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An automated HAZOP application for risk assessment in petrochemical facilities

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Acknowledgment

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Dedication

I dedicate this work to my beloved parents, for their endless love, support, and sacrifices throughout my life. Their encouragement has always been my source of strength.

To my family, for their patience and understanding during the completion of this work.

To my friends, who have supported me and stood by my side.

And to everyone who believed in me, this achievement is also yours.

Thank you.

AbdErrahmane

Dedication

It is a great pleasure to dedicate our work to:

My dear parents, who gave me everything I needed to reach where I am now, no words of thanks can express my gratitude to them.

My beloved sister, who never hesitated for a moment to stand by me and support me.

My entire family, my friends and all my colleagues in the field of petrochemical engineering.

And everyone who has done us a favor.

Kassim

Abstract:

This thesis presents a systematic approach to studying incidents and avoiding hazards in petrochemical industrial facilities using an automated method known as automated HAZOP. As a case study, the methodology was applied to the atmospheric heater in the atmospheric distillation unit U-10 at the Skikda petroleum refinery complex. Where we conducted a traditional HAZOP study on the heater, then created the cause-and-effect table for the dynamic simulation. The method provides automated results for interpreting specific phenomena and occurring deviations, enabling workers to respond quickly in order to avoid hazards.

Keywords: Deviations, heater,automated HAZOP, hazards.

Résumé:

Ce mémoire présente une approche méthodique pour l'étude des incidents et la prévention des risques dans les installations industrielles pétrochimiques, au moyen d'une méthode automatisée appelée HAZOP automatisé. À titre d'étude de cas, la méthodologie a été appliquée au four de chauffage de l'unité de distillation atmosphérique U-10 du complexe de raffinage pétrolier de Skikda. Où nous avons mené une étude HAZOP traditionnelle sur le four, puis élaboré le tableau de cause et effet pour la simulation dynamique. La méthode fournit des résultats automatisés pour l'interprétation des phénomènes spécifiques et des déviations survenues, permettant ainsi aux opérateurs de réagir rapidement afin d'éviter les risques.

Mots-clés: Déviations, four, HAZOP automatisé, risques.

ملخص:

تتناول الرسالة تقديم طريقة ممنهجة لدراسة الحوادث و تجنب الأخطار في المركبات الصناعية البتروكيماوية بطريقة آلية (أوتوماتكية) تسمى automated HAZOP. و كدراسة حالة طبقت المنهجية على فرن التسخين في وحدة التقطير الجوي U-10 بمركب تكرير البترول سكيكدة. حيث قمنا بدراسة HAZOP التقليدية على الفرن ثم انشاء جدول السبب و النتيجة من أجل المحاكاة الديناميكية. الطريقة تعطينا نتائج آلية لتفسير الظواهر الخاصة و الإنحرافات الواقعة و تمكن العمال من الإستجابة السريعة لتفادي الأخطار.

كلمات مفتاحية: الإنحرافات، فرن، الأخطار، automated HAZOP.

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Abreviations list

RA1K: Refinery 1 of Skikda

PRA: Preliminary Risk Analysis

FTA: Fault Tree Analysis

ETA: Event Tree Analysis

MOSAR: Organized Systemic Method for Risk Analysis

LOPA: Layer Of Protection Analysis

FMECA: Failure Mods, Effects and Criticality Analysis

HAZOP: Hazard and Operability

FG: Fuel Gas

PG: Pilot Gas

FT: Flow Transmitor

FE: Flow Element

FI: Flow Indicator

FIC: Flow Indicator and Controller

FAL: Flow Alarm Low

FALL: Flow Alarm Low Low

FAH: Flow Alarm High

FAHH: Flow Alarm High High

FV: Flow Valve

FSLL: Flow Switch Low Low

TT: Temperature Transmitor

TE: Temperature Element

TI: Temperature Indicator

TIC: Temperature Indicator and Controller

TAL: Temperature Alarm Low

TALL: Temperature Alarm Low Low

TAH: Temperature Alarm High

TAHH: Temperature Alarm High High

TV: Temperature Valve

PT: Pressure Transmitor

PE: Pressure Element

PI: Pressure Indicator

PIC: Pressure Indicator and Controller

PAL: Pressure Alarm Low

PALL: Pressure Alarm Low Low

PAH: Pressure Alarm High

PAHH: Pressure Alarm High High

PV: Pressure Valve

LT: Level Transmitor

LI: Level Indicator

LAL: Level Alarm Low

LALL: Level Alarm Low Low

LAH: Level Alarm High

LAHH: Level Alarm High High

LV: Level Valve

General introduction

General introduction:

Petroleum is the world's primary and essential energy source. Therefore, massive refineries and processing plants have been established to refine it and transform its derivatives into various materials used in our daily lives. Due to their large scale and extensive operations, these plants and facilities are susceptible to numerous risks and accidents, such as fires and explosions caused by extremely high temperatures and pressures. This has led many researchers, particularly in the 20th century, to develop methods for analyzing risks in petrochemical plants, aiming to mitigate damage in the event of accidents or prevent them altogether. Among these methods is the HAZOP method, which is crucial for identifying the causes of deviations in petrochemical plants and determining the necessary solutions. Researchers have recently proposed an automated HAZOP system to reduce the time wasted on traditional HAZOP studies, which can take up to 400 hours per session.

In this thesis, we will give a method to create an automatic HAZOP using MATLAB software.

First, in Chapter 1, we provide an overview of the Skikda RA1K refinery, outlining its various units and the processes implemented within each.

Then, in chapter 2 we discusse about different risk analysis methods in the petrochemical industry, focusing on prominent ones such as the LOPA and FMECA methods.

Chapter 3 delves into the HAZOP method, its importance, application, limitations, advantages, and disadvantages. It also addresses automatic HAZOP and the research efforts to develop it, outlining the steps proposed for its implementation.

Finally, in Chapter 4, we present an early method for an automated HAZOP application using MATLAB software, after applying a conventional HAZOP study to the heater 10-F-A in the atmospheric distillation unit U-10 of the Skikda refinery and conducting a dynamic simulation to diagnose deviations and identify their causes.

The aim of this thesis is to create an automatic HAZOP using MATLAB software, in order to improve the efficiency and effectiveness of the HAZOP, in addition to reducing the time and effort wasted during the application of the traditional HAZOP, and reducing the complete dependence on the human element.

CHAPTER I:

Skikda refinery presentation

Introduction:

Skikda Refinery is the largest oil refinery in Algeria, and it is also ranked among the largest in Africa, due to the enormous production capacity it generates annually. Among its most important units is the Atmospheric Distillation Unit U-10, which contains the heater 10-F-1A on which we applied our study, in addition to many other units that we will discuss in this chapter.

I. Geographical location:

This refinery is located in the industrial zone 7 km east of Skikda and 2 km from the sea. It covers an area of 256 hectares and currently employs approximately 2000 workers. It is supplied with Algerian crude oil from Hassi Messaoud. The crude oil is transported via a pipeline over a distance of 760 km from the oil fields to the complex. This refinery produces a huge annual quantity: 16.5 million tons **[2].**

Figure I.1: Skikda refinery location [1].

II. History of construction:

The refinery was built in January 1976 following a contract signed on April 30, 1974, between the Algerian government and the Italian construction companies SNAM PROGETTI and SAIPEM. Construction began on January 2, 1976, and the production units were progressively brought online by March 1980 as follows**[2]:**

Table I.1: Start dates of RA1K units and their capacities [2].

Unit	**Capacité T/an**	**Date**
Topping (U10)	7.500.000	1980
Topping (U11)	7.500.000	1980
LPG separation (U30)	306.500	1980
LPG separation (U31)	283.000	1980
Catalytic reforming (U100)	1.165.000	1980
Extraction and fractionation of aromatics (U200)	285.000	1980
Para-Xylene cristallization (U400)	430.000	1980
Vacuum distillation and oxidation of bitumen (U70)	277.000	1980
Reforming (U103)	1.165.000	1993
LPG separation (U104)	96.000	1993
Storage yard (U600)	2.700.000 m3	1980 and 1993
Thermoelectric power plant		1980 and 1993

III. Skikda refinery units:

III.1. Atmospheric Distillation Units 10/11:"TOPPING"

The two atmospheric distillation units are designed to fractionate the Hassi Messaoud crude oil into various stabilized fractions that can be used to obtain finished products (naphtha, kerosene, and gas oil) or to supply other downstream units (catalytic reforming, gas treatment, and separation). They have been renovated to increase the initial processing capacity from 15,000,000 t/year to 16,500,000 t/year and to produce the fractions whose destinations are listed in the schematic below **[3]:**

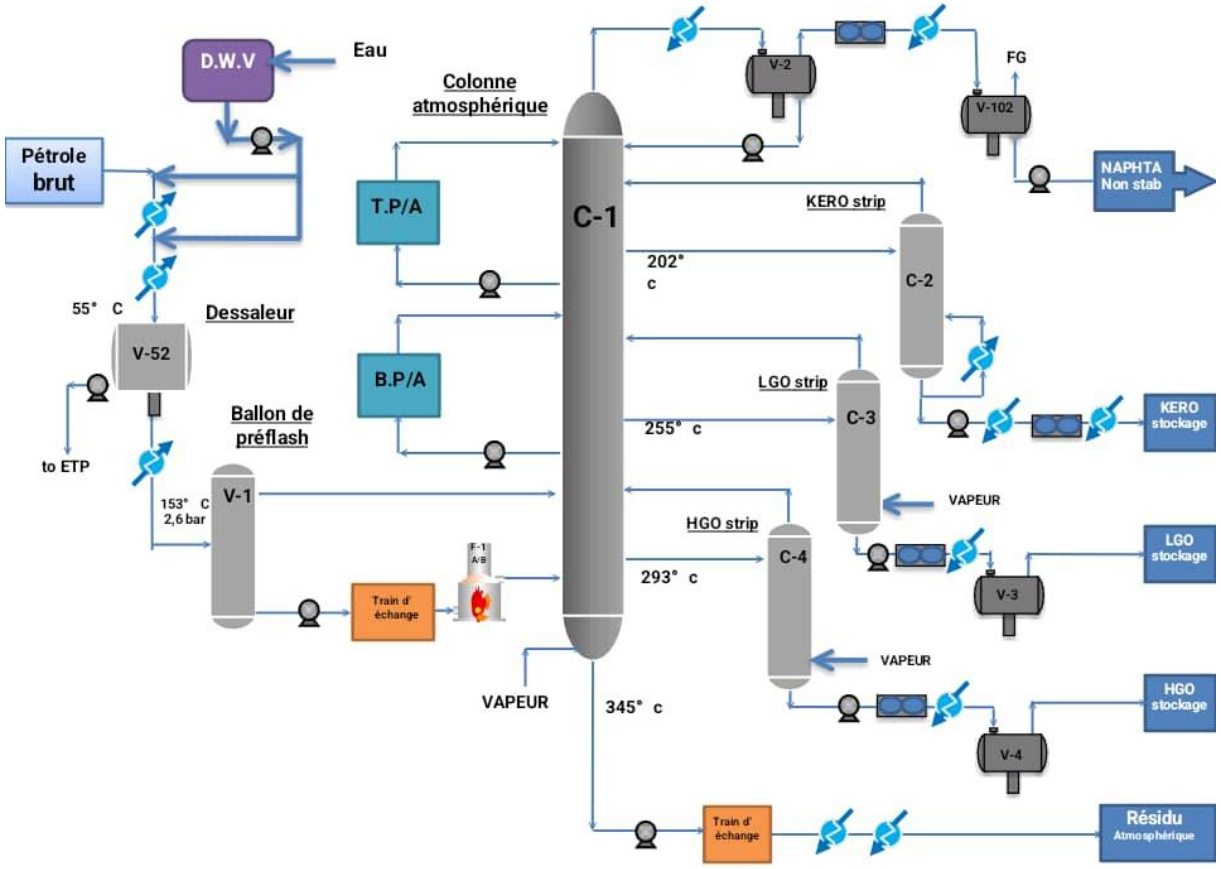


Figure I.2: Schematic of unit 10 process [4].

III.2. Catalytic Reforming Units U-100, U-101/103:

The Skikda refinery (RA1K) has two catalytic reforming units, one called "Magnaforming" (U-100) and the other called "Platforming" (U-101/103). The feed for these two units comes from the topping (naphtha B for U-100, and naphthas B+C for U-101/103).

Reforming I is intended for aromatics and should supply the aromatics extraction units and the paraxylene crystallization unit. Reforming II, intended for gasoline, is designed to address the gasoline shortage on the domestic market, initially, and to export surplus production as unleaded gasoline. It has also been proposed to compensate for the aromatics deficit observed in reforming I **[3].**

III.3. Platforming Gas Units U-30/31 and 104:

These units are designed to process liquefied gases from Units 10, 11, 100, and 103 in the following order **[3]:**

Unit 30: Processes liquefied gases from Unit 100, particularly those from the top of column C-7 where LPG is separated from pentane

Unit 31: Receives gases from the top of the gasoline stabilization columns of the two Topping Units;

Unit 104: Recently designed with the new Platforming Unit U-103 to process LPG from that unit. Each unit consists of a feed treatment section for the removal of moisture, a de-ethanation section for the separation of light hydrocarbons (C1 and C2) and a propane and butane separation section.

III.4. Aromatic Extraction Unit U-200:

The aromatic extraction unit is designed to process light reformates from the catalytic reforming units (U-100 and U-103). This unit consists of an aromatic extraction section and a section for fractionating aromatics into high-purity benzene and toluene.

