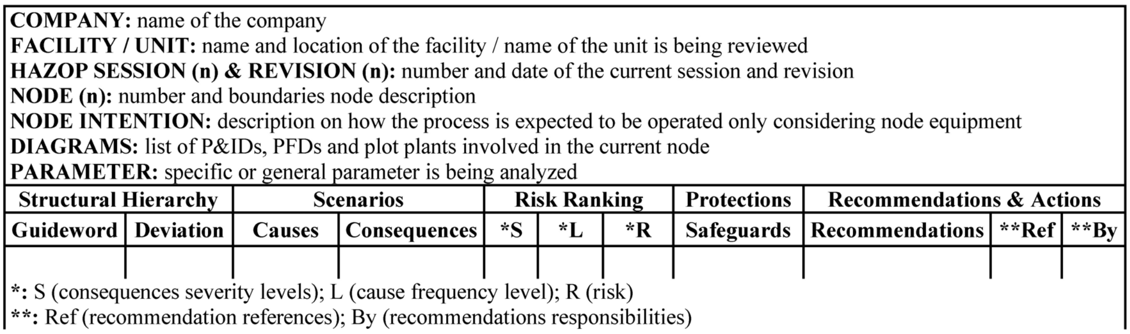
| Parameter | Guideword | Deviation | Meaning |
|---|---|---|---|
| **LEVEL** | More | More Level | High level with possible overflow. Flooding of pipes with inappropriate design for liquid phase fluid entries |
| | Less | Less Level | Low level with possible cavitations' phenomena of pump systems connected after vessels. Additionally, the vessel could be totally emptied and remain without liquid, producing problems with equipment designed for drying conditions |
| **FLOW** | No | No Flow | No flow in locations where it was expected flow circulation |
| | Less | Less Flow | Restriction of the fluid flow. Often it is analyzed jointly with the "No Flow" deviation |
| | More | More Flow | Excessive flow in fluid transport piping systems than the expected |
| | Reverse | Reverse Flow | The fluid circulates in the wrong direction than the expected |
| **PRESSURE** | More | More Pressure | High pressure with possible hazards on the mechanical integrity of the node equipment if design pressure is exceeded |
| | Less | Less Pressure | Hazardous scenarios due to piping cavitation, blockage in vessels, etc. Risk of vessel implosions for equipment not designed for these conditions |
| **TEMPERATURE** | More | More Temperature | High temperature with possible thermal damage risk in construction materials or possibility of activating undesirable reactions |
| | Less | Less Temperature | Low temperature with possible risk of fluid freezing, construction materials brittleness or undesirable crystallizations |
| **COMPOSITION** | Other than | Other than Composition | Presence of undesirable chemical substances by contamination or wrong addition (another product or impurities), by services access (water, oil, steam) and undesirable atmospheres generation (air) |
| **PHASE** | Other than | Other than Phase | Presence of a phase state (solid, liquid or gaseous) for which has not intended the operation |
| **UTILITIES** | No | No Utilities | Unexpected services failure. Experience highlights considering services analysis as a specific deviation allows identifying hazardous scenarios not identified in previous deviations |
| **OPERATION** | As well as | As well as Operation | Analysis of other modes of operation than normal (start-up, shutdown, etc.). Valuable to treat carrying out Procedural HAZOPs for operations subjected under written instructions |
| **CONTAINMENT** | No | No Containment | Identification of any operative condition able to cause the emission of hazardous materials off-site: opening valves connected directly to the atmosphere as well as leaks through joints, or breakable mechanical elements |
| **HUMAN FACTOR** | As well as | As well as Human Factor | Determination whether all significant human failures have been identified by considering all the people who are involved, the various functions they may perform, the different types of mistakes they may make |

## Deviations structural hierarchy for the global node:

**Table A.I.18.** Deviations Structural Hierarchy – Global Node.

| Parameter | Guideword | Deviation | Meaning |
|---|---|---|---|
| **UTILITIES** | No | No Utilities | Utilities failure considering the whole unit. Experience highlights this analysis allows identifying hazardous scenarios not identified in previous deviations |
| **OPERATION** | As well as | As well as Operation | Intended to identify modes of operation able to cause new hazardous scenarios overlooked in previous parameters. Valuable to treat carrying out Procedural HAZOPs for operations subjected under written instructions |
| **CONTAINMENT** | NO | No Containment | Identification of any operative condition able to cause the emission of hazardous materials off-site focusing the analysis as a "bird's eye view". Identification of direct ignition sources and specific locations where toxics leaks are possible |
| **IMPLANTATION** | As well as | As well as Implementation | Analysis of aspects affecting facility sitting: accessibility, get away routes, congestion equipment, vehicle impacts, drainage systems, slope, fire protection devices, facility location, process units spacing, spacing between equipment and potential ignition sources, domino effects, emergency response issues, hazardous area classifications |
| **EXTERNAL EVENT** | As well as | As well As External Event | Analysis of aspects away from process hazards which can cause hazardous scenarios regarding operational safety. Consider as minimum: lightning, flooding, deep cold, external fire and domino effect |
| **HUMAN FACTOR** | As well as | As well As Human Factor | Analysis of aspects focused on health and safety deficiencies of plant personnel as well as regarding the occurrence of major accidents caused for human failures in critical operations. Consider problems limiting personnel activities and emergency procedures |

## HAZOP worksheet sample:



**COMPANY:** name of the company
**FACILITY / UNIT:** name and location of the facility / name of the unit is being reviewed
**HAZOP SESSION (n) & REVISION (n):** number and date of the current session and revision
**NODE (n):** number and boundaries node description
**NODE INTENTION:** description on how the process is expected to be operated only considering node equipment
**DIAGRAMS:** list of P&IDs, PFDs and plot plants involved in the current node
**PARAMETER:** specific or general parameter is being analyzed

| **Structural Hierarchy** | | **Scenarios** | | **Risk Ranking** | | | **Protections** | **Recommendations & Actions** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Guideword** | **Deviation** | **Causes** | **Consequences** | ***S** | ***L** | ***R** | **Safeguards** | **Recommendations** | ****Ref** | ****By** |
| | | | | | | | | | | |

***:** S (consequences severity levels); L (cause frequency level); R (risk)
****:** Ref (recommendation references); By (recommendations responsibilities)

**Figure** A.I.**9.** HAZOP Worksheet Sample.

## Guidelines for treating safeguards:

**Table A.I.19.** Goals for treating Safeguards.

Do not brainstorm if safeguards are present or not (if doubtful , add a recommendation)
If adequacy of safeguards is suspect, do l not record it, but make a recommendation
Be specific and complete (see Figure 8) about causes (e.g., using names, tag numbers, or other identifiers)
Be careful of taking credit for, or relying on human safeguards (e.g., procedures, experience, training)
Include all safeguards for the scenario whether within the node or not
When possible, record set-points (e.g., pressure relief devices, interlocks, alarms)
Consider safeguards organization according the categories (prevention, detection, and mitigation)

## Guidelines for treating recommendations:

**Table A.I.20.** Goals for treating Recommendations.

Record an action if there is a breach of standards or the team unanimously agreed on a solution
Recommend a follow-up investigation if it is not obvious (not spend significant time)
Recommend further study of issues (e.g., more detailed risk analysis, conduct research)
Clearly define recommendations and unambiguously record them (e.g., third-parties understanding)
Consider qualifying recommendations with words such as “consider”, “verify”, “evaluate”, “review”, “study”, “investigate”
Ensure risk-reduction measures are practical and not introduce new hazards
Debate the value of a hierarchy of risk-reduction measures: Elimination, prevention over mitigation, and passive over active
Favor administrative- and procedural- controls before engineered safeguards
Identify the person or department responsible (“By” Column) for each recommendation
Avoid worksheet entries that combine more than one recommendation
Address changes that result from recommendations in the next HAZOP re-validation

# ANNEX II. PRETROLEUM-REFINING PROCESSES SAFETY INFORMATION

*Annex II*[11] is intended to overview the most relevant petroleum-refining processes by highlighting key factors to take into account from the point of view of process safety and hazard identification. Team leaders will be helped, both for starting the node selection procedure (principal sections are depicted) and for motivating the expert team, by having key health and safety information of specific refining units, i.e. valuable information during brainstorming sessions.

The main petroleum-refining processes that have been taken into account in the present annex are the following:

- Desalting
- Atmospheric distillation
- Vacuum distillation
- Fluid catalytic cracking
- Delayed coking
- Alkylation
- Hydrotreating
- Hydrocracking
- Catalytic Reforming
- Isomerization

The list of the shown petroleum-refining processes is the following according to figure AII.1, and each of them will cover four main topics:

1. Description of the main process design intent
2. Description of the main principal sections
3. Simplified process chart
4. Process key health, safety and environmental information

---

[11] Annex II contents have been readapted from OSHA Website

## Atmospheric and Vacuum Distillation

### Atmospheric Distillation:

**Process Design Intent**

To distill and separate valuable distillates (i.e., naphtha, kerosene, diesel) and atmospheric gas oil from the crude feedstock

**Products Obtained & Disposition**

| Products Obtained | Products Disposition |
|---|---|
| Light Ends | Liquified Petroleum Gas (LPG) |
| Light Naphtha | Naphtha Hydrotreating |
| Medium Naphtha | Naphtha Hydrotreating |
| Heavy Naphtha | Distillate Hydrotreating |
| Kerosene | Distillate Hydrotreating |
| Atmospheric Gas Oil | Fluid Catalytic Cracking |
| Reduced Crude | Vacuum Distillation Unit |

**Principal Sections**

**1.** Preheat the crude feed utilizing recovered heat from the product streams

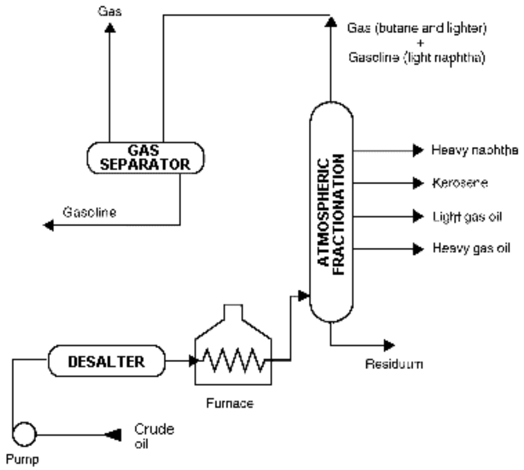
**2.** Desalt and dehydrate the crude using electrostatic enhanced liquid/liquid separation

**3.** Heat the crude to the desired temperature using fired heaters

**4.** Flash the crude in the atmospheric distillation column

**5.** Utilize pump around cooling loops to create internal liquid reflux

**Simplified process chart**



## Vacuum Distillation:

**Process Design Intent**

To recover valuable gas oils from reduced crude via vacuum distillation. The main process technique reduces the hydrocarbon partial pressure via vacuum and stripping steam

**Products Obtained & Disposition**

| Products Obtained | Products Disposition |
|---|---|
| Light Ends | LPG |
| Light Vacuum Gas Oil | Distillate Hydrotreating |
| Heavy Vacuum Gas Oil | Fluid Catalytic Cracking |
| Vacuum Residue | Cocking |

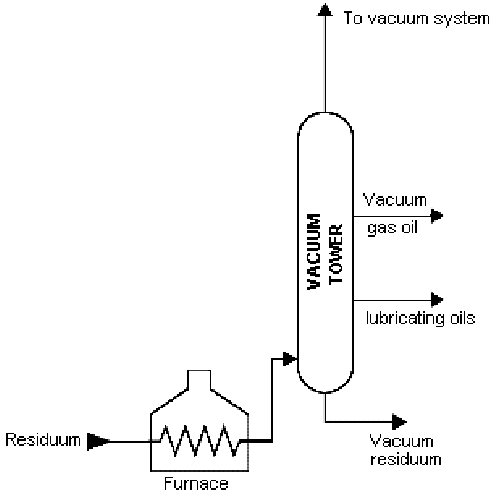
**Principal Sections**

**1.** Heat the reduced crude to the desired temperature using fired heaters

**2.** Flash the reduced crude in the vacuum distillation column

**3.** Utilize pump around cooling loops to create internal liquid reflux

**Simplified process chart**



## Key Health, Safety & Environment Information of Distillation processes

### Desalting

Potential fire due to a leak or release of crude from heaters in the crude desalting unit (low boiling point components of crude may also be released if a leak occurs)

Potential fouling of heater tubes and heat exchangers throughout the refinery (fouling restricts product flow and heat transfer and leads to failures due to increased pressures and temperatures)

Potential Equipment failures: a). corrosion due to the presence of hydrogen sulfide, hydrogen chloride, naphthenic (organic) acids, and other contaminants in the crude oil, b). corrosion due to the presence of neutralized salts (ammonium chlorides and sulfides), when moistened by condensed water, c). unit over pressurized

If elevated operating temperatures are used when desalting sour crudes, hydrogen sulfide will be present

Possibility of exposure to ammonia, dry chemical demulsifiers, caustics, and/or acids during this operation

The waste water could contain varying amounts of chlorides, sulfides, bicarbonates, ammonia, hydrocarbons, phenol, and suspended solids. If diatomaceous earth is used in filtration, exposures should be minimized or controlled. However, diatomaceous earth can contain silica in very fine particle size (potential respiratory hazard).

### Atmospheric & Vacuum distillation

Potential sources of ignition in heaters and exchangers with risk of fire if a leak or release occur

Potential thermal cracking within towers if automatic control devices fail (control of temperature, pressure, and reflux).

Relief systems should be provided for overpressure and operations monitored to prevent crude from entering the reformer charge.

Potential corrosion in the following sections: preheat exchanger (HCl and $H_2S$), preheat furnace and bottoms exchanger ($H_2S$ and sulfur compounds), atmospheric tower and vacuum furnace ($H_2S$, sulfur compounds, and organic acids), vacuum tower ($H_2S$ and organic acids), and overhead ($H_2S$, HCl, and water).

If sour crudes are processed, severe corrosion can occur in furnace tubing and where metal temperatures exceed 450° F. Wet $H_2S$ also will cause cracks in steel.

When processing high-nitrogen crudes, nitrogen oxides can form in the flue gases of furnaces. Nitrogen oxides are corrosive to steel when cooled to low temperatures in the presence of water.

If sufficient wash-water is not injected, deposits of ammonium chloride can form and cause serious corrosion. Crude feedstock may contain appreciable amounts of water in suspension which can separate during startup and, along with water remaining in the tower from steam purging, settle in the bottom of the tower. This water can be heated to the boiling point and create an instantaneous vaporization explosion upon contact with the oil in the unit.

Potential of exposure to hydrogen sulfide in the preheat exchanger and furnace, tower flash zone and overhead system, vacuum furnace and tower, and bottoms exchanger.

Hydrogen chloride may be present in the preheat exchanger, tower top zones, and overheads.

Waste water may contain water-soluble sulfides in high concentrations and other water-soluble compounds such as ammonia, chlorides, phenol, mercaptans, etc., depending upon the crude feedstock and the treatment chemicals.

## Fluid Catalytic Cracking:

### Process Design Intent

To convert low value gas oils to valuable products (naphtha and diesel), and slurry oil. The main process technique increases the hydrogen/carbon ratio by rejection in a continuous process

### Products Obtained & Disposition

| Products Obtained | Products Disposition |
|---|---|
| Light Ends | LPG; Alkylation |
| Naphtha | Naphtha Hydrotreating |
| Light Cyle Oil | Distillate Hydrotreating |
| Medium Cyle Oil | Hydrocracking |
| Slurry Oil | Heavy fuel oil; carbon black processing |
| Coke | Flue gas to CO boiler |

### Principal Sections

**1.** Gas oil feed is dispersed into the bottom of the riser using steam

**2.** Thermal cracking occurs on the surface of the catalyst

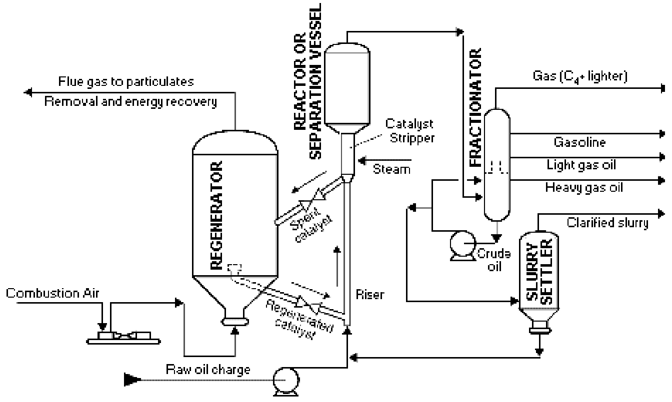
**3.** Disengaging drum separates spent catalyst from product vapors

**4.** Steam strips residue hydrocarbons from spent catalyst

**5.** Air burns away the carbon film from the catalyst in either a “partial-burn” or “full-burn” mode of operation

**6.** Regenerated catalyst enters bottom of riser-reactor

### Simplified process chart



## Key Health, Safety & Environment Information of Fluid Catalytic Cracking

Liquid hydrocarbons in the catalyst or entering the heated combustion air stream should be controlled to avoid exothermic reactions. Potential fire due to a leak or vapor release at cracking unit heaters location. Fire protection should be considered including: concrete or other insulation on columns and supports, and fixed water spray or fog systems where insulation is not feasible and in areas where firewater hose streams cannot reach.

Potential explosive concentrations of catalyst dust during recharge or disposal.

Potential iron sulfide fires when unloading any coked catalyst. Iron sulfide will ignite spontaneously when exposed to air and therefore must be wetted with water to prevent it from igniting vapors.

Corrosives or deposits in the feedstock can foul gas compressors

Inspections of critical equipment including pumps, compressors, furnaces, and heat exchangers should be conducted as needed. When processing sour crude, corrosion may be expected where temperatures are below 900° F.

When processing high-nitrogen feedstock, exposure to ammonia and cyanide may occur, subjecting carbon steel equipment in the FCC overhead system to corrosion, cracking, or hydrogen blistering. These effects may be minimized by water wash or corrosion inhibitors. Water wash may also be used to protect overhead condensers in the main column subjected to fouling from ammonium hydrosulfide.

Inspections should include checking for leaks due to erosion or other malfunctions such as catalyst buildup on the expanders, coking in the overhead feeder lines from feedstock residues, and other unusual operating conditions.

Potential exposure to extremely hot (700° F) hydrocarbon liquids or vapors, as well as hydrogen sulfide and/or carbon monoxide gas during process sampling or if a leak or release occurs.

Potential for hazardous exposures due to catalyst regeneration involves steam stripping and decoking, and produces fluid waste streams that may contain varying amounts of hydrocarbon, phenol, ammonia, hydrogen sulfide, mercaptan, and other materials depending upon the feedstock, crudes, and processes. Inadvertent formation of nickel carbonyl may occur in cracking processes using nickel catalysts

Safe work practices and/or the use of appropriate personal protective equipment may be needed for exposures to chemicals and other hazards such as noise and heat; during process sampling, inspection, maintenance and turnaround activities; and when handling spent catalyst, recharging catalyst, or if leaks or releases occur.

## Delayed Coking:

**Process Design Intent**

To convert low value resid to valuable products (naphtha and diesel) and coker gas oil. The main process technique (Thermocracking) increases the hydrogen/carbon ratio by rejection in a semi-batch process

**Products Obtained & Disposition**

| Products Obtained | Products Disposition |
|---|---|
| Light Ends | LPG; Alkylation |
| Naphtha | Naphtha Hydrotreating |
| Light Cyle Oil | Distillate Hydrotreating |
| Medium Cyle Oil | Hydrocracking |
| Slurry Oil | Heavy fuel oil; carbon black processing |
| Coke | Flue gas to CO boiler |

**Principal Sections**

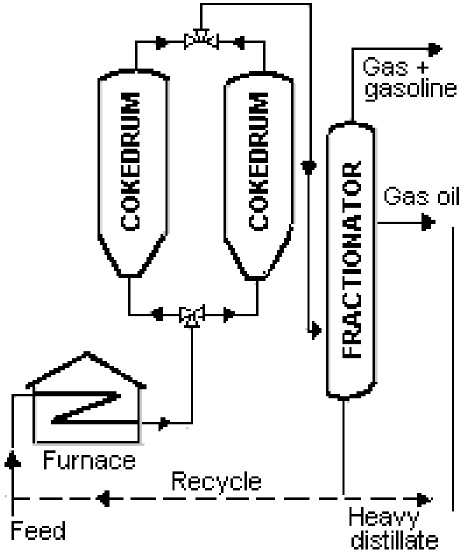
**1.** Preheat residue feed and provide primary condensing of coke drum vapors by introducing the feed to the bottom of the main fractionator

**2.** Heat the coke drum feed by fired heaters

**3.** Flash superheated feed in large coke drum where the coke remains and vapors leave the top and goes back to the fractionator

**4.** Off-line coke drum is drilled and the petroleum coke is removed via hydrojetting

**Simplified process chart**



### Key Health, Safety & Environment Information of Delayed Coking

Potential fire from leaks or releases of liquids, gases, or vapors reaching an ignition source such as a heater. The potential for fire is present in coking operations due to vapor or product leaks. Should coking temperatures get out of control, an exothermic reaction could occur within the coker.

When sour crudes are processed in thermal cracking, corrosion can occur where metal temperatures are between 450° and 900° F (above 900° F coke forms a protective layer on the metal). Hydrogen sulfide corrosion in coking can also occur when temperatures are not properly controlled above 900° F.

The furnace, soaking drums, lower part of the tower, and high-temperature exchangers are usually subject to corrosion.

Continuous thermal changes can lead to bulging and cracking of coke drum shells. In coking, temperature control must often be held within a 10°-20° F range, as high temperatures will produce coke that is too hard to cut out of the drum.

Low temperatures could result in a high asphaltic-content slurry. Water or steam injection may be used to prevent buildup of coke in delayed coker furnace tubes.

Water must be completely drained from the coker, so as not to cause an explosion upon recharging with hot coke. Provisions for alternate means of egress from the working platform on top of coke drums are important in the event of an emergency.

Potential exposure to hazardous gases such as hydrogen sulfide and carbon monoxide, and trace polynuclear aromatics (PNA) associated with coking operations.

When coke is moved as a slurry, oxygen depletion may occur within confined spaces such as storage silos, since wet carbon will adsorb oxygen.

Waste water may be highly alkaline and contain oil, sulfides, ammonia, and/or phenol.

Potential exposure to burns when handling hot coke or in the event of a steam-line leak, or from steam, hot water, hot coke, or hot slurry that may be expelled when opening cokers.

Safe work practices and/or the use of appropriate personal protective equipment may be needed for exposures to chemicals and other hazards such as heat and noise, and during process sampling, inspection, maintenance, and turnaround activities.

## Alkylation:

**Process Design Intent**

To combine light olefins (propylene and butylene) with isobutane to form a high octane gasoline (alkylate). The main process technique occurs in the presence of a highly acidic catalyst (hydrofluoric acid or sulphuric acid)

**Products Obtained & Disposition**

| Products Obtained | Products Disposition |
|---|---|
| Propane | LPG |
| n-butane | LPG; Gasoline |
| Alkylate | Gasoline |
| Acid Oils | Furnace |
| Isobutane consumption | |

**Principal Sections**

**1.** Olefins from FCC are combined with isobutane and fed to the HF reactor where alkylation occurs

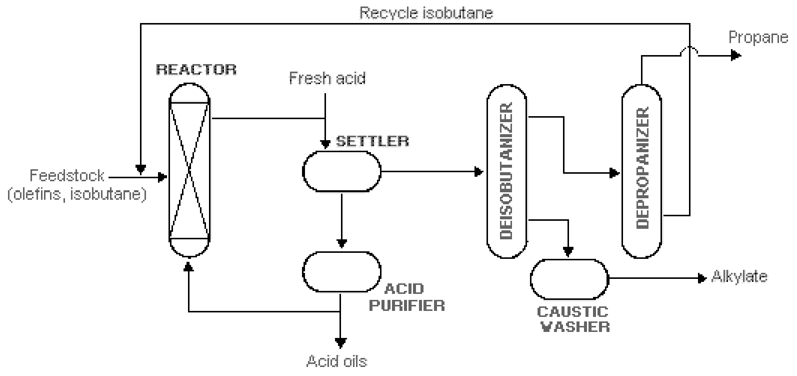
**2.** Acid settler separates the free HF from the hydrocarbons and recycles the acid back to the reactor

**3.** A portion of the HF is regenerated to remove acid oils formed by feed contaminants or hydrocarbon polymerization

**4.** Hydrocarbons from settler go to the deisobutanizer for fractionating the propane and isobutane to be recycled to the reactor

**5.** n-butane and alkylate are deflourinated in a bed of solid adsorbent and fractionated as separate products

**Simplified process chart**



## Key Health, Safety & Environment Information of Alkylation

Alkylation units are closed processes; however, the potential exists for fire should a leak or release occur that allows product or vapor to reach a source of ignition.

Loss of coolant water, which is needed to maintain process temperatures, could result in an upset.

Precautions are necessary to ensure that equipment and materials that have been in contact with acid are handled carefully and are thoroughly cleaned before they leave the process area or refinery. Immersion wash vats are often provided for neutralization of equipment that has come into contact with hydrofluoric acid. Hydrofluoric acid units should be thoroughly drained and chemically cleaned prior to turnarounds and entry to remove all traces of iron fluoride and hydrofluoric acid. Following shutdown, where water has been used, the unit should be thoroughly dried before hydrofluoric acid is introduced.

Leaks, spills, or releases involving hydrofluoric acid or hydrocarbons containing hydrofluoric acid can be extremely hazardous (care during delivery and unloading of acid is essential).

Process unit containment by curbs, drainage, and isolation so that effluent can be neutralized before release to the sewer system is considered.

Vents can be routed to soda-ash scrubbers to neutralize hydrogen fluoride gas or hydrofluoric acid vapors before release.

Pressure on the cooling water and steam side of exchangers should be kept below the minimum pressure on the acid service side to prevent water contamination.

To prevent corrosion from hydrofluoric acid, the acid concentration inside the process unit should be maintained above 65% and moisture below 4%.

Potential for exposure should leaks, spills, or releases occur. Sulfuric acid and (particularly) hydrofluoric acid are potentially hazardous chemicals.

Special precautionary emergency-preparedness measures and protection appropriate to the potential hazard and areas possibly affected need to be provided.

Safe work practices and appropriate skin and respiratory personal protective equipment are needed for potential exposures to hydrofluoric and sulfuric acids during normal operations such as reading gauges, inspecting, and process sampling, as well as during emergency response, maintenance, and turnaround activities.

Procedures should be in place to ensure that protective equipment and clothing worn in hydrofluoric acid activities are decontaminated and inspected before reissue. Appropriate personal protection for exposure to heat and noise also may be required.

