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# Towards phenomena-based HAZOP support


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# Abstract


This thesis explores the development of a partially automated Hazard and Operability Study (HAZOP) methodology designed to enhance early-stage hazard analysis. While traditional HAZOP is a well-established, team-based approach for identifying hazards in complex systems, its reliance on manual analysis can lead to lengthy processes, subjective judgments, and the potential for overlooked hazards due to the intricacy of system interdependencies. To address these challenges, this work integrates a phenomenological framework with graph-based modeling and Python-driven automation.

The proposed methodology begins with process flow diagrams (PFDs) to map system variables and their interrelationships, forming a foundation for early identification of potential deviations. A phenomenological approach rooted in mass and energy balances provides a scientific basis for tracking deviations and understanding their propagation through the system. This approach enhances reliability by grounding hazard identification in physical and chemical principles, reducing dependence on assumptions. Graph theory is employed to visually represent system interactions, facilitating the tracking of deviation pathways and ensuring consistency across analyses. Python-based tools automate the deviation analysis, generating paths from process variables to risk nodes, significantly reducing manual effort and expediting hazard identification.

A comparative analysis was conducted between a traditional HAZOP table following British Standards Institution (BSI) guidelines and the algorithm-generated results. This comparison highlighted the strengths and limitations of each approach. The automated methodology demonstrated enhanced scalability, efficiency, and comprehensiveness, although manual analysis remains essential for providing depth, context, and validation, particularly in complex or novel systems. Lessons learned from the study underscore the potential of combining traditional qualitative techniques with computational tools.

Future work will focus on refining the automated comparison process, incorporating quantitative assessment capabilities, and expanding the methodology’s applicability to more complex systems. By bridging the gap between traditional and automated methods, this thesis establishes a foundation for a more efficient, reliable, and holistic approach to hazard analysis, paving the way for safer and more adaptable industrial processes

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# Introduction

Process safety is a cornerstone of modern chemical engineering, where even small deviations from intended operating conditions can lead to significant hazards. Hazard and Operability (HAZOP) studies are central to the identification and evaluation of these risks and provide a systematic approach to hazard analysis that has been widely adopted across industries. This thesis, "Towards Phenomena-Based HAZOP Support", seeks to address the inherent limitations of traditional HAZOP techniques by integrating novel automation and modeling approaches.

In the industrial landscape, the complexity of processes has increased significantly, making it difficult to perform exhaustive hazard assessments manually. Traditional HAZOP analysis, while effective, is labor-intensive, prone to human error, and often requires a significant amount of time and expertise to perform thoroughly. The manual nature of HAZOP studies means that results can be inconsistent, rely heavily on the judgment of the expert team, and potentially miss non-obvious hazards due to cognitive biases or fatigue. These challenges highlight the need for more efficient methods that can augment human expertise with computational support.

This thesis explores a partially automated approach to HAZOP that aims to reduce time and effort while increasing consistency and scalability. By combining a phenomenological framework based on fundamental mass and energy balances with graph-based system modeling and Python-driven automation, this thesis proposes a more structured way to identify deviations early in the design phase. Graph-based representations are used to map process variables and interdependencies, while Python algorithms automate the identification of potential deviation paths, thereby accelerating the hazard identification process.

The integration of automated tools into HAZOP is not intended to replace the multidisciplinary expert team, but rather to enhance it. Automation handles repetitive tasks and ensures systematic analysis, allowing experts to focus on high-level judgment, interpretation, and validation of results. This paper illustrates how automation can bridge the gap between manual hazard identification and computational analysis, thereby improving the reliability and efficiency of HAZOP studies. It also demonstrates how this approach can be scaled to more complex systems where traditional methods may struggle.

The research presented in this thesis aims to lay the foundation for a new generation of HAZOP tools that support human decision making through computational efficiency and rigor. The ultimate goal is to contribute to a safer industrial environment where potential hazards are identified early and managed effectively to minimize risks to people, the environment, and economic assets.

# Chapter 1: The HAZOP analysis technique

## 1.1 Introduction

Hazard and Operability (HAZOP) analysis is a method used to identify and evaluate hazards and operational issues within a system. It is a highly organized, structured, and systematic approach for conducting hazard identification from the conceptual phase through decommissioning. While HAZOP may seem simple in theory, it requires strict adherence to the procedural steps to ensure the effectiveness of the methodology [1].

The HAZOP process uses key words and system diagrams to identify potential system hazards. These key words, such as "more," "no," "less," etc., are combined with system conditions such as speed, flow, and pressure during the hazard identification phase. HAZOP aims to identify hazards that could result from deviations from the intended operating design of the system [1].

A multidisciplinary team of experts performs a HAZOP analysis during sessions led by a HAZOP team leader [1]. Said team is usually composed of chemical, mechanical, electrical and automation engineers, with the addition of plant personnel in case of an already existing plant.

Essential elements of a HAZOP analysis include

- A structured, systematic and logical approach
- A multi-disciplinary team of experts
- An experienced team leader
- Controlled use of system design representations
- Careful selection of system entities, attributes, and keywords to identify hazards
- Technical documentation
- Records of previous HAZOP studies (in case of an already existing plant)

The basic concept behind the HAZOP technique is that any operating problem arising will be the cause of or have, as a consequence, a deviation from normal operative conditions of a process variable [1].

## 1.2 History [2]

HAZOP studies evolved from the Imperial Chemical Industries' "Critical Examination" technique formulated in the mid-1960s. One decade later, HAZOP was formally published as a disciplined procedure to identify deviations from the design intent. Lawley [3] defined and outlined the principles needed to carry out operability studies and hazard analysis due to the increasing complexity of new processes that could not be thoroughly examined using the then-conventional, equipment-oriented approaches. The need for process-oriented methods of examination led to the development of HAZOP. Lawley's paper details the planning, execution, and treatment of the operability study. Two years later [4], he specified the technical and managerial principles underlying HAZOP studies and detailed the factors necessary for successfully developing HAZOP. The planning of the study, the skills of the leader, the study procedure, the evaluation of potential problems, and the process of considering the changes proposed in the analyzed units were carefully set out. Additionally, he provided new examples to illustrate how HAZOP works. Just one year later, the Chemical Industries Association in the U.K. published the first guideline to HAZOP, establishing it as a technique used in the process industries for identifying hazards and planning safety measures [5].

Over the next 30 years, numerous other guidelines and books were published. Among the important contributions to adapting the technology for the processing industry are those of Knowlton [6], Nolan [7], Kletz [8] [9] [10] [11], Lees [12], Wells [13], EPSC [14], Macdonald [15], and Casal et al [16]. This wealth of publications illustrates the evolution of HAZOP as a vital, globally applied technique recognized by legislation and proven effective in identifying environmental, safety, and health hazards. Knowlton [17] was the first to develop a book focused solely on HAZOP applications, offering valuable information on the creative process of generating deviations. Nolan [7] shared his practical experience, discussing specific topics related to both HAZOP and What If techniques. His book fully describes both methodologies and introduces tools for estimating HAZOP time and costs. The document was intended as a typical guideline and reference book for use in petroleum, petrochemical, and chemical facilities, detailing the nature, responsibilities, methods, and documentation required for conducting such reviews. Kletz [8] [9] [10] [11], one of the most influential authors on process safety, wrote an excellent book that technically defines HAZOP while sharing his experience and insights in his characteristic, entertaining personal style. Lees [12] and Wells [13] contributed their concepts on HAZOP development and extended their focus to a wide range of aspects of hazard identification and loss prevention. In 2000, EPSC [14] formulated new

HAZOP guidelines, adapting the methodology to emerging technologies and sharing their extensive experience in using the technique most effectively. Finally, a British Standard [18] published in 2001 established and defined new requirements for conducting a HAZOP, underscoring its continuing importance as the most widely used technique in process plants and other types of facilities. Recently, Macdonald [15] updated the field with the latest data on HAZOP characteristics, documenting how to conduct a HAZOP and connect it with future studies focused on Safety Integrity Level (SIL) assignments. His book concentrates on the application of hazard study methods and the subsequent actions necessary for providing protection against hazards. Additionally, the book offers training in three basic steps—identifying hazards, evaluating risks, and specifying risk reduction measures—that form part of the overall risk management framework for process facilities.

