# HAZard and OPerability Study Analysis as a Semi-Automatic Approach

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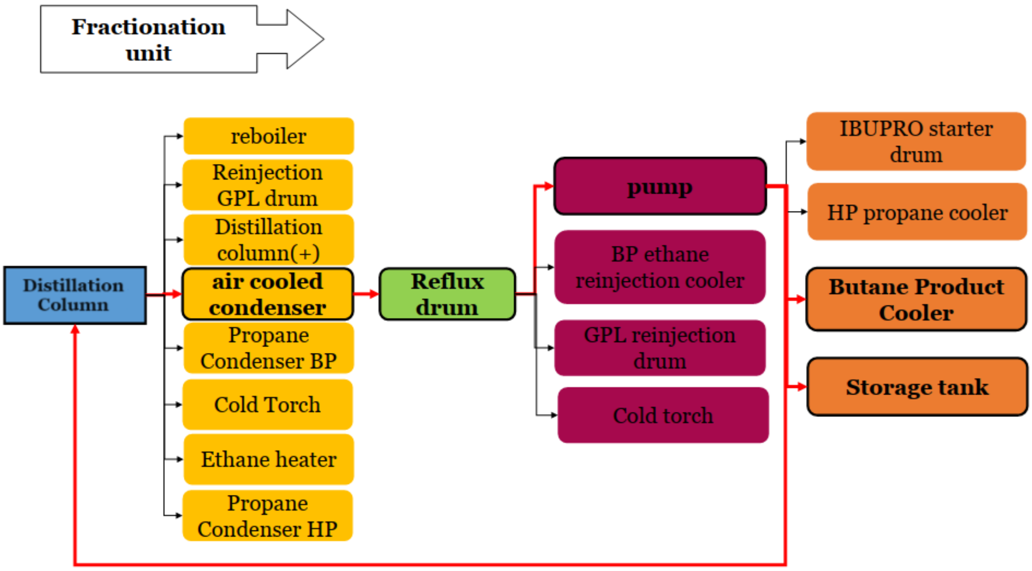

**ABSTRACT:** Risk analysis is crucial in industrial conception. HAZOP is the top risk analysis method for the oil and gas sector. This paper presents a semi-automatic method to address HAZOP's limitations and produce automatic results. The method uses a knowledge base, initially filled with gas liquefaction data, and is enhanced with subsequent case studies. An inference engine processes this data to conduct a HAZOP study. Propagation rules identify potential deviation paths, enabling risk analysis and consequence prediction based on the knowledge base. This method uniquely illustrates deviation paths and introduces nodes along these paths for further study. The findings derive from dynamic knowledge of each system in the knowledge base and can be reviewed and amended by experts.

**الملخص:** تَحْلِيلُ المَخاطِرِ هُوَ مَرْحَلَةٌ حاسِمَةٌ فِي مَفْهُومِ الصِناعَةِ. HAZOP هِيَ الأُسْلُوبُ الرَئِيسِيُّ فِي تَحْلِيلِ المَخاطِرِ لِصِناعَةِ البتروكيماويّاتِ. تُقَدِّمُ هٰذِهِ الوَرَقَةُ نَهْجاً شِبْهَ تِلْقائِيٍّ لِمُعالَجَةِ قُيُودِ HAZOP وَإِنْتاج نَتائِجَ تِلْقائِيَّةٍ. يَسْتَنِدُ النَهْجُ إِلَى قاعِدَةٍ مَعْرِفِيَّةٍ مَبْنِيَّةٍ عَلَى بَياناتِ تَسْيِيلِ الغازِ وَمُحَرِّكٍ لِلِاسْتِدْلالِ. تُساعِدُ قَواعِدُ الِانْتِشارِ فِي تَوْضِيح مَساراتِ اِنْحِرافٍ مُحْتَمَلَةٍ، مِمّا يُتِيحُ تَحْلِيلَ المَخاطِرِ وَتَقْدِيرَ النَتائِج بِاسْتِخْدامِ قاعِدَةِ المَعْرِفَةِ. يَتَمَيَّزُ النَهْجُ بِوُضُوحِهِ فِي عَرْضِ مَساراتِ الِانْحِرافِ وَتَقْدِيمِ نِقاطٍ مُتَعَدِّدَةٍ لِلدِراسَةِ. النَتائِجُ مَبْنِيَّةٌ عَلَى المَعْلُوماتِ الدِينامِيكِيَّةِ لِكُلِّ نِظامٍ ضِمْنَ قاعِدَةِ المَعْرِفَةِ، وَيُمْكِنُ مُراجَعَتُها وَتَعْدِيلُها مِنْ قِبَلِ الخُبَراءِ.

***Keywords:*** Automated HAZOP analysis; Computer-aided; Digraph; LNG Risk; Ontology; Process safety.

**الكلمات المفتاحية:** تحليل HAZOP الآلي ؛ المساعدة الحاسوبية ؛ Digraph ؛ مخاطر الغاز الطبيعي المسال ؛ علم الأنطولوجيا ؛ عملية السلامة.

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*DOI: 10.53540/tjer.vol.20iss1pp52-72*

## NOMENCLATURE

| | |
|---|---|
| **Eq** | set of equipment |
| **Eqq** | set of equivalent equipment |
| **Eqi** | set of initial equipment |
| **Eqqi** | set of initial equivalent equipment |
| **Eq i+1** | set of next equivalent equipment |

## 1. INTRODUCTION

In the chemical industry, incidents and accidents of varying severity have resulted in significant human, economic, and environmental losses. To prevent such occurrences, risk analysis methods have been developed to identify hazards and assess the associated risks in industrial processes (Khan & Abbasi, 1998).

Three approaches; qualitative, semi-quantitative, and quantitative, can be used to estimate accident risk levels. The semi-qualitative approach, employing tools like risk matrices, risk graphs, LOPA (Layers of Protection Analysis), PHA (Process Hazard Analysis), FMEA (Failure Modes and Effects Analysis), and HAZOP, help identify hazards and potential failure events. (Dziubiński et al., 2006).

The results given by these approaches in the form of relevant risk categories lead to easy identification of different risk levels.

Qualitative and semi-qualitative approaches are primarily employed to assess the compliance of industrial processes with safety requirements outlined in regulations and international standards. These approaches focus on individual equipment components and establish minimum safety requirements for maintaining an acceptable level of safety. They involve classifying hazardous events based on severity and occurrence modes and assigning relevant probabilities (Sellami et al., 2018).

The HAZOP (Hazard and Operability study) method was initially developed for the chemical industry and later adapted for use in other sectors such as petrochemical, pharmaceutical, and nuclear industries. It systematically examines deviations in operating parameters to identify and assess their causes and consequences. HAZOP is especially valuable for analysing thermo-hydraulic system parameters crucial for installation safety, including temperature, pressure, and level.

In addition, HAZOP does not focus on components but on the flow propagation between components. (Khan & Abbasi, 1998).

Therefore, HAZOP enables the identification of accident scenarios and the study of prevention and protection measures with the expertise of a dedicated group. It necessitates a thorough, precise, and rigorous process description, and its effectiveness relies on the skills and knowledge of the experts involved. Collaborative expertise enhances the HAZOP review, leading to a comprehensive systematic analysis of installations, operations, or procedures (Ghasemzadeh et al., 2013; Royer & Royer. 2013).

However, HAZOP is still criticised due to its limitations (Baybutt, 2015), including keyword restrictions, extensive documentation requirements, and the inability to analyse combined failures. Therefore, does not ensure the appropriate propagation of the consequences of deviations throughout the process elements.

Considerable efforts have been made to study and address the limitations of HAZOP through automation and knowledge-based systems. These approaches aim to facilitate data access and develop comprehensive databases to support HAZOP studies (Cameron et al., 2017).

Researchers have shown great interest in integrating expert systems into various fields of technology, including chemical engineering, medical diagnosis, petroleum engineering, and financial investing. They aim to automate classic HAZOP studies by emulating human reasoning and problem-solving approaches.

In the mid-1980s, researchers began automating HAZOP using expert systems based on Prolog (Weatherill & Cameron, 1989) and a rule-based approach (Parmar & Lees, 1987). Venkatasubramanian and his group introduced digraphs to enhance graphical representation during HAZOP automation (Vaidhyanathan & Venkatasubramanian, 1996). Their work led to the development of PHASUITE, an automatic qualitative tool (C. Zhao et al., 2005) and the HAZOP Expert tool (1990-1998). Another knowledge-based system called SERO was developed by (Leone, 1996) to enhance the expertise and creativity of HAZOP study teams.

(Khan & Abbasi, 1997a) Developed OptHAZOP, a tool based on experience feedback that enables efficient management and organisation of HAZOP study databases. Building upon this tool, they further created TOPHAZOP (Khan & Abbasi, 1997b), an expert system consisting of a database, an inference engine and a graphical user interface (GUI).

In 2000, (Khan & Abbasi, 2000) developed EXPERTOP, an enhanced version of optHAZOP that improved the database and graphical user interface (GUI). However, EXPERTOP had a limitation in tracking deviation propagation within the system(Rahman et al., 2009). To address this, Rahman et al. developed ExpHAZOP+, an extension of optHAZOP that enables deviation propagation to downstream equipment items in a process plant, incorporating the knowledge base concept from optHAZOP.