The process involves fractionating the feedstock (light reformate) by extractive distillation using a solvent (Techtiv-100SM) into two parts (reformate and extract). The raffinate, consisting mainly of paraffinic hydrocarbons, is sent to storage, while the extract is separated into aromatics and solvent by distillation. The solvent is then regenerated and reintroduced into the extraction column, while the aromatics are fractionated into benzene, toluene, and heavy aromatics in distillation columns **[3].**

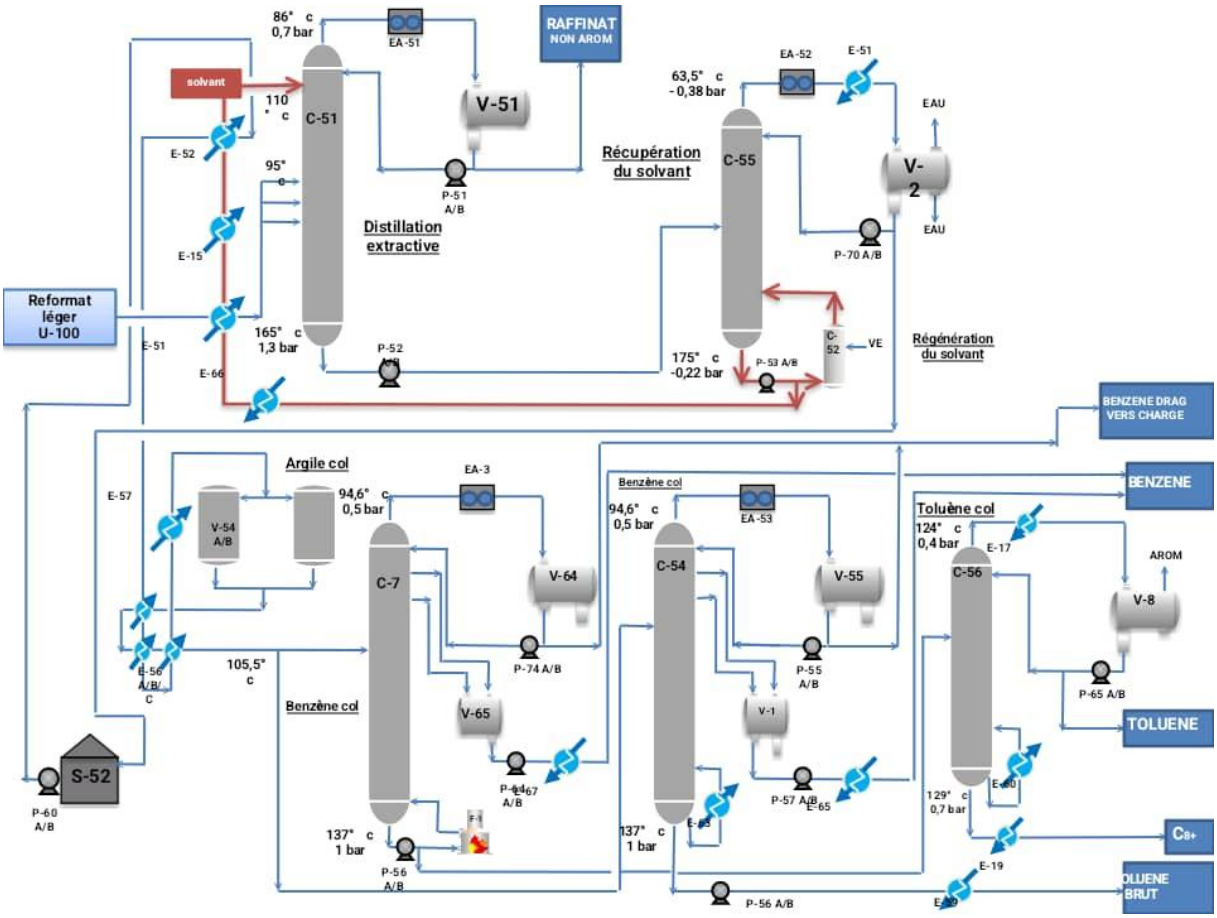


Figure I.3: Schematic of unit 200 process [4].

III.5. U-400 Paraxylene Crystallization and Separation Unit:

This unit is designed to recover paraxylene, a highly sought-after product on the market.

The feed from the Magnaforming unit allows, through crystallization, the separation of paraxylene from other xylenes (meta-ortho) and ethylbenzene, with cold as the separating agent.

The paraxylene is sold as is; the remaining paraxylene can be used as a base for producing gasoline or sold as a xylene mixture that can be used as a solvent in the manufacture of paints, etc **[3].**

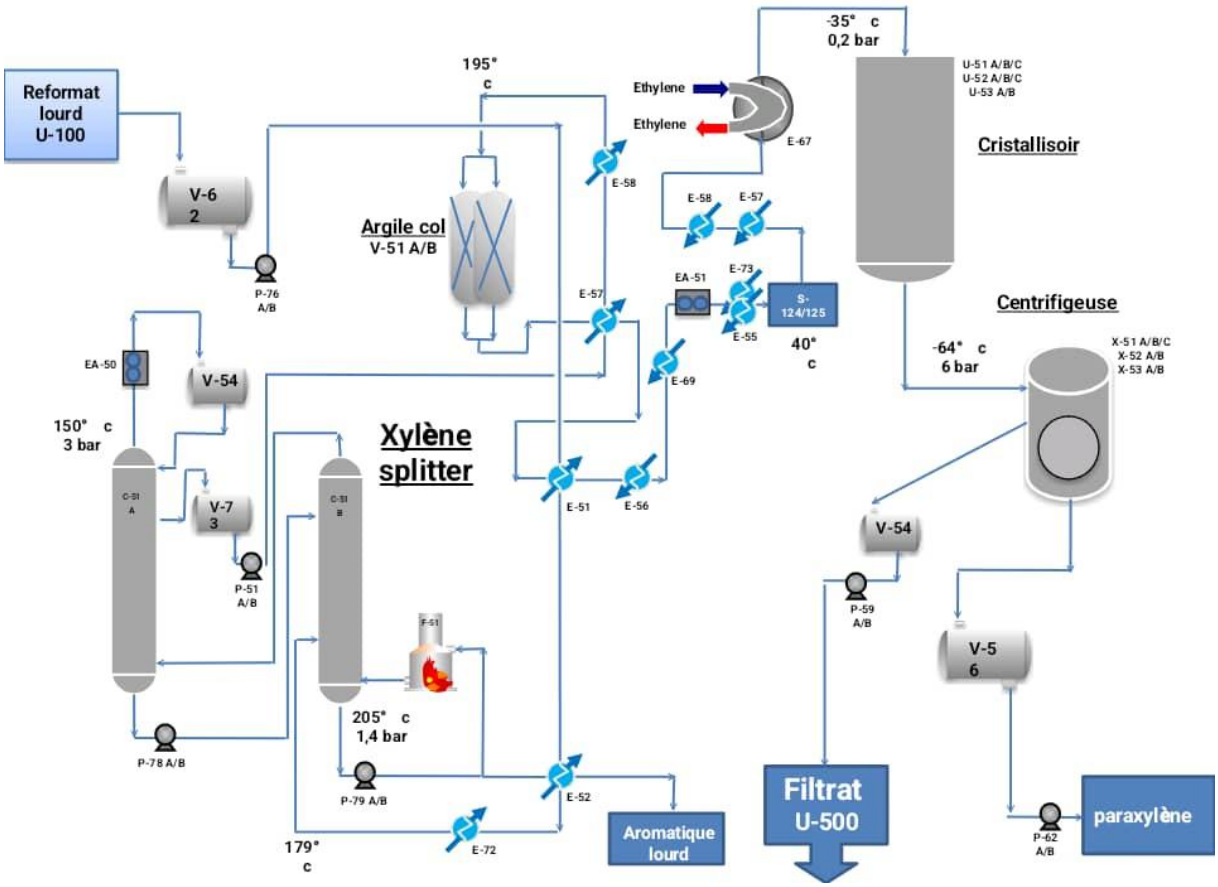


Figure I.4: Schematic of unit 400 process [4].

III.6. Xylene Isomerization Unit (Meta-Ortho) U-500:

The aromatic isomerization plant was designed to recover the filtrate from the crystallizers of Unit 400 (p-xylene crystallization unit). The resulting isomerate will be separated into two main fractions **[3]:**

- A benzene-rich fraction sent to Unit 200
- A p-xylene-rich fraction sent to Unit 400.

The main purpose of this unit is to increase p-xylene production.

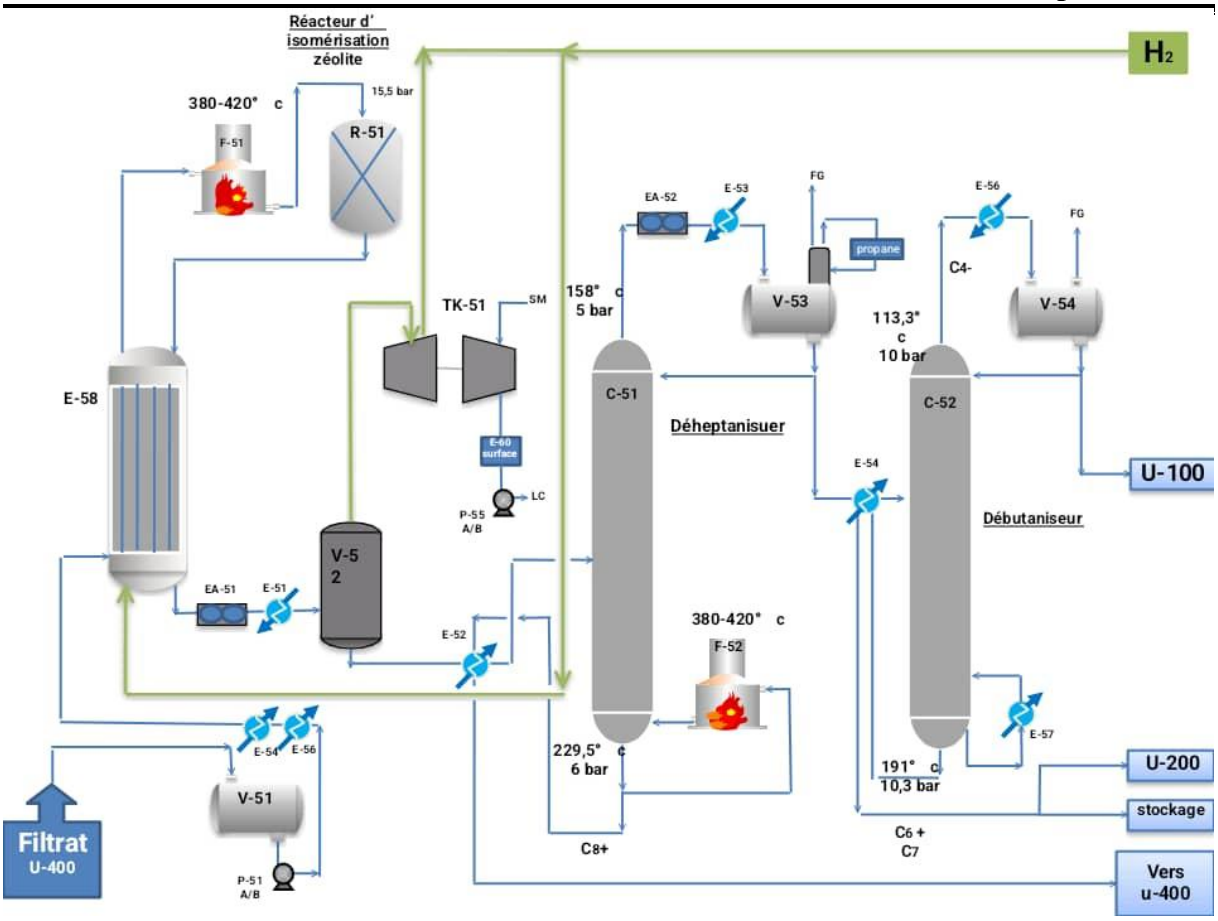


Figure I.5: Schematic of unit 500 process [4].

III.7. Paraffin isomerization Units 700/701 and 702/703:

The purpose of the Light Naphtha Hydrotreating Units (Units 700/702) is to produce clean hydrotreated feedstock to supply the isomerization Units 701/703. This feedstock must have sufficiently low levels of contaminants such as sulfur, nitrogen, water, olefins, and metals so as not to affect downstream units.