## Hydrotreating:

### Process Design Intent

To remove contaminants (sulfur, nitrogen, metals), saturated olefins and aromatics to produce a clean product for further processing or finished product sales. The main process technique is Hydrogenation, process that occurs in a fixed bed to improve hydrogen/carbon ratios and to remove sulfur, nitrogen and metals.

### Principal Sections

**1.** Feed is preheated using the reactor effluent

**2.** Hydrogen is combined with the feed and heated to the desired hydrotreating temperature using a fired heater

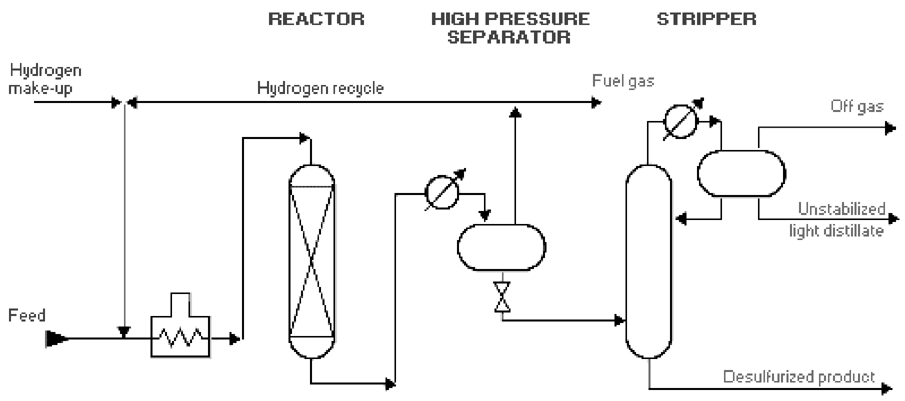
**3.** Feed and hydrogen pass downward in a hydrogenation reactor packed with various types of catalyst depending upon reactions desired

**4.** Reactor effluent is cooled and enter the high pressure separator which separates the liquid hydrocarbon from the hydrogen in the amine absorber

**5.** Hydrogen, minus purges, is recycled with make-up hydrogen

**6.** Further separation of LPG gases occurs in the low pressure separator prior to sending the hydrocarbon liquids to fractionation

### Simplified process chart (e.g., Hydrodesulfuration)



**Key Health, Safety & Environment Information of Hydrotreating**

Potential fire in the event of a leak or release of product or hydrogen gas.

Because of the operating temperatures and presence of hydrogen, the hydrogen sulfide content of the feedstock must be strictly controlled to a minimum to reduce corrosion.

Hydrogen chloride may form and condense as hydrochloric acid in the lower-temperature parts of the unit.

Ammonium hydrosulfide may form in high-temperature, high-pressure units. Excessive contact time and/or temperature will create coking.

Precautions need to be taken when unloading coked catalyst from the unit to prevent iron sulfide fires.

The coked catalyst should be cooled to below 120° F before removal, or dumped into nitrogen-inerted bins where it can be cooled before further handling.

Special antifoam additives may be used to prevent catalyst poisoning from silicone carryover in the coker feedstock.

There is a potential for exposure to hydrogen sulfide or hydrogen gas in the event of a release, or to ammonia should a sour-water leak or spill occur.

Phenol also may be present if high boiling-point feedstocks are processed.

Safe work practices and/or appropriate personal protective equipment may be needed for exposures to chemicals and other hazards such as noise and heat; during process sampling, inspection, maintenance, and turnaround activities; and when handling amine or exposed to catalyst.

## Hydrocracking:

**Process Design Intent**

To remove contaminants (sulfur, nitrogen, metals), and to convert low value gas oils to valuable products (naphtha, middle distillates, and ultra-clean lube base stocks). The main process technique (Hydrogenation) occurs in fixed hydrotreating catalyst beds to improve the hydrogen/carbon ratios and to remove sulfur, nitrogen, and metals. This is followed by one or more reactors with fixed hydrocracking catalyst beds to dealkylate aromatic rings, open naphthene rings, and hydrocrack paraffin chains.

**Products Obtained & Disposition**

| Products Obtained | Products Disposition |
|---|---|
| Light Ends | LPG |
| Naphtha | Gasoline; Catalytic Reformer |
| Diesel | Diesel |

**Principal Sections**

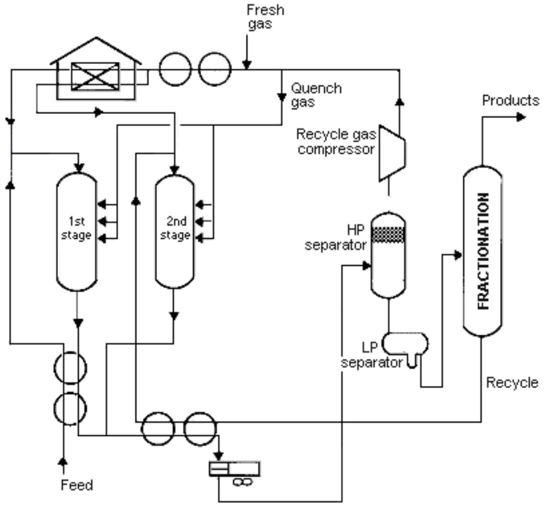
**1.** Preheated feed is mixed with hot hydrogen and passes through a multi-bed reactor with inter-stage hydrogen quenches for hydrotreating

**2.** Hydrotreated feed is mixed with additional hot hydrogen and passes through a multi-bed reactor with quenches for first pass hydrocracking

**3.** Reactor effluents are combined and pass through high and low pressure separators and are fed to the fractionator where valuable products are drawn from the top, sides, and bottom

**4.** Fractionator bottoms may be recycled to a second pass hydrocracker for additional conversion all the way up to full conversion

**Simplified process chart**



## Key Health, Safety & Environment Information of Hydrocracking

Because this unit operates at very high pressures and temperatures, control of both hydrocarbon leaks and hydrogen releases is important to prevent fires.

Care is needed to ensure that explosive concentrations of catalytic dust do not form during recharging.

Inspection and testing of safety relief devices are important due to the very high pressures in this unit.

Proper process control is needed to protect against plugging reactor beds.

Unloading coked catalyst requires special precautions to prevent iron sulfide-induced fires.

The coked catalyst should either be cooled to below 120° F before dumping, or be placed in nitrogen-inerted containers until cooled.

The hydrogen-sulfide content of the feedstock must be strictly controlled to a minimum to reduce the possibility of severe corrosion.

Corrosion by wet carbon dioxide in areas of condensation also must be considered.

When processing high-nitrogen feedstock, the ammonia and hydrogen sulfide form ammonium hydrosulfide, which causes serious corrosion at temperatures below the water dew point.

Ammonium hydrosulfide is also present in sour water stripping.
There is a potential for exposure to hydrocarbon gas and vapor emissions, hydrogen and hydrogen sulfide gas due to high-pressure leaks. Large quantities of carbon monoxide may be released during catalyst regeneration and changeover.

Catalyst steam stripping and regeneration create waste streams containing sour water and ammonia.

Safe work practices and/or the use of appropriate personal protective equipment may be needed for exposure to chemicals and other hazards such as noise and heat, during process sampling, inspection, maintenance, and turnaround activities, and when handling spent catalyst.

## Catalytic Reforming:

### Process Design Intent

To convert low-octane naphtha into a high-octane reformate for gasoline blending and/or to provide aromatics (benzene, toluene, xylene) for petrochemical plants. Reforming also produces high purity hydrogen for hydrotreating processes. The main process technique (Reforming reactions) occurs in chloride-promoted fixed-catalyst beds; or continuous catalyst-regeneration beds where the catalyst is transferred from one stage to another, through a catalyst -regenerator and back again. Desired reactions include: dehydrogenation of naphthenes to form aromatics; and isomeration of paraffins (hydrocracking of paraffins is undesirable due to increased ligh-end make).

### Products Obtained & Disposition

| Products Obtained | Products Disposition |
|---|---|
| Light Ends | LPG |
| Reformate | Gasoline; Petrochemical Plants |
| Hydrogen | Hydrotreating |

### Principal Sections

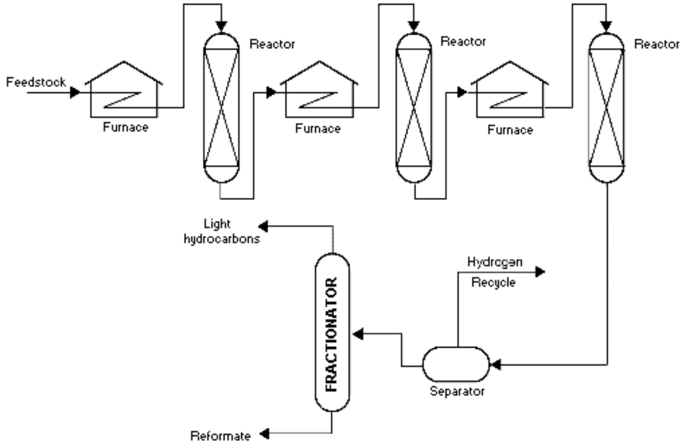
**1.** Naphtha feed and recycle hydrogen are mixed, heated and sent through successive reactor beds

**2.** Each pass requires heat input to drive the reactions

**3.** Final pass effluent is separated with the hydrogen being recycled or purged for hydrotreating

**4.** Reformate product can be further processed to separate aromatic components or be used for gasoline blending

### Simplified process chart



**Key Health, Safety & Environment Information of Catalytic Reforming**

The potential for fire exists should a leak or release of reformate gas or hydrogen occur.

Operating procedures should be developed to ensure control of hot spots during start-up.

Safe catalyst handling is very important. Care must be taken not to break or crush the catalyst when loading the beds, as the small fines will plug up the reformer screens.

Precautions against dust when regenerating or replacing catalyst should also be considered.

Also, water wash should be considered where stabilizer fouling has occurred due to the formation of ammonium chloride and iron salts.

Ammonium chloride may form in pretreated exchangers and cause corrosion and fouling.

Hydrogen chloride from the hydrogenation of chlorine compounds may form acid or ammonium chloride salt.

There is potential for exposure to hydrogen sulfide and benzene should a leak or release occur.

Small emissions of carbon monoxide and hydrogen sulfide may occur during regeneration of catalyst.

Safe work practices and/or appropriate personal protective equipment may be needed for exposures to chemicals and other hazards such as noise and heat during testing, inspecting, maintenance and turnaround activities, and when handling regenerated or spent catalyst.

## Isomerization:

**Process Design Intent**

To convert low-octane n-paraffins to high-octane iso-paraffins. The main process technique (Isomeration) occurs in a chloride-promoted fixed bed reactor where n-paraffins are converted to iso-paraffins. The catalyst is sensitive to incoming contaminants (sulfur and water).

**Products Obtained & Disposition**

| Products Obtained | Products Disposition |
|---|---|
| Hydrogen and Light Ends | LPG; Fuel Gas |
| Isomerate | Gasoline; iso-butane for Alkylation |

**Principal Sections**

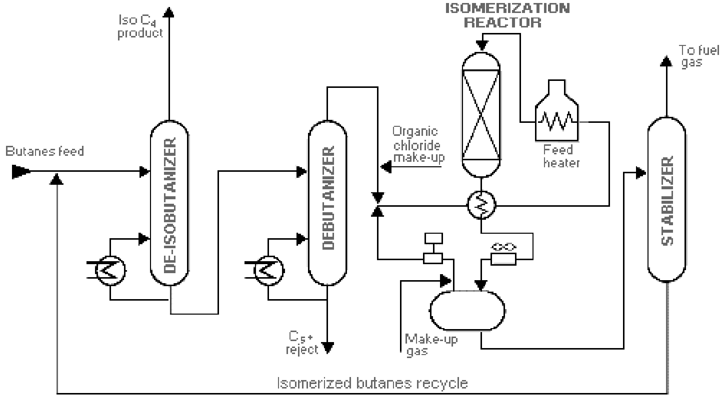
**1.** Desulfurized feed and hydrogen are dried in fixed beds of solid desiccant prior to mixing together

**2.** The mixed feed is heated and passes through a hydrogenation reactor to sature olefines to paraffins and saturate benzene

**3.** The hydrogenation effluent is cooled and passes through an isomeration reactor

**4.** The final effluent is cooled and separated as hydrogen and LPGs, which typically go to fuel gas, and isomerate product for gasoline blending

**Simplified process chart**



**Key Health, Safety & Environment Information of Isomerization**

The potential for a fire exists should a release or leak contact a source of ignition such as the heater.

If the feedstock is not completely dried and desulfurized, the potential exists for acid formation leading to catalyst poisoning and metal corrosion.

Water or steam must not be allowed to enter areas where hydrogen chloride is present.

Precautions are needed to prevent HCl from entering sewers and drains.

There is a potential for exposure to hydrogen gas, hydrochloric acid, and hydrogen chloride and to dust when a solid catalyst is used.

Safe work practices and/or appropriate personal protective equipment may be needed for exposures to chemicals and other hazards such as heat and noise, and during process sampling, inspection, maintenance, and turnaround activities.

# ANNEX III. EXPERIMENTAL DATA

The five continuous chemical processes “hazoped” are the following:

**(A)** ETBE production

**(B)** Hydrodesulfurization

**(C)** Gas Separation

**(D)** Atmospheric distillation (including Desalting)

**(E)** Alkylation (hydrofluoric acid process)

The following tables show the experimental data collected from each HAZOP conducted. The analysis of the present data has been treated and discussed in *Chapter V – Field Work and Data Analysis*. Additionally, the basic statistics of the main variables considered have been depicted with the aim of highlighting valuable related information.

The list of variables that have been recorded during the field work is the following:

- ✓ Time to select Principal Sections (PS) on PFDs
- ✓ Time to select preliminary Nodes (Nds) on PFDs
- ✓ Time to select detailed Nodes (Nds) on P&IDs
- ✓ Amount of Major Equipment (ME) present in a Nd
- ✓ Number of Flow Control Valves (FCVs) present in a Nd
- ✓ Number of Level Control Valves (LCVs) present in a Nd
- ✓ Number of Pressure Control Valves (PCVs) present in a Nd
- ✓ Number of Temperature Control Valves (TCVs) present in a Nd
- ✓ Number of Pumps present in a Nd
- ✓ Number of Exchangers present in a Nd
- ✓ Time required to brainstorm process nodes
- ✓ Number of Sessions per HAZOP
- ✓ Number of Team Members.

## AIII.I. HAZOP A - ETBE production

**Table A.III.1.** Main data from HAZOP A.

| Variable | Value | Unit |
|---|---|---|
| Number of process description pages | 22 | - |
| Number of Process Flow Diagrams (PFDs) | 1 | - |
| Number of Piping & Instrumentation Diagrams (P&IDs) | 14 | - |
| Amount of Major Equipment (ME) | 20 | |
| Number of Nodes | 14 | - |
| Total time required to prepare and organize the study | 16 | Hours |
| Total time required to execute the study | 40 | Hours |
| Total time required to write the draft report | 6 | Hours |

**Table A.III.2.** Node Selection Features – Principal Sections (HAZOP A).

| Variable | Principal Section | | | | | | |
|---|---|---|---|---|---|---|---|
| **Number of PS** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **Time to select PS (min)** | 13 | 7 | 11 | 6 | 12 | 8 | 6 |
| **Time to Select Nds on PFDs (min)** | 3 | 2 | 3 | 3 | 8 | 3 | 3 |
| **Number of Nds per PS** | 2 | 1 | 2 | 2 | 2 | 2 | 2 |

**Table A.III.3.** Node Selection Features – (HAZOP A).

| Node | Time Nds PFDs (min) | Time Nds P&IDs (min) |
|---|---|---|
| 1 | 2.00 | 10 |
| 2 | 1.00 | 7 |
| 3 | 2.00 | 11 |
| 4 | 1.20 | 9 |
| 5 | 1.80 | 6 |
| 6 | 1.00 | 7 |
| 7 | 2.00 | 2 |
| 8 | 3.00 | 5 |
| 9 | 5.00 | 8 |
| 10 | 1.50 | 1 |
| 11 | 1.50 | 4 |
| 12 | 2.00 | 3 |
| 13 | 1.00 | 2 |
| 14 (Global Nd) | - | - |

**Table A.III.4.** Nodes Structural Features – Detailed Nodes (HAZOP A).

| Node | ME | FCV | LCV | PCV | TCV | Pump | Exchanger |
|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 3 | 1 | 0 | 0 | 0 |
| 2 | 1 | 3 | 0 | 1 | 0 | 1 | 0 |
| 3 | 1 | 2 | 0 | 0 | 0 | 1 | 1 |
| 4 | 3 | 1 | 1 | 0 | 7 | 1 | 4 |
| 5 | 1 | 0 | 0 | 1 | 2 | 0 | 0 |
| 6 | 1 | 2 | 1 | 1 | 0 | 0 | 1 |
| 7 | 1 | 2 | 0 | 1 | 0 | 0 | 2 |
| 8 | 2 | 2 | 1 | 1 | 0 | 1 | 2 |
| 9 | 3 | 7 | 2 | 2 | 0 | 3 | 3 |
| 10 | 1 | 2 | 0 | 0 | 0 | 1 | 1 |
| 11 | 1 | 3 | 0 | 1 | 0 | 0 | 1 |
| 12 | 1 | 2 | 0 | 1 | 1 | 0 | 3 |
| 13 | 2 | 2 | 0 | 2 | 1 | 1 | 1 |
| 14 (Global Nd) | - | - | - | - | - | - | - |

**Table A.III.5.** Brainstorming Features – (HAZOP A).

| Node | Time (hour) | Nº of Session | Nº of Members |
|---|---|---|---|
| 1 | 5.30 | 1 | 6 |
| 2 | 2.00 | 1 | 7 |
| 3 | 2.65 | 2 | 6 |
| 4 | 2.80 | 2 | 7 |
| 5 | 3.00 | 2 | 6 |
| 6 | 2.55 | 3 | 4 |
| 7 | 2.70 | 3 | 4 |
| 8 | 3.10 | 3 | 5 |
| 9 | 2.35 | 4 | 4 |
| 10 | 3.10 | 4 | 4 |
| 11 | 2.50 | 4 | 3 |
| 12 | 3.10 | 5 | 5 |
| 13 | 2.75 | 5 | 6 |
| 14 (Global Nd) | 2.10 | 5 | 5 |

## AIII.II.HAZOP B - Hydrodesulfurization

**Table A.III.6.** Main data from HAZOP B.

| Variable | Value | Unit |
|---|---|---|
| Number of process description pages | 5 | - |
| Number of Process Flow Diagrams (PFDs) | 3 | - |
| Number of Piping & Instrumentation Diagrams (P&IDs) | 15 | - |
| Amount of Major Equipment (ME) | 21 | |
| Number of Nodes | 15 | - |
| Total time required to prepare and organize the study | 18 | Hours |
| Total time required to execute the study | 48 | Hours |
| Total time required to write the draft report | 5 | Hours |

**Table A.III.7.** Node Selection Features – Principal Sections (HAZOP B).

| Variable | Principal Section | | | |
|---|---|---|---|---|
| **Number of PS** | 1 | 2 | 3 | 4 |
| **Time to select PS (min)** | 12 | 12 | 5 | 6 |
| **Time to Select Nds on PFDs (min)** | 5 | 3 | 7 | 3 |
| **Number of Nds per PS** | 3 | 3 | 5 | 3 |

**Table A.III.8.** Node Selection Features – (HAZOP B).

| Node | Time Nds PFDs (min) | Time Nds P&IDs (min) |
|---|---|---|
| 1 | 2.00 | 9 |
| 2 | 1.80 | 6 |
| 3 | 1.20 | 8 |
| 4 | 1.00 | 2 |
| 5 | 1.00 | 3 |
| 6 | 1.00 | 7 |
| 7 | 2.00 | 4 |
| 8 | 2.00 | 4 |
| 9 | 1.00 | 7 |
| 10 | 1.00 | 7 |
| 11 | 1.00 | 7 |
| 12 | 1.00 | 10 |
| 13 | 1.00 | 4 |
| 14 | 1.00 | 4 |
| 15 (Global Nd) | - | - |

**Table A.III.9.** Nodes Structural Features – Detailed Nodes (HAZOP B).

| Node | ME | FCV | LCV | PCV | TCV | Pump | Exchanger |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 7 | 0 | 2 | 0 | 4 | 0 |
| 2 | 3 | 0 | 0 | 2 | 0 | 1 | 0 |
| 3 | 1 | 1 | 0 | 2 | 0 | 1 | 2 |
| 4 | 1 | 3 | 0 | 0 | 1 | 0 | 0 |
| 5 | 1 | 0 | 0 | 5 | 0 | 0 | 0 |
| 6 | 2 | 5 | 0 | 0 | 0 | 0 | 3 |
| 7 | 2 | 1 | 3 | 2 | 0 | 0 | 1 |
| 8 | 1 | 1 | 3 | 2 | 0 | 1 | 0 |
| 9 | 2 | 1 | 1 | 4 | 0 | 0 | 0 |
| 10 | 2 | 3 | 2 | 2 | 4 | 1 | 2 |
| 11 | 1 | 0 | 0 | 0 | 0 | 1 | 0 |
| 12 | 2 | 4 | 0 | 0 | 3 | 0 | 2 |
| 13 | 1 | 2 | 0 | 0 | 0 | 1 | 1 |
| 14 | 1 | 4 | 1 | 0 | 0 | 2 | 5 |
| 15 (Global Nd) | - | - | - | - | - | - | - |

**Table A.III.10.** Brainstorming Features – (HAZOP B).

| Node | Time (hour) | Nº of Session | Nº of Members |
|---|---|---|---|
| 1 | 6.00 | 1 | 5 |
| 2 | 3.80 | 2 | 4 |
| 3 | 2.75 | 2 | 5 |
| 4 | 2.35 | 2 | 5 |
| 5 | 2.50 | 3 | 4 |
| 6 | 3.70 | 3 | 5 |
| 7 | 3.00 | 3 | 6 |
| 8 | 2.10 | 4 | 4 |
| 9 | 3.20 | 4 | 6 |
| 10 | 2.50 | 4 | 5 |
| 11 | 3.20 | 4 | 6 |
| 12 | 3.10 | 5 | 5 |
| 13 | 2.90 | 5 | 6 |
| 14 | 2.40 | 5 | 4 |
| 15 (Global Nd) | 2.50 | 5 | 3 |

## AIII.III.HAZOP C - Gas Separation

**Table A.III.11.** Main data from HAZOP C.

| Variable | Value | Unit |
|---|---|---|
| Number of process description pages | 3 | - |
| Number of Process Flow Diagrams (PFDs) | 4 | - |
| Number of Piping & Instrumentation Diagrams (P&IDs) | 22 | - |
| Amount of Major Equipment (ME) | 19 | |
| Number of Nodes | 16 | - |
| Total time required to prepare and organize the study | 20 | Hours |
| Total time required to execute the study | 54 | Hours |
| Total time required to write the draft report | 8 | Hours |

**Table A.III.12.** Node Selection Features – Principal Sections (HAZOP C).

| Variable | Principal Section | | | |
|---|---|---|---|---|
| **Number of PS** | 1 | 2 | 3 | 4 |
| **Time to select PS (min)** | 6 | 7 | 4 | 4 |
| **Time to Select Nds on PFDs (min)** | 15 | 8 | 7 | 3 |
| **Number of Nds per PS** | 6 | 4 | 4 | 1 |

**Table A.III.13.** Node Selection Features – (HAZOP C).

| Node | Time Nds PFDs (min) | Time Nds P&IDs (min) |
|---|---|---|
| 1 | 2.50 | 2 |
| 2 | 2.50 | 7 |
| 3 | 2.50 | 7 |
| 4 | 2.50 | 6 |
| 5 | 3.00 | 4 |
| 6 | 2.00 | 9 |
| 7 | 2.00 | 4 |
| 8 | 2.00 | 5 |
| 9 | 2.00 | 3 |
| 10 | 2.00 | 4 |
| 11 | 1.00 | 8 |
| 12 | 1.00 | 4 |
| 13 | 3.00 | 5 |
| 14 | 2.00 | 4 |
| 15 | 3.00 | 8 |
| 16 (Global Nd) | - | - |

**Table A.III.14.** Nodes Structural Features – Detailed Nodes (HAZOP C).

| Node | ME | FCV | LCV | PCV | TCV | Pump | Exchanger |
|---|---|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 1 | 0 | 1 | 0 |
| 2 | 1 | 1 | 2 | 1 | 0 | 2 | 1 |
| 3 | 1 | 0 | 0 | 2 | 0 | 0 | 0 |
| 4 | 1 | 1 | 0 | 2 | 0 | 0 | 0 |
| 5 | 2 | 4 | 2 | 2 | 0 | 1 | 0 |
| 6 | 1 | 2 | 1 | 0 | 0 | 1 | 3 |
| 7 | 1 | 1 | 0 | 0 | 0 | 0 | 1 |
| 8 | 2 | 2 | 0 | 0 | 3 | 0 | 1 |
| 9 | 1 | 1 | 1 | 0 | 0 | 1 | 3 |
| 10 | 2 | 1 | 2 | 1 | 2 | 0 | 1 |
| 11 | 1 | 5 | 0 | 2 | 3 | 1 | 3 |
| 12 | 1 | 3 | 0 | 2 | 0 | 2 | 1 |
| 13 | 2 | 5 | 1 | 0 | 2 | 1 | 4 |
| 14 | 1 | 3 | 0 | 2 | 0 | 1 | 1 |
| 15 | 1 | 1 | 1 | 4 | 0 | 1 | 2 |
| 16 (Global Nd) | - | - | - | - | - | - | - |

**Table A.III.15.** Brainstorming Features – (HAZOP C).

| Node | Time (hour) | Nº of Session | Nº of Members |
|---|---|---|---|
| 1 | 4.90 | 1 | 4 |
| 2 | 3.50 | 1 | 3 |
| 3 | 2.70 | 2 | 2 |
| 4 | 2.80 | 2 | 4 |
| 5 | 3.40 | 2 | 4 |
| 6 | 2.70 | 3 | 2 |
| 7 | 2.70 | 3 | 3 |
| 8 | 3.60 | 3 | 4 |
| 9 | 3.00 | 4 | 4 |
| 10 | 2.70 | 4 | 3 |
| 11 | 3.60 | 4 | 4 |
| 12 | 2.70 | 4 | 3 |
| 13 | 3.00 | 5 | 4 |
| 14 | 2.80 | 5 | 4 |
| 15 | 2.70 | 5 | 3 |
| 16 (Global Nd) | 2.90 | 5 | 2 |