To improve the learning capability of HAZOP expert systems, a learning HAZOP expert system called PetroHAZOP has been developed by (J. Zhao et al., 2009), based on the integration of Case-Based Reasoning (CBR) and ontology, which can help to automate "non-routine" HAZOP analysis. In this context, further studies on the ontological approach have been carried out by (Wang et al., 2009) and (Chong-guang et al., 2013). Also, the integration of graph theory to identify the relationships between process equipment was presented by (Lü & Wang, 2007) and (HU et al., 2009). Far from that, (Zhou et al., 2020) studied the deviation duration as an essential analysis factor in the quantitative HAZOP intelligence analysis.

The literature review highlights the unresolved limitation of failure consequence propagation within the process. To address this, our work introduces a semi-automatic tool based on an expert system. This tool combines a new rule-based reasoning approach with graph theory to track deviation consequences in the process. It ensures the expert's input in modifying results that may not align with the specific process being studied. The paper is structured as follows: Section 2 presents the general methodology of semi-automated HAZOP, Section 3 discusses a detailed case study of an LNG process plant, and Section 4 concludes with final remarks and perspectives.

## 2. SEMI-AUTOMATED HAZOP METHODOLOGY AND STRUCTURE

Experts need a lot of data, information and knowledge about the process configuration when applying the classical HAZOP to industrial substructure processes, each of which includes the categories that fall under it, and it is necessary to identify all the equipment processes, the composition of the systems and the operating conditions. These elements can help to build a complete base that can be used to conduct the HAZOP analysis and generate all the results by developing an inference engine to generate reliable and practical results. In this step, the expert's role is to check the compatibility of the data and to correct the generated errors if they exist.

In this work, we present a novel approach that is represented in Fig. (1), where it's based practically on the detailed study of the equipment that composes a chemical process and all possible connections between them, a set of data and information must begin the study, which can be defined by covering the following elements:

- The type of equipment (pressure, thermal)
- Functional parameters (pressure, flow)
- Deviations of each parameter (‘’more pressure”, ‘’less flow”)
- Causes/consequences of each deviation
- Possible connection with other equipment (pump, compressor)

To carry out the production of market-oriented goods, industrial processes are often equipped with many interconnected operational flow units and distributed computer control systems that operate in a series of chemical, physical, electrical, or mechanical steps (Zhu et al., 2018). In HAZOP analysis, each unit is composed of nodes, where each node is composed of a set of interconnected equipment.

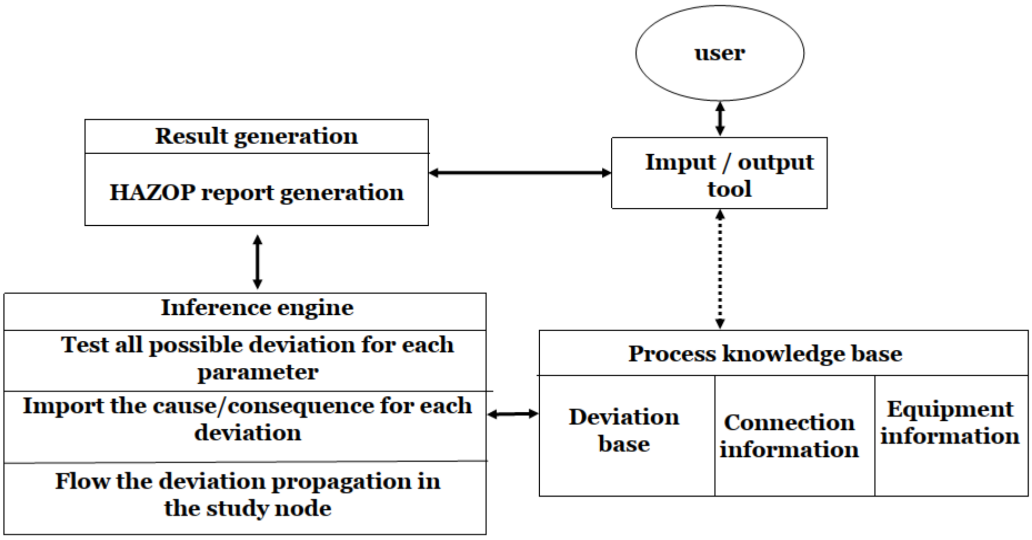

**Figure 1.** Structure approach (Rahman et al., 2009).

Following this approach, we can have all the possible configurations between the equipment that make up a well-defined process. These configurations are created following the possible connection study of each equipment set that composes a node. The combination of each equipment connection information gives us several possible node configurations that are specified by the first and last equipment. The different node configurations can help us to facilitate the HAZOP automation by facilitating the node creation and the selection of a node to perform a HAZOP analysis. This approach helps us to perform a HAZOP analysis by going beyond the classical HAZOP limitations. In this study, we have tried to simplify and reduce the complexity of the HAZOP analysis. This complexity is shown much more precisely in the configuration process and the node under study. Therefore, we tried to create a simple node to make the analysis easier and clearer. After selecting the node, the HAZOP analysis is performed in several steps, where each step represents a new system state. We studied in each state a combination of only two equipment sets at the end of the node. Each equipment set (i) is denoted by (Eqi).

As shown in Fig. (2), each of the two sets of combinations of actual equipment generates an imaginary equipment set. It has been called "equivalent equipment Eqq"; it contains the data union of the two sets. Furthermore, it represents the data generated by the influence of Eqn-1 on Eqn. This concept helps us to simplify the node as much as possible, using a rule set that ensures node rearrangement by preserving its functionality and connections.

The general structure of this semi-automatic approach consists of two key elements: a knowledge base and an inference engine.

### 2.1 Knowledge base

In a general approach, a knowledge base contains information about the process under study and a rule base. In this study, we develop our approach for the natural gas liquefaction process. This data has been collected from previous HAZOP studies, Process Flow Diagrams (PFD), Piping and Instrumentation Diagrams (P&ID) and expert studies. The hierarchy of this knowledge base is shown in Figure (3). This knowledge base consists of two main parts:

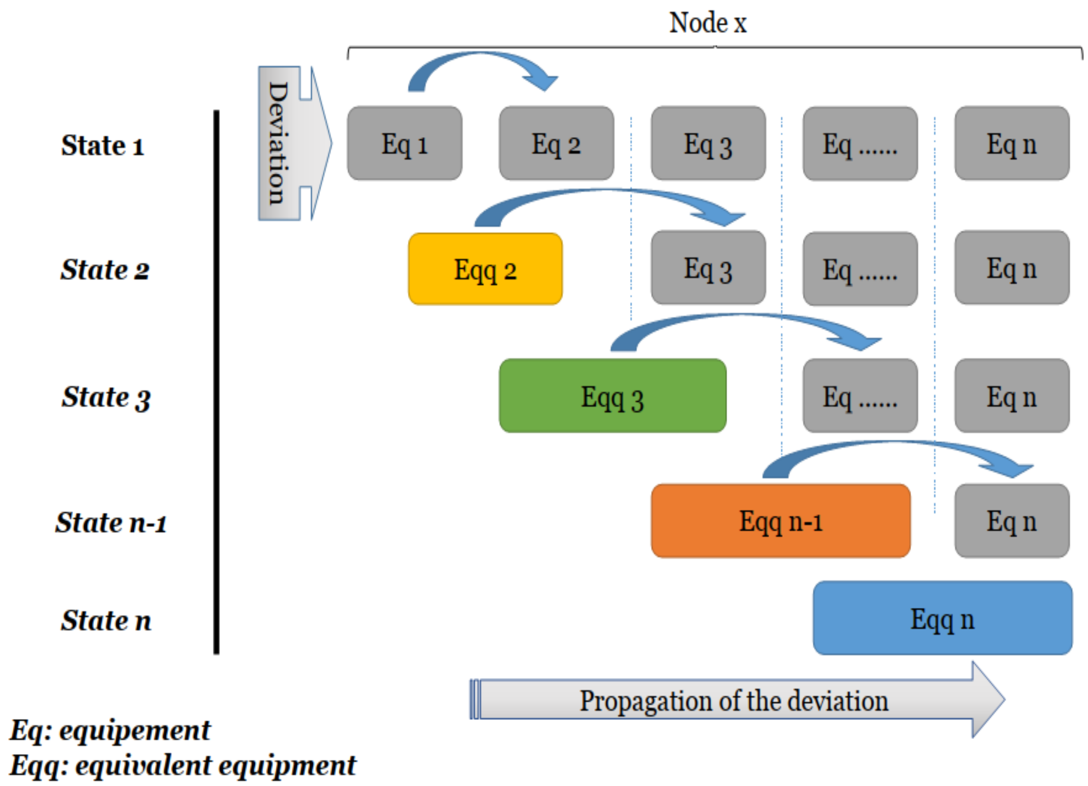

**Figure.2**. semi-automatic HAZOP methodology configuration.

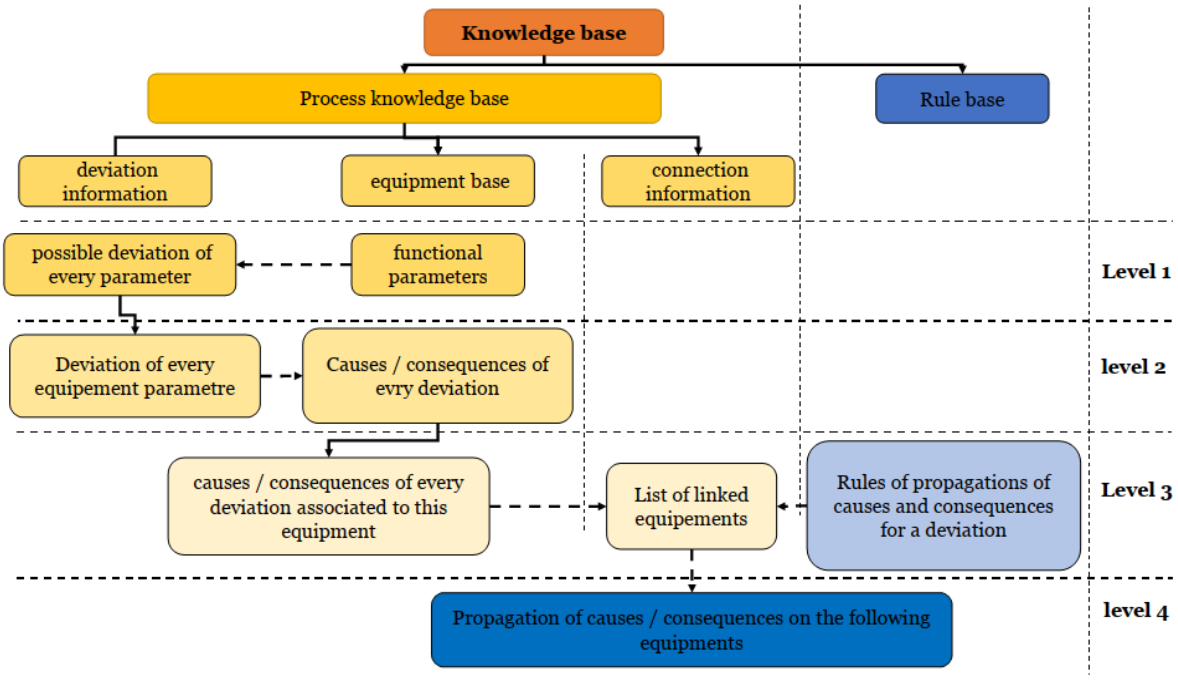

**Figure 3.** Knowledge base hierarchy.

### 2.1.1 Process Knowledge Base

The process knowledge base must consist of all the process information for the node under study, as shown above. We create a process knowledge base. To create this knowledge base, various unit information was collected and added to this knowledge base, such as:

- Type of equipment and unit configuration that compose a process,
- Equipment constituted,
- The connection between the equipment,
- Connection between units. A unit can be defined as a set of equipment.

An industrial process consists of a set of equipment connected to each other.
Where each piece of equipment has a piece of probable equipment that it can be attached to.
All the information about the equipment that makes up the process is arranged in the equipment base.

For example, in the LNG process, this base contains information about a lot of equipment (22 pieces of equipment) installed in the LNG process. This equipment is a distillation column, tank, valve, regeneration column, HP propane cooler, IBUPRO expansion flash tank, cryogenic heat exchanger, air-cooled condenser, cooler, reflux tank, flare, purge column, hot oil furnace, LNG loading arm, storage tank, reboiler, HP propane condenser, MR suction tank, pump, compressor and gas turbine.

For the LNG example, there are 12 units of natural gas processing and utilisation systems such as feed gas conditioning, decarbonisation, fractionation, dehydration, mercury removal, liquefaction, hot oil storage, cooling water system, hot oil system, propane circuit, external propane refrigeration, and fire water system.
This process knowledge base contains two types of information.

The first considers the equipment information that makes up the system under study, while the second shows the probable connections between the equipment of each process unit under study.
Once these data are obtained, we proceed to the classification phase, where each piece of equipment is associated with one or more units according to the PDF and P&ID analysis.

In addition, for each unit, every relationship of any equipment with other equipment is listed.
After understanding the relationship between these data, we obtain some information that characterises the process.

This process knowledge base consists of three parts:
Equipment Base:
An industrial process is composed of equipment that differs by its nature and the number of operating parameters that characterise it.
Figure (4) below shows the different types of parameters found in the industry.

**Table 1.** Set of possible deviations for each parameter (Royer & Royer, 2013)

| parameter keyword | Pressure | Temperature | Flow | Volume | Concentration | Level | Contamination | Viscosity | Composition |
|---|---|---|---|---|---|---|---|---|---|
| **More than** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **Less than** | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| **No** | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| **Other than** | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 0 | 1 |
| **earlier** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Before** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Later** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **After** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **Also** | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| **In part** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| **reverse** | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |

**1**: A possible combination

**0**: a not possible combination

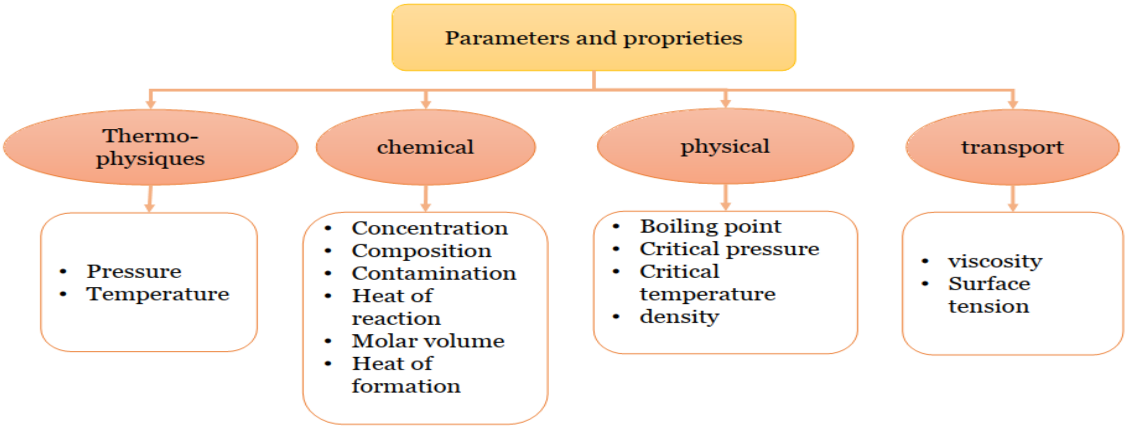

**Figure 4.** Classification of different parameters and proprieties (Jaksland et al., 1995)

## Deviation information

The definition of possible deviations is an essential and delicate step in performing a HAZOP analysis. A deviation is composed of a keyword and several parameters, so to build this base, we need:

- A list of all keywords in a HAZOP study.
- A list of parameters used

The combination of these two items gives us a general list of all probable deviations, as shown in Table 1. Where "1" indicates a possible combination between the parameter and the corresponding keyword, which can potentially create a deviation. It suggests that when the parameter aligns with that specific keyword, a deviation may occur in the system.

Conversely, "0" represents no possible combination between the parameter and the keyword. In this case, there is no association between the two, and therefore, no deviation is expected to arise. These keywords or guidelines have an interpretation.

For example, gave an interpretation of the guidelines and used it to generate the operational deviation. Fig. (5) shows the structure of the equipment base, where each piece of equipment is represented as a set that is composed of the following data:

- Set of operating parameters of this equipment.
- Set of deviations of each parameter.
- Set of causes/consequences of each deviation. These are divided into two categories.

## Cause set/specific consequence

The causes that originate from the equipment itself (breakdown, overheating, etc...) have generated a deviation, which is called a 'specific cause set'.

The consequences produced by these or other causes only affect the normal operation of this equipment. Where they do not cause a deviation or malfunction in the following equipment, they are called "specific consequences".

## Generic cause/generic consequence

Causes that cause a deviation in the equipment but are not caused by that equipment. In general, they are the consequence of the previous equipment deviation created by the deviation propagation. We call them "generic causes".

The consequences of a deviation can propagate and cause another deviation on the other equipment connected to the equipment where the deviation is displayed. We call them "generic consequences".

These causes and consequences are collected after a thorough study of each piece of equipment separately.

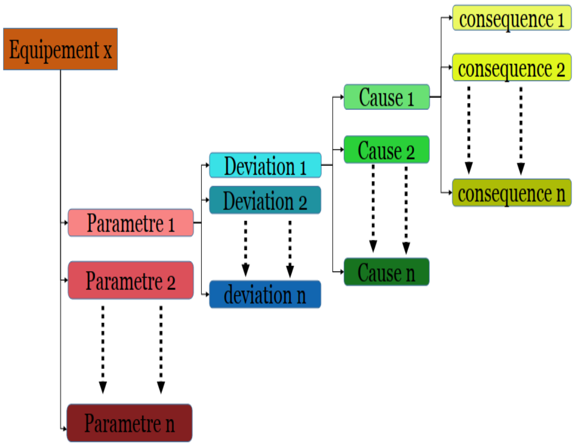

**Figure 5.** Structure of the equipment base.

### Connection information

The industrial process is composed of units that allow the generation of a final product, and each piece of equipment is connected to another to build the whole production system.

Where equipment can be connected to one or more other equipment.

This connection can be different for the same equipment depending on the functionalities of each process unit. Therefore, we need to add this connection information to the process knowledge base.