It is also worth noting that there are internal corporate guidelines from process industries that, while not publicly accessible due to confidentiality constraints, offer valuable information on performing HAZOP in processes with equivalent or similar technology and objectives (e.g., petroleum refining units). These guidelines typically establish criteria for a standardized methodology when conducting HAZOP on different processes within the same facility or corporation, including the minimum expert team required for brainstorming, the size of nodes to be reviewed, expectations for team leaders, and the deviations to be analyzed.

## 1.3 Background

This analysis technique falls under the preliminary design hazard analysis type (PDHAT) and the detailed design hazard analysis type (DD-HAT). HAZOP analysis is sometimes also called a hazard and operability study (HAZOPS) [1].

The purpose of HAZOP analysis is to identify potential deviations from a system's intended operational intent using key guide words. These deviations can lead to possible system hazards [1].

HAZOP analysis applies to all types of systems and equipment, including subsystems, assemblies, components, software, procedures, environment, and human error. It can be conducted at various levels of abstraction, such as conceptual design, top-level design, and detailed component design. HAZOP has been successfully used in a variety of systems, including chemical plants, nuclear power plants, oil platforms, and rail systems. By applying this technique early in the design process, developers can identify and address safety issues before they lead to test failures or mishaps [1].

When performed by experienced personnel, HAZOP analysis provides a thorough identification of hazards in a system or process. A solid understanding of hazard analysis theory and system safety concepts is essential. Experience with the specific type of system and the HAZOP process itself helps generate a complete list of potential hazards. The technique is straightforward and easy to learn, with clear HAZOP analysis worksheets and instructions provided in this chapter [1].

Initially developed for the chemical process industry, HAZOP methodology focuses on process design and operations. However, with practice and experience, it can be extended to other systems and functions. The HAZOP analysis technique is effective and, in essence, similar to preliminary hazard analysis (PHA) or subsystem hazard analysis (SSHA), with the main difference being the use of guide words. HAZOP analysis can also be utilized for PHA and/or SSHA techniques [1].

## 1.4 Theory

HAZOP analysis involves investigating deviations from the design intent of a process or system by a team of experts from various fields, such as engineering, chemistry, safety, operations, and maintenance. The process is carried out in a series of meetings where the multidisciplinary team systematically brainstorms the system design, guided by prescribed guide words and the team leader's experience. These guide words ensure that every design aspect is thoroughly examined [1].

The principle behind HAZOP is that a diverse team of experts working together can better identify problems than if they worked separately and combined their results afterward [1].

Fault trees can be used to complement the HAZOP process, but their purpose is solely to identify mishap scenarios, not to quantify probabilities [1].

HAZOP analysis is similar to Preliminary Hazard Analysis (PHA) and Subsystem Hazard Analysis (SSHA) in that it identifies hazards by evaluating the design against key guide words that suggest hazardous operation modes. PHA and SSHA similarly use hazard checklist [1].

The HAZOP procedure thoroughly describes a process or system and systematically questions every part to determine how deviations from the design intent could occur. Once identified, these deviations are assessed to determine if they could negatively affect the safe and efficient operation of the plant or system [1].

HAZOP is conducted through a series of team meetings led by a team leader. The success of a HAZOP analysis depends on selecting the right team leader and team members. The team applies the analysis in a structured manner, using their imagination to discover credible causes of deviations from the design intent. While many deviations may be obvious, such as a pump failure causing a loss of circulation in a cooling water facility, the technique's strength lies in encouraging the team to consider less obvious deviations. This approach goes beyond a simple checklist review, increasing the likelihood of identifying potential failures and problems that may not have been previously experienced in the type of plant or system being studied [1].

Figure 1 provides an overview of the basic HAZOP process and summarizes the key relationships involved:

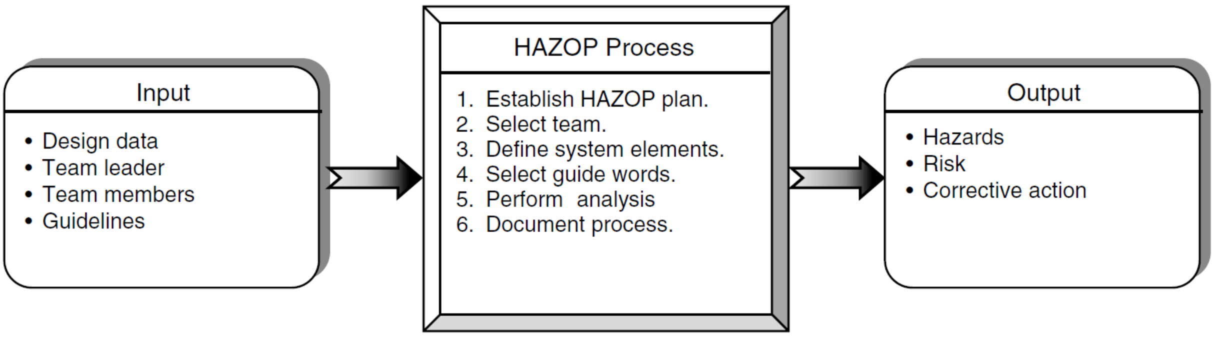



*Figure 1: Overview of the basic HAZOP process [1]*

## 1.5 Methodology

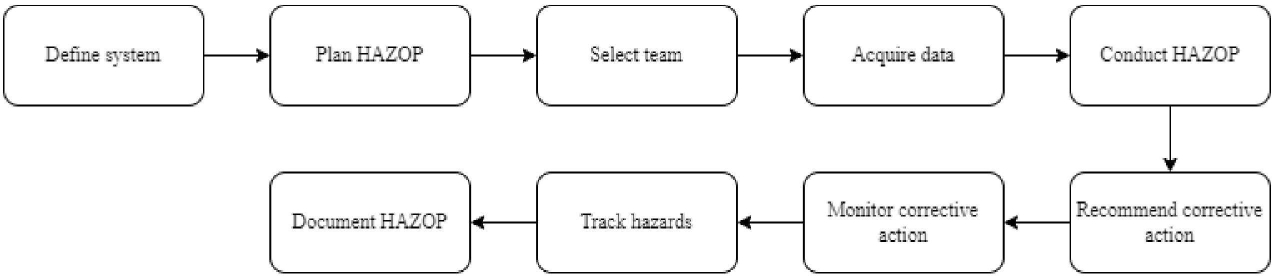



*Figure 2: HAZOP process basic steps*

Table 1 lists and describes the basic steps of the HAZOP process:

*Table 1: HAZOP process basic steps [1]*

| Step | Task | Description |
|---|---|---|
| 1 | Define system. | Define, scope, and bound the system. Define the mission, mission phases, and mission environments. Understand the system design and operation. Note that all steps are applicable to a software<br>HAZOP. |
| 2 | Plan HAZOP | Establish HAZOP analysis goals, definitions, worksheets, schedule and process. Divide the system under analysis into the smallest segments desired for the analysis. Identify items to be analyzed and establish indenture levels for items/functions to be analyzed. |
| 3 | Select team | Select team leader and all team members to participate in HAZOP analysis and establish responsibilities. Utilize team member expertise from several different disciplines (e.g., design, test, manufacturing, etc.). |
| 4 | Acquire data | Acquire all necessary design and process data (Process flow diagrams, Piping and instrumentation diagrams, Process descriptions, Equipment specifications, Material safety data sheets, Instrumentation and control data, Operating procedures, Past incident reports, Process design basis, Process hazards analysis reports, Environmental and regulatory requirements, Utility data, Layout and plot plans, Emergency response plans, Electrical and instrumentation diagrams, Mechanical design data, Human factors and ergonomics, Logistics and supply chain information, Maintenance and inspection records, Process simulation data, Safety instrumented system data) for the system, subsystems, and functions. Refine the system information and design representation for HAZOP analysis. |
| 5 | Conduct HAZOP | a. Identify and list the items to be evaluated.<br>b. Establish and define the appropriate parameter list.<br>c. Establish and define the appropriate guide word list<br>d. Establish the HAZOP analysis worksheet.<br>e. Conduct the HAZOP analysis meetings.<br>f. Record the HAZOP analysis results on the HAZOP worksheets.<br>g. Have the HAZOP analysis worksheets validated by a system engineer for correctness. |
| 6 | Recommend corrective action | Recommend corrective action for hazards with unacceptable risk.<br>Assign responsibility and schedule for implementing corrective action. |
| 7 | Monitor corrective action | Review the HAZOP at scheduled intervals to ensure that corrective action is being implemented. |
| 8 | Track hazards | Transfer identified hazards into the hazard tracking system (HTS). |
| 9 | Document HAZOP | Document the entire HAZOP process on the worksheets. Update for new information and closure of assigned corrective actions. |