## AIII.IV.HAZOP D - Atmospheric distillation (including Desalting)

**Table A.III.16.** Main data from HAZOP D.

| Variable | Value | Unit |
|---|---|---|
| Number of process description pages | 3 | - |
| Number of Process Flow Diagrams (PFDs) | 5 | - |
| Number of Piping & Instrumentation Diagrams (P&IDs) | 24 | - |
| Amount of Major Equipment (ME) | 23 | |
| Number of Nodes | 18 | - |
| Total time required to prepare and organize the study | 25 | Hours |
| Total time required to execute the study | 60 | Hours |
| Total time required to write the draft report | 9 | Hours |

**Table A.III.17.** Node Selection Features – Principal Sections (HAZOP D).

| Variable | Principal Section | | | |
|---|---|---|---|---|
| **Number of PS** | 1 | 2 | 3 | 4 |
| **Time to select PS (min)** | 12 | 4 | 4 | 3 |
| **Time to Select Nds on PFDs (min)** | 10 | 4 | 8 | 10 |
| **Number of Nds per PS** | 5 | 4 | 3 | 5 |

**Table A.III.18.** Node Selection Features – Detailed Nodes (HAZOP D).

| Node | Time Nds PFDs (min) | Time Nds P&IDs (min) |
|---|---|---|
| 1 | 1.50 | 4 |
| 2 | 3.00 | 11 |
| 3 | 3.00 | 9 |
| 4 | 1.50 | 14 |
| 5 | 1.00 | 6 |
| 6 | 1.00 | 12 |
| 7 | 1.00 | 6 |
| 8 | 1.00 | 3 |
| 9 | 1.00 | 9 |
| 10 | 2.50 | 10 |
| 11 | 2.50 | 6 |
| 12 | 3.00 | 3 |
| 13 | 1.50 | 4 |
| 14 | 1.00 | 5 |
| 15 | 2.50 | 8 |
| 16 | 3.00 | 7 |
| 17 | 2.00 | 8 |
| 18 (Global Nd) | - | - |

**Table A.III.19.** Nodes Structural Features – Detailed Nodes (HAZOP D).

| Node | ME | FCV | LCV | PCV | TCV | Pump | Exchanger |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 0 | 1 | 2 | 2 | 1 | 5 |
| 2 | 2 | 3 | 2 | 2 | 0 | 1 | 0 |
| 3 | 2 | 2 | 4 | 4 | 2 | 2 | 2 |
| 4 | 2 | 1 | 0 | 0 | 0 | 3 | 3 |
| 5 | 1 | 6 | 0 | 1 | 0 | 0 | 2 |
| 6 | 1 | 8 | 0 | 0 | 1 | 0 | 0 |
| 7 | 1 | 1 | 0 | 5 | 0 | 0 | 0 |
| 8 | 2 | 5 | 3 | 0 | 2 | 3 | 2 |
| 9 | 1 | 5 | 0 | 0 | 0 | 2 | 2 |
| 10 | 1 | 5 | 0 | 2 | 0 | 2 | 1 |
| 11 | 1 | 1 | 1 | 2 | 0 | 1 | 3 |
| 12 | 1 | 2 | 1 | 1 | 0 | 1 | 1 |
| 13 | 1 | 2 | 1 | 2 | 0 | 1 | 3 |
| 14 | 1 | 2 | 0 | 1 | 7 | 1 | 7 |
| 15 | 1 | 3 | 0 | 0 | 0 | 0 | 4 |
| 16 | 2 | 3 | 0 | 1 | 0 | 2 | 3 |
| 17 | 3 | 0 | 0 | 0 | 0 | 3 | 1 |
| 18 (Global Nd) | - | - | - | - | - | - | - |

**Table A.III.20.** Brainstorming Features – (HAZOP D).

| Node | Time (hour) | Nº of Session | Nº of Members |
|---|---|---|---|
| 1 | 5.60 | 1 | 5 |
| 2 | 2.80 | 1 | 6 |
| 3 | 3.70 | 2 | 5 |
| 4 | 3.40 | 2 | 5 |
| 5 | 2.80 | 2 | 5 |
| 6 | 2.70 | 3 | 5 |
| 7 | 3.60 | 3 | 4 |
| 8 | 3.50 | 3 | 4 |
| 9 | 3.70 | 4 | 5 |
| 10 | 2.70 | 4 | 4 |
| 11 | 3.00 | 4 | 5 |
| 12 | 2.80 | 5 | 4 |
| 13 | 3.10 | 5 | 5 |
| 14 | 3.30 | 5 | 5 |
| 15 | 2.80 | 6 | 6 |
| 16 | 2.60 | 6 | 5 |
| 17 | 3.10 | 6 | 4 |
| 18 (Global Nd) | 2.80 | 6 | 5 |

## AIII.V.HAZOP E - Alkylation

**Table A.III.21.** Main data from HAZOP E.

| Variable | Value | Unit |
|---|---|---|
| Number of process description pages | 21 | - |
| Number of Process Flow Diagrams (PFDs) | 3 | - |
| Number of Piping & Instrumentation Diagrams (P&IDs) | 25 | - |
| Amount of Major Equipment (ME) | 30 | |
| Number of Nodes | 19 | - |
| Total time required to prepare and organize the study | 30 | Hours |
| Total time required to execute the study | 65 | Hours |
| Total time required to write the draft report | 13 | Hours |

**Table A.III.22.** Node Selection Features – Principal Sections (HAZOP E).

| Variable | Principal Section | | | | | | |
|---|---|---|---|---|---|---|---|
| **Number of PS** | 1 | 2 | 3 | 4 | 5 | 6 | 7 |
| **Time to select PS (min)** | 19 | 13 | 7 | 18 | 14 | 27 | 6 |
| **Time to Select Nds on PFDs (min)** | 7 | 4 | 7 | 3 | 4 | 11 | 3 |
| **Number of Nds per PS** | 3 | 2 | 1 | 2 | 2 | 6 | 2 |

**Table A.III.23.** Node Selection Features – (HAZOP E).

| Node | Time Nds PFDs (min) | Time Nds P&IDs (min) |
|---|---|---|
| 1 | 3.00 | 7 |
| 2 | 2.00 | 5 |
| 3 | 2.00 | 8 |
| 4 | 2.50 | 4 |
| 5 | 1.50 | 9 |
| 6 | 7.00 | 12 |
| 7 | 1.50 | 8 |
| 8 | 1.50 | 6 |
| 9 | 1.75 | 7 |
| 10 | 1.25 | 12 |
| 11 | 1.00 | 7 |
| 12 | 2.00 | 5 |
| 13 | 1.00 | 5 |
| 14 | 2.00 | 3 |
| 15 | 3.00 | 3 |
| 16 | 2.00 | 4 |
| 17 | 2.00 | 3 |
| 18 | 1.00 | 4 |
| 19 (Global Nd) | - | - |

**Table A.III.24.** Nodes Structural Features – Detailed Nodes (HAZOP E).

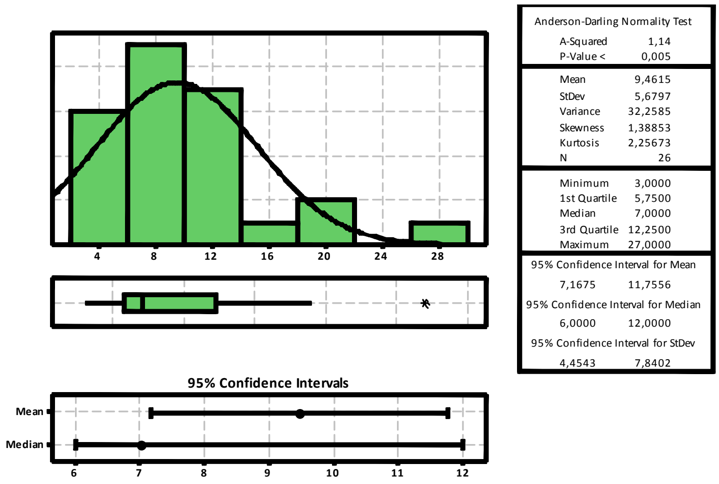
| Node | ME | FCV | LCV | PCV | TCV | Pump | Exchanger |
|---|---|---|---|---|---|---|---|
| 1 | 3 | 3 | 1 | 1 | 1 | 1 | 3 |
| 2 | 2 | 4 | 0 | 1 | 2 | 0 | 3 |
| 3 | 2 | 2 | 1 | 1 | 0 | 1 | 1 |
| 4 | 1 | 4 | 0 | 0 | 1 | 1 | 3 |
| 5 | 1 | 2 | 0 | 3 | 0 | 1 | 1 |
| 6 | 4 | 3 | 0 | 1 | 1 | 1 | 2 |
| 7 | 1 | 2 | 1 | 2 | 0 | 1 | 2 |
| 8 | 1 | 1 | 0 | 1 | 0 | 1 | 2 |
| 9 | 1 | 4 | 0 | 1 | 2 | 0 | 2 |
| 10 | 2 | 0 | 1 | 1 | 0 | 2 | 2 |
| 11 | 2 | 9 | 0 | 0 | 2 | 1 | 5 |
| 12 | 2 | 2 | 1 | 2 | 0 | 1 | 1 |
| 13 | 0 | 4 | 0 | 1 | 0 | 0 | 2 |
| 14 | 2 | 0 | 0 | 0 | 0 | 1 | 0 |
| 15 | 1 | 6 | 0 | 0 | 0 | 0 | 0 |
| 16 | 1 | 0 | 0 | 4 | 0 | 0 | 0 |
| 17 | 3 | 0 | 0 | 1 | 0 | 0 | 1 |
| 18 | 1 | 1 | 0 | 1 | 2 | 0 | 2 |
| 19 (Global Nd) | - | - | - | - | - | - | - |

**Table A.III.25.** Brainstorming Features – (HAZOP E).

| Node | Time (hour) | Nº of Session | Nº of Members |
|---|---|---|---|
| 1 | 5.80 | 1 | 2 |
| 2 | 3.50 | 1 | 3 |
| 3 | 3.75 | 2 | 4 |
| 4 | 3.70 | 2 | 5 |
| 5 | 2.80 | 2 | 4 |
| 6 | 2.50 | 3 | 4 |
| 7 | 3.70 | 3 | 5 |
| 8 | 3.70 | 3 | 4 |
| 9 | 2.75 | 4 | 5 |
| 10 | 3.40 | 4 | 4 |
| 11 | 3.60 | 4 | 5 |
| 12 | 2.90 | 5 | 4 |
| 13 | 2.80 | 5 | 5 |
| 14 | 3.50 | 5 | 4 |
| 15 | 3.40 | 6 | 5 |
| 16 | 2.70 | 6 | 5 |
| 17 | 2.90 | 6 | 4 |
| 18 | 3.50 | 7 | 3 |
| 19 (Global Nd) | 3.00 | 7 | 4 |

The following contents are intended to complete basic statistical information related to the key variables considered in *Chapter V – Field Work and Data Analysis*.

## Figures A.III.1. Time (minutes) required to select Principal Sections (PS):



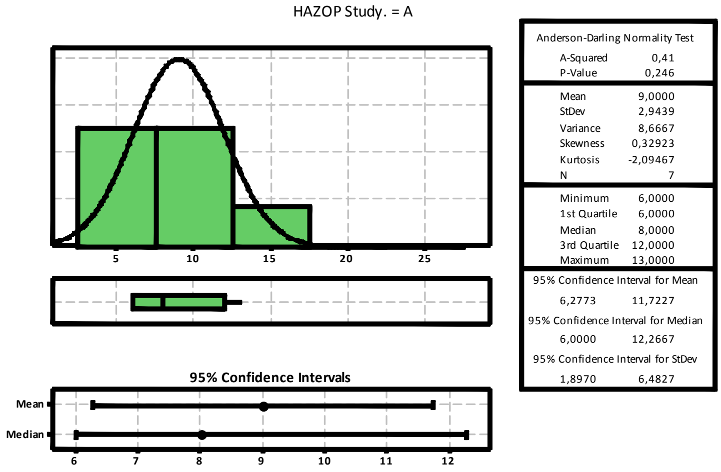
Anderson-Darling Normality Test
A-Squared 1,14
P-Value < 0,005

Mean 9,4615
StDev 5,6797
Variance 32,2585
Skewness 1,38853
Kurtosis 2,25673
N 26

Minimum 3,0000
1st Quartile 5,7500
Median 7,0000
3rd Quartile 12,2500
Maximum 27,0000

95% Confidence Interval for Mean
7,1675 11,7556
95% Confidence Interval for Median
6,0000 12,0000
95% Confidence Interval for StDev
4,4543 7,8402

**Figure A.III. 1.1.** Basic statistics summary of all HAZOPs - PS.



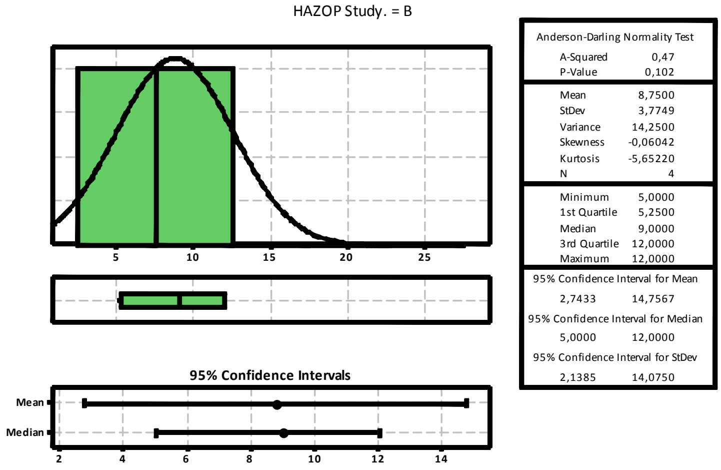
Anderson-Darling Normality Test
A-Squared 0,41
P-Value 0,246

Mean 9,0000
StDev 2,9439
Variance 8,6667
Skewness 0,32923
Kurtosis -2,09467
N 7

Minimum 6,0000
1st Quartile 6,0000
Median 8,0000
3rd Quartile 12,0000
Maximum 13,0000

95% Confidence Interval for Mean
6,2773 11,7227
95% Confidence Interval for Median
6,0000 12,2667
95% Confidence Interval for StDev
1,8970 6,4827

**Figure A.III. 1.2.** Basic statistics summary considering the HAZOP A – PS.



Anderson-Darling Normality Test
A-Squared 0,47
P-Value 0,102

Mean 8,7500
StDev 3,7749
Variance 14,2500
Skewness -0,06042
Kurtosis -5,65220
N 4

Minimum 5,0000
1st Quartile 5,2500
Median 9,0000
3rd Quartile 12,0000
Maximum 12,0000

95% Confidence Interval for Mean
2,7433 14,7567
95% Confidence Interval for Median
5,0000 12,0000
95% Confidence Interval for StDev
2,1385 14,0750

**Figure A.III. 1.3.** Basic statistics summary considering the HAZOP B – PS.

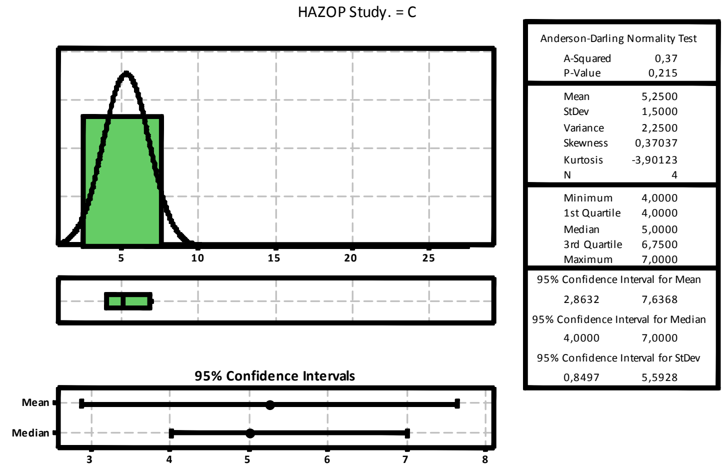


**Figure A.III. 1.4.** Basic statistics summary considering the HAZOP C – PS.

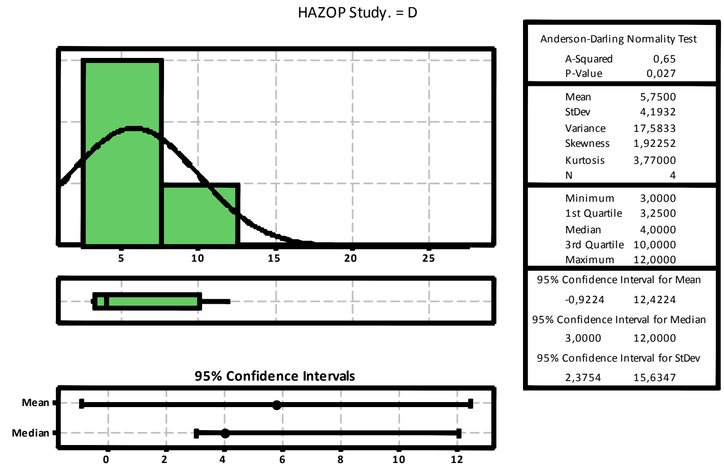


**Figure A.III. 1.5.** Basic statistics summary considering the HAZOP D – PS.

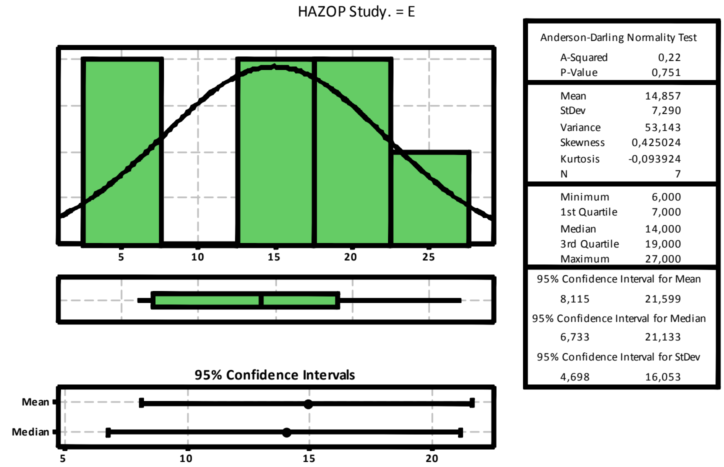
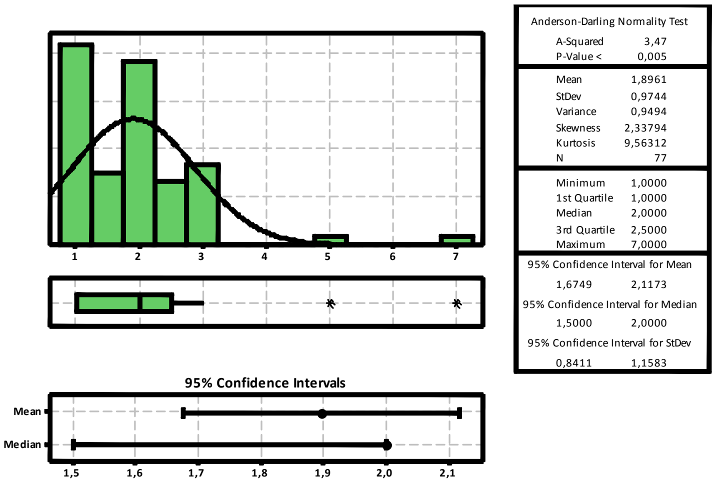


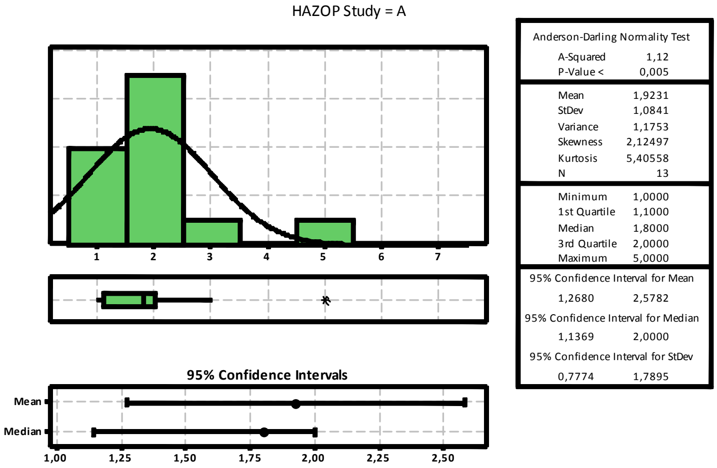
**Figure A.III. 1.6.** Basic statistics summary considering the HAZOP E – PS.

## Figures A.III.2. Time (minutes) required to select Preliminary Nodes on PFDs:



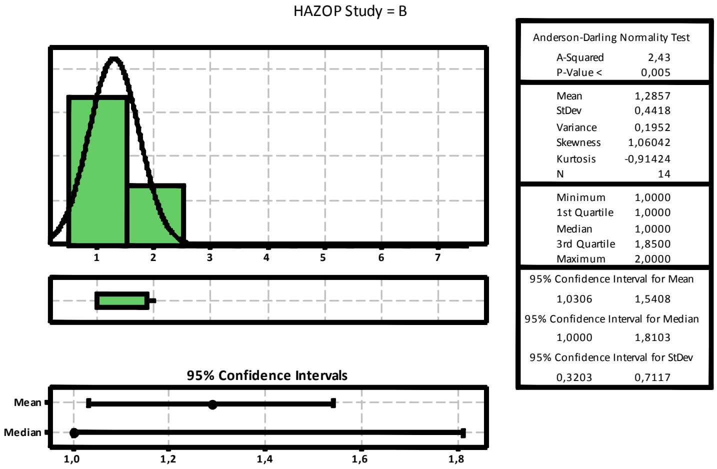
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 3,47 |
| P-Value < | 0,005 |
| Mean | 1,8961 |
| StDev | 0,9744 |
| Variance | 0,9494 |
| Skewness | 2,33794 |
| Kurtosis | 9,56312 |
| N | 77 |
| Minimum | 1,0000 |
| 1st Quartile | 1,0000 |
| Median | 2,0000 |
| 3rd Quartile | 2,5000 |
| Maximum | 7,0000 |
| 95% Confidence Interval for Mean | |
| 1,6749 | 2,1173 |
| 95% Confidence Interval for Median | |
| 1,5000 | 2,0000 |
| 95% Confidence Interval for StDev | |
| 0,8411 | 1,1583 |

**Figure A.III. 2.1.** Basic statistics summary of all HAZOPs – Preliminary Nd.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,12 |
| P-Value < | 0,005 |
| Mean | 1,9231 |
| StDev | 1,0841 |
| Variance | 1,1753 |
| Skewness | 2,12497 |
| Kurtosis | 5,40558 |
| N | 13 |
| Minimum | 1,0000 |
| 1st Quartile | 1,1000 |
| Median | 1,8000 |
| 3rd Quartile | 2,0000 |
| Maximum | 5,0000 |
| 95% Confidence Interval for Mean | |
| 1,2680 | 2,5782 |
| 95% Confidence Interval for Median | |
| 1,1369 | 2,0000 |
| 95% Confidence Interval for StDev | |
| 0,7774 | 1,7895 |

**Figure A.III. 2.2.** Basic statistics summary considering the HAZOP A - Preliminary Nd.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 2,43 |
| P-Value < | 0,005 |
| Mean | 1,2857 |
| StDev | 0,4418 |
| Variance | 0,1952 |
| Skewness | 1,06042 |
| Kurtosis | -0,91424 |
| N | 14 |
| Minimum | 1,0000 |
| 1st Quartile | 1,0000 |
| Median | 1,0000 |
| 3rd Quartile | 1,8500 |
| Maximum | 2,0000 |
| 95% Confidence Interval for Mean | |
| 1,0306 | 1,5408 |
| 95% Confidence Interval for Median | |
| 1,0000 | 1,8103 |
| 95% Confidence Interval for StDev | |
| 0,3203 | 0,7117 |

**Figure A.III. 2.3.** Basic statistics summary considering the HAZOP B - Preliminary Nd.

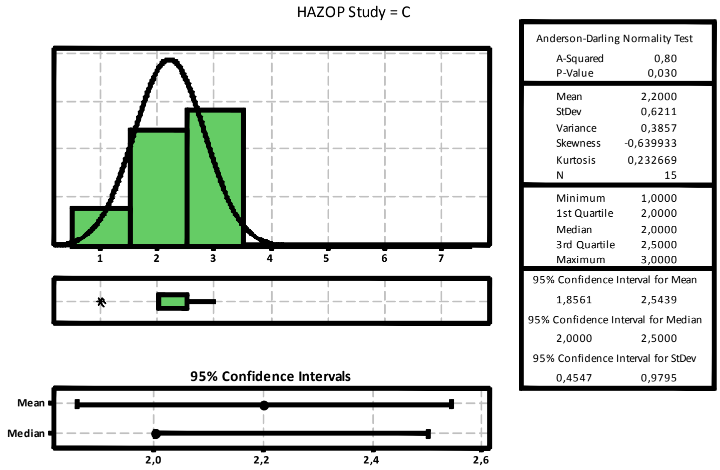


**Figure A.III. 2.4.** Basic statistics summary considering the HAZOP C - Preliminary Nd.

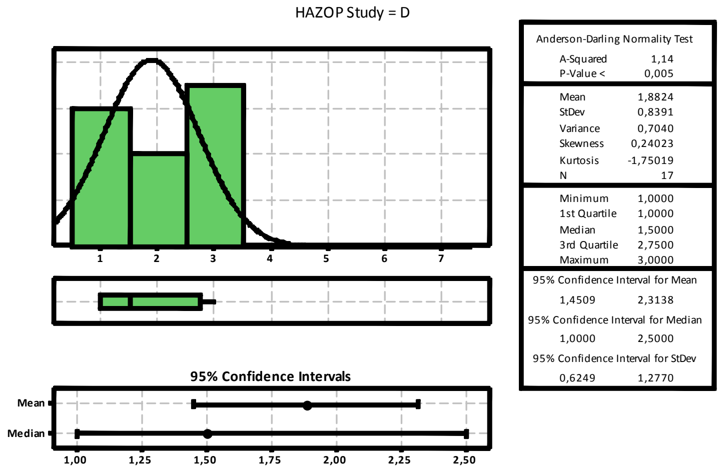


**Figure A.III. 2.5.** Basic statistics summary considering the HAZOP D - Preliminary Nd.

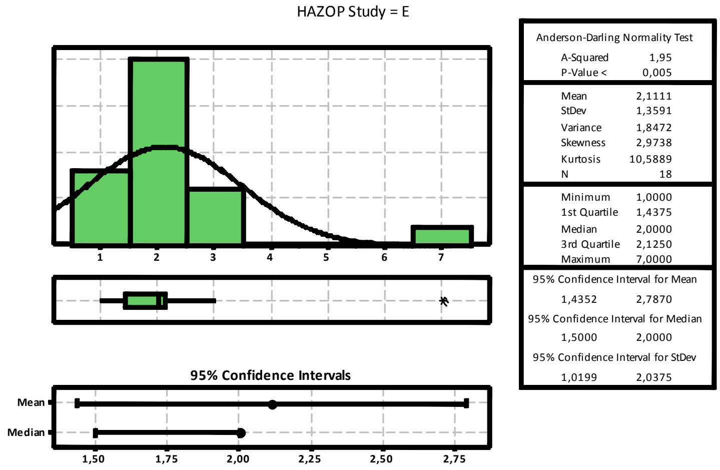
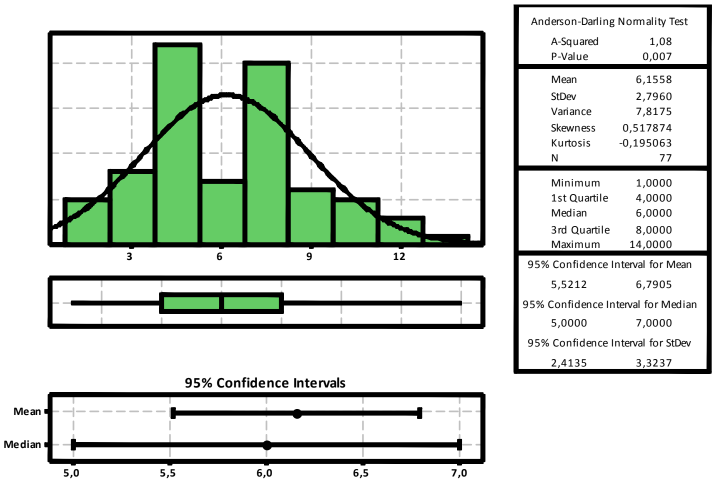


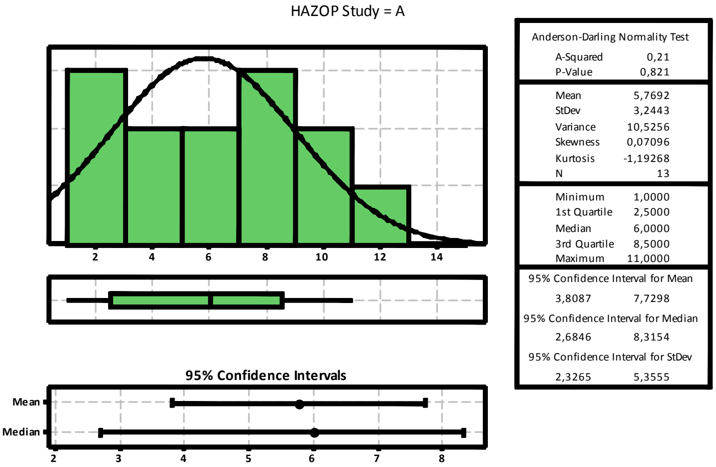
**Figure A.III. 2.6.** Basic statistics summary considering the HAZOP E - Preliminary Nd.