This information contains all possible equipment connections in different units.

In the final configuration of this equipment, the connection is called a node in the HAZOP study. In addition, this connection information helps us to generate all possible nodes that can be formed from a number of pieces of equipment.

This connection information is collected from the various PFD and P&ID processes, where it is structured in the proposed form in Fig. (6). These connections are classified according to the number of times a device is related to the same device in different units. This classification helps us to choose a study node based on the degree of connection between two pieces of equipment. Where the system can automatically define several nodes, starting with the equipment that has a high degree of connection.

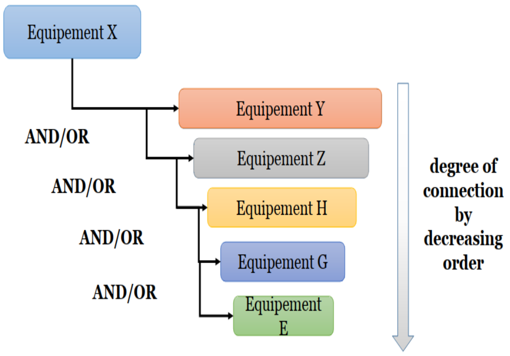

**Figure 6.** Basis of probable connections of an equipment .

### 2.1.2 Rule base

The most important point in an automated HAZOP study (via the expert system) is the deviation propagation in a selected node. Or the influence of the causes/consequences of the equipment Eqi on the following equipment in the node. For this, we propose a generic rule that organises the propagation of the deviation throughout the node.

According to our approach, any two-equipment connected set (Eqi and Eq i+1) is considered as an equivalent equipment set (Eqqi) (equivalent equipment i) that contains the information of both devices. Thus, we obtain the following relation (Eq 1):

$$\mathrm{Eqq(n)} = Eqq(n-1) \cup \mathrm{Eq(n)} \qquad (1)$$

According to Fig. (2), the deviation propagation in a node is performed in steps, where each step represents a system state under study. These states are shown in Fig. (7) and are given below:

**State 1:** is the initial state of the node after a deviation occurs in the first set of equipment. In this state, we will have the set cause/consequence of this deviation of the first equipment set.

**State 2:** In this state, the mismatch is propagated from Equipment 1 to Equipment 2. Here, we obtain the relationship between the two sets of equipment Eqq2. The equipment (2) will be affected by the generic consequences of the deviation represented in the equipment (1).

These consequences will cause a deviation for equipment 2. We call them "the Eq2 cause set". Moreover, equipment two will be influenced by the causes of this deviation when it is represented on itself.

From a theoretical point of view, the data that will be constructed for the equivalent equipment set Eqq2 are:

- The total cause (Cs) of the deviation on the equipment 1.
- All the consequences (Cq) of the deviation on the equipment 1.
- The whole cause of the deviation in the equipment 2.
- All the consequences of the deviation of the equipment 2.
- The set of generic consequences of Equipment 1 will be presented as causes for the deviation on Equipment 2.

For that, we will have the following relation:

$$\mathrm{CsEqq_2} = \mathrm{CsEq_1} \cup \mathrm{genericCqEq_1} \qquad (2)$$

First, the following relationship (eq 3) represents the constitution of all the consequences of the deviation on the equivalent equipment eqq2:

$$\mathrm{CqEqq2} = \mathrm{CqgenEqq_1} \cup \mathrm{CqspecEqq_2} \qquad (3)$$

In general, the propagation of a deviation in a well-defined node is ensured by the following rules:

$$\mathrm{CsEqqn} = \mathrm{CQg\acute{e}nEqq(n-1)} \cup \mathrm{CsEq(n)} \qquad (4)$$

$$\mathrm{CqEqqn} = \mathrm{Cqg\acute{e}nEq(n)} \cup \mathrm{CqEq(n)} \qquad (5)$$

These rules are applied to the two successive equipment connections using an inference engine that ensures this application. Once the process knowledge base is created, an inference engine is programmed according to the rules and a precise propagation equation. These rules can ensure the propagation of the deviation in the node as well as in the process in general.

### 2.2 Inference Engine

The inference engine of an expert system is its brain. Its role is to manage the data contained in the knowledge base. In order to ensure the propagation of deviations in a node, a set of rules has been provided to define the connection between equipment sets and the equipment that follows them. The node is defined by the user or automatically. The inference engine imports the data from each equipment set and combines it with the data of the following equipment set according to the given rules.

For more precise results, we have added a search by forward chaining to ensure the propagation of consequences in the node. Back chaining can be used in case we want to check if the cause of a consequence exists in our root cause (Rahman et al., 2009).

The program of the inference engine, as well as the forward chaining, is programmed using the PYTHON language (Anaconda 2.7).

To facilitate the graphical representation of the connection between the equipment, we used graph theory. After selecting the data and equipment, a representation of the nodes in the form of a digraph is provided by the system. This plays a role in the purpose of simplifying the node. This representation allows us to represent the data flow paths between the equipment sets. For this, we used the library "Networkx" of Python.

## 3. SEMI-AUTOMATIC METHODOLOGY

This semi-automatic reasoning, shown in Fig. (8), consists of three important steps to ensure the coordination of the knowledge base with the inference engine in a way that we can obtain a final HAZOP analysis for a new node study.

The first step is to define the process and the treatment zone. In order to specify the data in the knowledge base, the second is to define the node according to the previous data (process and treatment zone). Finally, generate the HAZOP report.

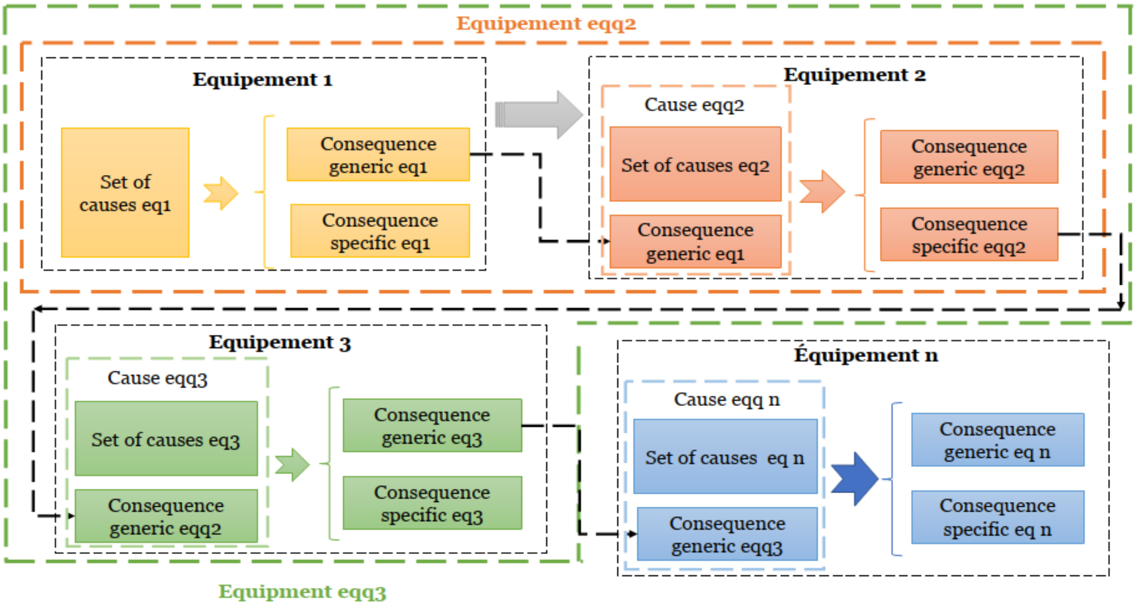

**Figure 7.** Design of each state of deviation propagation in the node.

### 3.1 Define the process studied

In this step, we need to present our process for study and provide the following information:

- Define the main function of the process: it must be presented the type of process (chemical, petrochemical, gas, etc.) after giving a general idea about how it works.

- Define the treatment units that make up the process: Each process is made up of several treatment units. In this step, we must specify the number of units and the function of each one.

- Define the causes/consequences of each piece of equipment for a defined deviation. Where each piece of equipment has its own cause/consequence base; these data are studied and recorded in the knowledge base in the sub-class "base equipment". In Fig. (9), we present the hierarchical phases/steps to model the knowledge base for each piece of equipment.

### 3.2 Node creation

The node is an equipment set connected together to perform a specific task. In this reasoning, the following conditions must be met:

- The number of equipment that characterises the node cannot exceed six.
- Consider valves and other instruments as instruments associated with the main equipment (such as column, pump, ebb, turbine, etc.) following them.
- The connections between these devices must be direct (following the same path).
- The selected node must be in the same production unit of a system.
- The equipment forming the node must be connected to each other.

With this reasoning, we can easily select the node by simply mentioning the treatment units.

The first equipment of the node that we want to study.

As shown in Fig. (8), to create a node, we should select a unit and specify the first and last equipment. By applying the connection information in the first equipment, a node will be created. Fig. (10) represents the progress of the operation.

Selecting a path and creating a node can be done in two ways:

- Manual creation: Here, the user must specify the equipment that constitutes the node, where we obtain the analysis path from the connection base. Fig. 10 shows the path selected by selecting equipment (manually).

Automatic creation: In this case, the system will create nodes of 6 or fewer consecutive pieces of equipment from the first defined equipment.