The objective of the Naphtha isomerization Units (U-701/U-703) is to improve the research octane rating and the engine octane rating of the light naphtha feedstock (primarily C5/C6) before blending into the gasoline pool **[3].**

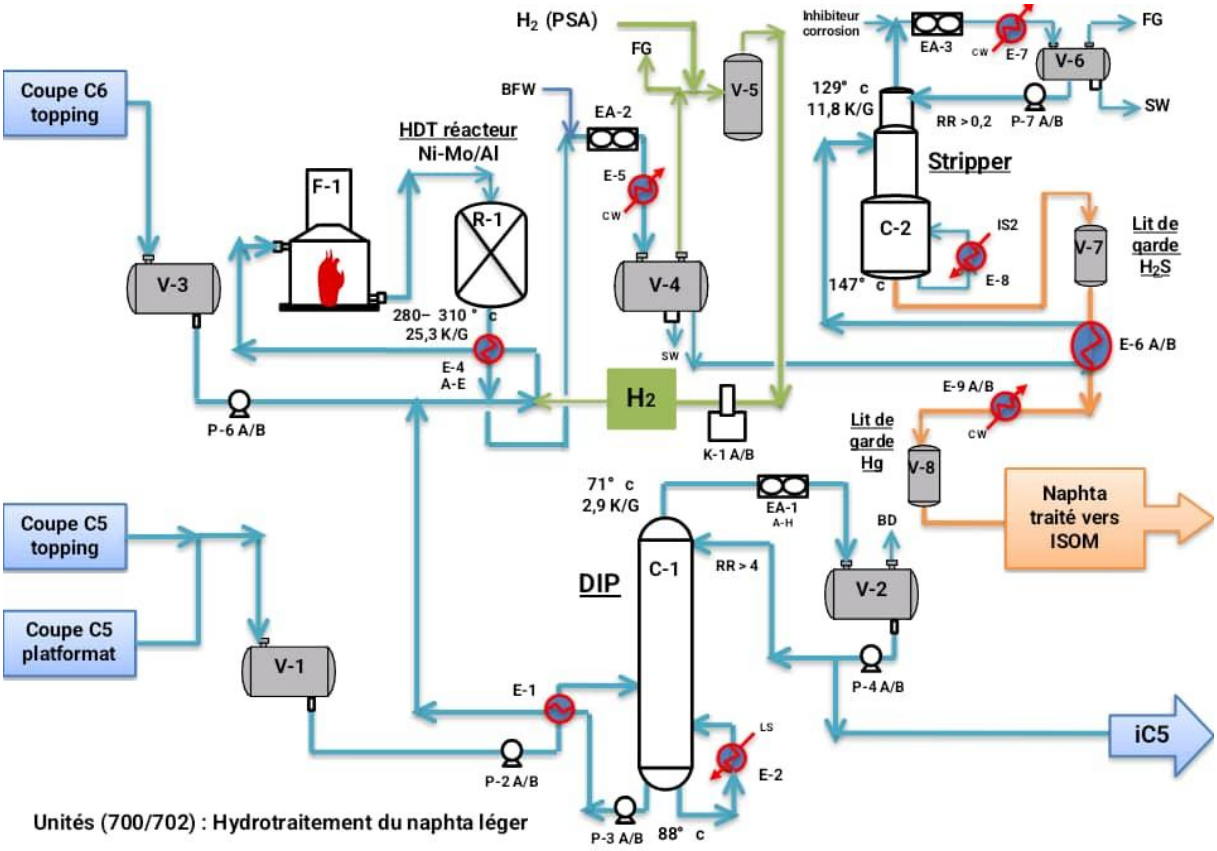


Figure I.6: Schematic of units 700/702 processes [4].

III.8. U-70 Vacuum Distillation Unit:

This unit is designed to process 277,000 tons/year of imported reduced bitumen (BRI) and produce road and oxidized bitumen. It consists primarily of a vacuum distillation column and a bitumen oxidation reactor. The column residue, constituting ordinary road bitumen, is sent in two parts **[3]:**

• Part to storage

• The other part is sent as feedstock to the oxidation section where it is oxidized by air into oxidized bitumen.

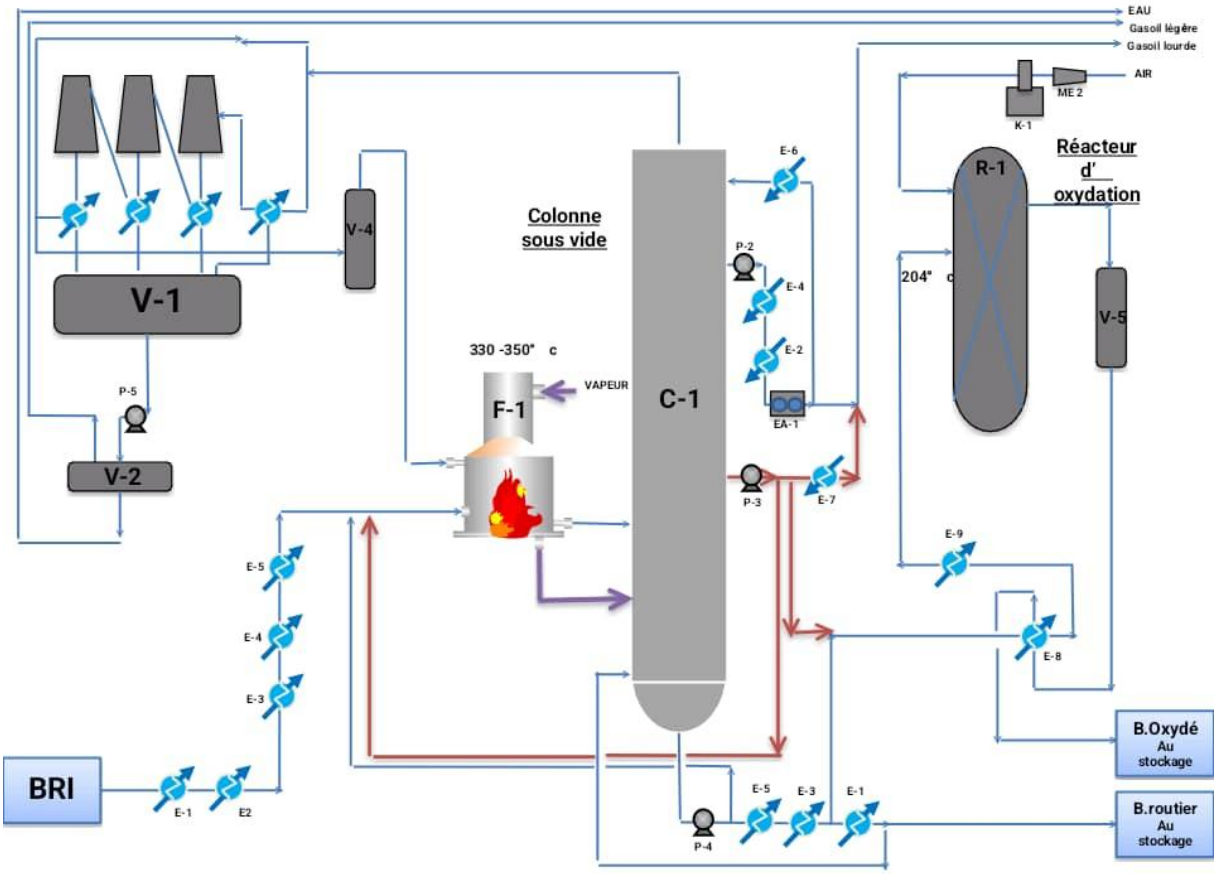


Figure I.7: Schematic of unit 70 process [4].

III.9. Unit 600 for Storage, Blending, and Shipping:

This unit comprises a blending and shipping section for petroleum products and a storage section for crude oil and petroleum products. It includes the equipment necessary for the blending and export of finished products.

Finished products are transported via a pipeline network to the two ports of Skikda, the Skikda LPG and fuel depots, and the integrated distribution center of Khroub (Constantine).

Road bitumen is transported by truck and pipeline to the port.

The majority of finished products are obtained by blending several base products, because it would be difficult to directly obtain (while remaining within profitability limits) products that meet specifications **[3].**

III.10. Hydrogen Purification Unit 900:

The hydrogen purification unit is designed to produce high-purity hydrogen for Unit 500 and Units 700/701, 702/703 from H2-rich gas originating from the Magnaforming Unit (Unit 100) and the Catalytic Reforming Unit (Unit 103).

The HPU consists of the feed gas compressor, the PSA package, and the exhaust gas compressor.

Hydrogen purification is carried out by the adsorption process in a system comprising eight adsorption tanks, some in operation and others in regeneration **[3].**

III.11. Utilities Units:

The Skikda refinery has two utilities units, one of which was installed during the renovation. These two units are the refinery's nerve center and are designed for the production, distribution, and packaging of the utilities necessary for the proper functioning of the refinery (RA1K). These utilities are **[3]:**

• Section 62 for the production of demineralized water

• Section 1020, for water cooling towers

• Section 1030 for the storage and pumping of dam water or drinking water

• Section 1040 for the storage and pumping of fire-fighting water

• Section 1050 for the generation of steam for the boilers

• Section 1060 for condensate recovery and treatment

• Section 1070 for Fuel-gas system

• Section 1080 for instrument air and service air production

• Section 1100 for effluent treatment

• Section 1110 for nitrogen (N2) production

• The electricity generation section.

Conclusion:

The Skikda refinery - especially after its rehabilitation project - remains one of the pillars of our nation’s economy due to its abundant production capacity and the availability of expertise and competencies within it.

CHAPTER II:

Risk analysis methods

Introduction:

In the industrial world, and especially in the petrochemical industry, workers face a wide range of hazards of varying severity and origin, causing significant human and financial losses. These risks have prompted researchers to develop numerous risk analysis methods to prevent accidents or mitigate their impact when they occur.

I. Some definitions:

I.1. Risk: A combination of the probability that a hazard will cause harm and the severity of that potential health impact **[5]**.

I.2. Risk analysis: Risk analysis is defined as an organized process in three interconnected parts: risk assessment, risk management and risk communication **[5]**.

I.3. Hazard: The hazard is a biological, chemical or physical agent present in food, feed or a condition of these products, that may have bad effects for health **[5]**.

I.4. Probability: It is a degree of likelihood that a hazard will cause a dangerous event.

I.5. Consequence: An effect resulting from the occurrence of an event related to a hazard.

I.6. Deviation: Any event or condition that deviates -because of parameters variation (T, P, Q……)- from the intended use of a system, process, or procedure.

I.7. Severity: The severity is a combination of the intensity of the impact of a hazardous phenomenon and the vulnerability of the exposed population. We can find it by this formula: Severity = Impact Intensity × Target Vulnerability.

I.8. Security: Security is protection, or assistance to people and property against unforeseen events: disasters, natural catastrophes... **[6]**.

II. Types of risks:

II.1. Industrial risk:

A risk of industrial accident is following with a major accident. It is defined as an event potentially harmful to human health and the environment, occurring in production plants,

storage facilities, or research laboratories.

II.2. Chemical risk:

Chemical risk refers to hazard associated with chemical products (toxic gases, benzene, highly volatile aromatics…), which can cause serious damage to the health and lives of workers on the one hand, and to the factory equipment on the other.

II.3. Electrical risk:

Electrical risk is a serious danger that can cause severe injury, burns or even death from electric shock or dangerous burns.

It can be happened in one of these situations:

- Contact with a live part of an electrical component.
- Existing near electrical equipment, especially high-voltage equipment (even without physical contact).
- Defective or inadequate insulation of electrical equipment.
- Electrostatic phenomena (discharges when touching electrically charged surfaces or objects).

II.4. Mechanical risk:

This refers to hazards related to mechanical elements (machines, tools, projected materials or fluids) that can cause injuries through impact, crushing, cutting or projection **[7]**.

II.5. Nuclear risk:

It refers to the hazards related with the application of radioactive materials that emit ionizing radiation. This radiation can cause irradiation or contamination of people, property, and the environment.

An accident involving these materials can have serious, long-lasting, and many bad effects, affecting the health of personnel, the public, and the ecological balance.

II.6. Biological risk:

It is associated to exposure to biological agents such as bacteria, viruses, and other pathogenic microorganisms. These agents can cause various illnesses: infections, poisoning, allergies, and in some cases, cancer.

This risk is particularly prevalent in several sectors: healthcare, personal services, agriculture, the food industry, and environmental professions.

These fields expose workers to pathogenic organisms or substances produced by these organisms, which can sorely harm their health.

In addition, biological risk also includes threats related to bioterrorism and the emergence of new infections.

III. Objective of Risk Analysis:

The objective of risk analysis is to identify the elements necessary to maintain the installation's safety at all times, both during normal operation and during degraded operation in the event of foreseeable deviations. Risk analysis must be combined with prevention, protection, and mitigation measures within a system involving **[8]**:

- Products
- Primary, secondary, and incidental processes
- Equipment
- Fluids
- Human factors
- Operator-machine interfaces
- The external environment

IV. The steps in a risk analysis:

Generally, implementing a risk analysis involves four main steps **[8]**:

1. The definition of the system studied
2. Identification of system risks

3. System modeling
4. Qualitative and/or quantitative analysis

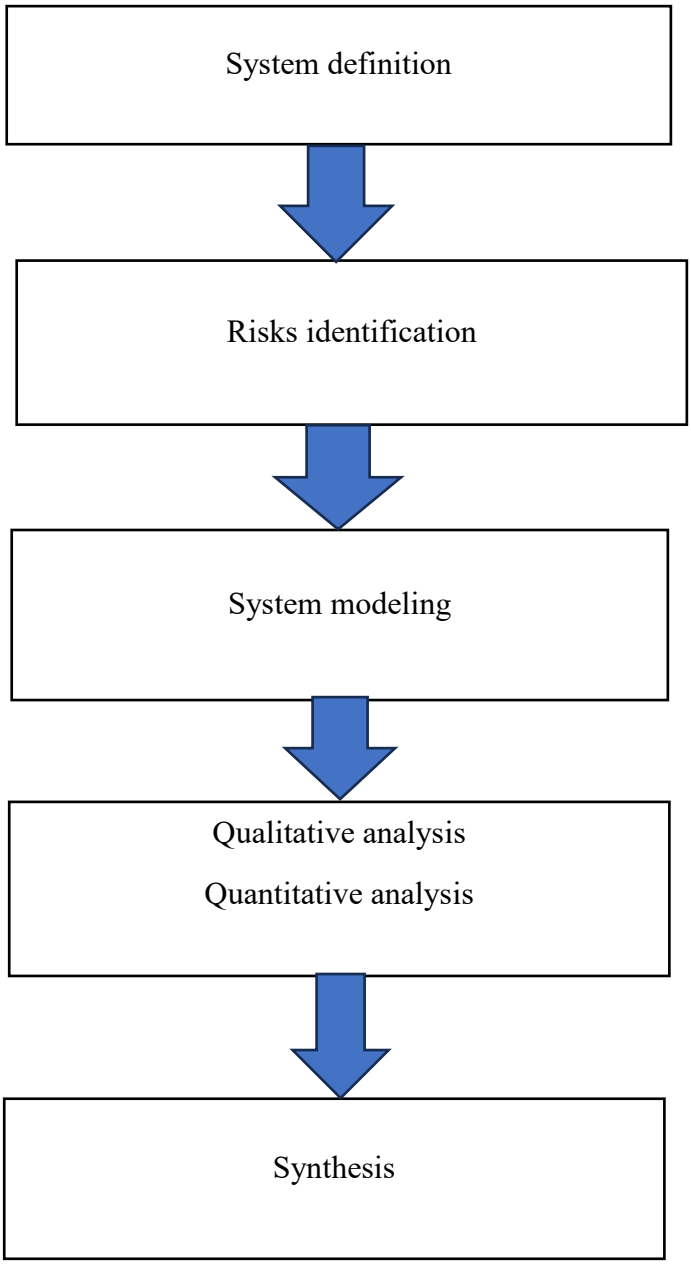


Figure II.1: A plan showing the sequence of the main steps in a risk analysis [8].