Key components of a HAZOP analysis include [1]:

- A structured, systematic, and logically planned process
- Proper selection of team members
- Selection of the right team leader (a critical element)
- Effective teamwork
- Essential HAZOP analysis training
- Controlled use of design representations
- Planned use of entities, attributes, and guide words to identify hazards

Recommendations for avoiding or mitigating identified hazards may not always be resolved during team meetings, often leading to action items. The primary purpose of a HAZOP study is to identify potentially hazardous scenarios, so the team should avoid spending excessive time engineering solutions during the analysis. If an obvious solution is identified, it should be documented in the HAZOP and the resulting Hazard Analysis Report (HAR) [1].

HAZOP analysis involves comparing a list of system parameters against a list of guide words. This process stimulates the identification of potential system deviations from the design intent and the resulting hazards. Establishing and defining the system parameters and guide words are crucial steps in the HAZOP analysis. Deviations from the intended design are generated by pairing the guide word with a variable parameter or characteristic of the plant, process or system, such as reactants, reaction sequence, temperature, pressure, flow, phase, etc. In other words:


*Figure 3: Deviation generation*

For example, when considering a reaction vessel in which an exothermic reaction is to occur with stepwise addition of one of the reactants, coupling the guide word "more" with the parameter "reactant" would generate the deviation "thermal runaway." Each part of a facility or system is examined systematically. It's important to note that not all combinations of guide words and parameters are meaningful. For example, "temperature/no" (absolute zero) or "pressure/reverse" may be considered nonsensical. [1].

The preparation required for a HAZOP analysis depends on the facility or system's size and complexity. Typically, the necessary data include various drawings such as line diagrams, flow sheets, facility layouts, isometrics and fabrication drawings, operating instructions, instrument sequence control charts, logic diagrams, and computer code. Occasionally, facility and equipment manufacturers' manuals are also needed. The data must be accurate and comprehensive. Line diagrams must be checked for existing facilities to ensure they are up-to-date and that no modifications have been made since construction [1].

HAZOP analyses are typically carried out by a multidisciplinary team, that typically reaches a size up to 12 people, selected for their individual knowledge and experience in design, operation, maintenance, or health and safety. A typical team consists of four to seven members, each with detailed knowledge of the facility or system's intended operation. This technique allows experts to systematically apply their knowledge and expertise, reducing the likelihood of missing potential problems. HAZOP brings fresh perspectives to problem-solving [1].

The team leader must be an expert in the HAZOP technique, ensuring the team follows the procedure and guiding members to focus on meticulous attention to detail. The team leader should be an independent figure, not associated with program management. While having sufficient technical knowledge to guide the study, the leader is not expected to make a technical contribution. Training in the HAZOP technique is beneficial for team members [1].

Many HAZOP studies can be completed in five to ten meetings, though small modifications might only require one or two meetings. Large projects could take several months, even with two or three teams working in parallel on different sections of the system. HAZOPs require significant resources, which should not be underestimated. For organizations introducing HAZOP analyses for the first time, it may be useful to apply the technique to one or two problems to assess its utility and applicability. If successful, the technique can be expanded to larger projects [1].

It is common practice to record each step of a HAZOP analysis. Recording includes maintaining a data file with copies of the data (flow diagrams, original and final process and instrument diagrams, running instructions, bar sheets, models, etc.) used by the team, marked by the study leader to show they have been examined [1].

The following table outlines key HAZOP activities or tasks and the responsible team members. These roles must be performed by the designated team members [1]:

*Table 2: HAZOP roles [1]*

| | Postulate | Explore | Explain | Conclude | Record |
|---|---|---|---|---|---|
| Leader | Yes | Possibly | Possibly | Yes | |
| Expert | | Yes | Yes | | |
| Designer | | Possibly | Yes | | |
| User | | Possibly | Yes | | |
| Recorder | | Possibly | | | Yes |

This table divides the activities in five macro-groups:

- "Postulate" is the team leader's act of introducing the analysis subject.
- "Explore" consists in the evaluation of the possible causes and consequences, conducted individually by the different experts in a team.
- "Explain" is the confrontation part of the session, where the individually developed ideas and theories are put on the table and confronted.
- "Conclude" is another Team Leader-exclusive part, where the final and official decision is taken.
- "Record" is the final part of the session, where the taken decision is put on paper.

## 1.6 Design representation

A design representation models the system design and conveys the system designers' intentions through various design features. The form and detail level of the design representation depend on the system development stage. It can be either physical or logical [1].

- Logical data models provide a high-level, abstract representation of data, focusing on structure and relationships rather than on physical implementation details. They act as blueprints for understanding data organization and the interconnections between different data entities, making them essential in the early stages of design for clarifying data requirements and business rules.
- Physical data models offer detailed, concrete representations of data, outlining how it will be stored, accessed, and retrieved within a database system. These models specify tables, columns, indexes, and storage mechanisms, and are used in the later stages of design to guide the implementation and optimization of the database structure.

A physical model depicts the real-world layout of the system, such as through drawings, schematics, or reliability block diagrams. A logical design representation, on the other hand, illustrates the logical relationships between system elements, showing how components should function together. This can be represented by functional flow diagrams, data flow diagrams, and similar tools. An extensive HAZOP analysis typically involves both physical and logical design representations [1].

The study leader uses the design representation to control the analysis process. It serves as an agenda for the study team meetings, allowing the team to sequentially evaluate each item in the design representation [1].

Utilizing design representation aids, such as functional block diagrams, reliability block diagrams, context diagrams, data flow diagrams, and timing diagrams, significantly simplifies the HAZOP analysis process. It is essential for each team member to understand the design representations used in the analysis [1].

## 1.7 Process variables

A system comprises a set of components, and on a design representation, a path between two components indicates an interaction or design feature. An interaction can consist of a flow or transfer from one component to another. A flow may be tangible (such as a fluid) or intangible (such as an item of data). In either case, the flow is designed with certain properties, referred to as process variables, which affect how the system operates. These process variables are key to identifying design deviations in a HAZOP analysis [1].

The correct operation of a system is determined by the process variables of the interactions and components maintaining their design values (i.e., design intent). Hazards can be identified by studying what happens when the process variables deviate from the design intent. This is the principle behind HAZOP analysis [1].

Table 3 contains a list of example system process variables. The list is purely illustrative, as the words employed in an actual HAZOP review will depend upon the plant or system being studied [1]:

*Table 3: Examples of system parameters used in the HAZOP analysis [1].*

| | |
|---|---|
| • Flow (gas, liquid, electric current) | • Temperature |
| • Pressure | • Level |
| • Separate (settle, filter, centrifuge) | • Composition |
| • Reaction | • Mix |
| • Reduce (grind, crush, etc.) | • Absorb |
| • Corrode | • Erode |
| • Isolate | • Drain |
| • Vent | • Purge |
| • Inspection, surveillance | • Maintain |
| • Viscosity | • Shutdown |
| • Instruments | • Startup |
| • Corrosion | • Erosion |
| • Vibration | • Shock |
| • Software data flow | • Density |

Note that some process variable words may not appear to be related to any reasonable interpretation of the design intent of a process. For example, one may question the use of the word corrode on the assumption that no one would intend for corrosion to occur. However, most systems are designed with a certain lifespan in mind, and implicit in the design intent is that corrosion should not occur, or if expected, it should not exceed a certain rate. An increased corrosion rate in such circumstances would be a deviation from the design intent [1].