Following Fig. 10, we can obtain several paths, such as

Eq1 → Eq 2.1 → Eq 3.1.1 → Eq n.1.1
Or Eqn → Eq 2.n → Eq 3.n.n → Eq n.n.n

After that, the user can choose the path or the study node.

### 3.3 Results and HAZOP Report

After selecting the unit, node and equipment, we go to the analysis application. Where the system extracts all the information about the equipment sets. The inference engine processes this data and applies the propagation rules, along with forward chaining, to provide a HAZOP analysis of the selected nodes, as shown in Fig. 7.

## 4. CASE STUDY

We will use this semi-automated approach to perform a HAZOP analysis of the Natural Gas Liquefaction Plant in Algeria. The LNG plant consists of several natural gas processing units. These units allow the conversion of natural gas from the gaseous phase to the liquid phase at a temperature of -162°C and pressure slightly above atmospheric pressure.

In this part, we will use the knowledge base to highlight all the knowledge related to this processing unit. As mentioned above, the process knowledge is stored in the process knowledge base in a hierarchical form. This makes it easy to access information about any selected treatment unit. In the following, we will introduce the treatment unit chosen for this study. And highlight the set of information related to it. This information allowed us to create the study node and apply the HAZOP analysis.

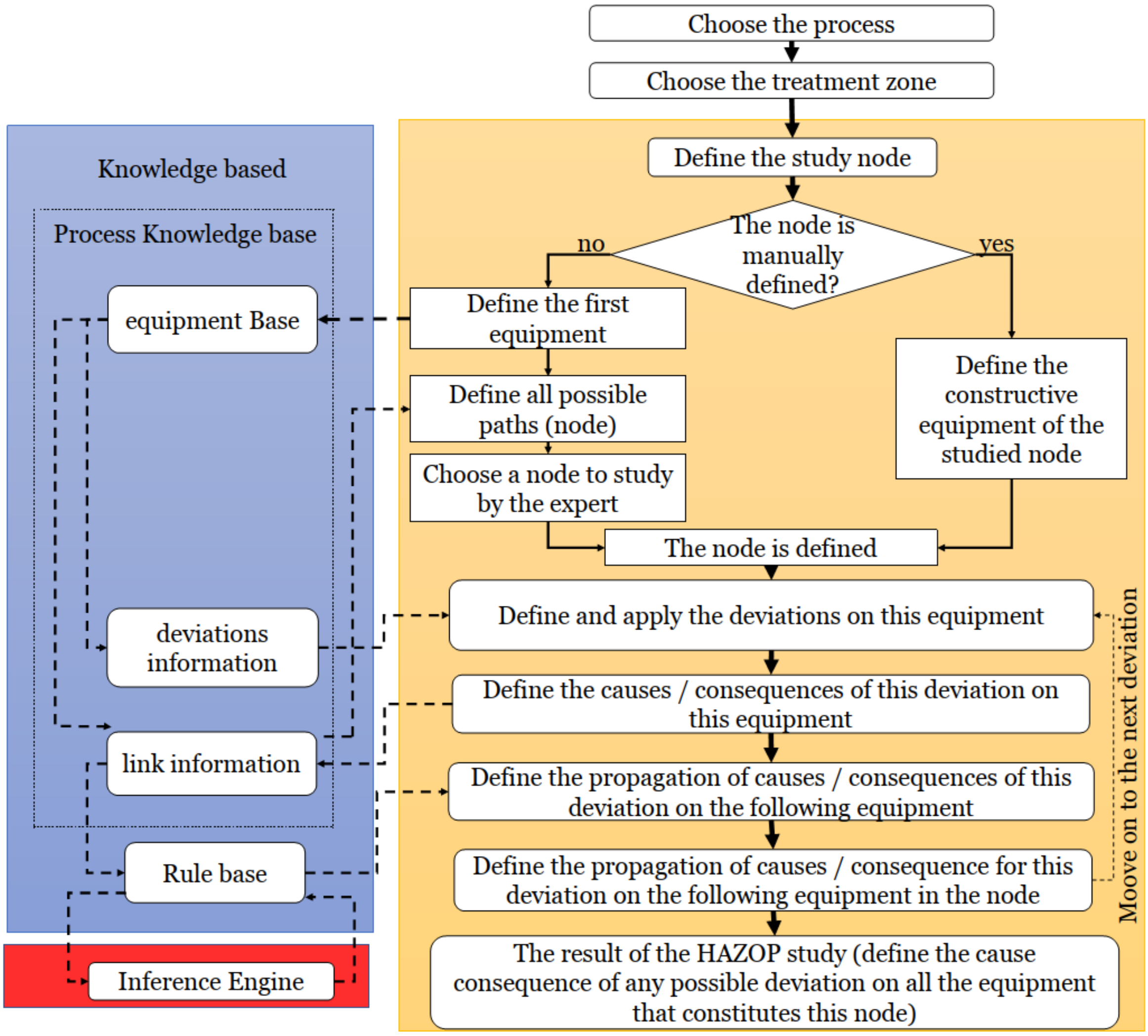

**Figure 8.** Methodology of the semi-automatic HAZOP analysis.

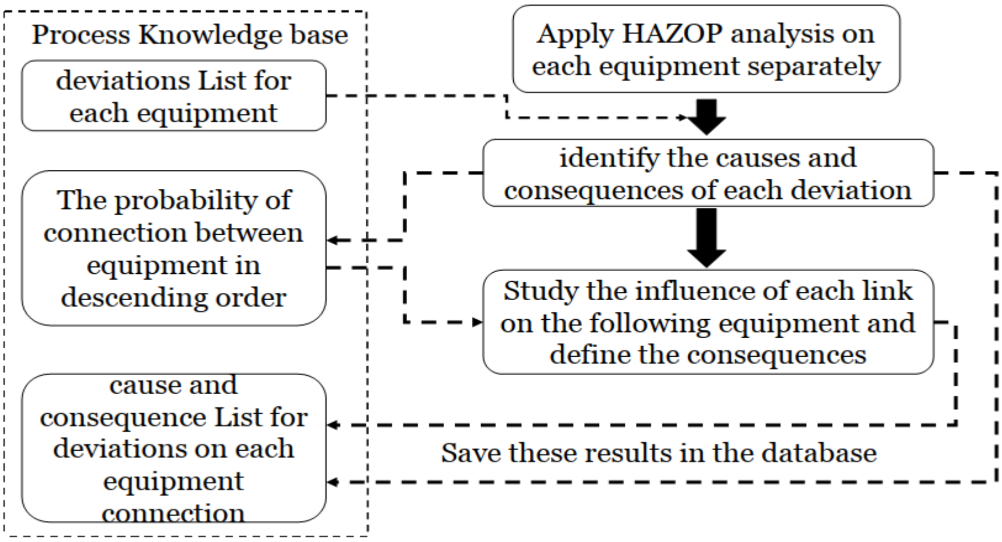

**Figure 9.** Creation of the cause/consequence basis of each piece of equipment.

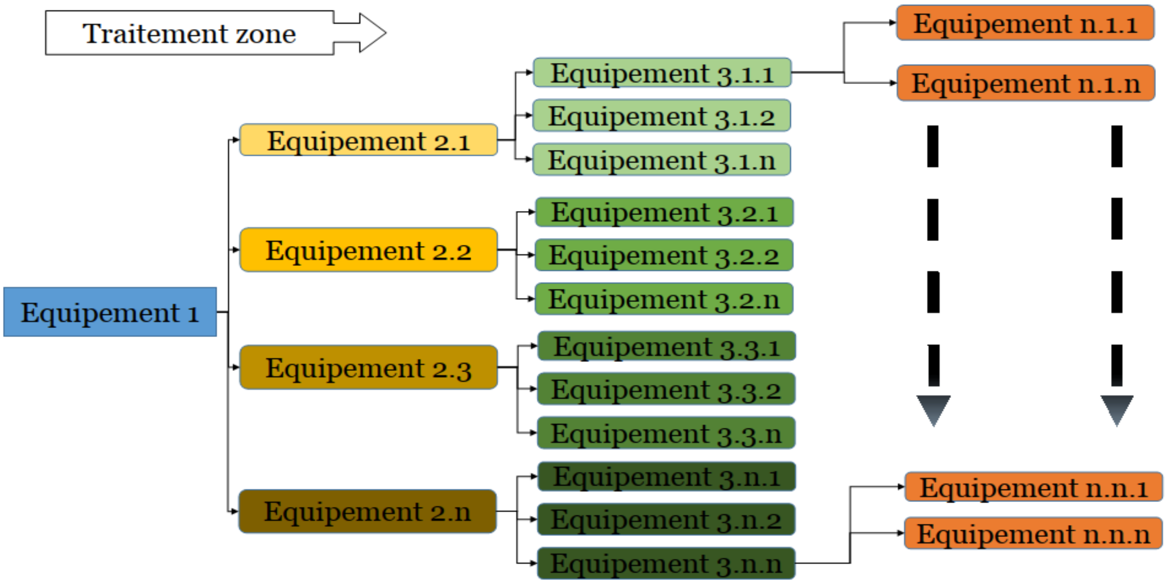

**Figure 10.** Standard representation of probable connection to each piece of equipment in the study unit.

## 4.1 Define the treatment unit to study

This case study is part of the fractionation unit. Its purpose is to remove the heavier hydrocarbons from the feed gas that affect the specifications of the LNG product and produce ethane, propane, butane and gasoline.