## Figures A.III.3. Time (minutes) required to select Detailed Nodes on P&IDs:



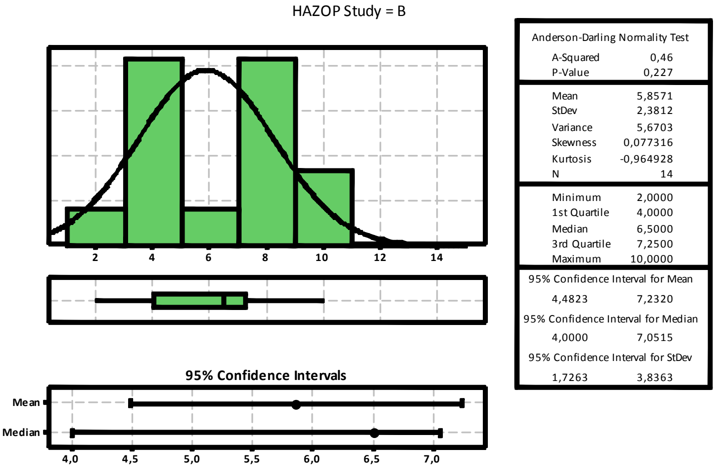
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,08 |
| P-Value | 0,007 |
| Mean | 6,1558 |
| StDev | 2,7960 |
| Variance | 7,8175 |
| Skewness | 0,517874 |
| Kurtosis | -0,195063 |
| N | 77 |
| Minimum | 1,0000 |
| 1st Quartile | 4,0000 |
| Median | 6,0000 |
| 3rd Quartile | 8,0000 |
| Maximum | 14,0000 |
| 95% Confidence Interval for Mean | |
| 5,5212 | 6,7905 |
| 95% Confidence Interval for Median | |
| 5,0000 | 7,0000 |
| 95% Confidence Interval for StDev | |
| 2,4135 | 3,3237 |

**Figure A.III. 3.1.** Basic statistics summary of all HAZOPs – Detailed Nd.



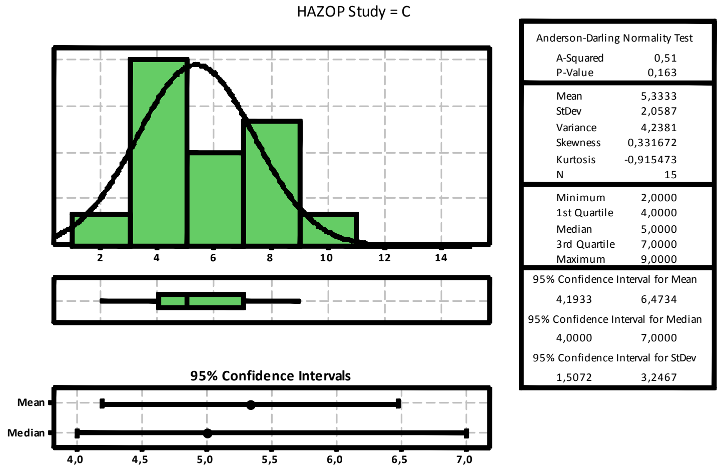
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,21 |
| P-Value | 0,821 |
| Mean | 5,7692 |
| StDev | 3,2443 |
| Variance | 10,5256 |
| Skewness | 0,07096 |
| Kurtosis | -1,19268 |
| N | 13 |
| Minimum | 1,0000 |
| 1st Quartile | 2,5000 |
| Median | 6,0000 |
| 3rd Quartile | 8,5000 |
| Maximum | 11,0000 |
| 95% Confidence Interval for Mean | |
| 3,8087 | 7,7298 |
| 95% Confidence Interval for Median | |
| 2,6846 | 8,3154 |
| 95% Confidence Interval for StDev | |
| 2,3265 | 5,3555 |

**Figure A.III. 3.2.** Basic statistics summary considering the HAZOP A - Detailed Nd.



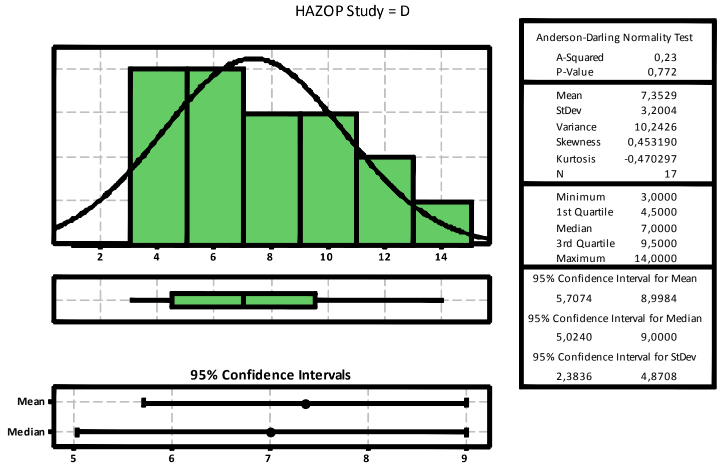
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,46 |
| P-Value | 0,227 |
| Mean | 5,8571 |
| StDev | 2,3812 |
| Variance | 5,6703 |
| Skewness | 0,077316 |
| Kurtosis | -0,964928 |
| N | 14 |
| Minimum | 2,0000 |
| 1st Quartile | 4,0000 |
| Median | 6,5000 |
| 3rd Quartile | 7,2500 |
| Maximum | 10,0000 |
| 95% Confidence Interval for Mean | |
| 4,4823 | 7,2320 |
| 95% Confidence Interval for Median | |
| 4,0000 | 7,0515 |
| 95% Confidence Interval for StDev | |
| 1,7263 | 3,8363 |

**Figure A.III. 3.3.** Basic statistics summary considering the HAZOP B - Detailed Nd.



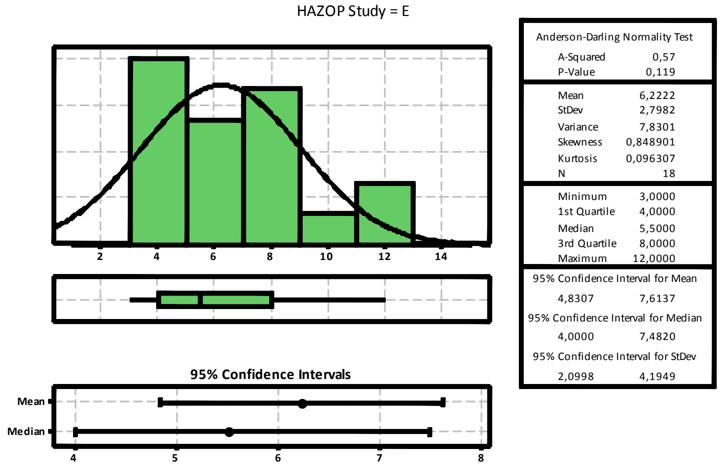
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,51 |
| P-Value | 0,163 |
| Mean | 5,3333 |
| StDev | 2,0587 |
| Variance | 4,2381 |
| Skewness | 0,331672 |
| Kurtosis | -0,915473 |
| N | 15 |
| Minimum | 2,0000 |
| 1st Quartile | 4,0000 |
| Median | 5,0000 |
| 3rd Quartile | 7,0000 |
| Maximum | 9,0000 |
| 95% Confidence Interval for Mean | |
| 4,1933 | 6,4734 |
| 95% Confidence Interval for Median | |
| 4,0000 | 7,0000 |
| 95% Confidence Interval for StDev | |
| 1,5072 | 3,2467 |

**Figure A.III. 3.4.** Basic statistics summary considering the HAZOP C - Detailed Nd.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,23 |
| P-Value | 0,772 |
| Mean | 7,3529 |
| StDev | 3,2004 |
| Variance | 10,2426 |
| Skewness | 0,453190 |
| Kurtosis | -0,470297 |
| N | 17 |
| Minimum | 3,0000 |
| 1st Quartile | 4,5000 |
| Median | 7,0000 |
| 3rd Quartile | 9,5000 |
| Maximum | 14,0000 |
| 95% Confidence Interval for Mean | |
| 5,7074 | 8,9984 |
| 95% Confidence Interval for Median | |
| 5,0240 | 9,0000 |
| 95% Confidence Interval for StDev | |
| 2,3836 | 4,8708 |

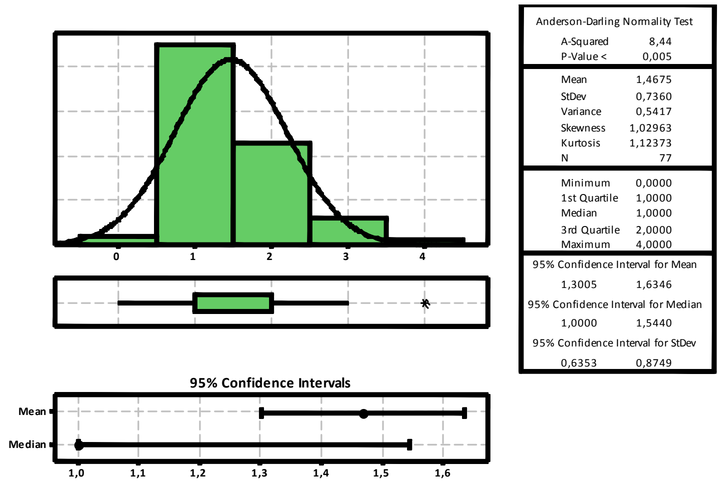
**Figure A.III. 3.5.** Basic statistics summary considering the HAZOP D - Detailed Nd.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,57 |
| P-Value | 0,119 |
| Mean | 6,2222 |
| StDev | 2,7982 |
| Variance | 7,8301 |
| Skewness | 0,848901 |
| Kurtosis | 0,096307 |
| N | 18 |
| Minimum | 3,0000 |
| 1st Quartile | 4,0000 |
| Median | 5,5000 |
| 3rd Quartile | 8,0000 |
| Maximum | 12,0000 |
| 95% Confidence Interval for Mean | |
| 4,8307 | 7,6137 |
| 95% Confidence Interval for Median | |
| 4,0000 | 7,4820 |
| 95% Confidence Interval for StDev | |
| 2,0998 | 4,1949 |

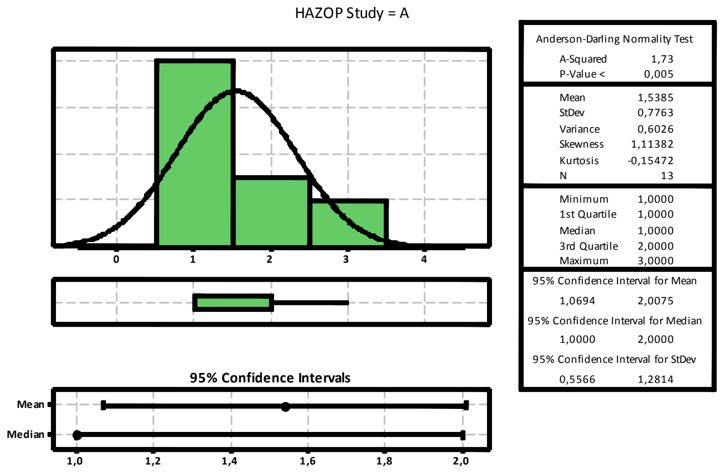
**Figure A.III. 3.6.** Basic statistics summary considering the HAZOP E - Detailed Nd.

## Figures A.III.4. Major Equipment (ME):



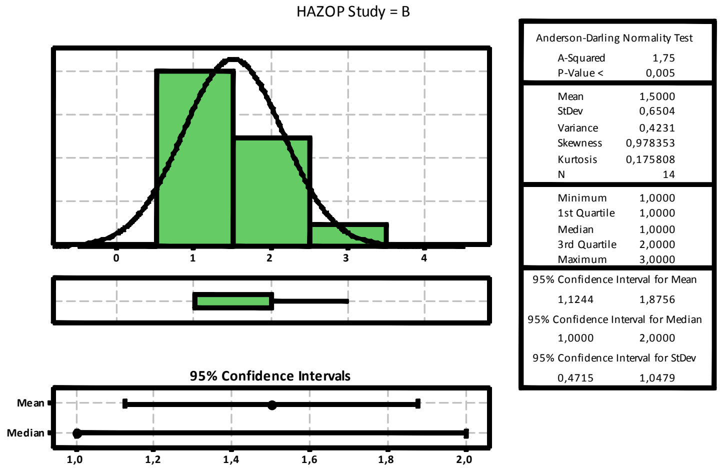
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 8,44 |
| P-Value < | 0,005 |
| Mean | 1,4675 |
| StDev | 0,7360 |
| Variance | 0,5417 |
| Skewness | 1,02963 |
| Kurtosis | 1,12373 |
| N | 77 |
| Minimum | 0,0000 |
| 1st Quartile | 1,0000 |
| Median | 1,0000 |
| 3rd Quartile | 2,0000 |
| Maximum | 4,0000 |
| 95% Confidence Interval for Mean | |
| 1,3005 | 1,6346 |
| 95% Confidence Interval for Median | |
| 1,0000 | 1,5440 |
| 95% Confidence Interval for StDev | |
| 0,6353 | 0,8749 |

**Figure A.III. 4.1.** Basic statistics summary of all HAZOPs – ME.



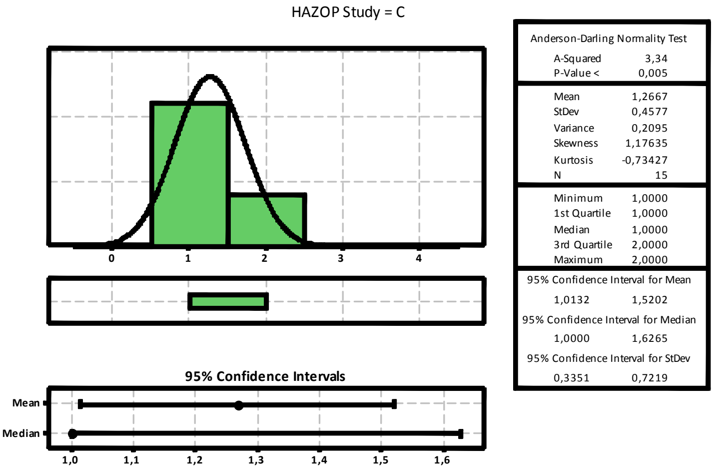
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,73 |
| P-Value < | 0,005 |
| Mean | 1,5385 |
| StDev | 0,7763 |
| Variance | 0,6026 |
| Skewness | 1,11382 |
| Kurtosis | -0,15472 |
| N | 13 |
| Minimum | 1,0000 |
| 1st Quartile | 1,0000 |
| Median | 1,0000 |
| 3rd Quartile | 2,0000 |
| Maximum | 3,0000 |
| 95% Confidence Interval for Mean | |
| 1,0694 | 2,0075 |
| 95% Confidence Interval for Median | |
| 1,0000 | 2,0000 |
| 95% Confidence Interval for StDev | |
| 0,5566 | 1,2814 |

**Figure A.III. 4.2.** Basic statistics summary considering the HAZOP A – ME.



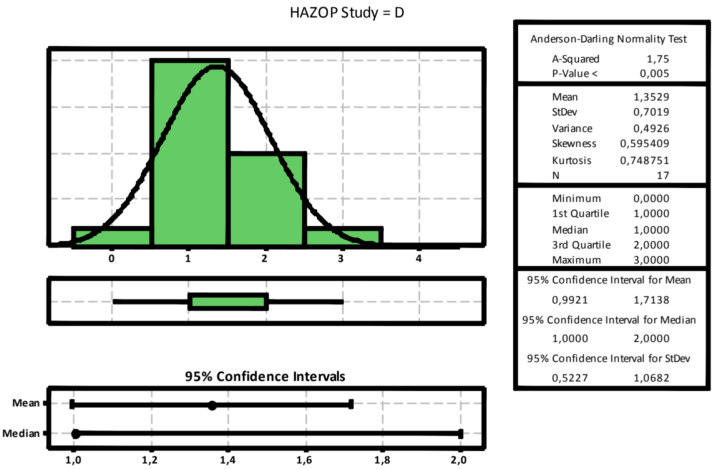
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,75 |
| P-Value < | 0,005 |
| Mean | 1,5000 |
| StDev | 0,6504 |
| Variance | 0,4231 |
| Skewness | 0,978353 |
| Kurtosis | 0,175808 |
| N | 14 |
| Minimum | 1,0000 |
| 1st Quartile | 1,0000 |
| Median | 1,0000 |
| 3rd Quartile | 2,0000 |
| Maximum | 3,0000 |
| 95% Confidence Interval for Mean | |
| 1,1244 | 1,8756 |
| 95% Confidence Interval for Median | |
| 1,0000 | 2,0000 |
| 95% Confidence Interval for StDev | |
| 0,4715 | 1,0479 |

**Figure A.III. 4.3.** Basic statistics summary considering the HAZOP B – ME.



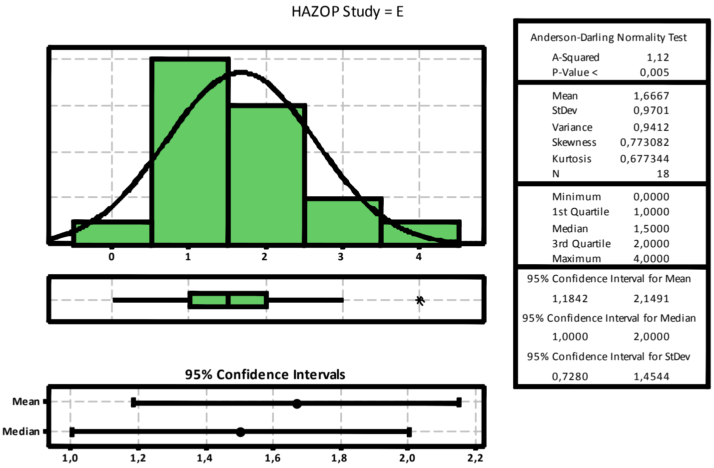
| | |
|---|---|
| Anderson-Darling Normality Test | |
| A-Squared | 3,34 |
| P-Value < | 0,005 |
| Mean | 1,2667 |
| StDev | 0,4577 |
| Variance | 0,2095 |
| Skewness | 1,17635 |
| Kurtosis | -0,73427 |
| N | 15 |
| Minimum | 1,0000 |
| 1st Quartile | 1,0000 |
| Median | 1,0000 |
| 3rd Quartile | 2,0000 |
| Maximum | 2,0000 |
| 95% Confidence Interval for Mean | |
| 1,0132 | 1,5202 |
| 95% Confidence Interval for Median | |
| 1,0000 | 1,6265 |
| 95% Confidence Interval for StDev | |
| 0,3351 | 0,7219 |

**Figure A.III. 4.4.** Basic statistics summary considering the HAZOP C – ME.



| | |
|---|---|
| Anderson-Darling Normality Test | |
| A-Squared | 1,75 |
| P-Value < | 0,005 |
| Mean | 1,3529 |
| StDev | 0,7019 |
| Variance | 0,4926 |
| Skewness | 0,595409 |
| Kurtosis | 0,748751 |
| N | 17 |
| Minimum | 0,0000 |
| 1st Quartile | 1,0000 |
| Median | 1,0000 |
| 3rd Quartile | 2,0000 |
| Maximum | 3,0000 |
| 95% Confidence Interval for Mean | |
| 0,9921 | 1,7138 |
| 95% Confidence Interval for Median | |
| 1,0000 | 2,0000 |
| 95% Confidence Interval for StDev | |
| 0,5227 | 1,0682 |

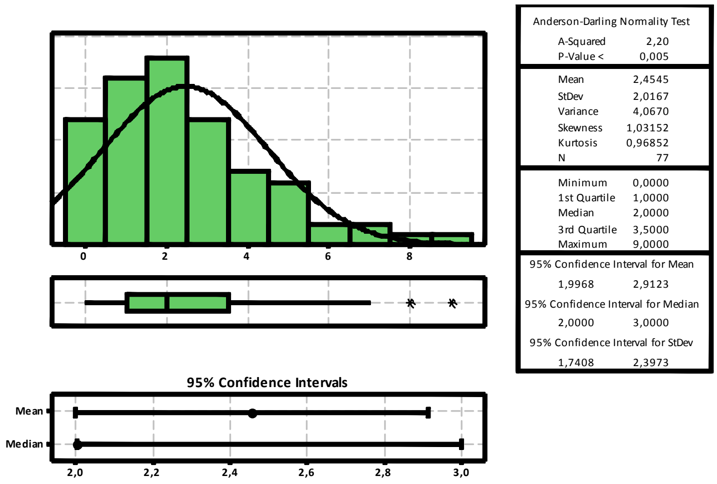
**Figure A.III. 4.5.** Basic statistics summary considering the HAZOP D – ME.



| | |
|---|---|
| Anderson-Darling Normality Test | |
| A-Squared | 1,12 |
| P-Value < | 0,005 |
| Mean | 1,6667 |
| StDev | 0,9701 |
| Variance | 0,9412 |
| Skewness | 0,773082 |
| Kurtosis | 0,677344 |
| N | 18 |
| Minimum | 0,0000 |
| 1st Quartile | 1,0000 |
| Median | 1,5000 |
| 3rd Quartile | 2,0000 |
| Maximum | 4,0000 |
| 95% Confidence Interval for Mean | |
| 1,1842 | 2,1491 |
| 95% Confidence Interval for Median | |
| 1,0000 | 2,0000 |
| 95% Confidence Interval for StDev | |
| 0,7280 | 1,4544 |

**Figure A.III. 4.6.** Basic statistics summary considering the HAZOP E – ME.

## Figures A.III.5. Flow Control Valves (FCVs):



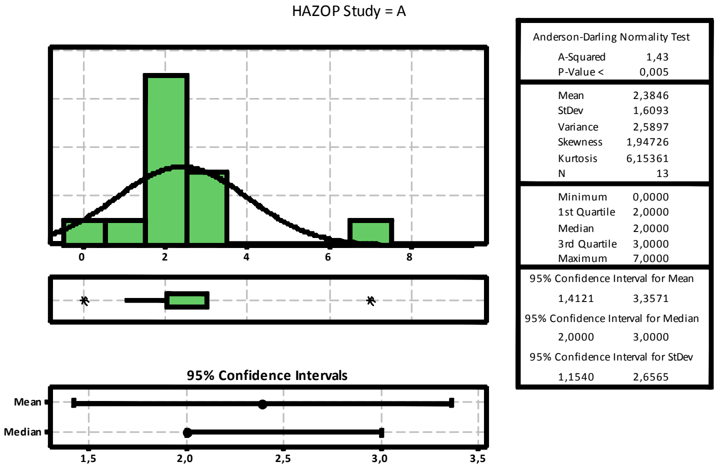
Anderson-Darling Normality Test
A-Squared 2,20
P-Value < 0,005

Mean 2,4545
StDev 2,0167
Variance 4,0670
Skewness 1,03152
Kurtosis 0,96852
N 77

Minimum 0,0000
1st Quartile 1,0000
Median 2,0000
3rd Quartile 3,5000
Maximum 9,0000

95% Confidence Interval for Mean
1,9968 2,9123
95% Confidence Interval for Median
2,0000 3,0000
95% Confidence Interval for StDev
1,7408 2,3973