## 1.8 Guide words

Guide words help to direct and stimulate the creative process of identifying potential design deviations. These guide words may be interpreted differently across various industries and at different stages of the system's life cycle. The interpretation of a guide word must consider these contexts to effectively explore plausible deviations from the design intent [1].

HAZOP analysis guide words are short words used to stimulate the imagination regarding deviations from the design intent. For example, for the process variable "data flow" in a computer system, the guide word "more" can be interpreted as more data being passed than intended, or being passed at a higher rate than intended. For the process variable "wire" in a system, the guide word "more" can be interpreted as higher voltage or current than intended. Table 4 contains an example list of HAZOP guide words [1]:

*Table 4:Examples of guide words used in the HAZOP analysis [1]*

| Guide Word | Meaning | Continuous | Batch |
|---|---|---|---|
| No | The design intent does not occur (e.g., Flow/No), or the operational aspect is not achievable (Isolate/No). | YES | YES |
| Less | A quantitative decrease in the design intent occurs (e.g., Pressure/Less). | YES | YES |
| More | A quantitative increase in the design intent occurs (e.g., Temperature/ More). | YES | YES |
| Reverse | The opposite of the design intent occurs (e.g., Flow/Reverse). | YES | YES |
| Also | The design intent is completely fulfilled, but in addition some other related activity occurs (e.g., Flow/Also indicating contamination in a product stream, or Level/Also meaning material in a tank or vessel that should not be there). | YES | YES |
| Other | The activity occurs, but not in the way intended (e.g., Flow/Other could indicate a leak or product flowing where it should not, or Composition/ Other might suggest unexpected proportions in a feedstock). | YES | YES |
| Fluctuation | The design intention is achieved only part of the time (e.g., an air lock in a pipeline might result in Flow/Fluctuation). | YES | NO |
| Early | The timing is different from the intention. Usually used when studying sequential operations, this would indicate that a step is started at the wrong time or done out of sequence. | NO | YES |
| Late | Same as for Early. | NO | YES |
| As Well As (more than) | An additional activity occurs. | YES | YES |
| Part of | Only some of the design intention is achieved. | YES | YES |
| Reverse | Logical opposite of the design intention occurs. | YES | YES |
| Where else | Applicable for flows, transfers, sources, and destinations. | YES | YES |
| Before/After | The step (or some part of it) is effected out of sequence. | NO | YES |
| Faster/Slower | The step is done/not done with the right timing. | YES | YES |
| Fails | Fails to operate or perform its intended purpose. | YES | YES |
| Inadvertent | Function occurs inadvertently or prematurely (i.e., unintentionally). | YES | YES |

## 1.9 Deviation from design intent

Since HAZOP analysis focuses on identifying deviations from design intent, understanding this concept is crucial. All systems are designed with an overall purpose in mind. For example, an industrial plant system may be intended to produce a certain tonnage of a particular chemical per year, manufacture a specified number of cars, or process and dispose of a certain volume of effluent annually. For a weapons system, the purpose is to hit the intended target. These are the primary design intents for these systems; however, a secondary intent would be to operate the system as safely and efficiently as possible [1]; secondary, but not less important.

Each subsystem must consistently function in a specific manner to achieve the overall goals. This specific manner of performance is the design intent for that particular item. For instance, if part of the overall production requirement for a system includes a cooling-water facility, this would involve circulating water through a pipe system driven by a pump. A simplified statement of the design intent for this small section of the plant would be "to continuously circulate cooling water at an initial temperature of x °C and at a rate of n gallons per hour." It is usually at this low level of design intent that a HAZOP analysis is directed [1].

The concept of deviation now becomes clearer. A deviation from the design intent in the case of the cooling facility could be a failure of circulation or the water being at too high an initial temperature. It is important to distinguish between a deviation and its cause. In this case, a pump failure would be a cause, not a deviation [1]. The distinction is crucial for several reasons:

1) Structured analysis: HAZOP is a methodical process that relies on a clear understanding of deviations to explore all possible hazard systematically. By identifying deviations first, the team can then explore various potential causes for deviations, ensuring a comprehensive analysis.
2) Effective mitigation: understanding the cause of a deviation allows for targeted interventions. If the pump failure is identified as the cause, then maintenance strategies, redundancy measures or alarms can be implemented specifically to address reliability, thereby preventing the deviation from occurring.
3) Risk assessment: accurately distinguishing between deviations and their causes is also important for risk assessment. The risk associated with a deviation depends not only on its potential consequences but also on the likelihood of its causes.

## 1.10 Worksheet

The HAZOP analysis technique is a detailed hazard analysis that employs structure and rigor. Using a specialized worksheet for HAZOP analysis is recommended. While the exact format of the worksheet is not crucial, matrix or columnar-type worksheets are typically used to maintain focus and structure during the analysis. HAZOP analysis sessions are primarily documented in these worksheets, where various items and proceedings are recorded. At a minimum, the following basic information is required in a HAZOP analysis worksheet [1]:

1. Item under analysis
2. Guide words
3. System effect if the guide word occurs
4. Resulting hazard or deviation (if any)
5. Risk assessment
6. Safety requirements for eliminating or mitigating the hazards

The recommended HAZOP analysis worksheet is shown in Figure 3. This particular worksheet uses a columnar format. Other worksheet formats may exist, as different organizations often tailor their HAZOP analysis worksheets to fit their specific needs. The specific worksheet to be used may be determined by the system safety program (SSP), system safety working group, or the HAZOP analysis team performing the analysis [1].

The following instructions describe the information required under each column entry of the HAZOP worksheet [1]:

1. No.: This column identifies each HAZOP line item and is used for reference purposes within the analysis.
2. Item: This column identifies the process, component, item, or function being analyzed.
3. Function/Purpose: This column describes the item's purpose or function in the system to ensure the operational intent is understood.
4. Parameter: This column identifies the system parameter that will be evaluated against the guide words.
5. Guide Word: This column identifies the guide words selected for the analysis.
6. Consequence: This column details the most immediate and direct effect of the guide word occurring, typically described as a system deviation from design intent.
7. Cause: This column lists all possible factors that can cause the specific deviation. Causal factors may include various sources such as physical failure, wear, temperature stress, vibration stress, and more. All conditions affecting a component or assembly should be

noted, indicating any special periods of operation, stress, personnel action, or combinations of events that might increase the probabilities of failure or damage.

8. Hazard: This column identifies the specific hazard formulated as a result of the specific consequence or deviation. It is important to document all hazard considerations, even if they are later proven non-hazardous.
9. Risk: This column provides a qualitative measure of mishap risk for the potential effect of the identified hazard. Risk measures are a combination of mishap severity and probability. The recommended qualitative values from MIL-STD-882 are shown below:

*Table 5: MIL-STD-882 recommended values*

| Severity | Probability |
|---|---|
| 1. Catastrophic | A. Frequent |
| 2. Critical | B. Probable |
| 3. Marginal | C. Occasional |
| 4. Negligible | D. Remote |
| | E. Improbable |

Severity describes the consequences of a deviation, based on the potential impact on safety, equipment and the environment. The standard defines four categories:

- Catastrophic: Potential of death, permanent total disability, irreversible environmental impact or monetary loss exceeding 10 million dollars.
- Critical: Permanent partial disability, hospitalization of three or more personnel, reversible environmental impact, or monetary loss between $1 million and $10 million.
- Marginal: Injury or occupational illness causing one or more lost workdays, moderate reversible environmental impact, or monetary loss between $100,000 and $1 million.
- Negligible: Injury or illness not resulting in lost workdays, minimal environmental impact, or monetary loss under $100,000.

Probability measures the likelihood of a hazard occurring and is divided into six levels:

- Frequent: Likely to occur often in the item's life, continuously experienced.
- Probable: Will occur several times during the item's life.
- Occasional: Likely to occur sometime during the item's life.
- Remote: Unlikely but possible to occur.
- Improbable: So unlikely that occurrence is assumed not to happen during the item's life.
- Eliminated: Hazard is no longer present, and no possibility of occurrence exists.