The fractionation unit consists of the following distillation columns and associated equipment:

- Demethanizer MD01.
- Deethanizer MD02.
- Depropanizer MD04.
- Debutanizer MD06.

In the example shown in Fig. (11), the analysis is applied to the Debutanizer MD06. This column is fed from the bottom of the Depropanizer MD04. The reboil heat is controlled to meet the condensate product specification for butane. The Reid vapour pressure of the condensate produced is 0.87 bar, measured by a PT1098, where the signal is sent to the pressure controller MD06-PIC1098.

The air-cooled Debutanizer condenser is designed to operate at 15°C; the inlet air temperature is based on the ambient air temperature of 24°C. The condensed butane is fed to the Debutanizer reflux drum, MD07. The liquid from the MD07 is pumped by the Debutanizer Reflux Pump, MJ03. The liquid butane stream from the MJ03 is split, with a portion refluxed to the MD06 and the remainder fed to the MC12 butane product. The butane product is cooled using MP propane refrigerant. The MP propane refrigerant has a controlled back pressure to prevent overcooling of the butane product. The distillate stream from MC1 is routed to storage or the LPG re-injection system.
(Facilities, 2006).

## 4.2 Define the deviations and their causes/consequences for each piece of equipment

After selecting the unit, we could find from the knowledge base information that our system may consist of the following equipment:

- Distillation column (debutanizer MD06).
- Air-cooled condenser (air-cooled debutanizer condenser) (MC07).
- Reflux drums (MD07).
- Pump (MJ03).
- Butane product cooler (MC12).
- The storage tank.

In this study, we will apply this approach for the "less temperature " deviation on each piece of equipment in the study unit. The information provided in the knowledge base is collected from the following application of HAZOP analysis on all of the equipment that constitutes the node and, obviously, in the technical documents and the previous HAZOPs, where we came to determine the various causes and consequences of the deviation " less temperature on all the equipment of the system under study. Tables 2 and 3 present an example of a standard HAZOP analysis of two pieces of equipment:

### Distillation column

Table 2 shows all the causes/consequences of the "lower temperature" deviation on the distillation column. Meanwhile, Fig. 12 shows the general layout of a distillation column and its associated equipment.

### Reflux drum

Table 3 shows all the causes/consequences of the "less temperature" deviation on the reflux drum. Meanwhile, Fig. 13 shows the general layout of a distillation column and its associated equipment.

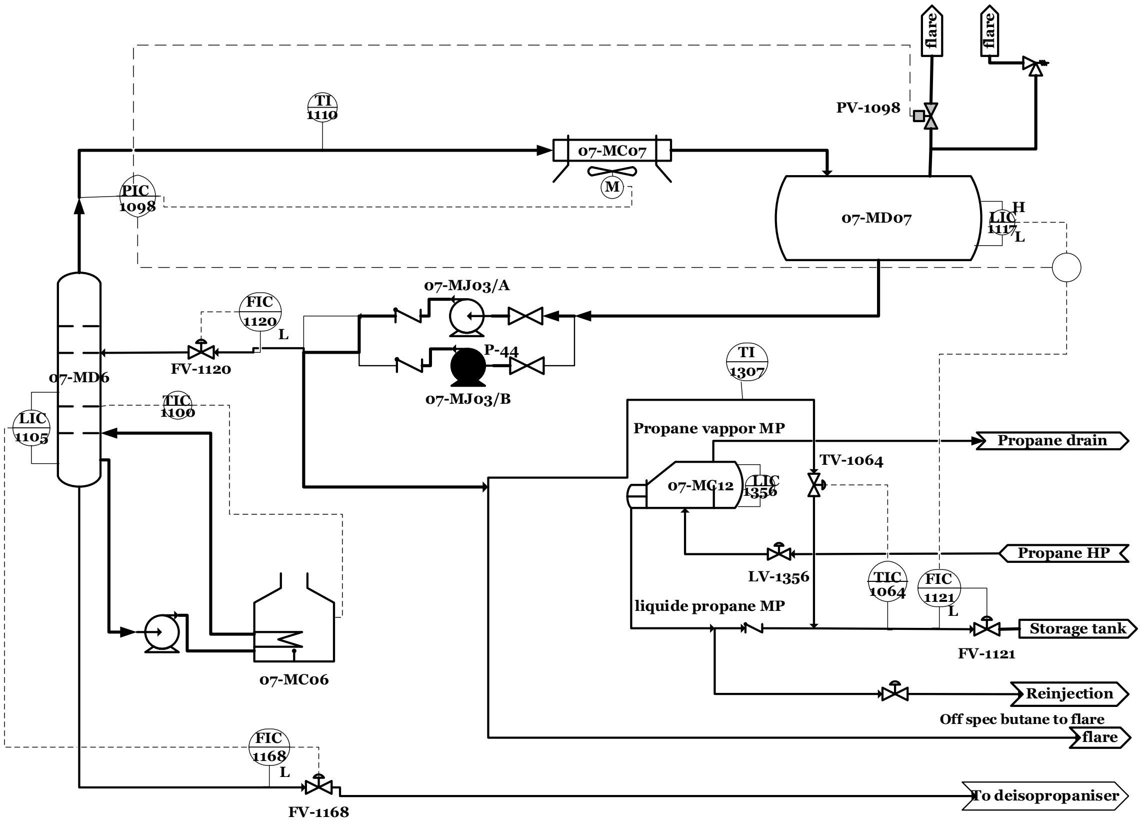

**Figure.11.** piping and instrumentation diagram (P&ID) of distillation column MD06.

**Table 2.** HAZOP Application on the column for the " less temperature " deviation.

| Deviation | Cause | Consequence |
|---|---|---|
| Less of temperature | Less reflux temperature<br>Stop or malfunction of the reboiler (possible shutdown of the pump at the level of the reboiler)<br>There is less flow at the entrance to the column<br>malfunction of TIC (the temperature Regulator of the column tray weir) | **Generic consequence**<br>Cooling of the column head<br>Poor separation and reduction of the vapour fraction at the top of the column<br>**Specific consequence**<br>Increase in the amount of internal reflux<br>Increasing the amount of steam in the reboiler.<br>Changing the temperature of each tray<br>Modification of the composition of the head of the column (lighter product) |

**Table 3.** HAZOP application on the reflux drum for the " less temperature " deviation.

| Deviation | Cause | Consequence |
|---|---|---|
| | | **Generic consequence** |
| Less of temperature | - Increase the liquid fraction in the mixture<br>- Malfunctioning of LICA | - Increase the flow of liquid at the exit of the drum.<br>- Low reflux temperature |
| | | **Specific consequence** |
| | | Nothing to report |

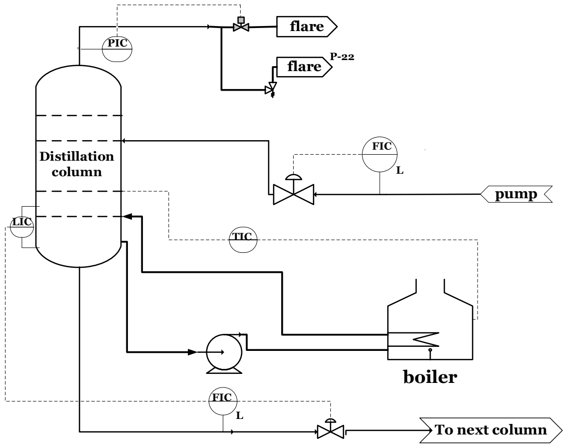

**Figure 12.** Representation of a distillation column with the associated regulation instruments.

## 4.3 Define the probable connections of each piece of equipment

This part is the most important part of the node creation phase. The information about the probable connections on each piece of equipment in the fractionation unit can be recorded in the process knowledge base as connection information.

After defining the treatment unit and the first piece of equipment, the system retrieves all the connection information that matches each piece of equipment that can be in the node. The connection information about each device is recorded after a total analysis of all PFDs of the plant, where each piece of equipment has connections well determined in each unit. Fig. 14 and 15 show two examples of probable equipment connections in all LNG processing units.

The first shows the probable connections of a distillation column in each processing unit. The second shows the probable connections of a pump in each unit.

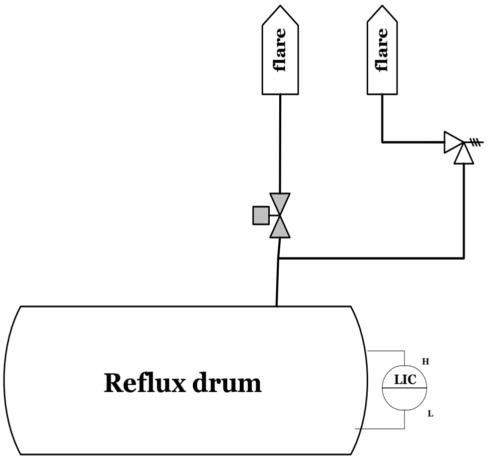

**Figure 13.** Diagram of a reflux balloon with associated regulation instruments.

***Noted well***: We note that:

- The distillation column in the LNG industry can be connected with a propane condenser in the case of the column: - Demethanizer - Deethanizer.
- The distillation column can be connected with aero in the case of the column: - Depropanizer - de-isopentane.