**Figure A.III. 5.1.** Basic statistics summary of all HAZOPs – FCVs.



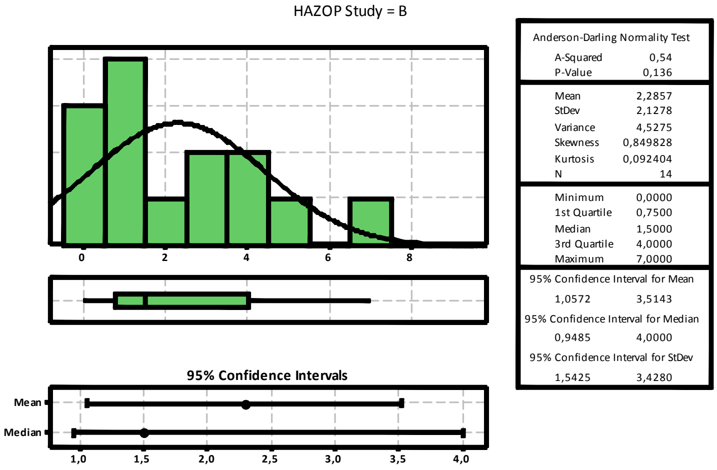
Anderson-Darling Normality Test
A-Squared 1,43
P-Value < 0,005

Mean 2,3846
StDev 1,6093
Variance 2,5897
Skewness 1,94726
Kurtosis 6,15361
N 13

Minimum 0,0000
1st Quartile 2,0000
Median 2,0000
3rd Quartile 3,0000
Maximum 7,0000

95% Confidence Interval for Mean
1,4121 3,3571
95% Confidence Interval for Median
2,0000 3,0000
95% Confidence Interval for StDev
1,1540 2,6565

**Figure A.III. 5.2.** Basic statistics summary considering the HAZOP A – FCVs.



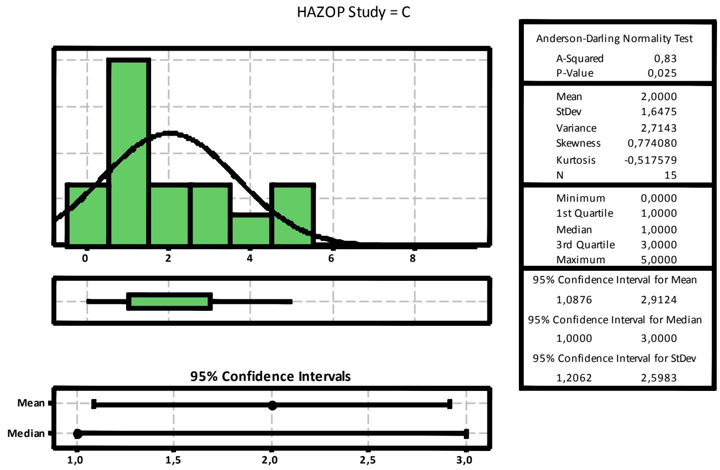
Anderson-Darling Normality Test
A-Squared 0,54
P-Value 0,136

Mean 2,2857
StDev 2,1278
Variance 4,5275
Skewness 0,849828
Kurtosis 0,092404
N 14

Minimum 0,0000
1st Quartile 0,7500
Median 1,5000
3rd Quartile 4,0000
Maximum 7,0000

95% Confidence Interval for Mean
1,0572 3,5143
95% Confidence Interval for Median
0,9485 4,0000
95% Confidence Interval for StDev
1,5425 3,4280

**Figure A.III. 5.3.** Basic statistics summary considering the HAZOP B – FCVs.



Anderson-Darling Normality Test

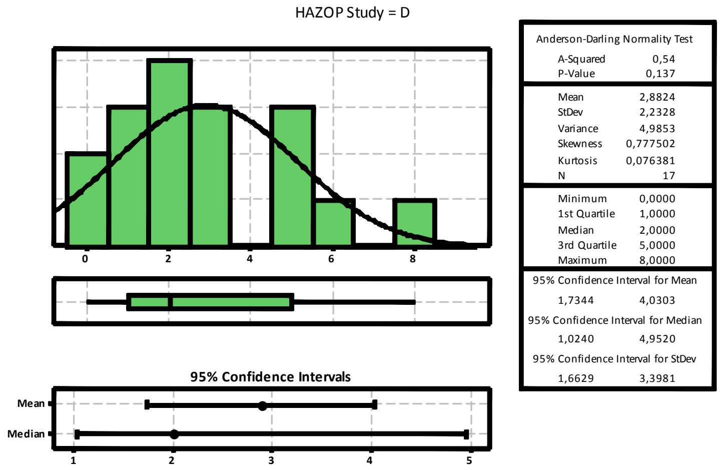
| | |
|---|---|
| A-Squared | 0,83 |
| P-Value | 0,025 |
| Mean | 2,0000 |
| StDev | 1,6475 |
| Variance | 2,7143 |
| Skewness | 0,774080 |
| Kurtosis | -0,517579 |
| N | 15 |
| Minimum | 0,0000 |
| 1st Quartile | 1,0000 |
| Median | 1,0000 |
| 3rd Quartile | 3,0000 |
| Maximum | 5,0000 |

95% Confidence Interval for Mean
1,0876 2,9124

95% Confidence Interval for Median
1,0000 3,0000

95% Confidence Interval for StDev
1,2062 2,5983

**Figure A.III. 5.4.** Basic statistics summary considering the HAZOP C – FCVs.



Anderson-Darling Normality Test

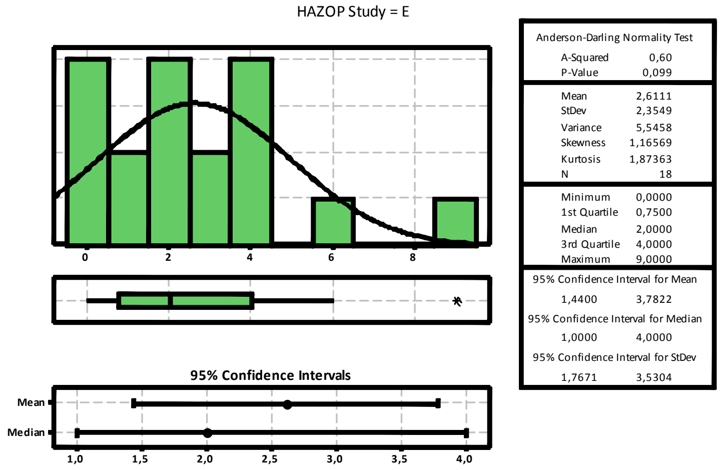
| | |
|---|---|
| A-Squared | 0,54 |
| P-Value | 0,137 |
| Mean | 2,8824 |
| StDev | 2,2328 |
| Variance | 4,9853 |
| Skewness | 0,777502 |
| Kurtosis | 0,076381 |
| N | 17 |
| Minimum | 0,0000 |
| 1st Quartile | 1,0000 |
| Median | 2,0000 |
| 3rd Quartile | 5,0000 |
| Maximum | 8,0000 |

95% Confidence Interval for Mean
1,7344 4,0303

95% Confidence Interval for Median
1,0240 4,9520

95% Confidence Interval for StDev
1,6629 3,3981

**Figure A.III. 5.5.** Basic statistics summary considering the HAZOP D – FCVs.



Anderson-Darling Normality Test

| | |
|---|---|
| A-Squared | 0,60 |
| P-Value | 0,099 |
| Mean | 2,6111 |
| StDev | 2,3549 |
| Variance | 5,5458 |
| Skewness | 1,16569 |
| Kurtosis | 1,87363 |
| N | 18 |
| Minimum | 0,0000 |
| 1st Quartile | 0,7500 |
| Median | 2,0000 |
| 3rd Quartile | 4,0000 |
| Maximum | 9,0000 |

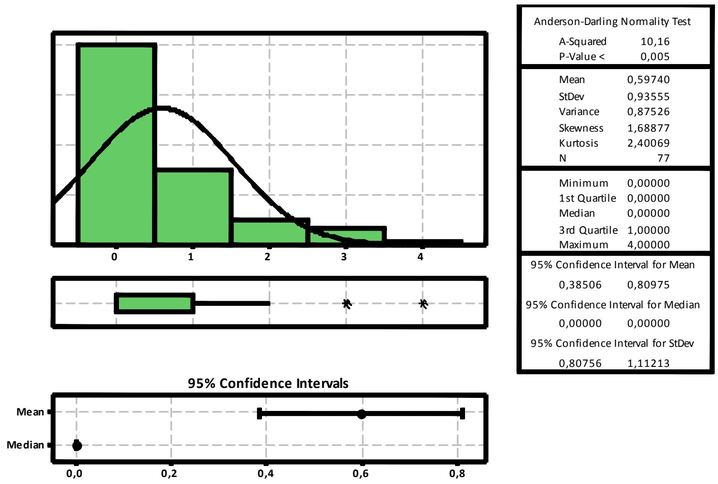
95% Confidence Interval for Mean
1,4400 3,7822

95% Confidence Interval for Median
1,0000 4,0000

95% Confidence Interval for StDev
1,7671 3,5304

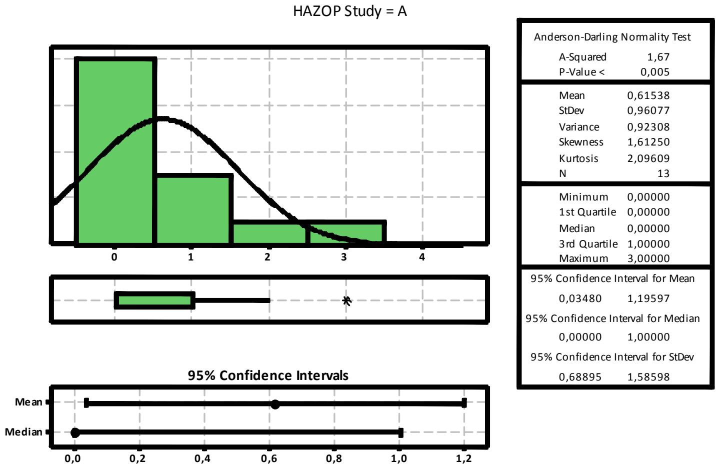
**Figure A.III. 5.6.** Basic statistics summary considering the HAZOP E – FCVs.

## Figures A.III.6. Level Control Valves (LCVs):



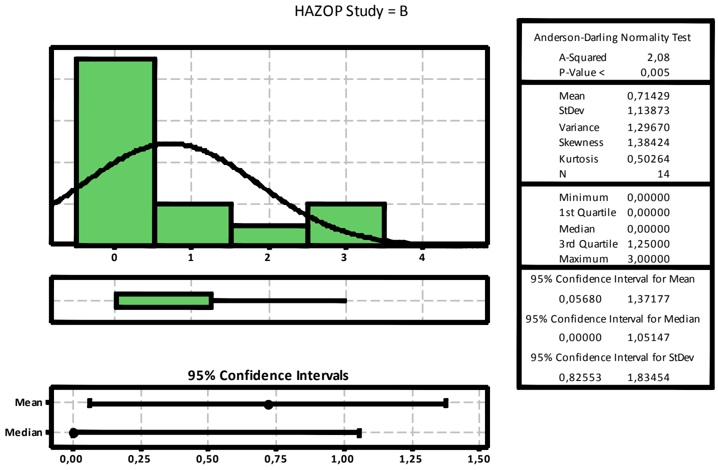
| | |
|---|---|
| Anderson-Darling Normality Test | |
| A-Squared | 10,16 |
| P-Value < | 0,005 |
| Mean | 0,59740 |
| StDev | 0,93555 |
| Variance | 0,87526 |
| Skewness | 1,68877 |
| Kurtosis | 2,40069 |
| N | 77 |
| Minimum | 0,00000 |
| 1st Quartile | 0,00000 |
| Median | 0,00000 |
| 3rd Quartile | 1,00000 |
| Maximum | 4,00000 |
| 95% Confidence Interval for Mean | |
| 0,38506 | 0,80975 |
| 95% Confidence Interval for Median | |
| 0,00000 | 0,00000 |
| 95% Confidence Interval for StDev | |
| 0,80756 | 1,11213 |

**Figure A.III. 6.1.** Basic statistics summary of all HAZOPs – LCVs.



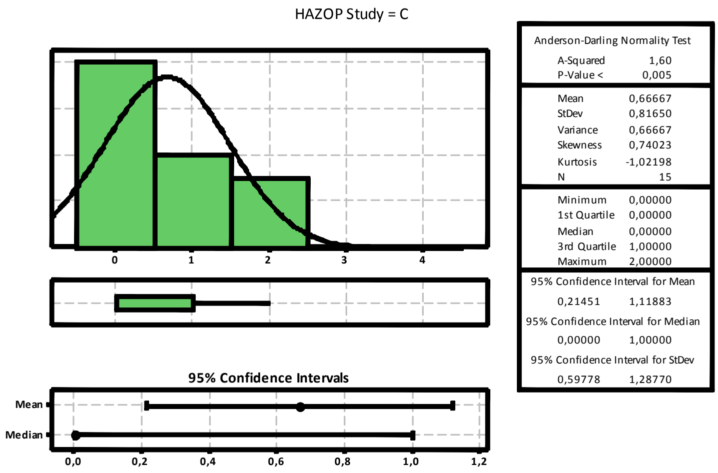
| | |
|---|---|
| Anderson-Darling Normality Test | |
| A-Squared | 1,67 |
| P-Value < | 0,005 |
| Mean | 0,61538 |
| StDev | 0,96077 |
| Variance | 0,92308 |
| Skewness | 1,61250 |
| Kurtosis | 2,09609 |
| N | 13 |
| Minimum | 0,00000 |
| 1st Quartile | 0,00000 |
| Median | 0,00000 |
| 3rd Quartile | 1,00000 |
| Maximum | 3,00000 |
| 95% Confidence Interval for Mean | |
| 0,03480 | 1,19597 |
| 95% Confidence Interval for Median | |
| 0,00000 | 1,00000 |
| 95% Confidence Interval for StDev | |
| 0,68895 | 1,58598 |

**Figure A.III. 6.2.** Basic statistics summary considering the HAZOP A – LCVs.



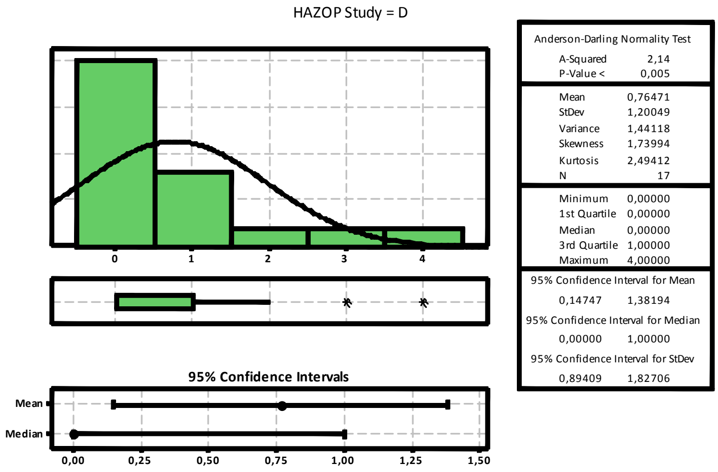
| | |
|---|---|
| Anderson-Darling Normality Test | |
| A-Squared | 2,08 |
| P-Value < | 0,005 |
| Mean | 0,71429 |
| StDev | 1,13873 |
| Variance | 1,29670 |
| Skewness | 1,38424 |
| Kurtosis | 0,50264 |
| N | 14 |
| Minimum | 0,00000 |
| 1st Quartile | 0,00000 |
| Median | 0,00000 |
| 3rd Quartile | 1,25000 |
| Maximum | 3,00000 |
| 95% Confidence Interval for Mean | |
| 0,05680 | 1,37177 |
| 95% Confidence Interval for Median | |
| 0,00000 | 1,05147 |
| 95% Confidence Interval for StDev | |
| 0,82553 | 1,83454 |

**Figure A.III. 6.3.** Basic statistics summary considering the HAZOP B – LCVs.



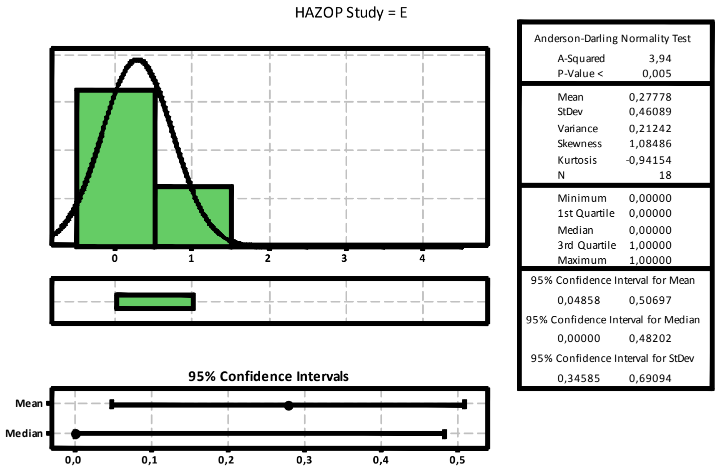
| Anderson-Darling Normality Test | | |
|---|---|---|
| A-Squared | 1,60 | |
| P-Value < | 0,005 | |
| Mean | 0,66667 | |
| StDev | 0,81650 | |
| Variance | 0,66667 | |
| Skewness | 0,74023 | |
| Kurtosis | -1,02198 | |
| N | 15 | |
| Minimum | 0,00000 | |
| 1st Quartile | 0,00000 | |
| Median | 0,00000 | |
| 3rd Quartile | 1,00000 | |
| Maximum | 2,00000 | |
| 95% Confidence Interval for Mean | 0,21451 | 1,11883 |
| 95% Confidence Interval for Median | 0,00000 | 1,00000 |
| 95% Confidence Interval for StDev | 0,59778 | 1,28770 |

**Figure A.III. 6.4.** Basic statistics summary considering the HAZOP C – LCVs.



| Anderson-Darling Normality Test | | |
|---|---|---|
| A-Squared | 2,14 | |
| P-Value < | 0,005 | |
| Mean | 0,76471 | |
| StDev | 1,20049 | |
| Variance | 1,44118 | |
| Skewness | 1,73994 | |
| Kurtosis | 2,49412 | |
| N | 17 | |
| Minimum | 0,00000 | |
| 1st Quartile | 0,00000 | |
| Median | 0,00000 | |
| 3rd Quartile | 1,00000 | |
| Maximum | 4,00000 | |
| 95% Confidence Interval for Mean | 0,14747 | 1,38194 |
| 95% Confidence Interval for Median | 0,00000 | 1,00000 |
| 95% Confidence Interval for StDev | 0,89409 | 1,82706 |

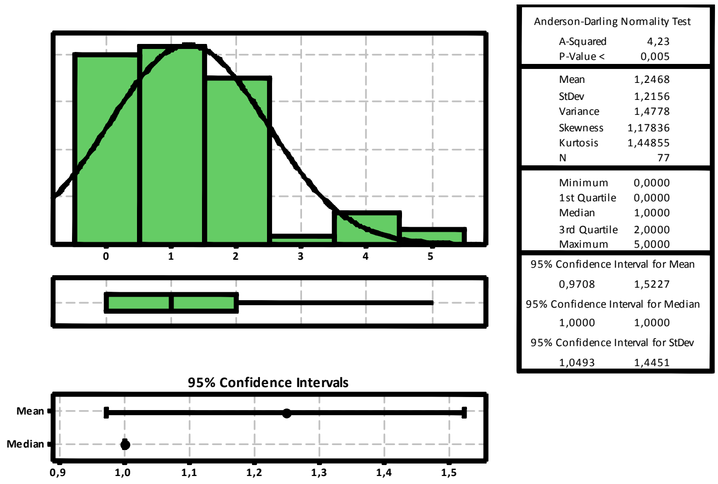
**Figure A.III. 6.5.** Basic statistics summary considering the HAZOP D – LCVs.



| Anderson-Darling Normality Test | | |
|---|---|---|
| A-Squared | 3,94 | |
| P-Value < | 0,005 | |
| Mean | 0,27778 | |
| StDev | 0,46089 | |
| Variance | 0,21242 | |
| Skewness | 1,08486 | |
| Kurtosis | -0,94154 | |
| N | 18 | |
| Minimum | 0,00000 | |
| 1st Quartile | 0,00000 | |
| Median | 0,00000 | |
| 3rd Quartile | 1,00000 | |
| Maximum | 1,00000 | |
| 95% Confidence Interval for Mean | 0,04858 | 0,50697 |
| 95% Confidence Interval for Median | 0,00000 | 0,48202 |
| 95% Confidence Interval for StDev | 0,34585 | 0,69094 |

**Figure A.III. 6.6.** Basic statistics summary considering the HAZOP E – LCVs.

## Figures A.III.7. Pressure Control Valves (PCVs):



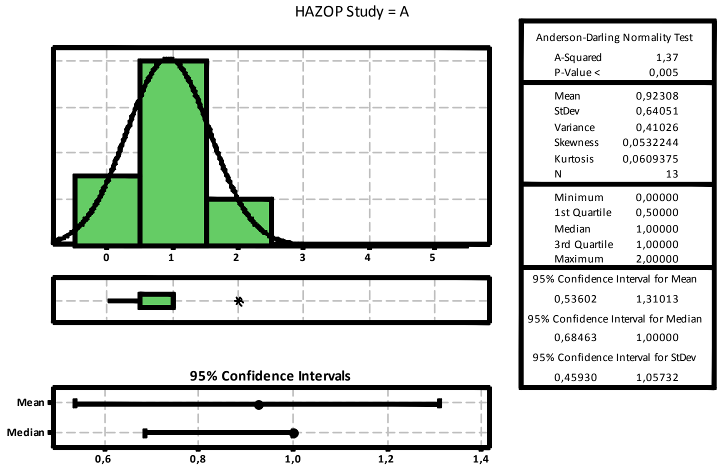
Anderson-Darling Normality Test
A-Squared 4,23
P-Value < 0,005

Mean 1,2468
StDev 1,2156
Variance 1,4778
Skewness 1,17836
Kurtosis 1,44855
N 77

Minimum 0,0000
1st Quartile 0,0000
Median 1,0000
3rd Quartile 2,0000
Maximum 5,0000

95% Confidence Interval for Mean
0,9708 1,5227
95% Confidence Interval for Median
1,0000 1,0000
95% Confidence Interval for StDev
1,0493 1,4451

**Figure A.III. 7.1.** Basic statistics summary of all HAZOPs – PCVs.



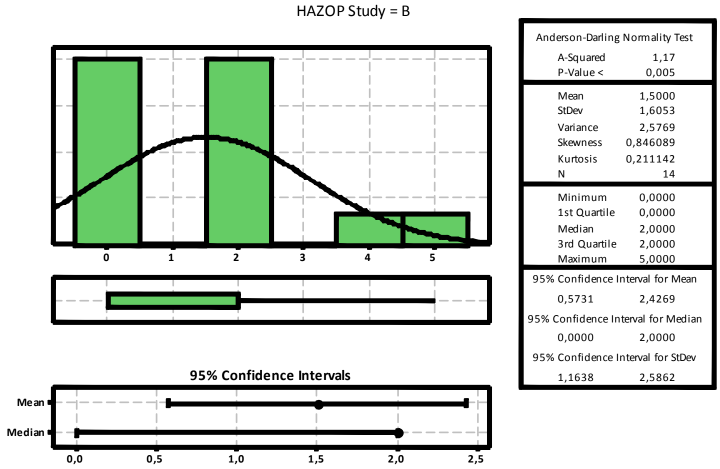
Anderson-Darling Normality Test
A-Squared 1,37
P-Value < 0,005

Mean 0,92308
StDev 0,64051
Variance 0,41026
Skewness 0,0532244
Kurtosis 0,0609375
N 13

Minimum 0,00000
1st Quartile 0,50000
Median 1,00000
3rd Quartile 1,00000
Maximum 2,00000

95% Confidence Interval for Mean
0,53602 1,31013
95% Confidence Interval for Median
0,68463 1,00000
95% Confidence Interval for StDev
0,45930 1,05732

**Figure A.III. 7.2.** Basic statistics summary considering the HAZOP A – PCVs.



Anderson-Darling Normality Test
A-Squared 1,17
P-Value < 0,005

Mean 1,5000
StDev 1,6053
Variance 2,5769
Skewness 0,846089
Kurtosis 0,211142
N 14

Minimum 0,0000
1st Quartile 0,0000
Median 2,0000
3rd Quartile 2,0000
Maximum 5,0000

95% Confidence Interval for Mean
0,5731 2,4269
95% Confidence Interval for Median
0,0000 2,0000
95% Confidence Interval for StDev
1,1638 2,5862