10. Recommendation This column provides any recommendations for hazard mitigation that are evident from the HAZOP analysis, such as design or procedural safety requirements. Its content should clearly and specifically outline the actions needed to address identified deviations, focusing on both prevention and mitigative measures. Recommendations may include physical modifications, procedural changes, further analysis or verification activities. Each recommendation should be practical, feasible and directly linked to mitigating the identified risk, ensuring that the team has a clear and actionable path forward to enhance process safety.
11. Comments This column provides any pertinent comments to the analysis that need to be remembered for possible future use.

| **HAZOP Analysis** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | Item | Function/ Purpose | Parameter | Guide Word | Consequence | Cause | Hazard | Risk | Recommendation | Comments |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |

*Figure 4: HAZOP worksheet example, obtained from [1]*

## 1.11 Weaknesses of the HAZOP technique

### *1.11.1 Time and energy consumption*

As mentioned in multiple papers, at the time present a HAZOP Study is an expensive process, mainly due to the high time consumption and effort consumption. These characteristics inevitably lead to companies performing only a limited number of studies, usually at the end of the design project, risking the identification of safety risks when its nullification or mitigation is costly, both in economic and time terms [19].

As reported in more than one of the analysed papers [20] [21] [2], one of the major issues with "traditional" HAZOP techniques is the very consistent time and effort required to complete an analysis. This inevitably results in HAZOP being prohibitively expensive, naturally leading to companies performing only a limited number of studies, usually at the end of the design project; this also applies to the repetition of studies on the same system. It also causes the possibility of safety risk identification when its nullification or mitigation is costly, both in economical and time-consuming terms. Finally, one last consequence regards studies review, that may not receive the deserved attention.

An analysis [22] has been conducted on five HAZOP studies to estimate how long does it take to complete a study. Key variables were collected and recorded for modeling purposes. Several parameters were studied:

1) The time required to gather and organize the essential data for the study ($T_P$).

2) The time needed to conduct the HAZOP sessions ($T_S$).

3) The time taken to prepare the first draft of the HAZOP report ($T_W$).

These parameters were explored to identify relationships with factors that inherently define the complexity of the process to be "HAZOPed," such as the number of major equipment pieces, P&IDs, PFDs, and the total amount of "minor" equipment (e.g., FCVs, pumps) present in the process [22].

By analyzing various combinations from both mathematical and process safety perspectives, a well-fitted regression model was established to predict the time required to complete a HAZOP study in continuous chemical processes based on these factors [22]. This modeling approach the expected number of nodes to be selected [22]. The two key predictors that allow for the evaluation of process complexity are:

a) the number of major equipment pieces (ME) illustrated on PFDs and

b) the number of P&IDs required to define the process (P&IDs).

Furthermore, the time required to brainstorm each selected node was recorded for a more in-depth analysis, which provided more reliable conclusions, particularly in estimating the time needed for HAZOP sessions. Table 3 lists the key data used to develop the model. As illustrated in Table 2, the total time required to conduct a HAZOP study is defined as follows:

$$TH = TP + TS + TW \tag{1}$$

*Table 6: Comparison between HAZOP time estimation models [22].*

| Model | Freeman et Al. (1992) $T_H = T_P + T_S + T_W$ | Khan and Abbasi (1997) $T_H = T_P + T_S + T_W + T_D$ | Proposed model $T_H = T_P + T_S + T_W$ |
|---|---|---|---|
| **Preparation time estimation ($T_P$)** | | | |
| Description | $T_P$ depends on the number of P&IDs and its complexity (simple, standard, complex, very complex) by counting the number of pieces of equipment, pipelines and interlocks per P&ID | $T_P$ depends on the number of P&IDs and its complexity (simple, standard, complex, very complex) by counting the number of pieces of equipment, and pipelines per P&ID | $T_P$ depends on the number of P&IDs (P&IDs), the total number of pieces of major equipment (ME), and requires to follow the proposed Nodes Selection Methodology (NSM) |
| Input data | Number of P&IDs, and P&IDs complexity | Number of P&IDs, and P&IDs complexity | P&IDs, ME, NSM |
| Output data | $T_P$ | $T_P$ | $T_P$ and the number of nodes $N_d$ |
| **Sessions Time Estimation ($T_S$)** | | | |
| Description | $T_S$ depends on the leader skills (novice, average or experienced; according to the number of previous HAZOPs carried out), the number of P&IDs, and P&IDs complexity | $T_S$ depends on the leader skills (novice, moderately experienced, experienced and highly experienced; according to the number of previous HAZOPs carried out), the number of P&IDs, and P&IDs complexity | $T_S$ depends on the number of nodes (Nd) = f(P&IDs, ME), and requires to follow the proposed Deviations Structural Hierarchy (DSH) |
| Input data | Number of P&ID, P&IDs complexity, leader skills | Number of P&IDs, P&IDs complexity, leader skills | P&IDs and ME (or which is the same: Nd), DSH |
| Output data | $T_S$ | $T_S$ | $T_S$ |
| **Writing Time Estimation ($T_W$)** | | | |
| Description | $T_W$ depends on the $T_P$ | $T_W$ depends on the $T_P$ | $T_P$ depends on the $T_P$ |
| Input data | $T_P$ | $T_P$ | $T_P$ |
| Output data | $T_W$ | $T_W$ | $T_W$ |
| **Delay time estimation ($T_D$)** | | | |
| Description | Not considered | $T_D$ includes the time lapsed due to non-availability of members, documents, or any other essential items, and individuals responding time | Not considered |
| Input data | | $T_P$,$T_W$ | |
| Output data | | $T_D$ | |

*Table 7: Assembled data for HAZOP time estimation [22].*

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

The modeling process involves not only simple regressions using least-square models but also includes:
- Storing regression statistics.
- Examining residual diagnostics.
- Generating prediction intervals (PI) and confidence intervals (CI).

Additionally, the HAZOP time-estimation model was designed to be as straightforward as possible, aiming to identify the minimum necessary set of predictors for the best fit [22].

### *1.11.2 Human-related limitations*

The very nature of a traditional HAZOP analysis means results are produced by the human team of Experts. The fact that every possible consequence and cause for every possible deviation in a plant should be at least considered results in a series of boring and repetitive tasks, inevitably causing voluntary or involuntary neglecting of some cases after repeated sessions, necessary for completion of an analysis [21]. Cognition, reliability and reasoning capacities may drastically decrease when repetitive tasks are carried out, or large amounts of data are presented. Also, it had been explored how, because of organizational issues, sometimes the team is forced to analyse a specific part of the system at a particular time, even if the optimal order (if found) suggests otherwise [23]. The primary reason is the team members availability, not to mention the process system complexity that may force a change in the sequence during the analysis to address unforeseen issues or dependencies between nodes [23]. Last but not least, during the analysis of a particular node, the team might discover that they need information or results from the analysis of a different node that was not previously analysed, requiring the team to switch to another node out of sequence to obtain the necessary data or clarification [23].
Another problem, naturally related to processes that involves a team of humans, is represented by cognitive biases, that could correspond to spurious and/or missing results; such biases are subconsciously employed during the course of the study and, more importantly, very difficult to override [20]. Some of them are:

- Anchoring Heuristic: it occurs when individuals rely too heavily on the first piece of information they encounter (the "anchor") when making decisions. A facilitator, or a team member, by suggesting an initial idea or risk estimate can unduly influence the team's subsequent judgments, potentially leading to overemphasis on certain risks, while neglecting others [20].
- Availability Heuristic: it involves making decisions based on information that is most readily available or easily recalled, rather  on all relevant data. This can lead to a focus on more familiar hazards or scenarios while overlooking less obvious, but equally significant, risks. For example, teams might concentrate on common process parameters, like temperature and pressure, but ignore less frequently considered factors like human errors or environmental siting issues [20].
- Confirmation Bias: it is the tendency to search for, interpret and remember information in a way that confirms one's preconceptions. Team members might unconsciously look for evidence that supports their belief that a process is safe, leading to the dismissal of potential hazards or the underestimation of risks [20].
- Conformity and Peer Pressure: Team members might feel pressured to align their opinions with the group consensus, even if they have doubts. This can suppress alternative viewpoints and lead to incomplete or biased analysis [20].
- Groupthink: this bias arises when a group's desire for harmony or conformity results in irrational or dysfunctional decision-making outcomes. This can cause the team to overlook risks or fail to challenge assumptions [20].
- Framing Effect: the way information is presented can influence decision-making [20].
- Representative Heuristic: people may judge the likelihood of an event by how closely it resembles a known situation, even if the situations are not truly comparable. This could lead to incorrect assumptions about the process risks based on superficial similarities to other processes [20].
- Satisficing: this occurs when the team settles for a solution "good enough" rather than optimal. Under time pressure, or due to cognitive overload, teams might miss critical scenarios, or fail to identify the best risk reduction measures [20].