V. Qualitative and/or quantitative analysis:

The final stage of risk analysis can be qualitative, quantitative, or both. The purpose of the analysis is to assess the level of specific risks to the system. Qualitative analysis involves

classifying undesirable events according to their relative importance and how they occur. Quantitative analysis consists of characterizing each of the preceding events by assigning probabilities of occurrence **[8]**.

VI. Risk analysis methods:

VI.1. Fault Tree Analysis Method:

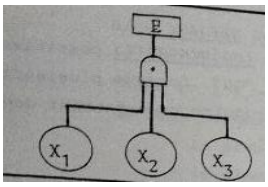
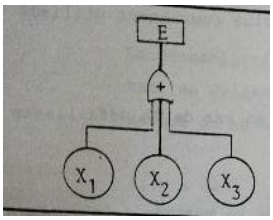
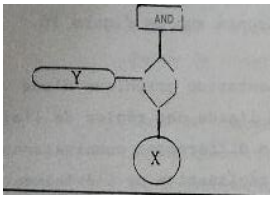
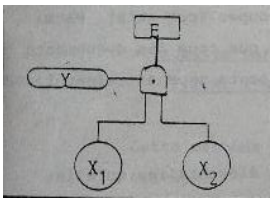
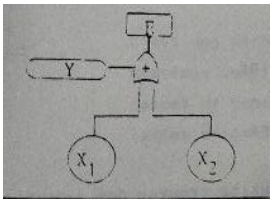
This method involves defining a feared event (fire, explosion, accidental release of a toxic substance, etc.) and identifying the failures in the system's components that could lead to it. It consists of using a graphical representation to determine the combination of different events. This results in the creation of a logic diagram that describes the logical sequence, in parallel or serially, of events that, within a given system, lead to an undesired final event **[5]**.

VI.2. Event Tree Analysis Method:

This method involves a systematic examination of potential failures or malfunctions that could occur in each of the component's elements, and determining how the unit under examination responds to the resulting disturbance, taking into account the compensation and intervention mechanisms in place.

Thus, starting from the hypothesis of a component failure, the evolution of the system must be analyzed. Therefore, using a logical approach, we construct a tree of events likely to occur downstream of the primary event, depending on whether the compensation, alarm, or safety devices have functioned or not **[5]**.

Table II.1: Presentation of some logic gates used in FTA and ETA [6].

Gate symbol	Gate name	Gate principale
	AND gate	Event E is generated if all input events (X1, X2, X3) are present.
	OR gate	Event E is generated if at least one of the input events (X1, X2, X3) is present.
	YES gate	Event E is generated if the input event (X) is present and the condition (Y) is met. If Y represents a probability p, event E is generated with probability p at the time X occurs.
	YES gate with condition	Event E is generated if the input events (X1, X2) are present and the condition (Y) is met. If Y= X1 before X2, it is an AND gate with priority.
	OR gate with condition	Event E is generated if at least one of the input events (X1, X2) is present and if the condition (Y) is satisfied, if Y, it is an exclusive OR gate.

Logic gates can be used also in many other risk analysis such us:

- Bow-Tie Analysis
- Reliability Block Diagram
- Layer of Protection Analysis
- Markov Analysis…….

VI.3. MOSAR Method: (Organized Systemic Method for Risk Analysis)

The MOSAR method is a risk analysis method comprising ten steps. The system to be analyzed (process, installation, etc.) is considered to be composed of subsystems in action. A grid is used to identify hazardous phenomena, hazardous actions, and hazardous events.

The adequacy of safety measures is studied using a second grid, and then a third grid that takes into account their interdependence. This leads to the construction of accident scenarios. The scenarios are classified, by consensus, in a severity grid.

A correspondence grid, also established by consensus, links the severity grid to the objectives to be achieved by the safety measures and specifies the performance level of the technical and organizational measures.

The safety measures are then integrated into the logic trees, and the residual risks are analyzed through an acceptability grid defined by consensus **[10]**.

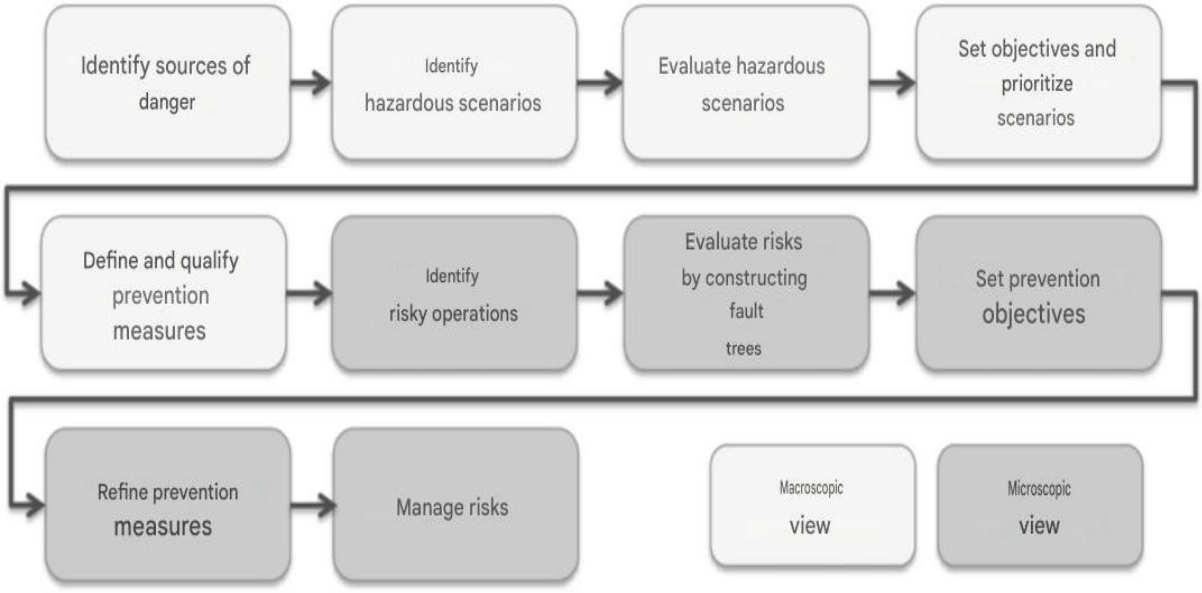


Figure II.2: Steps of MOSAR method [9].

VI.4. "What If" Method:

The "What If" method is an inductive method. For relatively simple processes, the operating procedure is reviewed. At each step, the question is asked what would happen if a particular malfunction occurs, and the answer is provided by describing the effects of equipment failures or procedural errors on the occurrence of damage.

For more complex processes, the method uses a checklist to cover all malfunctions and divides the work so that the study of certain phases is entrusted to those with the greatest experience or skill in assessing these aspects. It is quite similar to the HAZOP method, but requires a certain level of expertise from those who use it.

All these methods are, in fact, very similar. The important point to remember is the value of a dual approach: deductive, starting with damage, and inductive, starting with triggers, for a more comprehensive inventory of possible hazardous events **[10]**.

VI.5. Preliminary Risk Analysis: (PRA)

PRA is a general method used during the design phase of equipment, installations, or projects, particularly in the chemical industry. It initially requires identifying hazardous elements, which can include chemicals, fluids, equipment, and operations. PRA then seeks to identify all hazardous situations generated by these elements by imagining chains of events, ultimately leading to preventive measures. It therefore shares clear similarities with the method developed in this book **[10]**.

VI.6. Bow-Tie method:

More precisely, the bow tie method combines a fault tree and an event tree, respectively positioned upstream and downstream of a Central Feared Event. Since the fault tree relies on an inverse deductive method, while the event tree results from a direct inductive method, the bow tie method combines both deductive and inductive approaches.

The central point of the bow tie, the Central Feared Event (CFE), represents either a loss of containment for a finite object or a loss of physical integrity for a solid (for example, decomposition). The left side of the bow tie is a fault tree used to identify the causes generating the Central Feared Event. The right side is an event tree that determines the

consequences of the Central Feared Event. Safety barriers are represented by thick vertical bars, illustrating their role in preventing the unfolding of accident scenarios. It is therefore possible to visualize each potential path of an accident scenario from its initial causes to its final consequences on the targets **[8]**.

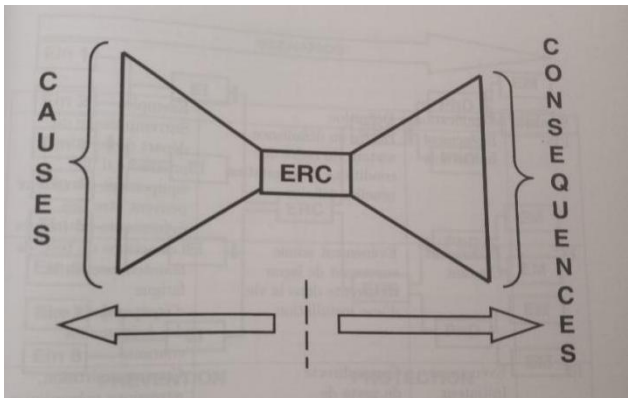


Figure II.3: Schematic diagram of a Bow-Tie [6].

VI.7. LOPA method:

VI.7.1. Definition:

The principle of the LOPA method consists, after the essential preliminary step of a classic qualitative risk analysis (HAZOP, risk trees, etc.), of quantifying the occurrence frequencies of initiating events (Ei) and the probabilities of failures associated with each layer of protection to assess the risk **[8]**.

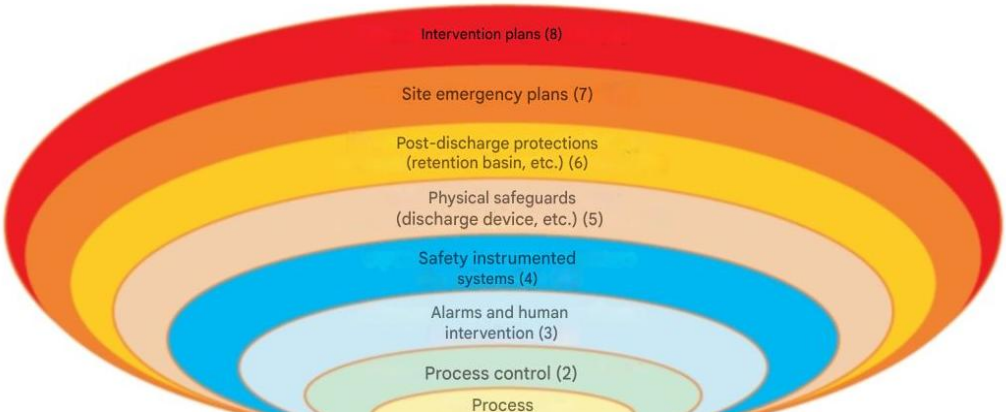


Figure II.4: Different protective layers according to LOPA [12].

VI.7.2. Steps of LOPA method:

The LOPA method is structured in seven steps **[12]**:

• Definition of risk acceptability criteria (e.g., maximum tolerated frequency for a given consequence).

• Development and selection of a representative accident scenario.

• Identification of the initiating event (primary cause) and estimation of its frequency.

• Identification of independent protection layers (IPLs) and estimation of their probability of failure on demand (PFD).

• Calculation of the frequency of the final consequence, after taking the IPLs into account.

• Evaluation of the residual risk by comparison to the defined tolerance.

• Decision-making: maintaining the current state, strengthening the IPLs, or implementing additional measures.

VI.7.3. LOPA advantages:

LOPA offers numerous advantages that explain its increasing adoption in the process industry **[13]**:

• Structured and rational method for risk assessment and decision-making.

• Simplicity and flexibility in analysis, while integrating quantitative elements (via PFDs, for example).

• Ability to quantify the effectiveness of each safety barrier and demonstrate its contribution to risk reduction.

• Time and cost savings compared to other more complex methods such as fault tree analysis.

• Adaptability to a wide range of scenarios, including those difficult to assess purely quantitatively.