**Figure A.III. 7.3.** Basic statistics summary considering the HAZOP B – PCVs.

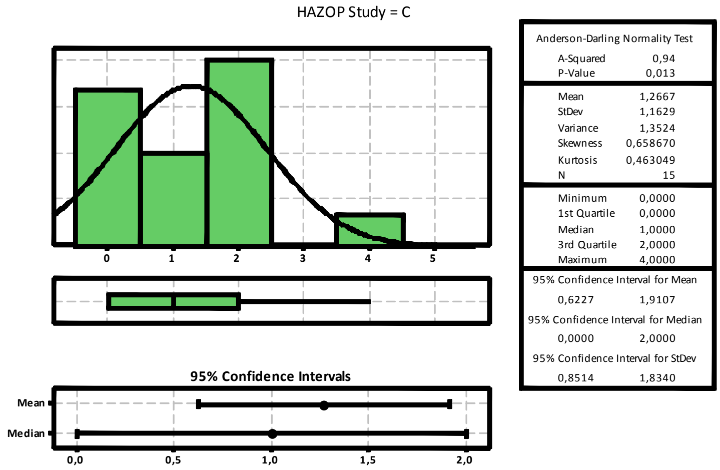


**Figure A.III. 7.4.** Basic statistics summary considering the HAZOP C – PCVs.

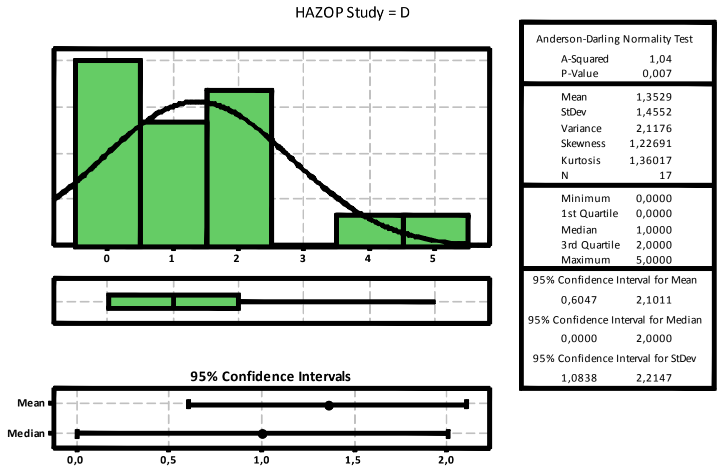


**Figure A.III. 7.5.** Basic statistics summary considering the HAZOP D – PCVs.

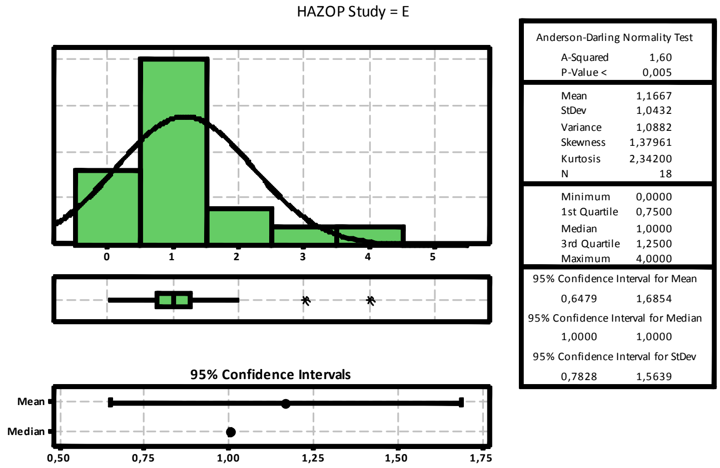


**Figure A.III. 7.6.** Basic statistics summary considering the HAZOP E – PCVs.

## Figures A.III.8. Temperature Control Valves (TCVs):

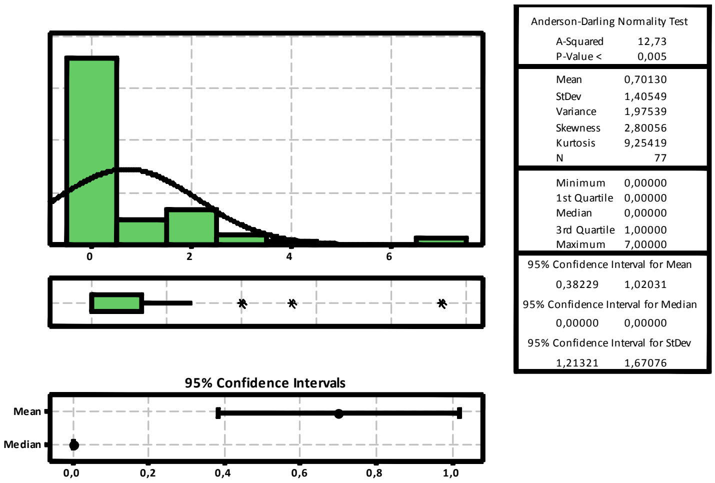


**Figure A.III. 8.1.** Basic statistics summary of all HAZOPs – TCVs.

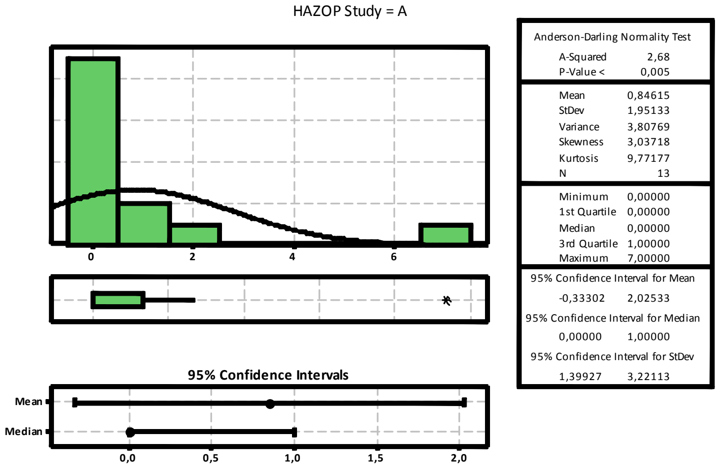


**Figure A.III. 8.2.** Basic statistics summary considering the HAZOP A – TCVs.

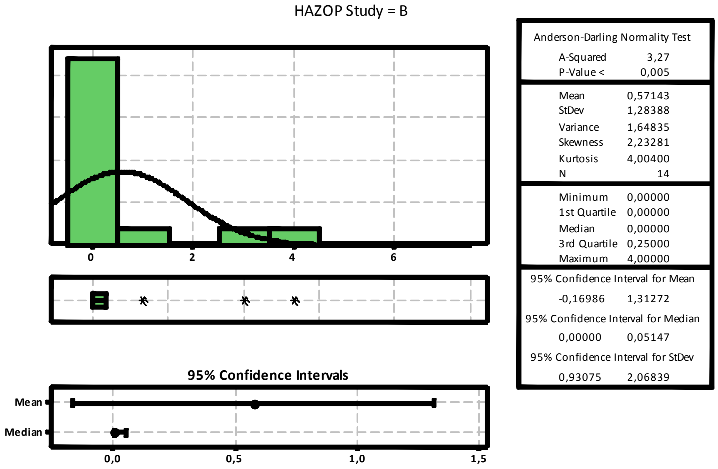


**Figure A.III. 8.3.** Basic statistics summary considering the HAZOP B – TCVs.

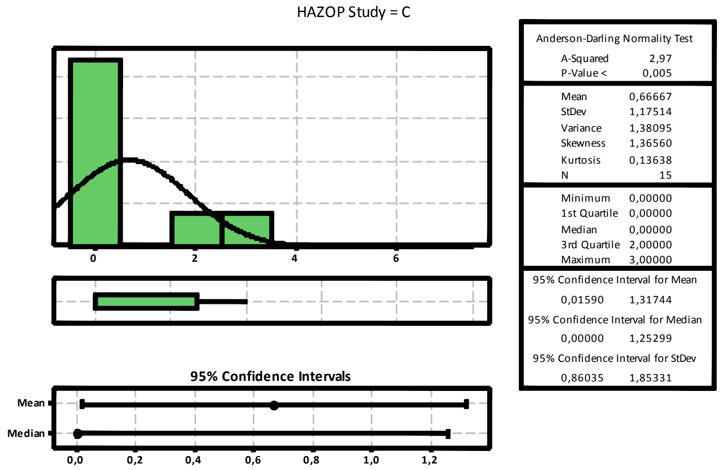


**Figure A.III. 8.4.** Basic statistics summary considering the HAZOP C – TCVs.

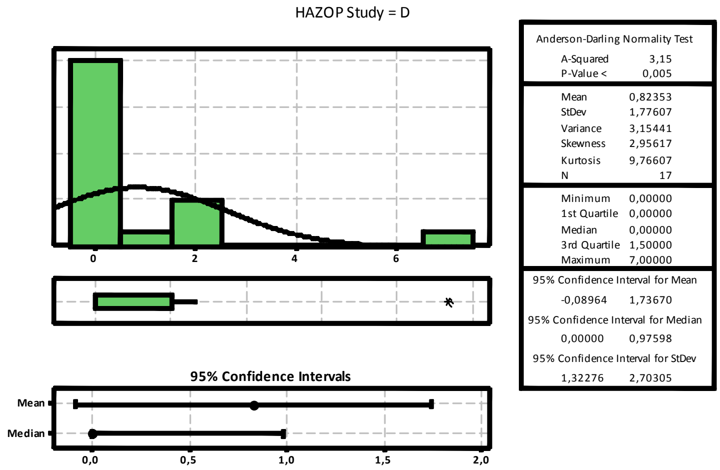


**Figure A.III. 8.5.** Basic statistics summary considering the HAZOP D – TCVs.

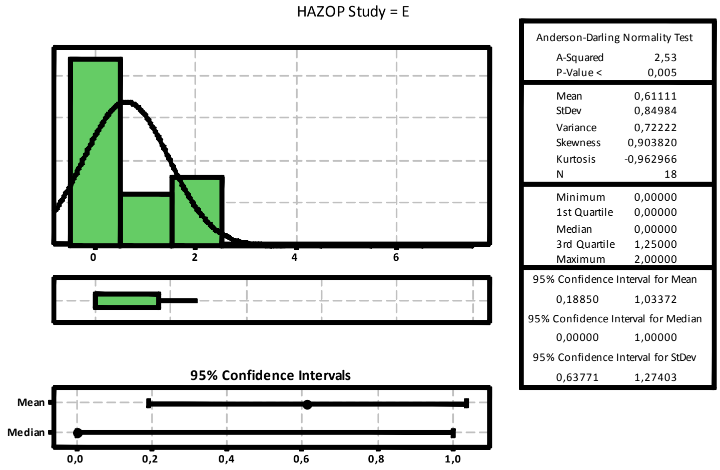
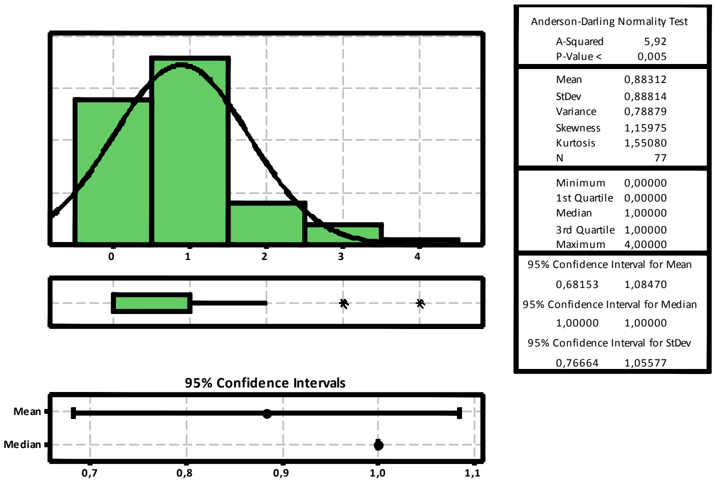


**Figure A.III. 8.6.** Basic statistics summary considering the HAZOP E – TCVs.

## Figures A.III.9. Pumps:



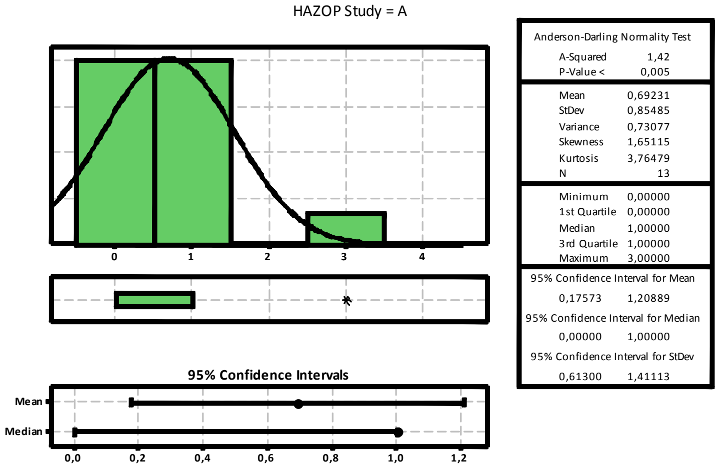
Anderson-Darling Normality Test
A-Squared 5,92
P-Value < 0,005

Mean 0,88312
StDev 0,88814
Variance 0,78879
Skewness 1,15975
Kurtosis 1,55080
N 77

Minimum 0,00000
1st Quartile 0,00000
Median 1,00000
3rd Quartile 1,00000
Maximum 4,00000

95% Confidence Interval for Mean
0,68153 1,08470
95% Confidence Interval for Median
1,00000 1,00000
95% Confidence Interval for StDev
0,76664 1,05577

**Figure A.III. 9.1.** Basic statistics summary of all HAZOPs – Pumps.



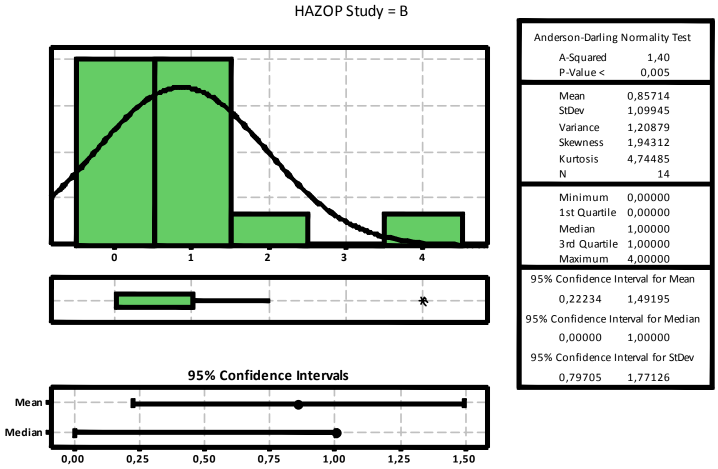
Anderson-Darling Normality Test
A-Squared 1,42
P-Value < 0,005

Mean 0,69231
StDev 0,85485
Variance 0,73077
Skewness 1,65115
Kurtosis 3,76479
N 13

Minimum 0,00000
1st Quartile 0,00000
Median 1,00000
3rd Quartile 1,00000
Maximum 3,00000

95% Confidence Interval for Mean
0,17573 1,20889
95% Confidence Interval for Median
0,00000 1,00000
95% Confidence Interval for StDev
0,61300 1,41113

**Figure A.III. 9.2.** Basic statistics summary considering the HAZOP A – Pumps.



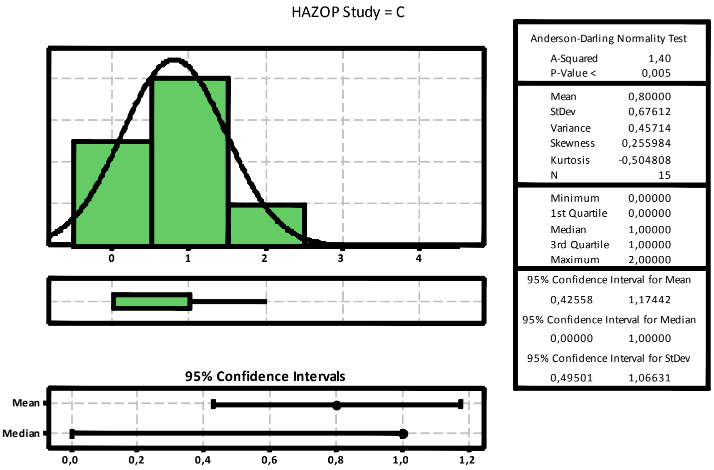
Anderson-Darling Normality Test
A-Squared 1,40
P-Value < 0,005

Mean 0,85714
StDev 1,09945
Variance 1,20879
Skewness 1,94312
Kurtosis 4,74485
N 14

Minimum 0,00000
1st Quartile 0,00000
Median 1,00000
3rd Quartile 1,00000
Maximum 4,00000

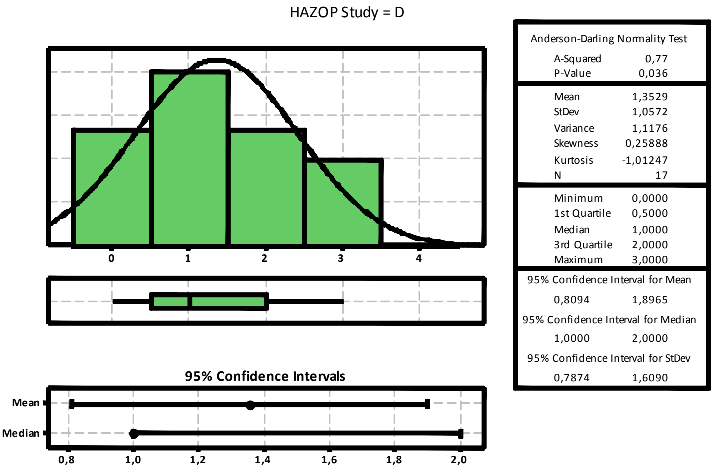
95% Confidence Interval for Mean
0,22234 1,49195
95% Confidence Interval for Median
0,00000 1,00000
95% Confidence Interval for StDev
0,79705 1,77126

**Figure A.III. 9.3.** Basic statistics summary considering the HAZOP B – Pumps.



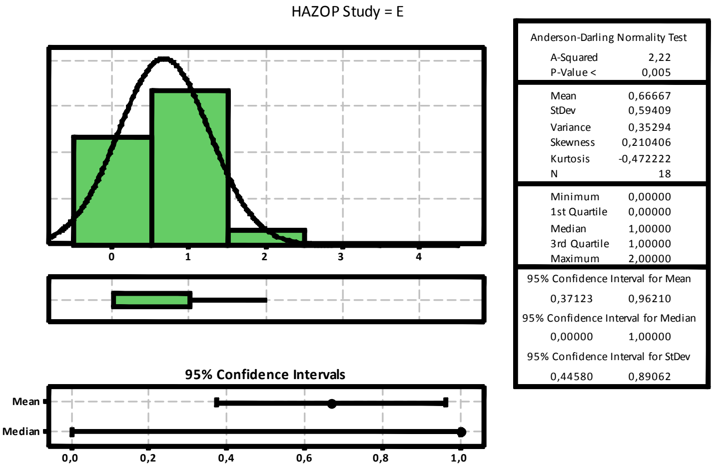
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,40 |
| P-Value < | 0,005 |
| Mean | 0,80000 |
| StDev | 0,67612 |
| Variance | 0,45714 |
| Skewness | 0,255984 |
| Kurtosis | -0,504808 |
| N | 15 |
| Minimum | 0,00000 |
| 1st Quartile | 0,00000 |
| Median | 1,00000 |
| 3rd Quartile | 1,00000 |
| Maximum | 2,00000 |
| 95% Confidence Interval for Mean | |
| 0,42558 | 1,17442 |
| 95% Confidence Interval for Median | |
| 0,00000 | 1,00000 |
| 95% Confidence Interval for StDev | |
| 0,49501 | 1,06631 |

**Figure A.III. 9.4.** Basic statistics summary considering the HAZOP C – Pumps.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,77 |
| P-Value | 0,036 |
| Mean | 1,3529 |
| StDev | 1,0572 |
| Variance | 1,1176 |
| Skewness | 0,25888 |
| Kurtosis | -1,01247 |
| N | 17 |
| Minimum | 0,0000 |
| 1st Quartile | 0,5000 |
| Median | 1,0000 |
| 3rd Quartile | 2,0000 |
| Maximum | 3,0000 |
| 95% Confidence Interval for Mean | |
| 0,8094 | 1,8965 |
| 95% Confidence Interval for Median | |
| 1,0000 | 2,0000 |
| 95% Confidence Interval for StDev | |
| 0,7874 | 1,6090 |

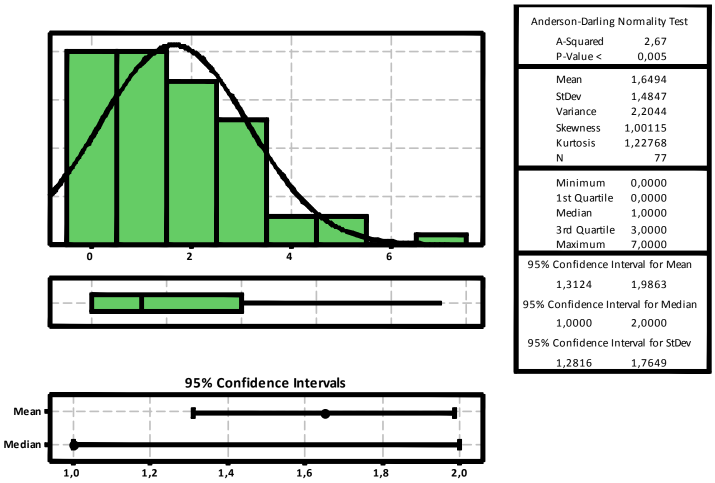
**Figure A.III. 9.5.** Basic statistics summary considering the HAZOP D – Pumps.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 2,22 |
| P-Value < | 0,005 |
| Mean | 0,66667 |
| StDev | 0,59409 |
| Variance | 0,35294 |
| Skewness | 0,210406 |
| Kurtosis | -0,472222 |
| N | 18 |
| Minimum | 0,00000 |
| 1st Quartile | 0,00000 |
| Median | 1,00000 |
| 3rd Quartile | 1,00000 |
| Maximum | 2,00000 |
| 95% Confidence Interval for Mean | |
| 0,37123 | 0,96210 |
| 95% Confidence Interval for Median | |
| 0,00000 | 1,00000 |
| 95% Confidence Interval for StDev | |
| 0,44580 | 0,89062 |

**Figure A.III. 9.6.** Basic statistics summary considering the HAZOP E – Pumps.

## Figures A.III.10. Exchangers:



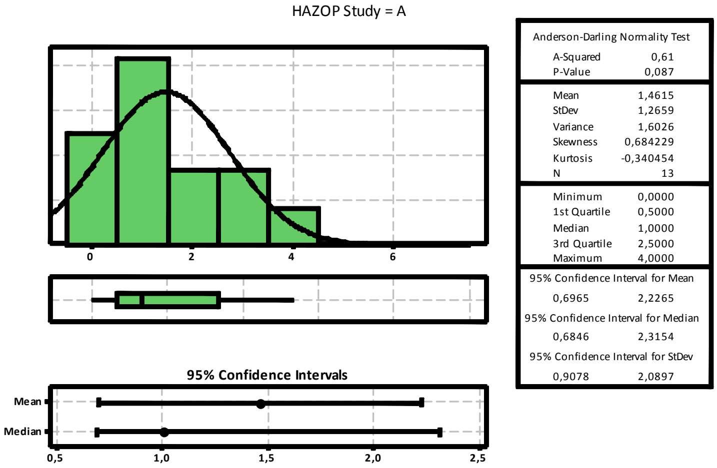
Anderson-Darling Normality Test
A-Squared 2,67
P-Value < 0,005

Mean 1,6494
StDev 1,4847
Variance 2,2044
Skewness 1,00115
Kurtosis 1,22768
N 77

Minimum 0,0000
1st Quartile 0,0000
Median 1,0000
3rd Quartile 3,0000
Maximum 7,0000

95% Confidence Interval for Mean
1,3124 1,9863
95% Confidence Interval for Median
1,0000 2,0000
95% Confidence Interval for StDev
1,2816 1,7649

**Figure A.III. 10.1.** Basic statistics summary of all HAZOPs – Exchangers.



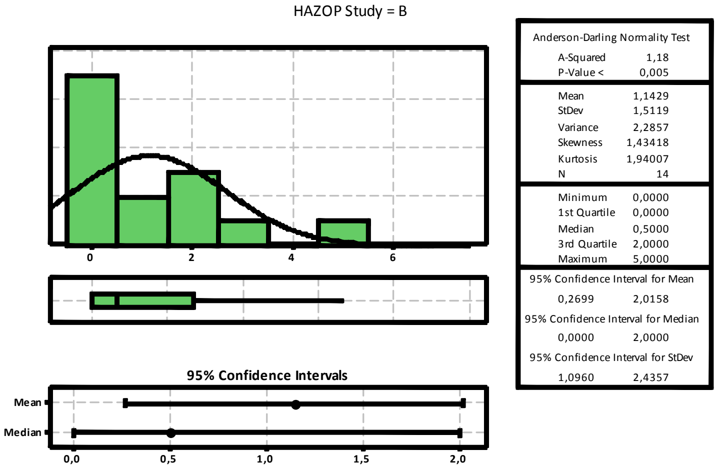
Anderson-Darling Normality Test
A-Squared 0,61
P-Value 0,087

Mean 1,4615
StDev 1,2659
Variance 1,6026
Skewness 0,684229
Kurtosis -0,340454
N 13

Minimum 0,0000
1st Quartile 0,5000
Median 1,0000
3rd Quartile 2,5000
Maximum 4,0000

95% Confidence Interval for Mean
0,6965 2,2265
95% Confidence Interval for Median
0,6846 2,3154
95% Confidence Interval for StDev
0,9078 2,0897

**Figure A.III. 10.2.** Basic statistics summary considering the HAZOP A – Exchangers.



Anderson-Darling Normality Test
A-Squared 1,18
P-Value < 0,005

Mean 1,1429
StDev 1,5119
Variance 2,2857
Skewness 1,43418
Kurtosis 1,94007
N 14

Minimum 0,0000
1st Quartile 0,0000
Median 0,5000
3rd Quartile 2,0000
Maximum 5,0000

95% Confidence Interval for Mean
0,2699 2,0158
95% Confidence Interval for Median
0,0000 2,0000
95% Confidence Interval for StDev
1,0960 2,4357

**Figure A.III. 10.3.** Basic statistics summary considering the HAZOP B – Exchangers.

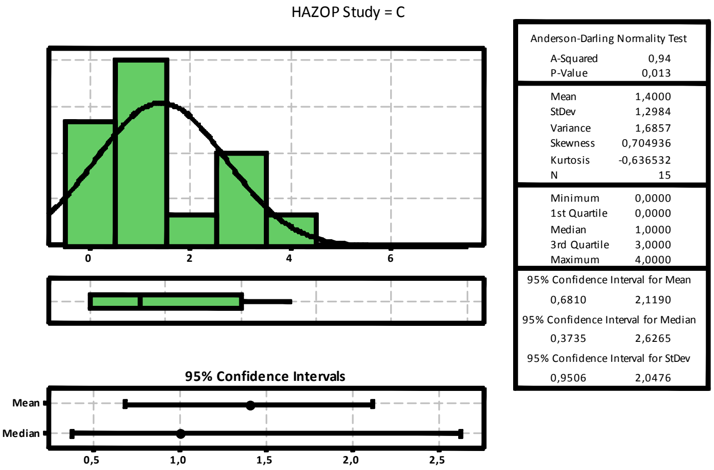


**Figure A.III. 10.4.** Basic statistics summary considering the HAZOP C – Exchangers.

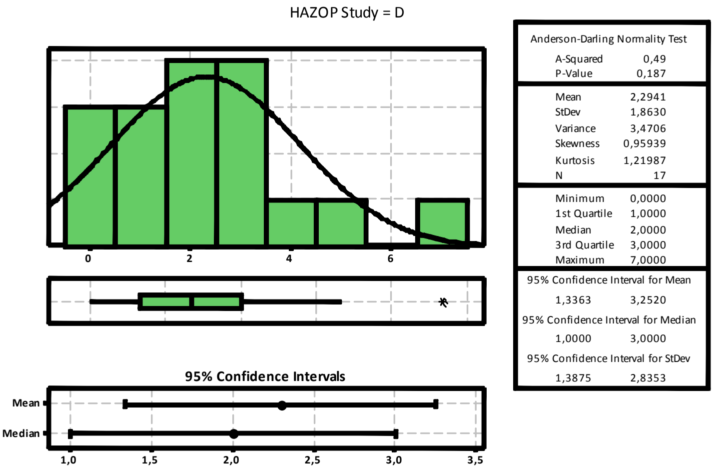


**Figure A.III. 10.5.** Basic statistics summary considering the HAZOP D – Exchangers.

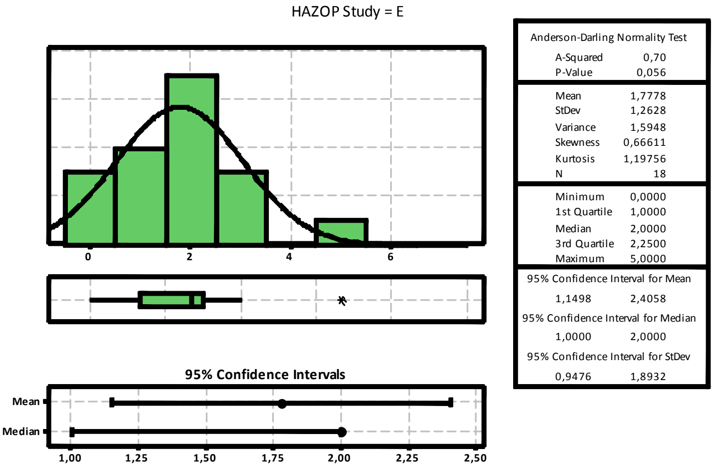
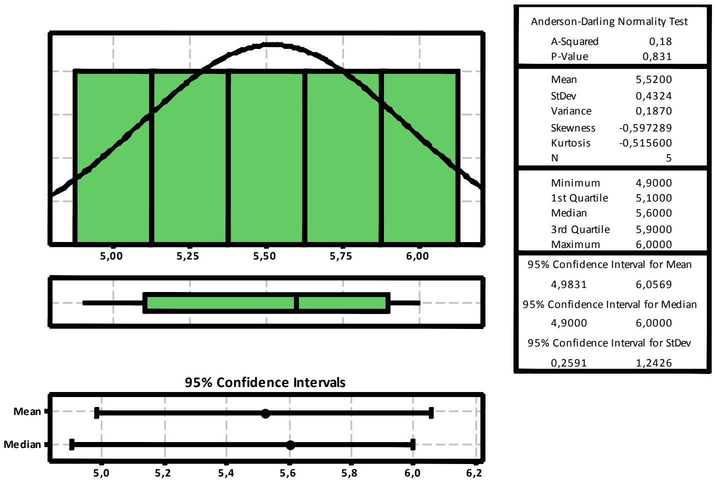


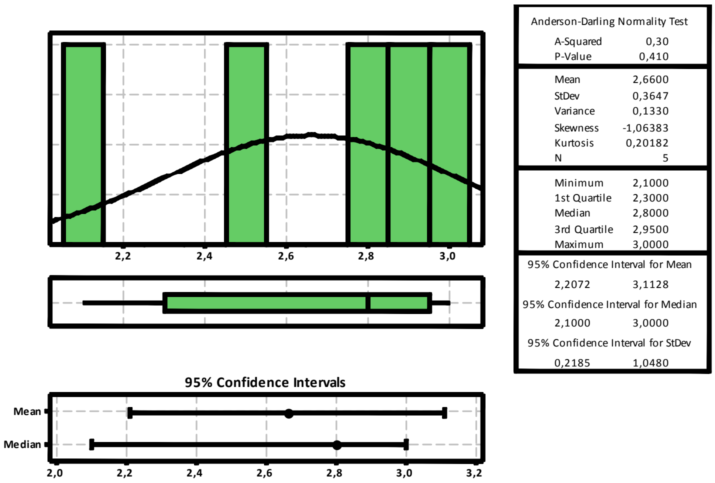
**Figure A.III. 10.6.** Basic statistics summary considering the HAZOP E – Exchangers.