### *1.11.3 Cost-benefit analysis*

One key weakness of HAZOP is that it does not inherently include a cost-benefit analysis for its recommendations. While it effectively identifies hazards and provides safety and operability improvements, it does not assess the financial or resource implications of implementing these recommendations. As a result, decision-makers must conduct separate cost-benefit analyses to determine whether the proposed safety measures are feasible and justified based on their costs versus the benefits of risk reduction. This limits HAZOP's ability to offer a complete risk management solution on its own.

### *1.11.4 Steady-state analysis*

Since HAZOP primarily focuses on deviations from design intent during normal, steady-state operations, it may not fully address hazards that arise during non-steady-state conditions, such as system startups, shutdowns, transitions, or abnormal operating phases. These dynamic conditions often introduce different risks and operational challenges that may not be captured in a steady-state analysis. As a result, relying solely on a HAZOP study may leave certain transient or infrequent scenarios under-analyzed, requiring supplementary analysis methods like dynamic risk assessment or specialized reviews for non-steady-state operations.

### *1.11.5 Results clustering*

Clustering of results is a notable weakness in traditional HAZOP analysis. In many cases, not only are consequences grouped together, but deviations and possible causes are also grouped into single entries. While this approach can simplify the presentation of results, it often results in a loss of detail and clarity. Clustering multiple deviations, causes or consequences can obscure important distinctions between different risk scenarios, making it more difficult to identify and prioritize specific hazards. In addition, this clustering makes it difficult to compare with other methods, such as automated approaches that treat each element separately. This can ultimately reduce the accuracy of the analysis and the effectiveness of the risk mitigation strategies derived from it.

## 1.12 Strengths of the HAZOP techniques

The HAZOP (Hazard and Operability Study) methodology is highly regarded for its systematic and rigorous approach to identifying potential hazards and operability issues in complex processes. One of its primary strengths is its ability to detect hazards early in the design phase, which significantly enhances safety and reduces the cost of modifications. By methodically examining each part of a process, HAZOP can uncover potential issues that might be missed by other analysis methods. This detailed examination helps in developing effective safeguards and mitigation strategies, ensuring that risks are managed proactively. Additionally, the collaborative nature of HAZOP, involving multidisciplinary teams, brings diverse perspectives to the table, enriching the analysis and leading to more robust and innovative safety solutions. This collaborative approach not only improves the quality of the analysis but also fosters a culture of safety and continuous improvement within organizations [2]

## 1.13 Automated HAZOP techniques

### 1.12.1 *Introduction*

It is worth mentioning that, prior to the abovementioned analysis, it had been discussed whether the ultimate goal of this project would be to produce either an almost completely automatic Expert-assisted Software or a complete (in terms of assistance) possible Tool for the expert team assistance in a HAZOP analysis. It has been decided that, arguably, the best choice is to opt for automated software capable of exploiting as much as reasonably possible what is the biggest advantage that comes from using software, i.e. information processing speed and properly sorted data generation.

It is important to mention, at this point, how imperative it is to safeguard and maintain human contribution to HAZOP analysis. The HAZOP expert role must be shifted from the majority (if not all) of the tasks involved to consistency checking and filtering of software-produced results. This project aims to create a technique that makeshumans and machines work chorally and exploits the best part of both, rather than excluding the first one completely in favour of the latter.

Future developments and improvements of these techniques should be focused on furtherly automate the analysis procedure, develop an international standard for data and implement additional tools for finding the optimal order of execution, sorting output data more efficiently and speeding up both consistency check and filtering of produced results.

### *1.13.2 State of the art*

This sub-paragraph will briefly present an overview of the state of the art in HAZOP automation. Two core elements in every HAZOP analysis technique will be briefly discussed, as graphs are at the base of every model mathematical representation of systems as much as matrices are for making it digestible to computer machines. Later, an overview of HAZOP techniques in general is outlined.

#### 1.13.2.1 Graphs

All analysed techniques have at their core a model, used to represent the plant from the point of view of one variable influence on the other. Different representations had been used, but in one way or another all can be seen as evolutions of the Signed Directed Graph. This type of graph, in its simplest form of the ones analysed, is made of nodes that can represent process variables, process parameters or single pieces of equipment; arrows, called arcs, indicate associations between two variables or deviations [24].

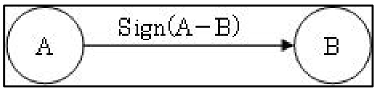



*Figure 5: Example of a SDG: process variable A influences process variable B [24]*

Over the years, researchers have proposed numerous variations of this model. Some present minimal modifications and/or additions, like multiple arcs to take into account the control instrumentation action [25], while others show a substantially more complex approach, like implementing a multi-layer graph [26] or grouping process variables in well-defined subset rather than singularly connecting nodes [27].

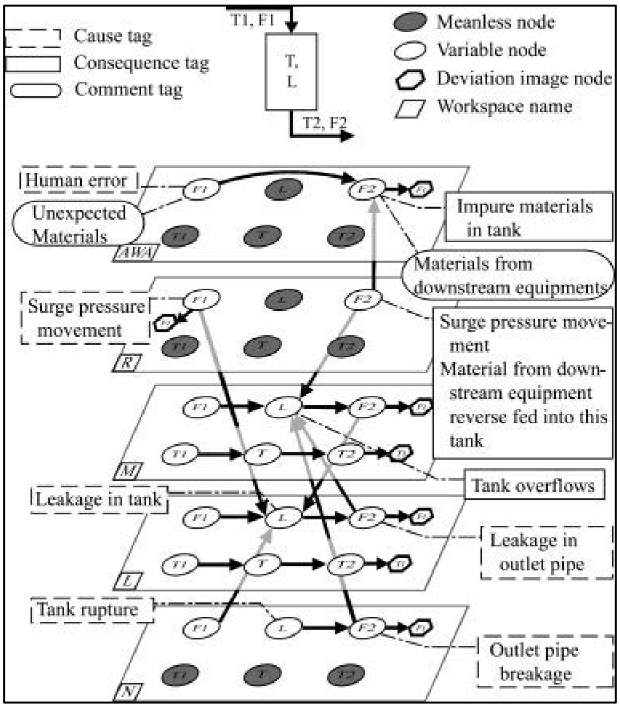



*Figure 6: Layered Directed Graph [26]*

Taking into consideration control instrumentation makes the model representation closer to the actual system under analysis; a multi-layered graph takes into account the effect of process variables deviations on others not connected in traditional SDGs. Different models and approaches tackles different weaknesses of the original approach.