In the connection base, the equipment is classified in decreasing order according to the degree of connection of each piece of equipment with the other, where the degree of connection is the number of times that a connection is repeated in relation to the total number of connections in each device.

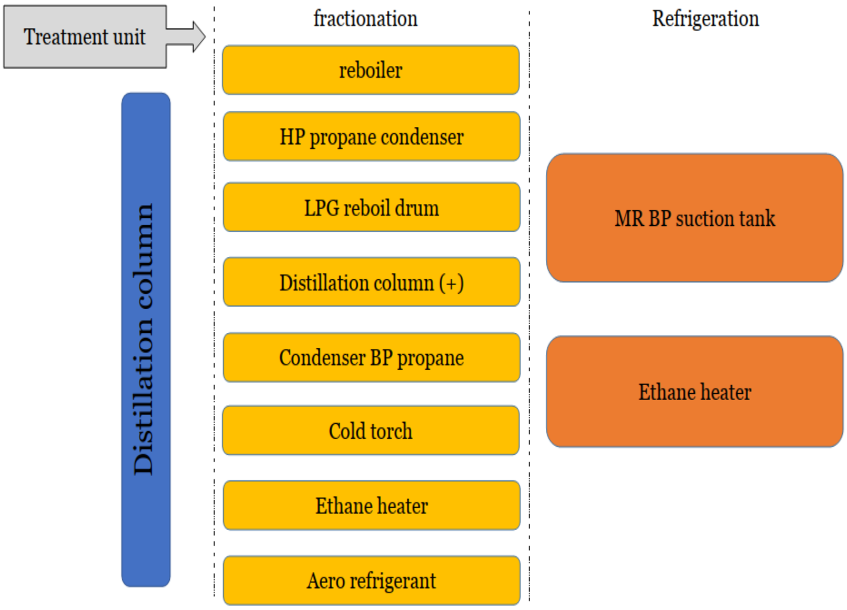

**Figure 14.** Distillation column interconnection in each LNG treatment unit.

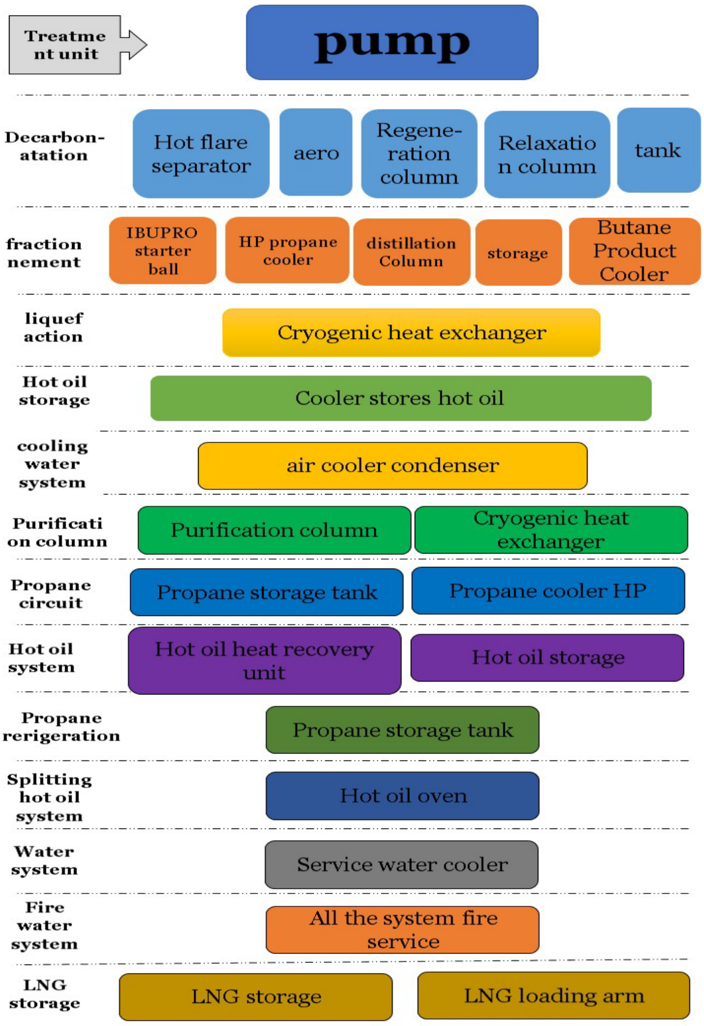

**Figure 15.** Pump interconnection in each LNG treatment unit.

## 4.4 Node creation

After selecting a study unit and obtaining information about all the equipment that can constitute it, we move to the creative part of the study node. Here, each piece of equipment information obtained from the process knowledge base is combined to have all possible combinations and variation propagation paths. Fig. 16 below shows the possible combinations of equipment that make up the fractionation unit. As mentioned before, the creation of the node can be done in two ways. The first is done automatically by the system. The second is manual, where the user selects a node from the possible paths given by the system. In the following, we will apply both methods in our study unit and see the possible paths before that. The equipment "Distillation Column" has been selected as the first equipment of the node.

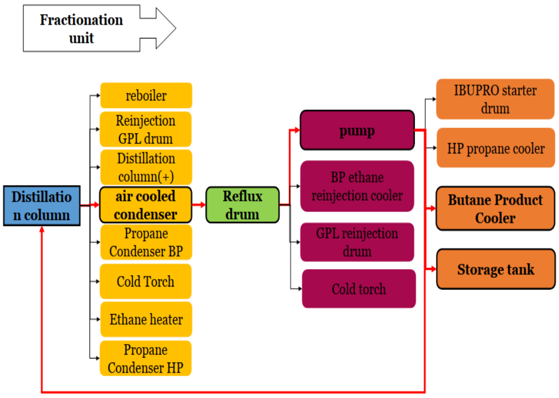

**Figure 16.** Application of the approach to the system to study.

### 4.4.1 Automatic creation

Applying this method to our example in Fig. 16, we get a lot of possible paths. Here, the expert must choose one path to study. Or, apply the HAZOP study to all possible paths and define the results at the end.

### 4.4.2 Manual creation

Here, the expert must add the equipment that makes up the study node. The selected equipment is represented by a red line in Fig. 16, so our study node consists of the following equipment: Distillation Column (MD06) - Air Cooled Condenser (MC07) - Reflux Drum (MD07) - Pump (MJ03 A/B) - Butane Product Cooler (MC12) - Storage Tank.

After selecting the path, the system creates a digraph representation and presents all the connections between each equipment set (Fig. 17) for the purpose of representing and simplifying the study node. This digraph representation is created using the "NetworkX" library of Python (NetworkX is a Python package for creating, manipulating, and studying the structure, dynamics, and functions of complex networks (Hagberg et al., 2011) ), that we can precise all the connections of each equipment of our study system, from the distillation column arriving to the storage tank and come back to the distillation column. Moreover, in a digraph representation, we have nodes and edges, where the nodes represent the information of an equipment set, and the edges represent a connection between sets of equipment with precision in the direction. It also represents the propagation of information between two successive pieces of equipment.

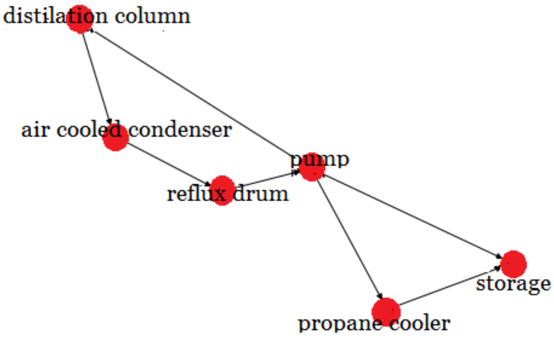

**Figure 17.** Digraph representation of the study node.

## 4.5 HAZOP report generation

During the execution of the previous steps. Our system has released all the knowledge specific to the study node (Fig. 17) and the equipment that makes it up. In this part, we proceed to the application of the HAZOP analysis to this node by applying the deviation propagation rules. Our deviation is applied to the distillation column (as stated), and we use the propagation rules to follow its propagation until the final equipment of the node, such as the storage tank, the butane product cooler and the return to the distillation column. The results of this HAZOP analysis are shown in Table 04.