## Figures A.III.11. Time (hours) required to brainstorm Nodes:



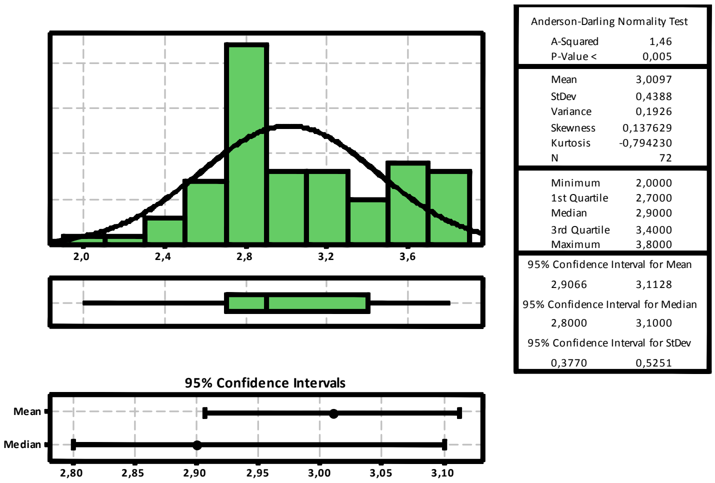
| Anderson-Darling Normality Test | | |
|---|---|---|
| A-Squared | 0,18 | |
| P-Value | 0,831 | |
| Mean | 5,5200 | |
| StDev | 0,4324 | |
| Variance | 0,1870 | |
| Skewness | -0,597289 | |
| Kurtosis | -0,515600 | |
| N | 5 | |
| Minimum | 4,9000 | |
| 1st Quartile | 5,1000 | |
| Median | 5,6000 | |
| 3rd Quartile | 5,9000 | |
| Maximum | 6,0000 | |
| 95% Confidence Interval for Mean | 4,9831 | 6,0569 |
| 95% Confidence Interval for Median | 4,9000 | 6,0000 |
| 95% Confidence Interval for StDev | 0,2591 | 1,2426 |

**Figure A.III. 11.1.** Basic statistics summary of all HAZOPs – First Nodes.



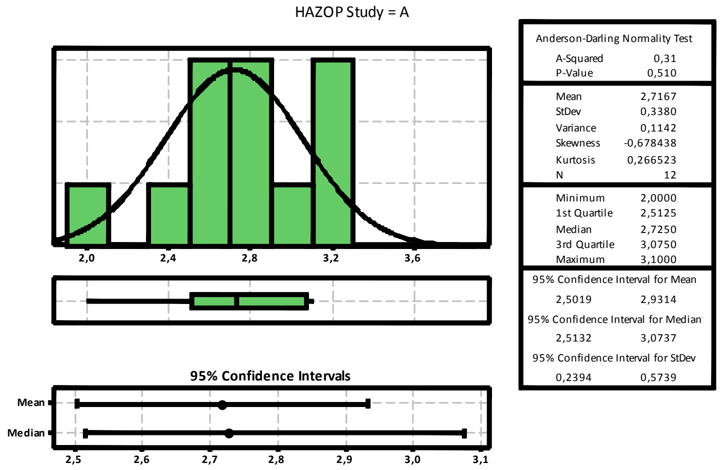
| Anderson-Darling Normality Test | | |
|---|---|---|
| A-Squared | 0,30 | |
| P-Value | 0,410 | |
| Mean | 2,6600 | |
| StDev | 0,3647 | |
| Variance | 0,1330 | |
| Skewness | -1,06383 | |
| Kurtosis | 0,20182 | |
| N | 5 | |
| Minimum | 2,1000 | |
| 1st Quartile | 2,3000 | |
| Median | 2,8000 | |
| 3rd Quartile | 2,9500 | |
| Maximum | 3,0000 | |
| 95% Confidence Interval for Mean | 2,2072 | 3,1128 |
| 95% Confidence Interval for Median | 2,1000 | 3,0000 |
| 95% Confidence Interval for StDev | 0,2185 | 1,0480 |

**Figure A.III. 11.2.** Basic statistics summary of all HAZOPs – Global Nodes.



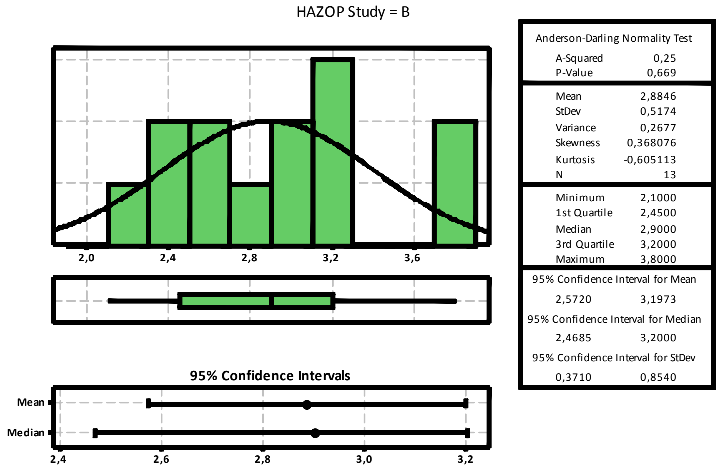
| Anderson-Darling Normality Test | | |
|---|---|---|
| A-Squared | 1,46 | |
| P-Value < | 0,005 | |
| Mean | 3,0097 | |
| StDev | 0,4388 | |
| Variance | 0,1926 | |
| Skewness | 0,137629 | |
| Kurtosis | -0,794230 | |
| N | 72 | |
| Minimum | 2,0000 | |
| 1st Quartile | 2,7000 | |
| Median | 2,9000 | |
| 3rd Quartile | 3,4000 | |
| Maximum | 3,8000 | |
| 95% Confidence Interval for Mean | 2,9066 | 3,1128 |
| 95% Confidence Interval for Median | 2,8000 | 3,1000 |
| 95% Confidence Interval for StDev | 0,3770 | 0,5251 |

**Figure A.III. 11.3.** Basic statistics summary of all HAZOPs – Process Nodes.



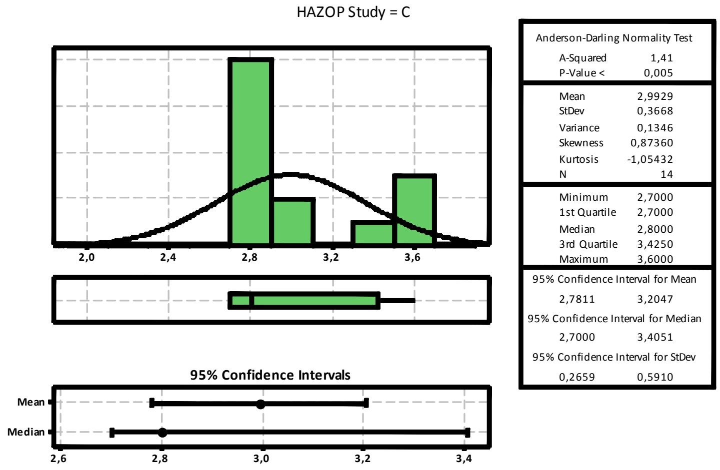
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,31 |
| P-Value | 0,510 |
| Mean | 2,7167 |
| StDev | 0,3380 |
| Variance | 0,1142 |
| Skewness | -0,678438 |
| Kurtosis | 0,266523 |
| N | 12 |
| Minimum | 2,0000 |
| 1st Quartile | 2,5125 |
| Median | 2,7250 |
| 3rd Quartile | 3,0750 |
| Maximum | 3,1000 |
| 95% Confidence Interval for Mean | |
| 2,5019 | 2,9314 |
| 95% Confidence Interval for Median | |
| 2,5132 | 3,0737 |
| 95% Confidence Interval for StDev | |
| 0,2394 | 0,5739 |

**Figure A.III. 11.4.** Basic statistics summary considering the HAZOP A – Process Nodes.



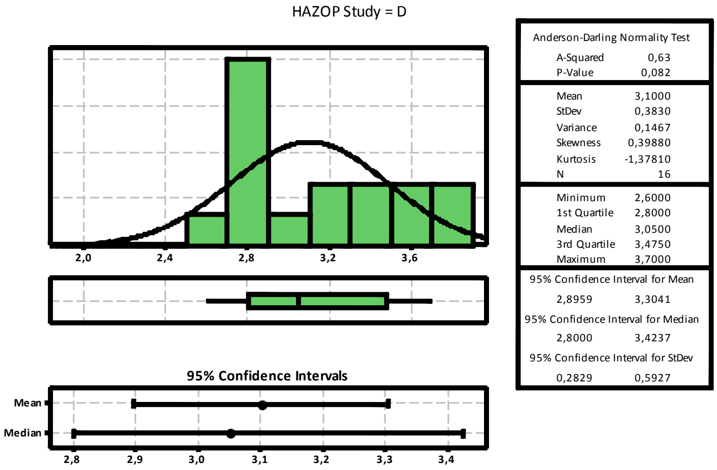
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,25 |
| P-Value | 0,669 |
| Mean | 2,8846 |
| StDev | 0,5174 |
| Variance | 0,2677 |
| Skewness | 0,368076 |
| Kurtosis | -0,605113 |
| N | 13 |
| Minimum | 2,1000 |
| 1st Quartile | 2,4500 |
| Median | 2,9000 |
| 3rd Quartile | 3,2000 |
| Maximum | 3,8000 |
| 95% Confidence Interval for Mean | |
| 2,5720 | 3,1973 |
| 95% Confidence Interval for Median | |
| 2,4685 | 3,2000 |
| 95% Confidence Interval for StDev | |
| 0,3710 | 0,8540 |

**Figure A.III. 11.5.** Basic statistics summary considering the HAZOP B – Process Nodes.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,41 |
| P-Value < | 0,005 |
| Mean | 2,9929 |
| StDev | 0,3668 |
| Variance | 0,1346 |
| Skewness | 0,87360 |
| Kurtosis | -1,05432 |
| N | 14 |
| Minimum | 2,7000 |
| 1st Quartile | 2,7000 |
| Median | 2,8000 |
| 3rd Quartile | 3,4250 |
| Maximum | 3,6000 |
| 95% Confidence Interval for Mean | |
| 2,7811 | 3,2047 |
| 95% Confidence Interval for Median | |
| 2,7000 | 3,4051 |
| 95% Confidence Interval for StDev | |
| 0,2659 | 0,5910 |

**Figure A.III. 11.6.** Basic statistics summary considering the HAZOP C – Process Nodes.



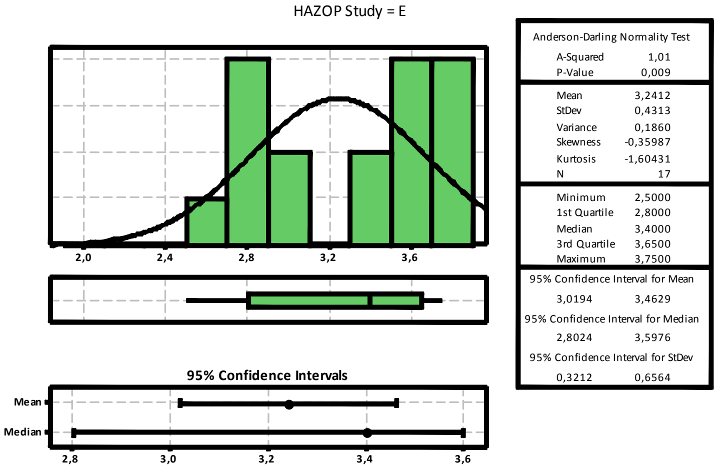
Anderson-Darling Normality Test
A-Squared 0,63
P-Value 0,082

Mean 3,1000
StDev 0,3830
Variance 0,1467
Skewness 0,39880
Kurtosis -1,37810
N 16

Minimum 2,6000
1st Quartile 2,8000
Median 3,0500
3rd Quartile 3,4750
Maximum 3,7000

95% Confidence Interval for Mean
2,8959 3,3041
95% Confidence Interval for Median
2,8000 3,4237
95% Confidence Interval for StDev
0,2829 0,5927

**Figure A.III. 11.7.** Basic statistics summary considering the HAZOP D – Process Nodes.



Anderson-Darling Normality Test
A-Squared 1,01
P-Value 0,009

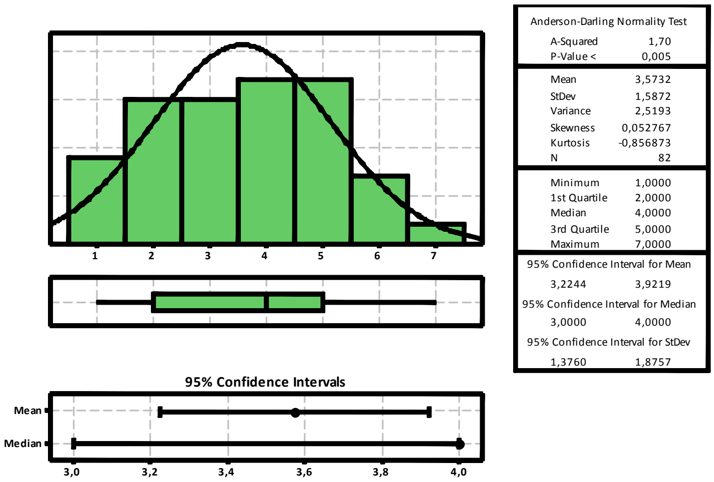
Mean 3,2412
StDev 0,4313
Variance 0,1860
Skewness -0,35987
Kurtosis -1,60431
N 17

Minimum 2,5000
1st Quartile 2,8000
Median 3,4000
3rd Quartile 3,6500
Maximum 3,7500

95% Confidence Interval for Mean
3,0194 3,4629
95% Confidence Interval for Median
2,8024 3,5976
95% Confidence Interval for StDev
0,3212 0,6564

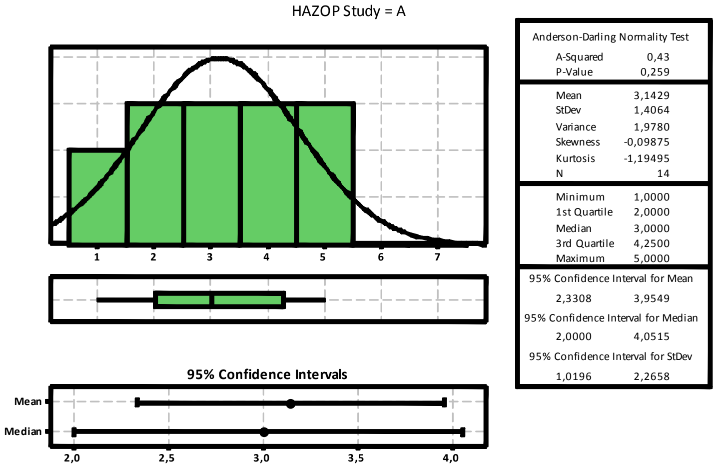
**Figure A.III. 11.8.** Basic statistics summary considering the HAZOP E – Process Nodes.

## Figures A.III.12. Number of Sessions:



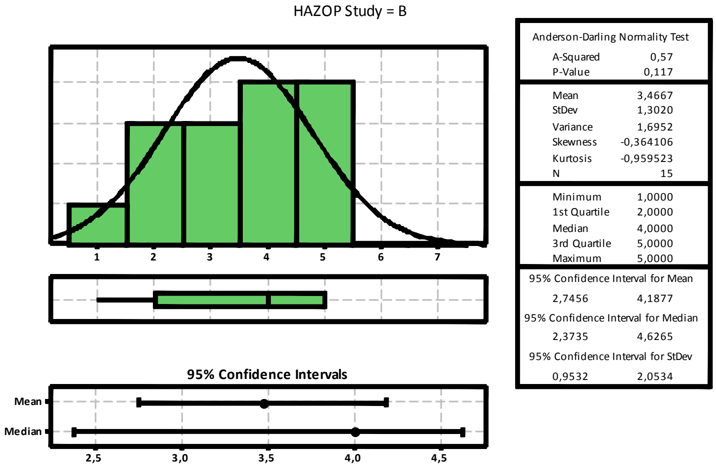
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,70 |
| P-Value < | 0,005 |
| Mean | 3,5732 |
| StDev | 1,5872 |
| Variance | 2,5193 |
| Skewness | 0,052767 |
| Kurtosis | -0,856873 |
| N | 82 |
| Minimum | 1,0000 |
| 1st Quartile | 2,0000 |
| Median | 4,0000 |
| 3rd Quartile | 5,0000 |
| Maximum | 7,0000 |
| 95% Confidence Interval for Mean | |
| 3,2244 | 3,9219 |
| 95% Confidence Interval for Median | |
| 3,0000 | 4,0000 |
| 95% Confidence Interval for StDev | |
| 1,3760 | 1,8757 |

**Figure A.III. 12.1.** Basic statistics summary of all HAZOPs – Sessions.



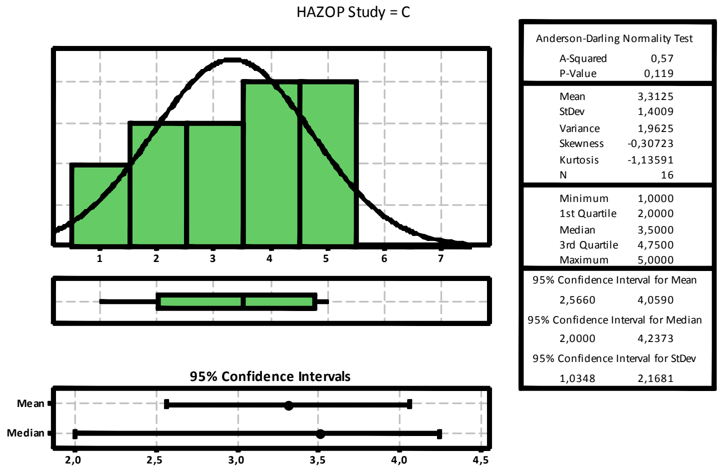
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,43 |
| P-Value | 0,259 |
| Mean | 3,1429 |
| StDev | 1,4064 |
| Variance | 1,9780 |
| Skewness | -0,09875 |
| Kurtosis | -1,19495 |
| N | 14 |
| Minimum | 1,0000 |
| 1st Quartile | 2,0000 |
| Median | 3,0000 |
| 3rd Quartile | 4,2500 |
| Maximum | 5,0000 |
| 95% Confidence Interval for Mean | |
| 2,3308 | 3,9549 |
| 95% Confidence Interval for Median | |
| 2,0000 | 4,0515 |
| 95% Confidence Interval for StDev | |
| 1,0196 | 2,2658 |

**Figure A.III. 12.2.** Basic statistics summary considering the HAZOP A – Sessions.



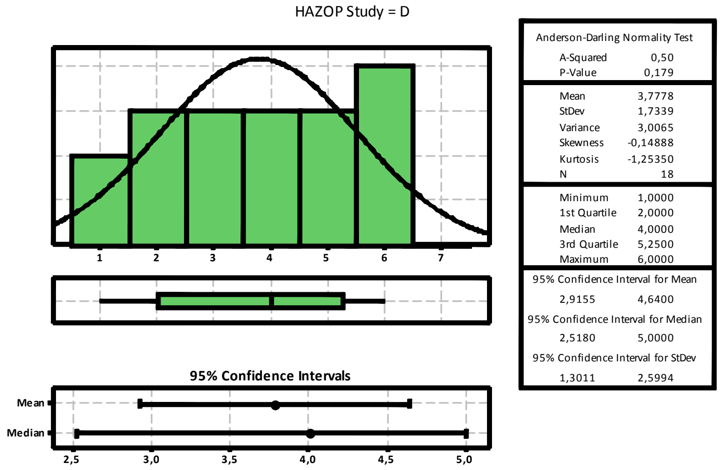
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,57 |
| P-Value | 0,117 |
| Mean | 3,4667 |
| StDev | 1,3020 |
| Variance | 1,6952 |
| Skewness | -0,364106 |
| Kurtosis | -0,959523 |
| N | 15 |
| Minimum | 1,0000 |
| 1st Quartile | 2,0000 |
| Median | 4,0000 |
| 3rd Quartile | 5,0000 |
| Maximum | 5,0000 |
| 95% Confidence Interval for Mean | |
| 2,7456 | 4,1877 |
| 95% Confidence Interval for Median | |
| 2,3735 | 4,6265 |
| 95% Confidence Interval for StDev | |
| 0,9532 | 2,0534 |

**Figure A.III. 12.3.** Basic statistics summary considering the HAZOP B – Sessions.



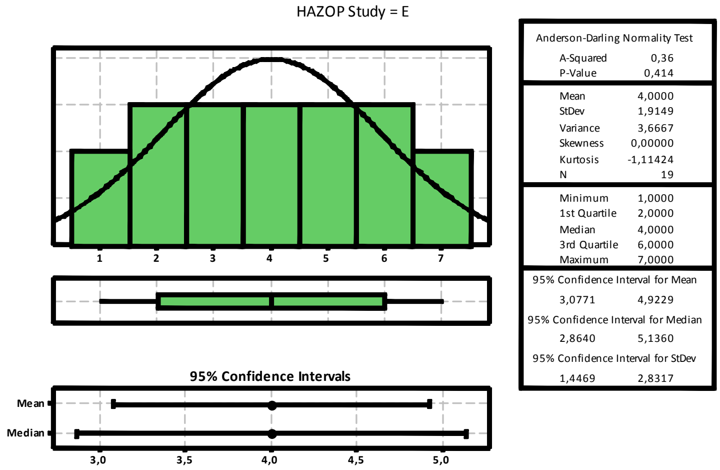
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,57 |
| P-Value | 0,119 |
| Mean | 3,3125 |
| StDev | 1,4009 |
| Variance | 1,9625 |
| Skewness | -0,30723 |
| Kurtosis | -1,13591 |
| N | 16 |
| Minimum | 1,0000 |
| 1st Quartile | 2,0000 |
| Median | 3,5000 |
| 3rd Quartile | 4,7500 |
| Maximum | 5,0000 |
| 95% Confidence Interval for Mean | |
| 2,5660 | 4,0590 |
| 95% Confidence Interval for Median | |
| 2,0000 | 4,2373 |
| 95% Confidence Interval for StDev | |
| 1,0348 | 2,1681 |

**Figure A.III. 12.4.** Basic statistics summary considering the HAZOP C – Sessions.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,50 |
| P-Value | 0,179 |
| Mean | 3,7778 |
| StDev | 1,7339 |
| Variance | 3,0065 |
| Skewness | -0,14888 |
| Kurtosis | -1,25350 |
| N | 18 |
| Minimum | 1,0000 |
| 1st Quartile | 2,0000 |
| Median | 4,0000 |
| 3rd Quartile | 5,2500 |
| Maximum | 6,0000 |
| 95% Confidence Interval for Mean | |
| 2,9155 | 4,6400 |
| 95% Confidence Interval for Median | |
| 2,5180 | 5,0000 |
| 95% Confidence Interval for StDev | |
| 1,3011 | 2,5994 |

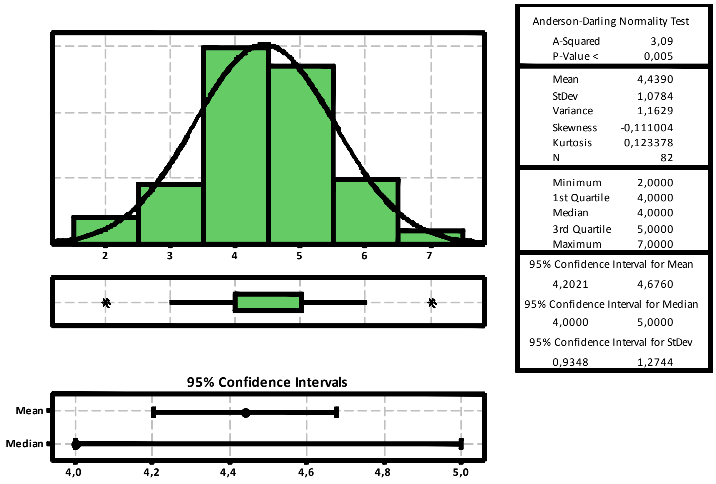
**Figure A.III. 12.5.** Basic statistics summary considering the HAZOP D – Sessions.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,36 |
| P-Value | 0,414 |
| Mean | 4,0000 |
| StDev | 1,9149 |
| Variance | 3,6667 |
| Skewness | 0,00000 |
| Kurtosis | -1,11424 |
| N | 19 |
| Minimum | 1,0000 |
| 1st Quartile | 2,0000 |
| Median | 4,0000 |
| 3rd Quartile | 6,0000 |
| Maximum | 7,0000 |
| 95% Confidence Interval for Mean | |
| 3,0771 | 4,9229 |
| 95% Confidence Interval for Median | |
| 2,8640 | 5,1360 |
| 95% Confidence Interval for StDev | |
| 1,4469 | 2,8317 |

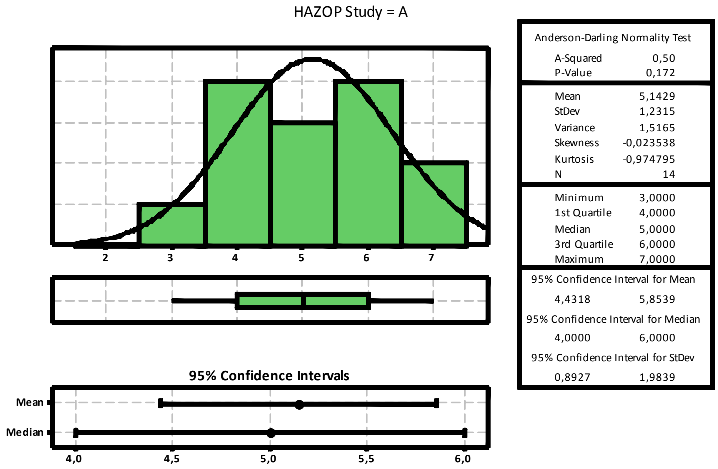
**Figure A.III. 12.6.** Basic statistics summary considering the HAZOP E – Sessions.