VI.8. Failure Mode, Effects, and Criticality Analysis: (FMECA)

VI.8.1. History of FMEA(C):

Humans are always questioned about the consequences of tool or system failures, but the increasing complexity of systems has amplified the stakes, from ancient plows to 19th-century industrial furnaces and railways. In the 1950s and 1960s in the United States (nuclear, aeronautical), and then in Europe around 1970 (chemical, nuclear), reliability analysis methods emerged: preliminary risk analysis, FMEA/FMECA, fault trees, failure combinations, and probabilistic approaches. In the 1980s, the French automotive industry integrated FMEA into supplier contracts, popularizing the method in other sectors despite sometimes inappropriate adaptations. Today, reliability affects all areas (industry, consumer goods, software); FMEA is central, integrated into ISO 9000 standards and standardized (e.g., NF EN 60812 of 2006), with specific standards in the automotive industry and among certain large groups **[11]**.

VI.8.2. Definition:

The FMEA(C) method aims to identify all failure modes that could affect the system under study. Its scope extends beyond safety to encompass other areas such as quality. It is primarily applied to sub-assemblies identified based on their importance within the system. The method consists of **[5]**:

- Identifying all possible failure modes for each component of the sub-assembly under study
- Defining an ordered ranking of these failure modes according to their associated risks
- Proposing risk reduction measures by prioritizing the failure modes that generate the most significant risks
- The method leads to formalizing the entire process in a two-dimensional matrix: "probability - criticality" for the failure modes studied

VI.8.3. Importance of FMEA(C):

The FMEA(C) is more effective than the guide by its object if it follows a strict norm. She identifies internal system deficiencies in order to evaluate risks and propose solutions.

These general benefices include **[5]**:

- Assess the gravity of these situations and the risks global
- Identify and prioritize the weaknesses of the system
- Expect the correct maintenance.
- It values the modifications of conception or preventive maintenance.
- Adapt operations, measures, and prioritize maintenance/operation rules
- Integrate multidisciplinary expertise.

VI.8.4. Conditions for Success in FMEA(C):

FMEA(C) is most relevant when the following conditions are met **[5]**:

- It is necessary to be able to decompose the entire system under study into components with a level of detail such that all the failure modes that can affect each component can be associated with it.
- It is necessary to understand the system's operation in order to describe what happens when a component's failure mode appears and to trace the chain from cause to effect.

Under these conditions, FMEA(C) will be carried out optimally and produce the expected results!

It is crucial to firmly combat the widespread illusion that, in the presence of a poorly understood system or one that appears to us as a "black box," FMEA(C) would be a welcome precaution. An FMEA(C) on a system whose operation is unknown is a trap. If the aura of the method inspires confidence in such circumstances, it is deceptive. Like any method, FMEA(C) uses information, it does not create it from nothing **[5]**.

VI.8.5. Areas of Application:

FMEA(C) is particularly relevant when applied to mechanical and/or analog systems. It also applies well at a functional level (the term "component" has been used consistently here to designate the basic elements of the decomposition, both in the domain of functions and that of physical objects).

It is not readily applicable to software as such, but a software-specific method has been developed in the spirit of FMEA: AEEL (Analysis of Errors and their Effects on Software) **[5]**.

VI.9. Hazard and Operability Study: (HAZOP)

A HAZOP study is a highly disciplined procedure that identifies 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 malfunctioning potential of individual components of an equipment, and the consequential effects on the facility as a whole. This method's success lies in its strength in analyzing a system's Piping & Instrumentation Diagrams (P&IDs), breaking the design into manageable sections with definite boundaries called nodes, so as to ensure the analysis of each equipment piece in the process.

A small multi-disciplinary team undertakes the analysis, whose members should have sufficient experience and knowledge to answer most questions on the spot. The members are selected carefully, and are given the authority to recommend any needed changes in the design.

Executing the method relies on using guidewords (such as no, more and less) combined with process parameters (e.g., temperature, flow, pressure) that aim to reveal deviations (such as less flow, more temperature) of the process intention or normal operation (guideword + parameter = deviation). This procedure is applied in a particular node as a part of the system characterized for a nominal intention of the operative parameters. Having determined the deviations, the expert team explores their possible causes and their possible consequences.

HAZOP is useful to apply to systems that involve human performance and behavior or any system that involves hazards that are hard to quantify or detect. On the other hand, HAZOP does not take into account the cognitive ability of human as of why they would commit an unsafe act, which is a weakness of HAZOP. Thus, HAZOP analysis is not standardized worldwide; hence, the analysis is performed differently with variation in results for the same system. Moreover, HAZOP study does not take into account the interaction between different components in a system or a process, and it also can be lengthy, time consuming and expensive.

However, HAZOP is time consuming. According to one evaluation, for a process with many P&ID ranging from simple or complex drawings, a team of five people led by an

experienced team leader needs more than 400 man-hours for the finalization of the HAZOP analysis, and the overall spent time is about 8 weeks. So, an automated analysis is helpful in reducing time, minimizing the errors and can be used as an aid for human expert **[14]**.

Table II.2: Example of a table for HAZOP.

Key word	Parameter	Causes	Consequences	Severity	Likelihood	Risk	Recommandations

Table II.3: A comparative table between a group of risk analysis [15].

Detailed Name	History	Area of Application	Definition, Objective	Key Principle	Specificity, strengths and weaknesses
PHA: Preliminary Hazard Analysis **PRA:** Preliminary Risk Analysis		Industrial Installation, transportation system, technological product, equipment	Identify all risks at the highest (macroscopic) level Define safety objectives by: - identifying relevant feared events - identifying more detailed analyses required If necessary, recommend initial measures	Identifying hazardous entities, hazardous situations, potential accidents, and their effects **-PHA:** Prioritization based on severity **-PRA:** Prioritization based on probabilities and severity >Prior development of grids characterizing these parameters for the problem posed	Inductive analysis to be conducted upstream to prioritize and sort (funnel effect) events Formalization using a table outlining the steps of the approach Different approaches: -functional -external aggression towards the system or vice versa -based on a list of feared events (the inductive character is then less pronounced)
FMECA: Failure Mode, Effects, and Criticality Analysis	1950s, US Military Domain	Product, Process, Means	Systematic Analysis Method: - Identify the risks of system malfunctions and their equipment -Investigate their consequences	Failures are prioritized according to their overall influence on the system, the process, the customer... are all critical. This can be expressed by a single	Inductive analysis Formalized using a table. Material/functional approach Horizontal consistency of severity is sometimes difficult to establish

			(effects) and origins (causes) -Evaluate and prioritize the risks associated with these	parameter or a combination of parameters such as severity and occurrence (the concept of risk), but also detection, the ability to recover from a situation, and parameters specific to the particularities of the study. A rating table must be defined for each of these parameters.	when it requires considering several parameters simultaneously Cumbersome management for complex systems Does not highlight potential combinations between failures
HAZOP: Hazard and Operability Study or Hazard and Operability Analysis or Hazard and Operating Conditions Study	Early 1970s *Imperial Chemical Industries*	Study or extension of fluid conveying systems, such as installations Thermo-hydraulics Method applied in the chemical	Systematic review of the design and operating principles based on: (1) identifying all causes of deviations in the various operating parameters (2) analyzing the consequences related to these deviations. This allows us to study: (3) the corrective or protective measures to be implemented, if necessary.	Critical examination, based on guide words - Do not, No, More, Less, Incomplete - of variations in key parameters, their Causes and Consequences	Inductive Analysis Formalized by a table Simplified analysis because there is no systematic study of each component and its failure modes; but difficulty in assigning/decomposing the system. Is it exhaustive? No study of deviation combinations

		industry			
FTA: Fault Tree Analysis		Any system or piece of equipment where the technical component is dominant, complex, and the level of detail of the component is sufficiently known.	Detailed and exhaustive determination of the various mechanisms (events, failures, and their combinations) leading to the occurrence of a feared event.	Identification, through successive stages, of the direct causes leading to the higher-level event. Logical tree representation using AND and OR gates.	Deductive Analysis Highlighting all combinations of events leading to a feared event. An effective tool for calculating the probabilities of occurrence of feared events (software exists for this purpose). A practical means of analyzing and evaluating the consequences of a design change.
ETA: Event Tree Analysis		Industrial Installations	Study, starting from an initial event, of the propagation and the various subsequent events that result from it, particularly with regard to the functioning or non-	Development of a logical tree presenting two paths at each stage depending on the success or failure of the safety measures (technical and organizational	Inductive Analysis Analysis of both the operation of technical devices, particularly automated ones, and the application of procedures. Allows the temporal

			functioning of prevention, compensation, alarm, and safety systems.	barriers).	dimension to emerge. This method is cumbersome due to the rapidly increasing number of combinations and is therefore reserved for limited subsets of a more complex system. Requires the ability to identify a unique order in which safety barriers are activated.
Bow Tie Diagram	Implemented in countries with a probabilistic approach to risk management (e.g., Netherland) and particularly in industrial	Industrial Installation, Transportation System, Technological Product, Equipment	Identification of a range of scenarios associated with a central feared event and representation of safety barriers. opposing the development of an accident scenario	Combination of a failure tree and a consequence tree around a central feared event, which generally corresponds to a loss of containment or a loss of physical integrity.	Combination of inductive and deductive approaches Concrete visualization of a range of scenarios. Highlighting the action of the safety barriers, contributing to strengthening the demonstration. Time-consuming to develop (requires the prior implementation of other tools such as APR, FMEA, and ADD), therefore best reserved for cases requiring such a high level

	activities stemming from the oil sector.				of detail.

Conclusion:

After identifying the most important methods of risk analysis used in chemical and petrochemical plants, it became clear that there is no way to do without them due to their great importance in maintaining the continuity of production as well as increasing it, in addition to preserving the lives of workers and industrial facilities and equipment.

CHAPTER III:

HAZOP & automated HAZOP

Introduction:

The HAZOP (Hazard and Operability Study) method was originally developed by Imperial Chemical Industries (ICI) in 1970, mainly for application in the chemical industry. HAZOP analysis is a relatively complex qualitative procedure for systematically investigating failures in continuous processes. This study relies on the development of questionnaires focusing on the effects of deviations from normal parameters (temperature, flow rate, pressure, composition, etc.). This methodology requires multidisciplinary teamwork. The experience gained during its development is difficult to formalize; current expertise is limited to the methodology for allocating responsibilities for its application **[10]**.

Despite the effectiveness of the conventional HAZOP study, it causes time consuming, labor-intensive, expensive, and heavily reliant on human judgement. To address these challenges, intelligent systems and different levels of automation have been developed, including knowledge-based approaches that use domain-specific rules, and expertise and data-driven models that identify potential hazards from historical data patterns **[19]**.

I. HAZOP: (Hazard and Operability Study)

I.1. Definition:

The HAZOP method is designed to assess process-related risks and is therefore particularly well-suited to the chemical industry, especially with regard to the risks of uncontrolled reactions. It involves selecting a specific system, identifying all the factors that affect it, and studying all potential deviations.

This methodology is recommended for risk analysis of any new project involving the installation of new units and/or the expansion or redesign of existing facilities. This methodology requires up-to-date knowledge of fluid diagrams and/or piping and instrumentation diagrams (P&IDs, PFD) **[8][10]**.

I.2. The principle of the HAZOP:

The principle of the HAZOP method is the use of "guide words" to systematically search for deviations from the design intent. To facilitate the review, a system is divided into parts

(subsystems, also called "nodes") so that the design intent can be adequately defined for each one. The size of the chosen part varies according to the complexity of the system and the severity of the hazard. It is small for complex systems or those presenting significant hazards. For simple systems or those generating minor hazards, using large parts reduces the study time. The design intent for a part of a system is formulated based on the elements that possess the essential characteristics of the part and represent its natural divisions. The choice of elements to examine is, to some extent, a subjective decision since several combinations can lead to the desired outcome. The elements of the system can be discrete steps or phases of a procedure, individual signals and entities of a control system, equipment or components of a process or electronic system, etc.

It is important to clearly identify the origin, function, and output of the node, for example, using the following terms: input material from a specific source, operation on a material, output product(s) transported to a destination. The design intent of a node will therefore include the following elements: materials, activities, sources, and destinations, which can be considered as node components. It is also useful to define the components in terms of quantitative or qualitative characteristics. For example, in a chemical system, the "material" component can be defined in terms of characteristics such as temperature, pressure, and composition. For the "transport" component, characteristics such as speed or passenger capacity might be relevant. For computer systems, information rather than materials will be considered in each component.

The HAZOP team examines each element (and, where applicable, its characteristic) to look for deviations from the design intent that could lead to undesirable consequences.

To identify these deviations, they use a question system that incorporates predefined "guide words."

The role of a guide word is to stimulate the imagination, focus the investigation, and generate ideas and discussions, thereby increasing the likelihood of a comprehensive study **[16]**.

Table III.1: HAZOP method procedures [16].

Phases	Procedures
Phase 1: Definition	**1.** Determine the scope and objectives **2.** Select the team and define responsibilities
Phase 2: Preparation	**3.** Draw up the study plan **4.** Gather the data **5.** Agree on the reporting method **6.** Establish a timeline
Phase 3: Review	**7.** Design description • Divide the system into parts (nodes) • Select a part and define the design intent **8.** Identify the guide words and parameters to be examined and the applicable deviations **9.** Perform the review • Identify the deviation with the guide words on each parameter • Identify the probabilities, consequences, and causes • Check if there is a significant problem • Identify the safety barriers (protection, detection, and signaling mechanisms) • Identify proposed improvements • Agree on the actions to be taken Repeat according to the parameter-first sequence or the guide word-first sequence
Phase 4: Evaluation and documentation	**10.** HAZOP Worksheet • Record the review • Assess the risks **11.** HAZOP Study Report • Sign the documentation • Monitor the implementation of the measures • Re-examine parts of the system • Prepare the final report

Table III.2: HAZOP guide words meaning [16].