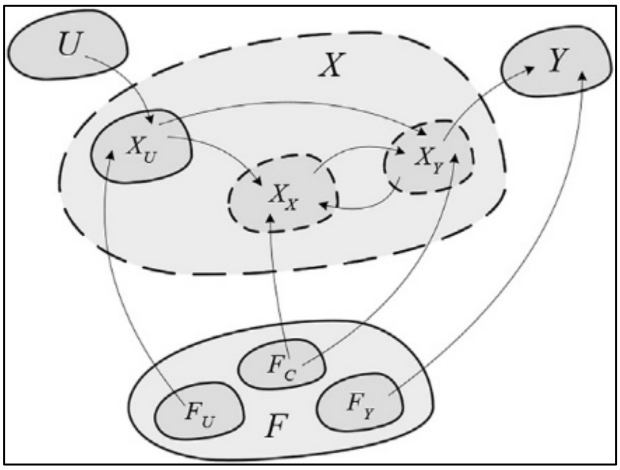



*Figure 7: Variables grouped into subsets [27]*

#### 1.13.2.2 Matrix representation

It is also important to mention that the more advanced and complex model usually makes use of a matrix representation. This is particularly relevant in the field of automated HAZOP, since said representation makes a model more compatible with software implementation and, consequently, also a better candidate in HAZOP automation procedures. The structured and mathematical nature of matrices aligns well with computational capabilities of digital systems for different reasons:

- Matrices allow for a compact and organized representation of complex system, especially when dealing with large amounts of interconnected data. It makes easier to store, retrieve and manipulate system information within a digital environment.
- As system grow in complexity, matrices can scale efficiently, maintaining a clear structure that digital systems can handle without significant loss of performance.
- Matrices are excellent at representing the relationships between different components of a system, such as in a network, where nodes and their connections can be modelled as entries in an adjacency matrix. This is crucial for understanding and optimizing system performance during digitalization.
- In digital systems, matrices are often used in conjunction with graph theory to model complex interactions and dependencies, making it easier to visualize and analyse system dynamics.
- Many digital tools and software platforms, especially those used in system design, simulation and analysis, are built to work with matrix representations. This ensures smooth integration and reduces the complexity of converting data between different formats during the digitalization process.

- Matrix operations can be parallelized effectively, allowing for faster computation on modern multi-core processors or GPUs. This is particularly beneficial in digital systems that require high-speed processing of large datasets or real-time analysis.
- Many optimization algorithms, crucial in digital system design and improvement, rely on matrix representations to efficiently solve complex problems involving numerous variables and constraints.

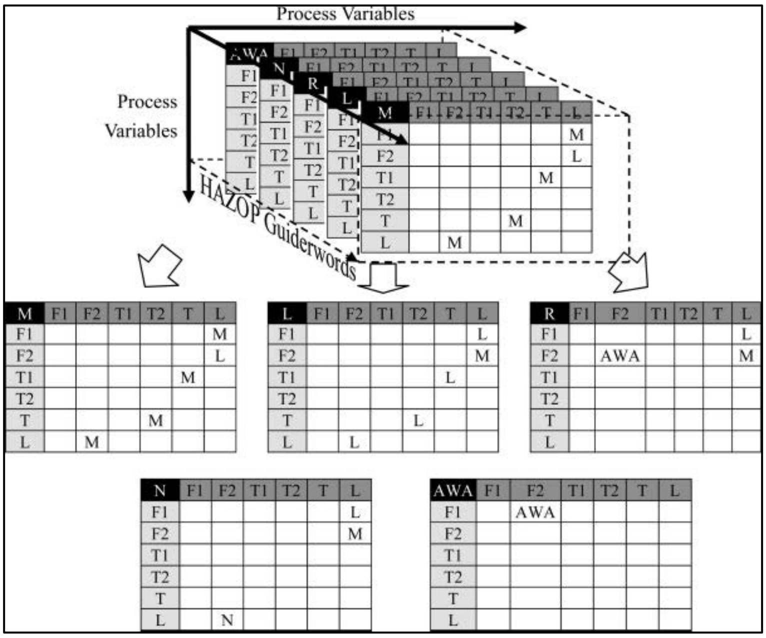



*Figure 8:Example of matrix representation of a model (relational matrix, LDG graph) [26]*

Depending on the technique reviewed, these matrices can vary substantially in terms of content, complexity in terms of dimension, obtaining method and properties. Key features include content such as risk matrices, deviation matrices, and action matrices; complexity ranging from simple 2D matrices to multi-dimensional ones; obtaining methods like manual input and automated data collection; and properties that can be dynamic or static.

The pros of using matrices in HAZOP automation include improved efficiency, consistency, clarity, and traceability. However, there are also cons, such as complexity, over-reliance on automation, initial setup cost, and the dependence on data quality. Using matrices in HAZOP automation offers numerous benefits, including improved efficiency, consistency, and clarity. However, it’s essential to balance automation with human oversight to ensure a comprehensive and accurate risk assessment. Understanding the specific needs of the process and choosing the right type of matrix can help maximize the benefits while mitigating potential drawbacks.

In Figure 7, for example, a tri-dimensional matrix with strings corresponding to guidewords (M = more, L = less, AWA = As Well As) as coefficients had been implemented for knowledge storage and management [26].

As previously said, matrix representation capability makes a model more compatible with software, as they are easily digestible by computers when used as storage for knowledge about how all the variables in a unit (or a system, when interlinking is conducted) affect each other.

#### 1.13.2.3 The automated techniques

In the realm of modern HAZOP techniques, there has been significant development toward the automation of hazard identification processes. Various projects and propositions are currently under exploration, each offering different levels of automation. Some tools focus on automating only specific tasks, such as the propagation of deviations for cause and consequence analysis [24] [21]. These tools act as decision aids to assist human teams in systematically analyzing deviations while still relying heavily on human expertise for the interpretation and development of corrective actions. For instance, software tools like this might automate deviation identification but still require the human team to assess the significance of deviations and devise appropriate mitigation strategies [21].

On the other hand, more advanced methodologies have been developed using cutting-edge technologies such as SmartPlant P&ID (SPPID). This technology aims to automate nearly every step of the HAZOP analysis process. With systems like SPPID, many traditional tasks, such as identifying nodes, generating deviations, and analyzing potential hazards, are fully digitized [19]. The human role in these systems is reduced to input delivery, validating the software-generated results, and ensuring consistency checks [19]. This represents a significant shift, with the software taking over much of the labor-intensive work traditionally performed by HAZOP teams, thus reducing the time and effort required for comprehensive hazard assessments.

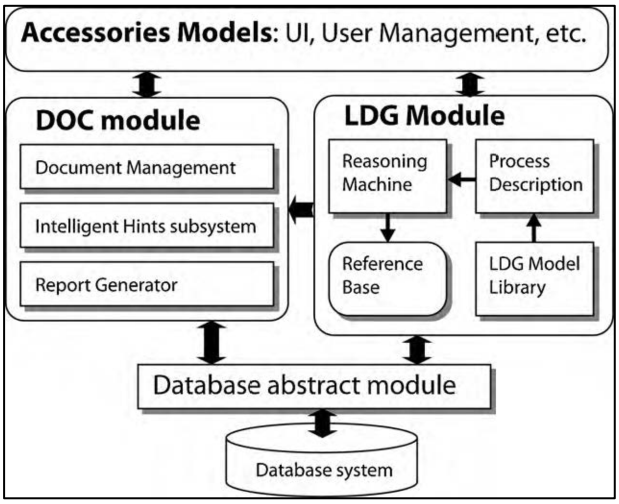



*Figure 9:Example of an evolved HAZOP technique (LDGHAZOP) [19]*

Between these two approaches lie numerous software solutions that automate HAZOP processes to varying degrees. Typically, these tools differ in the way they integrate units and models, offering different methods for associating process units with their corresponding digital models [25]. Some software environments incorporate modules for automatically compiling results, while others provide more advanced propagation models [23]. For example, certain tools use event-tree structures to model hazard propagation, while others employ block or layered designs where nodes are interconnected to trace deviations [28]. These approaches offer flexibility in how hazards and their potential consequences are modelled and visualized, depending on the complexity of the system and the software in use.

Despite these advancements, full automation of the HAZOP process remains a challenge. The most widely automated task thus far is the propagation of deviations [24]. Other tasks, such as node identification, input of process data, and the analysis of more complex systems, still require substantial human intervention. Even though the steps of HAZOP have been digitalized in many tools [19], they still require expert input to construct the case for the software to analyse. For instance, the software might automate the analysis of a heat exchanger by tracing deviations in temperature or flow, but the initial setup and interpretation of the analysis must be performed by experienced engineers. This blend of automation and human expertise is crucial for ensuring the accuracy and reliability of the results generated by these systems.