## Figures A.III.13. Number of Members:



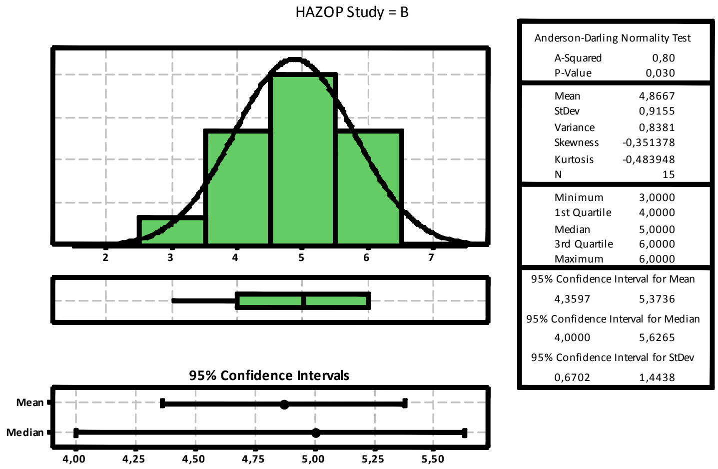
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 3,09 |
| P-Value < | 0,005 |
| Mean | 4,4390 |
| StDev | 1,0784 |
| Variance | 1,1629 |
| Skewness | -0,111004 |
| Kurtosis | 0,123378 |
| N | 82 |
| Minimum | 2,0000 |
| 1st Quartile | 4,0000 |
| Median | 4,0000 |
| 3rd Quartile | 5,0000 |
| Maximum | 7,0000 |
| 95% Confidence Interval for Mean | |
| 4,2021 | 4,6760 |
| 95% Confidence Interval for Median | |
| 4,0000 | 5,0000 |
| 95% Confidence Interval for StDev | |
| 0,9348 | 1,2744 |

**Figure A.III. 13.1.** Basic statistics summary of all HAZOPs – Members.



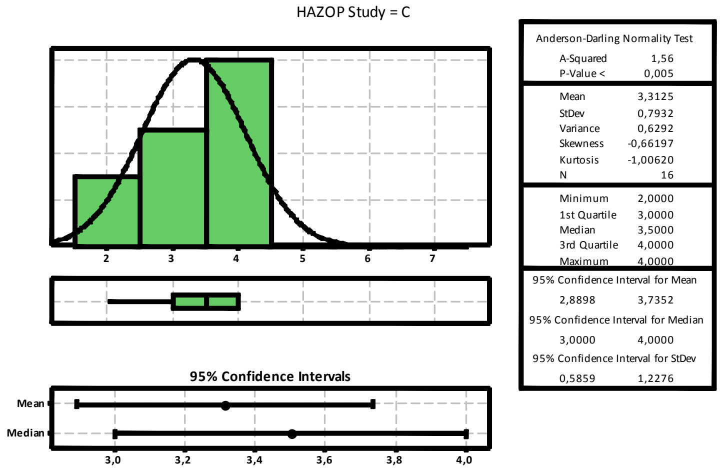
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,50 |
| P-Value | 0,172 |
| Mean | 5,1429 |
| StDev | 1,2315 |
| Variance | 1,5165 |
| Skewness | -0,023538 |
| Kurtosis | -0,974795 |
| N | 14 |
| Minimum | 3,0000 |
| 1st Quartile | 4,0000 |
| Median | 5,0000 |
| 3rd Quartile | 6,0000 |
| Maximum | 7,0000 |
| 95% Confidence Interval for Mean | |
| 4,4318 | 5,8539 |
| 95% Confidence Interval for Median | |
| 4,0000 | 6,0000 |
| 95% Confidence Interval for StDev | |
| 0,8927 | 1,9839 |

**Figure A.III. 13.2.** Basic statistics summary considering the HAZOP A – Members.



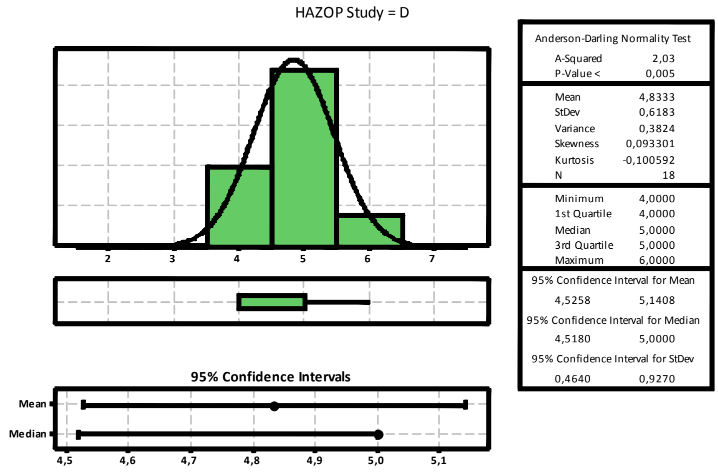
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 0,80 |
| P-Value | 0,030 |
| Mean | 4,8667 |
| StDev | 0,9155 |
| Variance | 0,8381 |
| Skewness | -0,351378 |
| Kurtosis | -0,483948 |
| N | 15 |
| Minimum | 3,0000 |
| 1st Quartile | 4,0000 |
| Median | 5,0000 |
| 3rd Quartile | 6,0000 |
| Maximum | 6,0000 |
| 95% Confidence Interval for Mean | |
| 4,3597 | 5,3736 |
| 95% Confidence Interval for Median | |
| 4,0000 | 5,6265 |
| 95% Confidence Interval for StDev | |
| 0,6702 | 1,4438 |

**Figure A.III. 13.3.** Basic statistics summary considering the HAZOP B – Members.



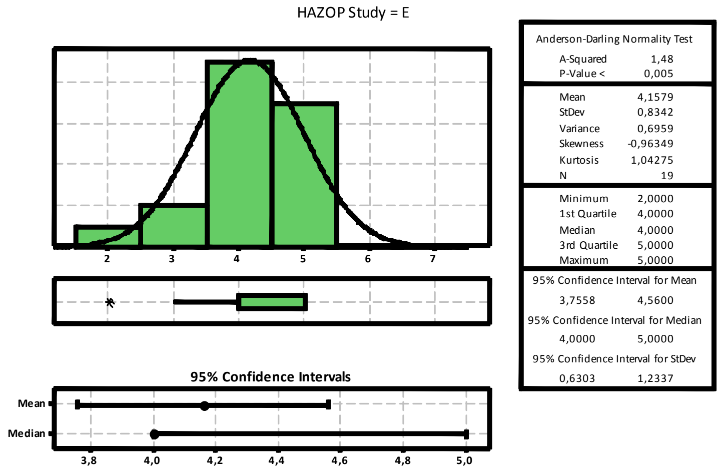
| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,56 |
| P-Value < | 0,005 |
| Mean | 3,3125 |
| StDev | 0,7932 |
| Variance | 0,6292 |
| Skewness | -0,66197 |
| Kurtosis | -1,00620 |
| N | 16 |
| Minimum | 2,0000 |
| 1st Quartile | 3,0000 |
| Median | 3,5000 |
| 3rd Quartile | 4,0000 |
| Maximum | 4,0000 |
| 95% Confidence Interval for Mean | |
| 2,8898 | 3,7352 |
| 95% Confidence Interval for Median | |
| 3,0000 | 4,0000 |
| 95% Confidence Interval for StDev | |
| 0,5859 | 1,2276 |

**Figure A.III. 13.4.** Basic statistics summary considering the HAZOP C – Members.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 2,03 |
| P-Value < | 0,005 |
| Mean | 4,8333 |
| StDev | 0,6183 |
| Variance | 0,3824 |
| Skewness | 0,093301 |
| Kurtosis | -0,100592 |
| N | 18 |
| Minimum | 4,0000 |
| 1st Quartile | 4,0000 |
| Median | 5,0000 |
| 3rd Quartile | 5,0000 |
| Maximum | 6,0000 |
| 95% Confidence Interval for Mean | |
| 4,5258 | 5,1408 |
| 95% Confidence Interval for Median | |
| 4,5180 | 5,0000 |
| 95% Confidence Interval for StDev | |
| 0,4640 | 0,9270 |

**Figure A.III. 13.5.** Basic statistics summary considering the HAZOP D – Members.



| Anderson-Darling Normality Test | |
|---|---|
| A-Squared | 1,48 |
| P-Value < | 0,005 |
| Mean | 4,1579 |
| StDev | 0,8342 |
| Variance | 0,6959 |
| Skewness | -0,96349 |
| Kurtosis | 1,04275 |
| N | 19 |
| Minimum | 2,0000 |
| 1st Quartile | 4,0000 |
| Median | 4,0000 |
| 3rd Quartile | 5,0000 |
| Maximum | 5,0000 |
| 95% Confidence Interval for Mean | |
| 3,7558 | 4,5600 |
| 95% Confidence Interval for Median | |
| 4,0000 | 5,0000 |
| 95% Confidence Interval for StDev | |
| 0,6303 | 1,2337 |

**Figure A.III. 13.6.** Basic statistics summary considering the HAZOP E – Members.

# NOMENCLATURE

| Symbol | Meaning | Units |
|---|---|---|
| Exchangers | Number of Exchangers | - |
| FCVs | Number of Flow Control Valves | - |
| LCVs | Number of Level Control Valves | - |
| ME | Number of Major Equipment | - |
| Members | Number of Members attending a HAZOP session | - |
| MH | Total Man Hours | h |
| N | Number of sessions required to conduct a HAZOP | - |
| Nd | Number of Nodes | - |
| Nd/PS | Number of nodes per Principal Section | - |
| PCVs | Number of Pressure Control Valves | - |
| PDescription | Number of Process Description pages | - |
| PFDs | Number of Process Flow Diagrams | - |
| P&IDs | Number of Piping & Instrumentation Diagrams | - |
| PS | Number of Principal Sections | - |
| Pumps | Number of Pumps | - |
| TCVs | Number of Temperature Control Valves | - |
| $T_{BTNd}$ | Time required to brainstorm a node | h |
| $T_H$ | Total time required to conduct the HAZOP study | h or w |
| $T_{Nd}$ | Total time required to select nodes | min |
| $T_{NdPFD}$ | Time to select Nodes on PFDs | min |
| $T_{NdP\&ID}$ | Time to transfer Nodes from PFDs to P&IDs | min |
| $T_P$ | Total time required to prepare and organize the study | h |
| $T_{PS}$ | Time to select Principal Sections on PFDs | min |
| $T_S$ | Total time required to execute the study | h |
| $T_W$ | Total time required to write the draft report | h |

min: minutes; h: hours; w: weeks

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## ABBREVIATIONS AND ACRONYMS

| **ACRONYM** | **MEANING** |
|---|---|
| **ACMH** | Advisory Committee on Major Hazards |
| **AEA** | Action Error Analysis |
| **AHA** | Automatic Hazard Analyzer |
| **AIChE** | American Institute of Chemical Engineers |
| **ANSI** | American National Standards Institute |
| **ALARP** | As Low As Reasonable Practicable |
| **API** | American Petroleum Institute |
| **ARIP** | Accidental Release Information Program |
| **ASME** | American Society of Mechanical Engineers |
| **ASSE** | American Society of Safety Engineers |
| **ASTM** | American Society for Testing and Materials |
| **CAA** | Clean Air Act |
| **CAER** | Community Awareness & Emergency Response |
| **CCPS** | Center for Chemical Process Safety |
| **CEC** | Commission of the European Communities |
| **CEPP** | Chemical Emergency Preparedness Program |
| **CHAZOP** | Control or (Computer) Hazard and OPerability analysis |
| **CIA** | Chemical Industries Association |
| **CIMAH** | Control of Industrial Major Accident |
| **CMA** | Chemical Manufacturers Association |
| **COMAH** | Control of Major Accidents Hazards |
| **COMHAZOP** | Computer program as an aid for HAZOP studies |
| **CPI** | Chemical Process Industry |
| **CSB** | Chemical Safety and Hazard Investigation Board |
| **DOE** | US Department Of Energy |
| **EPA** | Environmental Protection Agency |
| **EPCRA** | Emergency Planning and Community Right-to-Know Act |
| **EPSC** | European Process Safety Center |
| **ETA** | Event Tree Analysis |
| **ETBE** | Ethyl Tert Butyl Ether |
| **ETD** | Event Time Diagram |
| **FTA** | Fault Tree Analysis |
| **FMEA** | Failure Modes and Effects Analysis |
| **FRR** | Facility Risk Review |
| **FTA** | Fault Tree Analysis |
| **HAZAN** | HAZard ANalysis |
| **HAZOP** | HAZard & Operability study |
| **HAZROP** | HAZard, Reliability, and Operability Analysis |
| **HDG** | HAZOP-Digraph Model |
| **HHCs** | Highly Hazardous Chemical |
| **HMS** | HAZOP Management System |
| **HSE** | Health & Safety Executive |
| **IEEE** | Institute of Electrical and Electronics Engineers |
| **IChemE** | Institution of Chemical Engineers |
| **ICI** | Imperial Chemical Industries |
| **ICMESA** | Industrie Chimiche Meda Società |
| **IEC** | International Electrotechnical Commission |
| **IHAS** | Integrated Hazard Analysis System |
| **INPO** | Institute of Nuclear Power Operations |
| **IPL** | Independent Protection Layers |

| ACRONYM | MEANING |
|---|---|
| **ISA** | International Standards Association |
| **LCD** | Liquid Crystal Display |
| **LEPCs** | Local Emergency Planning Committees |
| **LFL** | Lower Flammable Limit |
| **LOPA** | Layer Of Protection Analysis |
| **LPG** | Liquefied Petroleum Gas |
| **MAPP** | Major Accident Prevention Policy |
| **MCS** | Minimal Cut Set |
| **MHA** | Major Hazard Analysis |
| **MIC** | Methyl isocyanate |
| **MOC** | Management Of Change |
| **MORT** | Management Oversight and Risk Tree |
| **MSDS** | Material Safety Data Sheets |
| **NAICS** | North American Industrial Classification System |
| **NCSR** | National Centre of Systems Reliability |
| **NFPA** | National Fire Protection Association |
| **NIHHS** | Notification of Installations Handling Hazardous Substances |
| **NSC** | National Safety Council |
| **OCA** | Offsite Consequence Analysis |
| **OREDA** | Offshore Reliability Data |
| **OSHA** | Occupational Safety and Health Administration |
| **PCED** | Process Control Event Diagram |
| **PES** | Programmable Electronic Systems |
| **PFD** | Probability of Failure on Demand |
| **PFDs** | Process Flow Diagrams |
| **PHA** | Process Hazard Analysis |
| **P&IDs** | Piping and Instrumentation Diagrams |
| **PLM** | Product Lifecycle Management |
| **PMRC** | Plant Maintenance Resource Centre |
| **PSI** | Process Safety Information |
| **PSM** | Process Safety Management |
| **QHI** | Qualitative Hazard Identifier |
| **QRA** | Quantitative Risk Analysis |
| **QUEEN** | QUalitative Effects Engine |
| **RCM** | Reliability Centered Maintenance |
| **RMP** | Risk Management Plan |
| **ROA** | Recursive Operability Analysis |
| **SDG** | Signed Directed Digraph |
| **SERCs** | State Emergency Response Commissions |
| **SHARD** | Software Hazard Analysis and Resolution in Design |
| **SIL** | Safety Integrity Level |
| **SIS** | Safety Instrumented System |
| **SMS** | Safety Management System |
| **SRA** | Society for Risk Analysis |
| **STOPHAZ** | Support Tool for Process Hazard Analysis |
| **TCB** | 1,2,4,5-tetrachlorobenzene |
| **TCP** | 2,4,5-trichlorophenol |
| **TNT** | Trinitrotoluene |
| **UCIL** | Union Carbide India Limited |
| **UFL** | Upper Flammable Limit |
| **VCE** | Vapor Cloud Explosion |
| **WSA** | Work Safety Analysis |

## GLOSSARY

**Acceptable risk:** The average rate of loss that is considered tolerable for a given activity

**Action item:** an item identified during a study that requires follow-up; it is entered in the Recommendations column of the worksheet

**Acute hazard:** The potential for injury or damage to occur as a result of an instantaneous or short duration exposure to the effects of an accident

**As Low As Reasonably Possible (ALARP):** A principle that is associated with the design and development of safety systems, and captures the notion that the risk to individuals, society, and the environment should be “As Low As Reasonably Possible”

**Basic event:** a basic initiating fault requiring no further development (term used in FTA)

**Bottoms:** Tower bottoms are the residue remaining in a distillation unit after the highest boiling-point material to be distilled has been removed. Tank bottoms are the heavy materials that accumulate in the bottom of storage tanks, usually comprised of oil, water, and foreign matter.

**Catastrophic Release:** A major, uncontrolled emission, fire, or explosion, involving one, or more, highly-hazardous chemicals that present serious danger to employees in the workplace or to the public

**Cause:** also known as a critical factor, causal factor or contributing cause, is a major unplanned, unintended contributor to the incident (a negative occurrence or undesirable condition), that if eliminated would have either prevented the occurrence, or reduced its severity or frequency

**Checklist:** An experience-based list of hazards, potential accident situations, or other process safety concerns used to stimulate the identification of hazardous situations for a process or operation

**Chronic hazard:** The potential for injury or damage to occur as a result of prolonged or repeated exposure to an undesirable condition

**Consequence:** The direct, undesirable result of an accident, usually measured in health/safety effects, environmental damage, loss of property, or business costs

**Design intent:** overall statement of what the process involves

**Deviation:** departure from the intention of the node

**Dry gas:** Natural gas with so little natural gas liquid that it is nearly all methane with some ethane.

**Enabling event:** condition that must be present or active for the scenario to proceed

**Equipment failure:** in which a mechanical, structural or operating failure results in the release of hazardous material

**Event:** An occurrence involving process, equipment or human performance, either internal or external, to a system that causes system upset. In terms of accidents, an event is either a cause or a contributing cause of a "near miss" or accident, or a response to the accident initiating event

**Event tree:** A logic model that graphically portrays the combinations of events and circumstances in an accident sequence

**External event:** factors outside the unit being reviewed that could affect the process design intent. External events include upsets on adjacent units affecting the safe operation of the unit (or node) being studied

**Failure Modes and Effects Analysis (FMEA):** A systematic, tabular method for evaluating and documenting the causes and effects of known types of component failures

**Fault tree:** A logic model that graphically portrays the combinations of failures that can lead to a specific main failure or accident of interest (Top Event)

**F-N curve:** A graphical illustration of the cumulative frequency (F) of accidents resulting in a consequence of greater-than or equal-to (N) impacts. A way of illustrating societal risk

**Frequency:** Number of occurrences of an event per unit of time

**General parameter:** other aspects of the design intent complementing specific parameter information

**Guideword:** simple word or phrase used to qualify or quantify the intention

**Hazard:** A chemical or physical condition that has the potential for causing damage to people, property, or the environment

**HAZard & OPerability (HAZOP) study:** A systematic method in which process hazards and potential operating problems are identified using a series of guide words to investigate process deviations

**Header:** A manifold that distributes fluid from a series of smaller pipes or conduits

**Human error:** major cause of almost all of the catastrophic accidents that have occurred in the chemical process industries

**Incident:** An unplanned release of hazardous chemicals or energy

**Individual risk**: The likelihood that any one person will be injured within a given time period (typically per year or per working lifetime)

**Inherent safety:** A system is inherently safe if it remains in a nonhazardous situation after the occurrence of non-acceptable deviations from normal operating conditions

**Initiating event:** First event in an event sequence. Can result in an accident unless engineered protection systems or human actions intervene to prevent or mitigate the accident

**Intention:** The purpose, goal or aim that a specific item is expected to operate

**Intermediate event:** An event that propagates or mitigates the initiating event during an accident sequence. Executing FTA, is defined as a fault event that occurs because of one or more antecedent causes

**Knockout drum:** A vessel wherein suspended liquid is separated from gas or vapor

**Lean oil:** Absorbent oil fed to absorption towers in which gas is to be stripped. After absorbing the heavy ends from the gas, it becomes fat oil. When the heavy ends are subsequently stripped, the solvent again becomes lean oil

**Likelihood:** A measure of the expected probability or frequency of occurrence of an event

**Layer Of Protection Analysis (LOPA):** A simplified and semi-quantitative technique for risk assessment, which uses order of magnitude categories for initiating event frequency, consequence severity, and the likelihood of failure of independent protection layers to approximate the risk of a scenario

**Loss prevention**: the prevention of accidents through the use of appropriate technologies to identify the hazards of a chemical plant and eliminate them before an accident occurs

**Minimal Cut Set:** A combination of failures necessary and sufficient to cause the occurrence of the Top event in a Fault Tree

**Near miss:** an occurrence in which an accident (that is, property damage, material loss, environmental impact, or human loss) or an operational interruption could have plausibly resulted if circumstances had been slightly different

**Node:** Process section within which parameters are investigated for deviations from its design intent

**Node intention:** defines how the process is expected to be operated, only considering node equipment

**Operability:** any operation inside the design envelope that would cause a shutdown that could possibly lead to a violation of environmental, health or safety regulations or negatively impact profitability

**Operational interruption:** an occurrence in which production rates or product quality is seriously impacted

**Parameter intention:** range of allowable values for the parameter during process operations

**Probability:** The expression for the likelihood of occurrence of an event or an event sequence during an interval of time; or the likelihood of the success or failure of an event on test or on demand. By definition, probability must be expressed as a number ranging from 0 to 1

**Process Hazard:** An inherent chemical or physical characteristic with the energy potential for damaging people, property, and/or the environment

**Process Hazards Analysis (PHA):** The application of one or more analytical methods to identify and evaluate process hazards for the purpose of determining the adequacy of or need for control measures

**Process Safety Audit:** An inspection of a plant or process unit, drawings, procedures, emergency plan, and/or management systems by an independent team

**Process Safety Management (PSM):** The application of management principles, methods, and practices to prevent and control accidental releases of process chemicals or energy

**Quantitative risk analysis (QRA):** The systematic development of numerical estimates of the expected frequency and/or consequence of potential accidents associated with a facility or operation based on engineering evaluation and mathematical techniques

**Recommendation:** Suggested action to prevent, detect, control, or mitigate the scenario identified

**Residual Risk:** Risk remaining after the application of resources for prevention or mitigation

**Risk:** A measure of human injury, environmental damage, or economic loss in terms of both the incident likelihood and the magnitude of the loss or injury

**Risk analysis:** The development of a quantitative estimate of risk based on engineering evaluation and mathematical techniques for combining estimates of incident consequences and frequencies

**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 contour:** Lines that connect points of equal risk around the facility (“isorisk” lines)

**Risk estimation:** Combining the estimated consequences and likelihood of all incident outcomes from all selected incidents to provide a measure of risk

**Risk management:** The systematic application of management policies, procedures, and practices to the tasks of analyzing, assessing, and controlling risk in order to protect employees, the general public, and the environment, as well as company assets, while avoiding business interruptions

**Risk profile:** graphical risk representation that shows the expected frequency of accidents of a particular category or level of consequence

**Risk targets:** Objective-based risk criteria established as goals or guidelines for performance

**Root cause:** a fundamental, underlying, system-related reason why an incident occurred that identifies a correctable failure(s) in management systems

**Safeguard:** physical- or procedural-measure that will eliminate or reduce the likelihood of a hazard

**Safety Management System (SMS):** synonym of PSM; see Process Safety Management

**Scenario:** situation motivated by a design departure which is completely defined by a cause-consequence pair

**Societal risk:** The grand total of all individual risks over a given time period (usually per year or per plant lifetime)

**Sour gas:** Natural gas that contains corrosive, sulfur-bearing compounds such as hydrogen sulfide and mercaptans

**Specific parameter:** physical- or chemical-parameters of process materials

**Top event:** The undesired event or incident at the “top” of a Fault Tree

**What-if:** Creative methodology used to evaluate any aspect of a process by brainstorming a series of questions that begin "What if...”

**Wet gas:** A gas containing a relatively high proportion of hydrocarbons that are recoverable as liquids