GUIDE WORD	MEANING
DO NOT	Total negation of the design intent
MORE	Quantitative increase
LESS	Quantitative decrease
IN ADDITION TO	Qualitative modification/decrease
INVERT	Logical opposite of the design intent
OTHER THAN	Total replacement
EARLIER	Relative to time
LATER	Relative to time
BEFORE	Relative to an order or sequence
AFTER	Relating to an order or sequence

I.3. Purpose of a HAZOP Study:

The main objective of a HAZOP study is to detect and assess any hazards that may still exist in a planned process or operation, especially those that were not identified or eliminated during earlier design stages. These hazards can affect people, equipment, and property, both within and outside the site, and may also have environmental impacts. Regardless of their nature, most hazards can lead to financial losses.

In addition, HAZOP studies are commonly used to identify important operability and quality issues, which are often included as key objectives. According to a survey conducted among EPSC members in 1999, more than 90% considered significant operability problems within the scope of HAZOP studies. These issues may result from equipment reliability or the way the plant is operated, leading to consequences such as downtime, equipment damage, and financial losses due to wasted or off-spec products that require reprocessing or disposal.

The importance of quality considerations depends on the type of industry, but in some cases, it is essential. Many operability problems are closely linked to hazards, making their identification and control even more important.

Furthermore, HAZOP studies should also address maintenance activities, such as equipment isolation, preparation, and removal, as these can introduce both hazards and

operability challenges. When manual tasks are involved, it may also be necessary to evaluate ergonomic aspects to ensure safe and efficient operations **[17].**

I.4. Limitation of use:

Several challenges can arise during a HAZOP study, particularly when the scope or terms of reference are not clearly defined. It is important to remember that a HAZOP is not intended to serve as a design review or redesign session. However, some recommendations may still lead to modifications in the design, especially when issues are identified within the expected operating conditions.

HAZOP studies are generally qualitative in nature. That said, basic risk evaluation techniques are increasingly applied to support decision-making regarding whether corrective actions are necessary and what form they should take. In certain cases, more detailed quantitative methods, such as Quantitative Risk Assessment (QRA), may be required. These analyses are typically carried out separately from the HAZOP sessions.

It is also important to note that HAZOP is not a flawless method capable of detecting every possible hazard or operational issue. The effectiveness of the study depends heavily on the expertise and experience of the team involved. Other factors influencing the outcome include the quality and completeness of the available information, the defined scope, and how the study is conducted.

Even with a structured, creative, and thorough approach, some risks may remain unidentified. Moreover, the value of a HAZOP study ultimately depends on the implementation of the recommended actions. Without proper follow-up and execution, the study itself will not achieve its intended purpose **[17]**.

I.5. Advantages and disadvantages:

The following table summarizes a range of advantages and disadvantages of the HAZOP application:

Table III.3: Advantages and disadvantages of HAZOP application [18].

Advantages	Disadvantages
• The method can identify operating problems as well as hazards. • Due to the structured approach, there is a high probability of identifying the hazards. • A wide range of hazards can be assessed, including chemical, mechanical, electrical, control and human interaction. • New and novel processes can be investigated. • The team gains a deep understanding of how the process is likely to operate. • Much better operating procedures can be written after the study. • There can be a financial payback from a faster start-up, fewer operating problems and increased reliability.	• The high resource requirements, both in manpower and data. • The need for a multidisciplinary team and an experienced leader. • The need to carry out the study during a narrow window in the project life. • Great care must be taken if a plant or section is treated as a repeat of one studied previously as two systems are seldom truly identical

I.6. HAZOP applications:

Although the HAZOP method was originally developed for new process designs, it was quickly extended to cover plant modifications and the review of existing installations. It is applicable to both continuous and batch processes. Conducting a new HAZOP after a certain period is recommended to ensure that all interactions resulting from modifications have been properly assessed. This is also important when new process knowledge becomes available and needs to be integrated.

HAZOP can be applied to a wide range of situations, including computer-controlled processes, repeated or standardized designs, plant commissioning, and even small-scale pilot

plants or laboratory operations. In principle, it can be used for any system where a conceptual model and a clear design intention can be defined. By systematically identifying deviations, the method helps reveal potential issues.

The method can also be adapted for computer systems, although the parameters must be adjusted. Similarly, when performing a Procedural HAZOP that includes human factors, a modified approach is required.

Many industries benefit from HAZOP, such as chemical, petrochemical, oil and gas (onshore and offshore), pharmaceutical, manufacturing, food, water, and transport sectors.

It is also important to mention the preliminary HAZOP, which is carried out during the FEED (Front-End Engineering Design) phase. This early analysis helps eliminate common issues before moving into detailed design and the full HAZOP study, often using a checklist approach **[18]**.

II. Automated HAZOP:

II.1. Definition:

Automated HAZOP uses software tools or information models (knowledge bases, code rules, dynamic simulations, etc.) to suggest potential deviations, link them to equipment and piping types, and generate draft HAZOP tables (point, process variable, routing word, deviation, possible cause, outcome, measures). Some tools are used in the early design phases and incorporate dynamic simulations to accelerate scenario generation and analyze the impact of disturbances on the system **[19][20][21]**.

II.2. Necessary steps to make an automated HAZOP:

The need to reduce time and effort consuming and human dependencies has been increased over the years for more efforts to improve the performance of the HAZOP application. Therefore, automation of HAZOP studies has been a research topic for more than 30 years. Basically, automated HAZOP is concerned with four main tasks (1) creating a digital representation of the process plant to automatically identify potential hazardous events, (2) data pre-processing, (3) knowledge representation to transform data and information into

machine readable knowledge and (4) reasoning system to infer conclusions regarding cause-and-effect fect relationships and identify consequences **[19]**.

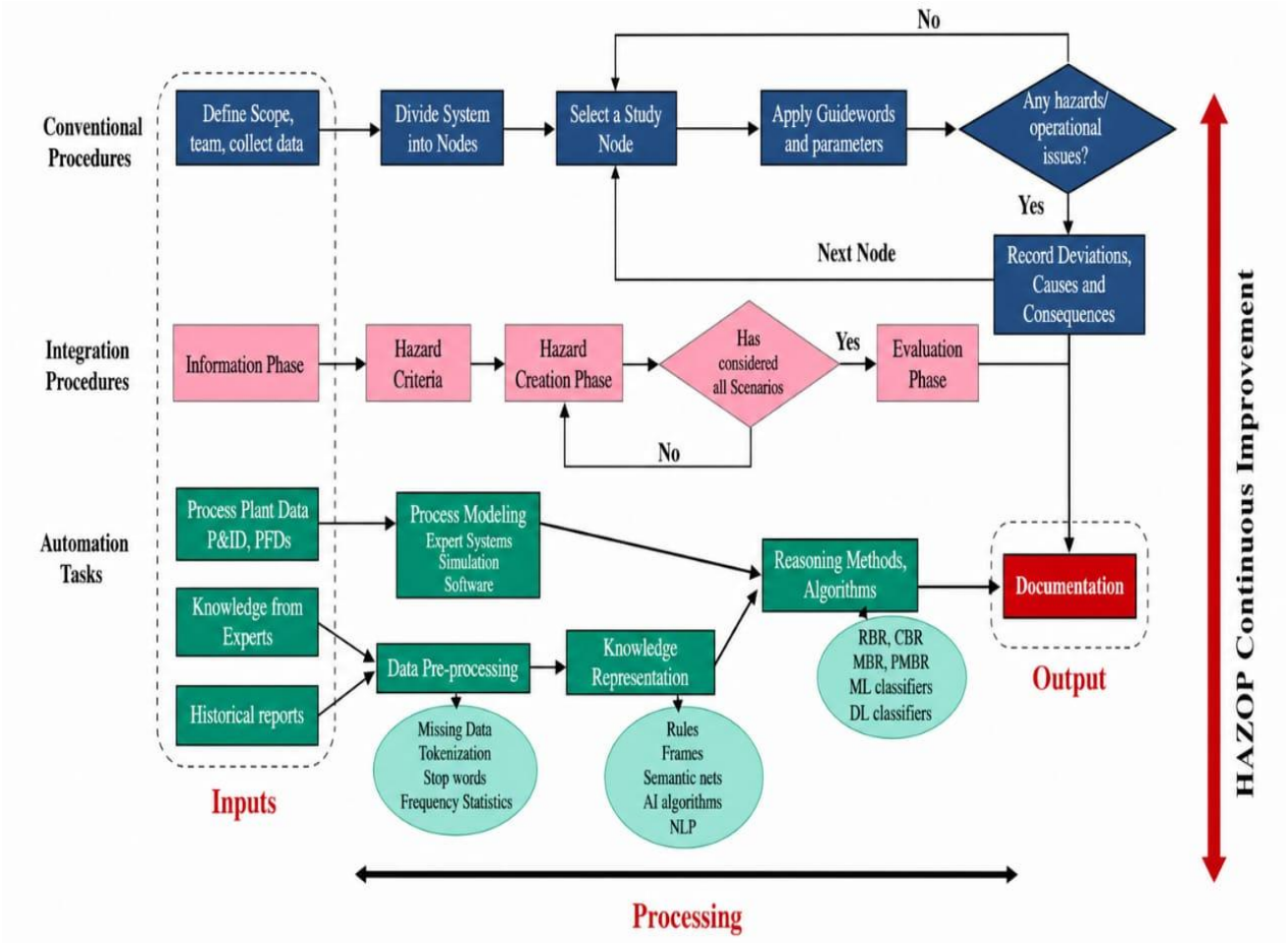


Figure III.1: HAZOP framework (transition from conventional to automated procedures)[19].

II.2.1. Inputs:

The main inputs for traditional HAZOP methods consist of data from the processing plants being analyzed and the expertise of the participants in the analysis process. Data analyzed in HAZOP workshops typically includes pipe and instrument diagrams (P&IDs) and process flow diagrams (PFDs), which contain the design and engineering details of the plants. Participants contribute their knowledge of processes, equipment, variables, causes and effects, and safety procedures, drawn from their experience. These components, along with HAZOP reports from previous projects, have been used to automate various aspects of the HAZOP process, with the aim of streamlining operations, reducing time, and minimizing reliance on human intervention.

II.2.2. Process Modeling:

The process plant must be digitally represented to identify potential hazardous events. Many different design representations were used by process designers to describe a process such as PFD, P&ID, Block flow diagram, Flow sheet, Functional block diagram, Cause and effect diagram (shutdown matrix), Isometric, Engineering data sheet.... ete. Often, the process plant is represented using data from P&IDs or PFDs, and qualitatively modeled by listing nodes manually or using a specific modeling language and a graphical editor. Some approaches are based on graph theory which use a higraph-based modeling representation and require the usage of graphical editors to draw a schematic process plant using a specific modeling language such as LDGHAZOP, MFM HAZOP Assistant and D-higraphs HAZOP Assistant, while methods provide their own graphical editor to model the process. Based on the review in these relevant studies, these methods have challenges. For example, PFD shows only major equipment relationships. P&ID symbols are not to scale and not dimensionally accurate and do not represent physical locations and proximity of each component. Other systems are time consuming and error-prone, making it more expensive than conventional HAZOP. Other approaches integrate hazard identification into CAD software or process simulators. Simulation and software tools enable engineers to create virtual representations of the plant processes in HAZOP studies, allowing them to simulate various scenarios and analyze the potential hazards associated with each scenario. For instance, the usage of data models that can be extracted from CAD software or process simulators could be done by exporting an XML. file which includes all process plant components, connections and instrumentation. Afterwards, this plant representation is processed by the computer aided HAZOP systems (CAHS) and serves as a data basis. This is challenging since objects need to be translated since structure of systems, e.g. CAD software and CAHS, can be very different. Furthermore, this translation process can cause confusion between objects.

II.2.3. Data Preprocessing:

In text analysis and data mining-based methods, prior to classification and conversion of text into numerical form, data pre-processing is essential. This involves several steps, Initially, missing data imputation is conducted to address common occurrences of missing data, which can significantly affect conclusions drawn from the data. The treatment of missing data can be roughly divided into three categories: not processing, direct deletion, and filling in

the cluster processes of HAZOP data, blank cells were filled using t I using the word 'None", aiding cluster analysis. Subsequently, word segmentation is employed to divide written text into meaningful units, such as words or sentences. Following this, stop words filtering is applied to remove non-essential words like adverbs, adjectives, and conjunctions. The vectorization and word frequency statistics are computed to calculate and record the frequencies.