**Table 4.** HAZOP study results.

| Keyword | Less than |
|---|---|
| Parameter | Temperature |
| Deviation | Less of temperature |
| Cause | Consequence |
| **1-** Less reflux temperature | 1-1- Cooling of the column head<br>1-2- Increasing the amount of steam in the reboiler<br>1-3- Changing the temperature of each tray<br>1-4- Modification of the top composition of the column (lighter product)<br>1-5- Increase the liquid fraction in the mixture at the exit of the aero<br>1-6- Low temperature at the output of the aero<br>1-7- Poor separation and reduction of the vapour fraction at the top of the column<br>1-8- Increase of the liquid flow at the exit of the drum<br>1-9- Low reflux temperature<br>1-10- Low product temperature at the outlet<br>1-11- Low product temperature at the pump outlet to the storage bin<br>1-12- Low reflux temperature at the outlet of the pump<br>1-13- A low temperature of the liquid in the tank |
| 2- Stopping or malfunctioning of the reboiler (possible shutdown of the pump at the level of the reboiler) | 2-1- Increasing the amount of steam in the reboiler<br>2-2- Changing the temperature of each tray<br>2-3- Modification of the composition of the head of the column (product lighter)<br>2-4- Increase the liquid fraction in the mixture at the exit of the aero<br>2-5- Low temperature at the exit of the aero<br>2-6- Poor separation and decrease of the vapour fraction at the top of the column<br>2-7- Increase of the flow of liquid at the exit of the drum<br>2-8- Low reflux temperature<br>2-9- Low temperature of the product with the outlet<br>2-10- Low product temperature at the pump outlet to the storage bin<br>2-11- Low reflux temperature at the outlet of the pump<br>2-12- Low temperature of the liquid in the tank |
| 3- Less flow at the entrance of the column | 3-1- Cooling of the top of the column<br>3-2- Increasing the amount of steam in the reboiler<br>3-3- Changing the temperature of each tray<br>3-4- Modification of the composition of the head of the column (lighter product)<br>3-5- Increase the liquid fraction in the mixture at the exit of the aero<br>3-6- Low temperature at the output of the aero<br>3-7- Poor separation and reduction of the vapour fraction at the top of the column<br>3-8- Increasing the flow of liquid at the outlet of the drum |

| | | |
|---|---|---|
| | | 3-9- Low reflux temperature<br>3-10- Low-output product temperature<br>3-11- Low product temperature at the pump outlet to the storage bin<br>3-12- Low reflux temperature at the pump outlet<br>3-13- Low temperature of the liquid in the tank |
| 4- | Over-cooling caused by TIC malfunction | 4-1- Increase the liquid fraction in the mixture at the exit of the aero<br>4-2- Low temperature at the output of the aero<br>4-3- Increasing the flow of liquid at the outlet of the drum<br>4-4- Low reflux temperature<br>4-5- Low-temperature output product<br>4-6- Low product temperature at the pump outlet to the storage bin<br>4-7- Low reflux temperature at the pump outlet<br>4-8- low temperature of the liquid in the tank |
| 5- | Low external temperature | 5-1- Increase the liquid fraction in the mixture at the exit of the aero<br>5-2- Low temperature at the output of the aero<br>5-3- Increase of the flow of liquid at the exit of the drum<br>5-4- Low reflux temperature<br>5-5- Low temperature of the product at the output.<br>5-6- Low product temperature at the pump outlet to the storage bin<br>5-7- Low reflux temperature at the outlet of the pump<br>5-8- Low temperature of the liquid in the tank |
| 6- | Increase the liquid fraction in the mixture | 6-1- Increase of the flow of liquid at the exit of the drum<br>6-2- Low reflux temperature<br>6-3- A low temperature of the product at the outlet<br>6-4- Low product temperature at the pump outlet to the storage bin<br>6-5- Low reflux temperature at the outlet of the pump<br>6-6- Low temperature of the liquid in the tank |
| 7- | Malfunction of LICA | 7-1- Increase of the flow of liquid at the exit of the drum<br>7-2- Low reflux temperature<br>7-3- Low temperature of the product with outlet<br>7-4- Low product temperature at the pump outlet to the storage bin<br>7-5- Low reflux temperature at the pump outlet<br>7-6- Low temperature of the liquid in the tank |
| 8- | Climate factor | 8-1- Low temperature of the liquid in the tank |

## 4.6 Results discussion

After manually selecting the node and defining a deviation, the knowledge of the first equipment set of the node corresponding to this deviation was imported from the equipment base. This knowledge will be combined with all the following equipment knowledge of the node, arriving at the last equipment by using the propagation rules. These rules will lead us to the main objective of this study, which is to follow the propagation of the deviation on the node and bring out all the possible paths.

For this objective, we applied the "less temperature" deviation as an example to test the efficiency of our approach. This deviation was first applied to the distillation column, which is considered the first equipment of the node. The causes and consequences of this deviation are imported from the equipment base. Once the knowledge is imported, we take the first cause of this deviation on the first equipment, which has four consequences on this equipment. This last one can be propagated on our system (referring to Fig. 1 and 6) and cause another deviation. For this purpose, we applied the propagation rules that facilitate the execution of this consequence propagation on all the equipment of the node. Table 04 presents the results of this analysis, where the different causes and consequences of the "less temperature" deviation are identified on the applied node.

From these results, we can see that the integration of the propagation rules helps us to define more consequences for each cause. Each of these causes has a list of consequences in the equipment base for defining equipment. However, when we integrated this equipment into the study node, a new list of consequences was created by applying the variance propagation rules. In this list, more consequences have appeared that affect all the equipment that follows this equipment in the node.

For example, if we consider the cause of "Low reflux temperature" in the distillation column (Table 2), we find that this cause has six consequences in the equipment base of the "distillation column". Two of them are specific, and four are generic. If we go back to the final results of the analysis, we find that the number of this consequence has increased from six to thirteen for the same cause. These additional consequences are due to the propagation of the "less temperature" variance to the rest of the nodes. The propagation rules built into our system approach ensured this spread. The remaining causes of this deviation are treated in the same way. After applying all the cases, we arrive at the final results presented in Table 4. This report is similar to the SONATRACH reported results of the treatment gas unit in Hassi R'mel (Algeria) (Facilities, 2006), with more precision than the figure in 5 more consequences for the same deviation.

If the case when we choose the automatic creation of the node, we get all possible propagation of this deviation with all possible paths.

Through a comparison of our semi-automated approach with a classic HAZOP study conducted on a similar node (Hamada & Omura, n.d.), we found that our approach provided more specific and precise information about the causes and consequences of deviations in the process. Our approach also identified more potential causes and consequences than the classic HAZOP study. The result obtained with this approach for the deviation "less temperature" is more specific than the result of the (Hamada & Omura, n.d.) study for the same deviation, where this approach generates eight causes for this deviation, while in the other study, we have found just two causes.

Furthermore, this approach allows for the tracing of the propagation path of any deviation in different nodes, regardless of their composition. In another similar case, we compared our results to those of the SONATRACH process gas unit at Hassi R'mel (Algeria) (Facilities, 2006). this approach provided the same results for the same deviation but with greater precision and more comprehensive identification of potential causes and consequences.

These findings suggest that our semi-automated approach can provide more accurate and comprehensive results compared to the traditional manual methods used in classic HAZOP studies.

Our approach provided more specific and precise information about the causes and consequences of deviations in the process, while the classic HAZOP did not provide such a level of detail, indicating that it has a broader scope and is more comprehensive.

Moreover, this approach allows for the tracing of the propagation path of any deviation in different nodes, regardless of their composition. This means that it can provide a better understanding of how deviations can affect the entire system and enable more effective risk management.

## CONCLUSION

A semi-automatic approach has been developed to perform a HAZOP study using an expert system knowledge base. The objective of this work is to develop a semi-automatic tool that allows the combination or integration between the process knowledge bases and the propagation rules in order to have a detailed and complete HAZOP study.

As indicated in the introduction, referring to (Baybutt, 2015),(Venkatasubramanian et al., 2000) and (Cameron et al., 2017) studies. Furthermore, the automation of the classic HAZOP may overcome such limitations as reducing the time and cost of the study. Furthermore, the automation removes the routine and allows the team to focus on the important aspects of the investigation: the errors and their causes and effects. As a result, and taking our approach as a semi-automated approach, we conclude that this approach also reduces the cost and the length of the study.

This semi-automatic approach was initially intended for LNG, natural gas liquefaction processes. It allows the user to choose the method of node creation. Either manually or automatically. In the case of automatic selection, the system generates all possible paths, or nodes, for a well-defined processing unit. Here, the user can choose one of the paths to study it or study all possible paths to reveal the difference.

The contribution of this approach is the large collection of basic knowledge. This knowledge base contains all possible information about any equipment that builds this process, including the information about each processing unit, the existing safety loops, and the probable connections of each equipment. Another strength of this approach is that it allows the user to create a logical node in the case where this node is excluded from the process knowledge base. It should just bring out the equipment data in the equipment base. And its probable connection information in the process knowledge base after building the node. Finally, apply the study and automatically generate the results.

Moreover, the flexibility of the knowledge stored in the knowledge base allows us to follow the propagation path of any deviation in different nodes regardless of their composition. As a semi-automatic approach, the user or the expert has the right to treat and modify the final results of the analysis according to his experience, where this approach serves as a learning initialisation platform.

While the semi-automatic approach may be more efficient and accurate compared to traditional HAZOP studies, it may not completely eliminate the need for human expertise and input. Therefore, it's essential to strike a balance between automation and manual analysis to ensure the best outcomes.

Our future development perspectives on this semi-automatic approach are as follows:

1. Graphical interface: adding a dynamic graphical interface adapted to each type of process.
2. Knowledge base: Improve the knowledge base by adding knowledge from all gas and petrochemical processes. This will make the tool applicable to all petrochemical industries.
3. The rules of propagation: improve the rules of propagation to avoid the repetition of knowledge.
4. Inference Engine: Add tips that automatically refine the results without expert input.
5. Result generation: develop an automatic generation of results in the form of classic HAZOP tables.

## CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest regarding this article.

## FUNDING

The research underpinning this publication was undertaken independently and was not contingent upon any external financial endorsements or grants.

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