II.2.4. Knowledge Representation:

Knowledge representation involves the transformation of data and information into machine readable knowledge. The quality of the knowledge representation directly influences the inferred results. Therefore, time and effort are required in the thoughtful design of the knowledge representation. Some approaches address this subject superficially. To provide added value to the HAZOP team, solid knowledge regarding safeguards and safety concepts based on sound process safety knowledge is required within the knowledge representation of automated systems. There are various formalisms for knowledge representation, such as rules, semantic nets, frames and Bayesian networks, ontologies and recently NLP strategies. Rules are formulated to model relationships. The semantic context of strict rules is difficult to map, so there must be a male for every single relationship, while the context cannot be illustrated. In semantic-nets, knowledge is stored using graphs, where nodes represent objects while the edges (connections) represent the relationships between the objects. Frames can be used to represent stereotypical situations, hut frames lack formal semantics, which means that there is no explicit notation to illustrate the meaning of the knowledge. This can lead to ambiguity. Ontologies can be time-consuming and error-prone, making them more expensive than conventional HAZOP studies. Equipment cannot always be accurately modeled, and ontologies require complicated design. To be used for HAZOP automation, ontologies must be carefully established and documented. As a probability-based uncertainty inference method, Bayesian networks (BNs) have been adopted extensively to characterize the uncertain interrelationships of various factors, including two steps: establishing the network structure, and calculating network parameters. For the network structure, the risk factors characterized by nodes and the interrelationships represented by directed arcs need to be identified first. The joint probability distribution is used to characterize the probable relationships among the nodes. Based on the prior probability value of the root node and the conditional probability of the intermediate the intermediate nodes, the occurrence probability of the target node can be

predicted. Building BNs requires expert knowledge to specify the network structure and define prior probabilities, which can be subjective and difficult to elicit. Recently, NLP techniques have been applied in HAZOP study, including traditional methods and advanced algorithms and topic modeling. to enable the reasoning systems to infer conclusions.

II.2.5. System Reasoning:

To automatically reason potential hazardous events within HAZOP study's conclusions, cause-and-effect relationships or consequences need to be identified based on the knowledge representation. The process of inferring conclusions is called reasoning presented in his review four main reasoning approaches: rule-based, case-based, model-based qualitative and quantitative, and process-history-based. In rule-based reasoning, rules must be accurately aligned with problem information, the strategy fails if rules do not fir. The case-based reasoning method is a pattern-based problem-solving method. Knowledge about past situations (cases) is utilized to reuse it in new situations, which means it is a memory-based process. In case-based reasoning (CBR), a significant number of cases are necessary for practical results, thus, this method's quality depends on the size of stored data. Model-based quantitative reasoning is based on mathematical models expressed using differential-algebraic equations (DAEs). Model-based qualitative reasoning is concerned with the inference of conclusions in a symbolic manner, without using mathematical relationships. Another major group of reasoning techniques is (process) history-based reasoning, where historical process data is analyzed to draw conclusions regarding potential hazards. The predictions made by history-based reasoning method depend on the process data's reliability. Classified reasoning techniques as inductive, deductive, or abductive. Knowledge-based and data-driven reasoning can be distinguished. While knowledge-based reasoning can be divided into Bayesian, deductive and analogical reasoning, data-driven reasoning is usually inductive. Building Bayesian networks involves creating probabilistic models that represent the dependencies between different variables and Bayesian reasoning can manage uncertainty and probabilistic relationships but this depends on having extensive and reliable data to estimate probabilities, which can be time-consuming to gather and validate. Deductive reasoning starts from general facts and rules to derive conclusions, encompassing HermiT reasoner used to create ontology models which determines the relationship between a new concept and other concepts network and rule-based reasoning. On the other hand, analogical reasoning is based on heuristics to calculate similarity between a new situation and past cases, but the case-based reasoning

(CBR) effectiveness depends on the richness of stored cases or knowledge repository of past experiences. Recently, data driven reasoning techniques, including machine learning classifiers and deep learning models have been applied to identify patterns using training data to predict deviations and their corresponding countermeasures in HAZOP studies.

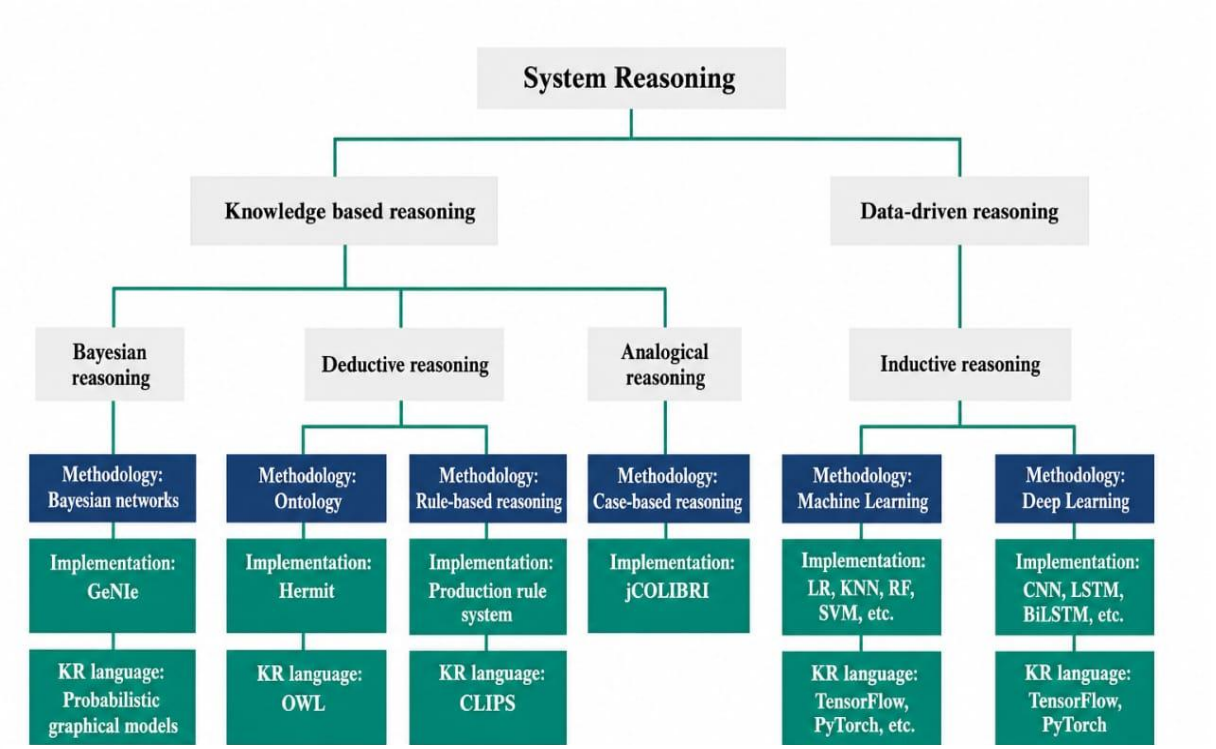


Figure III.2: Overview of reasoning technics used in HAZOP study within the research period [19].

II.3. Obstacles to automated HAZOP:

The main obstacles for the use of automated HAZOP are the fact that **[22]**:

1. Even for the licensed processes, due to limitations imposed by available plant area, different plant capacities, and application of different technology, the configuration of connected unit operations for each process plant is unique. To design an effective artificial intelligence algorithm, all very diverse tactile and untactile knowledge of the HAZOP team should be standardized. This can be achieved hardly through the predefined rule sets.

2. HAZOP is a social process in which engineers and operators interact, jointly contribute to safety, achieve consensus and jointly take responsibility. Automated HAZOP will only be

useful to work for HAZOP teams if it supports all these functions or at least does not get in the way of any of them.

Conclusion:

Currently, factory workers should use automated HAZOP, which can diagnose hazards just like a traditional HAZOP study, except that the latter is time-consuming, requires a lot of effort, is expensive, and depends heavily on human judgment, unlike the automated one, which reduces effort and time, and thus increases production.

CHAPTER IV:

Creating an automatic HAZOP using MATLAB software

We will apply the automatic HAZOP study to the atmospheric heater 10-F1 A/B of unit 10 in Skikda refinery.

I. System description:

Preheated crude oil is partially vaporized in two parallel furnaces (10-F-1A/B). The vaporized crude exits via a common transfer line to the flash area in column C1.

Each furnace has eight passes with individual flow control and a balancing system to ensure a uniform outlet temperature of 356°C. The outlet temperature is measured and controlled by indicators and thermostats, and fuel is controlled using a cascade system.

The two furnaces are equipped with 32 burners fueled by natural gas or refinery gas, with gas pressure monitoring systems. The furnace also includes a low-pressure steam superheater (up to 505°C) used in stripping operations, with a desuperheater to reduce the temperature to 330°C **[23]**.

The furnace is equipped with multiple safety systems to cut off fuel and acid gases in emergencies such as **[23]**:

• Severe drop in flow through passages

• Severe rise in outlet temperature

• Severe rise in combustion chamber pressure or temperature

• Fuel line shutdown

Oxygen monitoring in the flue and indicators for combustion gas temperature and pressure are also provided at various points. Utilities include low and medium pressure steam, air, and service water, along with dedicated systems for decoking the pipes.

II. Main risks:

- Temperature runaway

- Conflagration

- Explosion

- Coke formation due to poor feed flow (supplying a large amount of heat to a small amount of feed)

- The interruption of fuel gas combustion process i due to an increase in the amount of air.

Based on these risks, we can deduce a set of deviations that we will study.

Some important points:

- The maximum temperature at which the heater turns off: 370 C (It will be puted in block)
- The minimum feed flow for which the heater will be puted in block: 45 m/h in each pass
- The proportion of air inside the oven should be around 3.5 %

III. HAZOP application:

Guide words: more, less, no.

Parameters:

1- Flow:

- Fuel gas flow
- Pilot gas flow
- Feed flow
- Air flow

2- Temperature (inside heater)

3- Pressure:

- Heater internal pressure
- Fuel gas pressure

4- Level (inside the preflash drum)

Company: Skikda refinery RA1K

Facility: Atmospheric heater 10-F-A

Node: Pass A

Parameter: Flow

Table IV.1: Extended HAZOP sheet for flow parameter.

Guidewords	Deviation	Causes	Consequences	Safeguards	Recommendations
No	No feed flow	- The valve FV 2A malfunction to close fully. - The valve FV 2A-1 malfunction to close fully. - Perturbation in the up stream units	The empty coil receives an unsustainable quantity of heat, which, when feed is present, is divided into two parts: one part is absorbed by the feed and the other by the coil. This leads to a rise in the temperature of the empty coil, causing it to expand. - Coke formation	- Flow indications in the pass is provided FE/FT 2A-1 and FIC 2A - Skin temperature are provided TE/TI 150 - FSLL 2A on FT 1551 to provide I-1551 - I- 1555 is provided.	Install ZSL/ZSH 2A on FV 2A to confirm her position in case it fails to close.

	No fuel gas flow	- The valve FV 1559 malfunction to close fully. - The strainer Y malfunction to removing impurities. - Perturbations in the upstream unit.	- The burner will be put off - Possibility of perturbation in distillation process column because of the low temperature on the heater outlet.	- Fuel gas flow indication is provided FAL on FI-1551 - Fuel gas pressure indication is provided PT/PI 1552 PT/PI 1553 - Plugging detection is provided PDT 1551 - I-1551 is provided to close UV-1562 and UV-1563	- Install FIC on FG line - Add FALL on FI-1551 - Install ZSC/ZSO-1562 on UV-1562 and ZSC/ZSO-1563 on UV-1563 to confirm their positions in case their closure fails.
	No pilot gas flow	- The strainer Y malfunction to removing impurities.	The burner will be put off witch can lead to problems in distillation process because of low feed temperature.	- Pilot gas pressure indication is provided PAL on PI 2555 - I- 1556 is provided to close	- Install PALL on PG line to close UV-2551, UV-2552, UV-1552 and UV-1563 upon low low PG pressure -Install

				UV-2551	ZSC/ZSO-2551 on UV-2551 and ZSC/ZSO-2552 on UV-2552 to confirm their positions in case their closure fails.
	No air flow	The dampers or stack damper malfunction.	- The temperature inside the heater will increase. - The combustion process to light the burner does not occur because of the absence of one element of the fire triangle.	- FAL on FIC-65 (air flow must be 3,5 %).	
More	More feed flow	- The valve FV 2A malfunction to open fully. - The valve FV 2A-1 malfunction to	- Increased pressure inside the coil. - The crude arrives to C1 at a low temperature.	- FIC-2A and FE/FT 2A-1 flow indications is provided. - PT/PI 1566 pressure indication is provided. - Valves PSV-1551 A	- Install ZSL/ZSH 2A on FV 2A to confirm her position in case it fails to open - Add PAHH 1566 and FAHH 2A

		open fully.		PSV-1552 A opening is provided.	
	More fuel gas flow	- The valve FV 1559 malfunction to open fully.	- The fire in the heater may be put-off. - Feed temperature increase.	- PAH is provided with FG pressure indications PT/PI 1552 and PT/PI 1553. - FAH is provided with FG flow indication FI 1551. - I- 1555 is provided to open UV-1562 and UV-1563.	Add ZSC/ZSO-1562 on UV-1562 and ZSC/ZSO-1563 on UV-1563 to confirm their positions in case they fail to open. - Add FAHH 1551 on FI 1551
	More air flow	- Unnecessary opening of the stack damper. - The dampers or stack damper malfunction.	- The burner ignites but doesn't heat up. - The temperature inside the heater will decrease.	- TAL on TI-87 is provided. - FAH on FI-66 and FAH on FIC-65 are provided.	

	More pilot gas flow	Flame detector malfunction if the flame goes out.	Pilot gas accumulation witch may lead to an explosion.	- PAH on PI-2559 A/B/C - I- 1557 is provided to close UV-2552	- Install FT/FI 2559 with FAH 2559 -Install ZSC/ZSO-2551 on UV-2551 and ZSC/ZSO-2552 on UV-2552 to confirm their positions in case they fail to open.
Less	Less feed flow	The same as above for No feed flow - Presence of a plugging inside the pipe.	The same as above for No feed flow	The same as above for No feed flow	The same as above for No feed flow
	Less FG flow	The same as above for No FG flow	- The burner does not provide the necessary heat for heating, and it can be put-off. - Possibility of perturbation in distillation process column because of the low temperature	The same as above for No FG flow	The same as above for No FG flow

			on the heater outlet.		
	Less PG flow	The same as above for No PG flow	The same as above for No PG flow	The same as above for No PG flow	The same as above for No PG flow
	Less air flow	- Insufficient stack damper opening. - The dampers or stack damper malfunction.	The burner does not ignite.	- FAL on FIC-65 air flow indication is provided.	

Company: Skikda refinery RA1K

Facility: Atmospheric heater 10-F-A

Node: Pass A

Parameter: Temperature

Table IV.2: Extended HAZOP sheet for temperature parameter.

Guidewords	Deviations	Causes	Consequences	Safeguards	Recommendations
More	More temperature inside the heater (convection and radiation zones)	TV-1551 malfunction to open fully.	- Coil dilation - Temperature runaway witch can cause fire or explosion - Pressure increase - Coke formation.	- TE/TI 150 temperature indication is provided. - TAH on TE/TI-48 - TAH on TIC 40 temperature indication and control is provided. - I-1553 is provided to open dampers. - I-1559 is provided.	- Install TAHH on TIC-40 to trip the heater upon high high temperature - TV-1551 should be equipped by limit switch ZSL/ZSH 1551 to confirm her position
Less	Less temperature inside heater	- TV-1551 malfunction to close fully.	The arrival of the feed at the column C1 with a low temperature witch leads to	- TAL on TIC 40 - TE/TI 150 temperature indication is	- The stack damper should be equipped by a limit switch

	(convection and radiation zones)	- The stack damper malfunction to open fully.	process perturbation.		ZSL/ZSH - TV-1551 should be equipped by limit switch ZSL/ZSH 1551 to confirm her position - TALL on TIC-40 should be added

Company: Skikda refinery RA1K

Facility: Atmospheric heater 10-F-A

Node: Pass

Parameter: Pressure

Table IV.3: Extended HAZOP sheet for pressure parameter.

Guidewords	Deviations	Causes	Consequences	Safeguards	Recommendations
More	More fuel gas pressure	- FV- 1559 malfunction to open fully. - TV-12 malfunction to open fully.	- Fire put-off because of high pressure in the burner. - Distillation process perturbation because of higher temperature effected by the high pressure.	- PT/PI 1552 FG pressure indication is provided. - FI 1551 FG flow indication is provided.	- Add PAHH to open UV-1562 and UV-1563 upon high high FG pressure.
	More pressure inside the heater	- PV-1551 malfunction to open fully. - Dampers are	- Possibility of explosion. - Damage to heater.	- PT/PI 1551 pressure indication is provided. - TE/TI 150 temperature indication is provided.	Add PAHH to open PV-1551

		malfunction to close.		- Valves PSV-1551 A PSV-1552 A opening is provided.	
Less	Less fuel gas pressure	- FV- 1559 malfunction to close fully. - TV-12 malfunction to close fully. - Perturbation in the upstream unit.	- The burner will be put-off - Perturbation of distillation process.	- FAL on FI-1551 - PT/PI 1552 FG pressure indication is provided. - I-1551 is provided to close UV-1562 and UV-1563.	
	Less pressure inside the	The stuck damper is malfunction to open.	Pressure will fall and temperature will decrease, so, process perturbation.	- PT/PI 1551 pressure indication is provided. - TE/TI 150 temperature indication is provided.	

Company: Skikda refinery RA1K

Facility: Atmospheric heater 10-F-A

Node: Preflash drum 10-V-15

Parameter: Level

Table IV.4: Extended HAZOP sheet for level parameter.

Guidewords	Deviations	Causes	Consequences	Safeguards	Recommendations
More	More level inside the preflash drum	LV-1551 malfunction to open fully.	The crude is not heating to the required temperature due to the large quantity that entered the heater.	LT/LI 1551 level indication is provided.	- Add LAHH on LT/LI 1551 - Install ZSL/ZSH on LV-1551
Less	Less level inside the preflash drum	LV-1551 malfunction to close fully.	Damage to coil because the crude stops entering the heater.	- LAL on LT 1551 - LALL on LT1551 to activate I-1554	
No	No level inside the p. drum	LV-1551 malfunction to close.	As above for Less level	LALL on LT1551 to activate I-1554	

IV. Dynamic simulation:

After conducting a traditional HAZOP study, the results (recommendations) of the study become the program inputs, which are in the form of signals sent from programmer logic controller to distributed control system, to display the cause of the deviation directly to the operator. We can resume this procedure in a cause and effect table for dynamic simulation.

Table IV.5: Cause and effect table for dynamic simulation.

Deviation	Causes-Digital inputs	Display
No feed flow Less feed flow	ZSH-FV 2A	Valve FV 2A malfunction to close fully
More feed flow	ZSL-FV 2A **AND** PAHH 1566 **OR** ZSL-FV 2A **AND** FAHH 2A	Valve FV 2A malfunction to open fully

No FG flow Less FG flow	ZSO-UV 1562 **AND** FALL 1551	Valve UV-1562 malfunction to close
	ZSO-UV 1563 **AND** FALL 1551	Valve UV-1563 malfunction to close
More FG flow	ZSC-UV 1562 **AND** FAHH 1551	Valve UV-1562 malfunction to open
	ZSC-UV 1563 **AND** FAHH 1551	Valve UV-1563 malfunction to open
No PG flow Less PG flow	PALL-2555 **AND** ZSO-UV 2551	Valve UV-2551 malfunction to close

	PALL-2555 **AND** ZSO-UV 2552	Valve UV-2552 malfunction to close
More PG flow	ZSC-UV 2551 **AND** FAH 2559	Valve UV-2551 malfunction to open
	ZSC-UV 2552 **AND** FAH 2559	Valve UV-2552 malfunction to open
More temperature inside the heater	TAHH-40 **AND** ZSL-TV 1551	TV-1551 malfunction to open fully.
Less temperature inside the heater	TALL-40 **AND** ZSH-TV 1551	TV-1551 malfunction to close fully.

More FG pressure	PAHH 1552 **AND** **NOT** ZSC-UV 1562	The valve UV-1562 malfunction to open.
	PAHH 1552 **AND** **NOT** ZSC-UV 1563	The valve UV-1563 malfunction to open.
More pressure inside the heater	PAHH 1551	The valve PV-1551 malfunction to open fully.
More level in the preflash drum	LAHH 1551 **AND** ZSL-LV 1551	The valve LV 1551 malfunction to open.

V. Results and discussions:

V.1. HAZOP study:

After a thorough review of the P&ID for the 10-F-1A atmospheric heater and applying the HAZOP methodology to the four parameters (flow, temperature, pressure and level), we analyzed them using the three guide words (no, more, less). This analysis yielded a comprehensive set of potential deviations that could occur at the pass A of the heater. Our analysis revealed that the most critical deviation is the absence of feed flow (No feed flow), which directly leads to the heating of the empty coil, resulting in excessive thermal expansion, coke formation, and a risk of cracking. This necessitates multiple, integrated safeguards for detection and rapid intervention.

It is important to note a fundamental methodology we employed throughout the preparation of these tables: distinguishing between existing safeguards and proposed recommendations. Every safeguard listed in the safeguards column is a tool or system already present on the P&ID, while every proposed recommendation is a genuine addition that addresses an actual vulnerability in the protection system and does not duplicate existing safeguards. This distinction is a fundamental quality standard that cannot be compromised in any professional HAZOP study.

It is also noteworthy that most of our recommendations focus on installing limit switches (ZSL/ZSH/ZSC/ZSO) on critical valves. The purpose of this is to obtain confirmation of the actual valve position, rather than relying solely on the control signal, which may indicate a command issued to the valve without verification of its actual execution. Furthermore, high high (FAHH, TAHH, PAHH, LAHH) or low low (FALL, TALL, PALL, LALL) alarms are added where only first-level alarms (FAL, TAL, etc.) are available to ensure differentiation between alarm states and critical states requiring immediate shutdown.

The recommendations we have proposed will play a pivotal role in the next stage: building the cause-and-effect table for the dynamic simulation.

V.2. Dynamic simulation:

The cause-and-effect table represents the true bridge between a completed traditional HAZOP analysis and the automated system being built in MATLAB. This table translates the

results of qualitative analysis into a numerical logical language that the program can understand and execute.

The principle behind the table is simple in concept yet profound in application: each deviation has a unique numerical signature. That is, each specific cause generates a particular combination of numerical signals from limit switches and/or alarms, and this specific combination distinguishes it from other causes. The automated system not only recognizes that a deviation has occurred but goes further to identify the exact component responsible for this deviation and presents this information to the operator immediately and directly.

In constructing the conditional logic for each deviation, we relied on three fundamental logical operations: AND, OR, and NOT. Each has a clear geometric meaning:

AND means that the cause is only confirmed by the simultaneous occurrence of two or more signals.

OR means that either signal is sufficient to confirm the cause, thus providing multiple possible states for the same deviation.

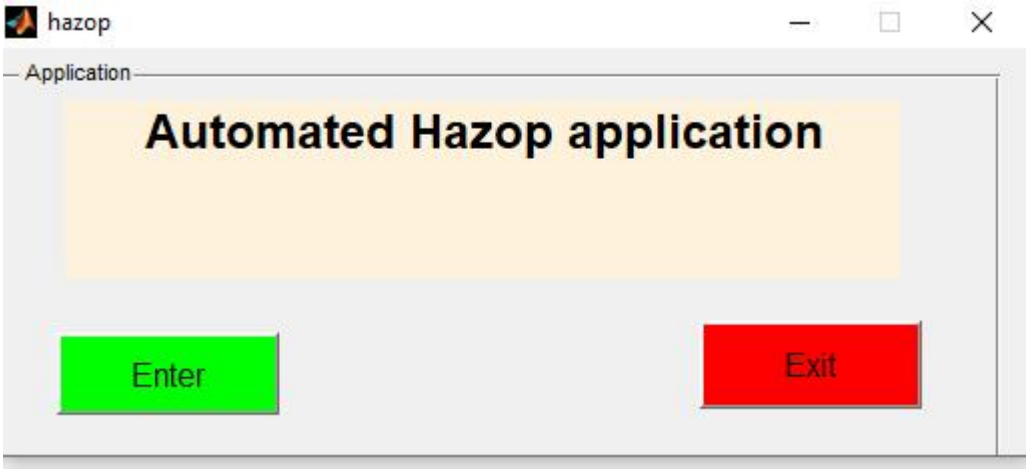
NOT adds a precise diagnostic dimension, distinguishing between a valve not responding and a correct response.

A key feature of this table is that previous HAZOP recommendations have been transformed into actual digital signals within the conditional logic. This demonstrates the organic link between the two operational phases and shows that each recommendation we proposed had a clear technical justification that would be implemented in the automated system. For example, the limit switches we recommended for installation on the valves (ZSL, ZSH, ZSC, ZSO) and the Level 2 alarms (FAHH, TAHH, PALL, etc.) have become key inputs in the conditional statement.

Regarding the limitations of this table, it should be noted that the system's diagnostic accuracy depends on the correctness of the incoming signals. If a measuring device fails and gives a false signal, the system may diagnose an incorrect cause. Therefore, regular maintenance and calibration of measuring devices are essential for maintaining the system's reliability. Furthermore, the table covers the deviations studied in HAZOP, and any new deviation not studied necessitates updating the table and revising the conditional logic.

VI. General structure:

The general structure of the program we aim to develop at the Graphical User Interface Development Environment (GUIDE) is as follows:



Conclusion:

In conclusion, the HAZOP study conducted on the 10-F-1A heater demonstrated that this facility has a good protection base, but it requires specific enhancements, which we have precisely identified in the recommendations column. These recommendations became the inputs of the cause and effect table, this table forms the cornerstone of the automated system implemented in MATLAB. It transforms what was previously a human decision made in a HAZOP session into a programmatic logic rule capable of making the same diagnostic decision in fractions of a second, around the clock, with a degree of consistency that a human alone cannot achieve.

General conclusion

General conclusion:

The work accomplished in this thesis represents the initial step toward developing an automated HAZOP system-the project we intend to pursue and refine in the future.

Chapter One is not merely an introductory overview of the refinery; rather, it served as a conceptual roadmap addressing a fundamental question: Why this specific refinery, and why is this particular furnace the subject of study?

The answer is clear: given its immense scale, interconnected units, complex processes, and high operating temperatures and pressures, the refinery harbors significant inherent risks. Furnace 10-F-1A represents the hottest point in the entire system, operating at temperatures exceeding 350°C and feeding the primary distillation unit. Any malfunction here could result in a total production shutdown or, in a worst-case scenario, an industrial catastrophe.

This underscores the necessity for the specialized HAZOP analysis and automation strategies explored in the subsequent chapters of this thesis.

The second and the third Chapters demonstrated that the HAZOP method is the most suitable approach, as it operates directly on P&IDs, covers the entire system systematically, simultaneously identifies causes, consequences, safeguards and recommendations, and is internationally recognized as an industry standard. Its only drawback is the time-intensive nature of the process - precisely the issue we aimed to resolve through automation.

Automated HAZOP is neither science fiction nor an off-the-shelf solution; it is an ongoing research journey, and this thesis represents a modest yet sincere practical step in that direction.

The primary objective of this thesis was to take the first step toward creating an automated HAZOP system: converting HAZOP outcomes -specifically the recommendations- into programmable digital logic. Furthermore, we developed a diagnostic system that translates signal patterns into causes understandable to the operator.

Ultimately, we conclude that automated HAZOP is not a substitute for the human expert, but rather a digital extension that frees up their energy for creative thinking and ensures continuous, round-the-process diagnosis.

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