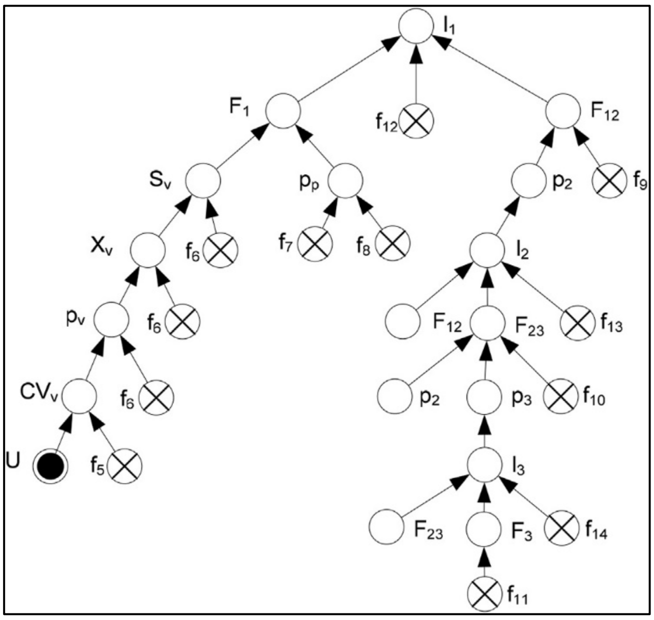



*Figure 10: Example of a Causes and Consequences Tree [27]*

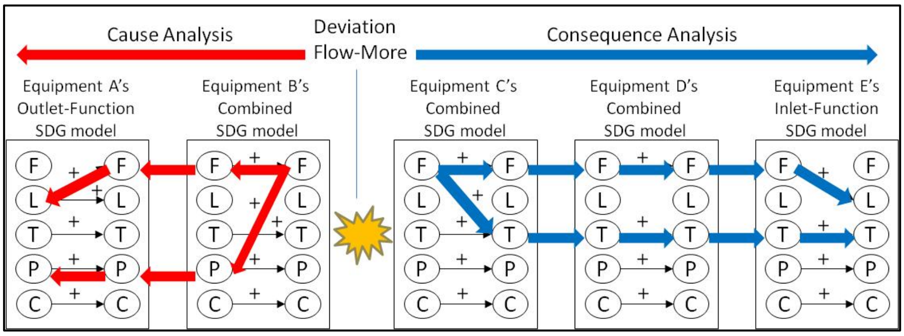



*Figure 11:SDG-based Cause and Consequences Analysis example. [24]*

## *1.13.3 Gap analysis*

After analysing a consistent quantity of scientific literature HAZOP automation, a series of gaps have been identified and will be reported in this sub-paragraph.

### 1.13.3.1 Standard for data

When it comes to the interoperability between interacting computer systems in the context of chemical process industries, numerous challenges remain [29]. A key issue is the lack of a universally accepted standard for the exchange of process data between heterogeneous systems [29]. This has led to inefficiencies and increased costs, as stakeholders such as engineering procurement construction companies (EPCs), owner-operators, and vendors rely on disparate systems, often necessitating manual data transfer and reformatting [29]. Various solutions have been proposed to mitigate these problems, such as a Data Map based on an ontology library, designed to act as an interpreter between different technology standards. However, such tools are proprietary and limited to specific software products, which restricts their general applicability.

One prominent example is ISO 15926, which is widely used in the design and construction phases but rarely transitioned into the operational phases of plant management. ISO 15926 defines a common ontology for representing physical assets throughout their life cycle. However, barriers such as the pre-existence of legacy systems, the need for costly conversions, and gaps in compliance during the design phase limit its adoption [30]. Another initiative, the DEXPI standard, focuses on Piping & Instrumentation Diagrams (P&IDs), offering a solution for data exchange in the process industry. The DEXPI initiative has integrated with the OPC Unified Architecture (UA) [31], enhancing its ability to support the flow of information between P&IDs and process control systems, thus helping bridge the gap between these critical aspects of plant operations.

Despite these advancements, a common problem is that many of the solutions still focus on certain phases of the plant lifecycle or specific systems [29]. For example, ISO 15926 addresses plant items such as equipment and piping but falls short in representing the early-phase process design [29]. Furthermore, both DEXPI and ISO 15926 encounter challenges in their widespread implementation due to the need for consistent data modelling across systems, particularly when transitioning between CAE systems and plant management tools [30]. Overall, while there has been progress in developing standards and technologies for interoperability, much of the industry continues to rely on custom, proprietary solutions, which limits the broader scalability and applicability of these tools.

#### 1.13.3.2 Human involvement

As already explained, heavily relying on the Team of Experts for a HAZOP analysis has, inevitably, a negative impact on results [32]. Unfortunately, the majority of proposed techniques still relies on humans, and even though some of the burden had been put on built-in tools, often it’s required to the team on creating a list of possible deviations for the propagation algorithm.

# Chapter 2: HAZOP analysis criticalities

While HAZOP (Hazard and Operability Study) remains a cornerstone of risk management and hazard identification, it is imperative to critically evaluate its limitations to enhance its effectiveness. This chapter delves into the major criticalities inherent in the HAZOP methodology. Key areas of concern include the reliance on subjective expert judgment, the risk of overlooking non-obvious hazards, the intensive time and resource demands, and the potential for cognitive biases during the analysis process. Additionally, we will explore how the rigid structure of HAZOP may inadvertently constrain creative problem-solving and fail to account for dynamic system changes. Through a comprehensive examination of these issues, we aim to provide a nuanced understanding of the challenges faced in HAZOP analyses and suggest pathways for mitigating these criticalities to improve overall safety and operability outcomes.

## 2.1 Method's criticalities

### *2.1.1 No PHA Method can identify all accidents that could occur in a process*

Systematic approaches that identify all accident scenarios for processes do not exist due to the lack of available technical means. Even with the best efforts, the possibility of unidentified accidents occurring remains. Consequently, there are no guarantees that a particular accident scenario will be identified by Process Hazard Analysis (PHA). This uncertainty is inherent in the very definition of the word 'accident,' which is described as 'an unfortunate incident that happens unexpectedly and unintentionally' or 'something that happens by chance or without apparent cause [33]

### 2.1.2 *Some accidents may have been excluded from the HAZOP study scope*

Hazards such as falls from ladders, exposure to chemicals not covered by the regulation, and similar risks may have been intentionally excluded from the scope of the study. Consequently, accidents involving these hazards will not be identified [33]

### *2.1.2 Accidents related to new phenomena or previously unknown failure mechanisms are not addressed*

New phenomena and failure mechanisms are discovered periodically. Therefore, by definition, they cannot be addressed in PHA. [33]

### *2.1.3 The Experts team may have been unaware of the accident cause*

PHA does not, by itself, identify hazards or failure mechanisms that cause accidents. Instead, it provides an opportunity for the team conducting the study to use their knowledge and experience to identify accident sequences involving the occurrence of failure mechanisms and the hazards thus realized. If the team lacks knowledge or experience of the failure mechanisms involved in certain accidents, these will not be identified in the study. [33]

Typical PHA teams do not include individuals experienced in all the phenomena that could occur in process plants. Rather, teams are staffed with people who have knowledge and experience of the particular plant under study. This ensures that accident scenarios specific to the plant are identified, but scenarios involving unusual phenomena or failure mechanisms may not be recognized. [33]

## 2.2 Criticalities related to human involvement

### *2.2.1 The Experts team may judge the accident not credible*

For a PHA team to consider an accident scenario possible, team members must believe there are credible causes for the scenario that could result in a hazard being realized, i.e., that a certain combination of events is possible. Often, during a PHA study, the team debates the likelihood of a particular accident scenario occurring. Individuals who believe a scenario is not credible may persuade other team members to share their views [33].

Various factors influence a team’s perception of the credibility of hazard scenarios, including the age and history of the process. For well-established processes that have operated successfully for many years, teams tend to judge some hazard scenarios as not credible. Human nature tends to downplay risks that have not been encountered [33].

Familiarity with hazards can also cause them to be underrated by team members who have worked with a process for many years. In a PHA study, hazards that have been previously accepted by team members may be judged as having low significance compared to other hazards that may not have been considered before [33].

### 2.2.2 *The Experts team may judge the accident not significant*

Similarly to what, according to the previous sub-paragraph, could happen, if a team member has encountered accident conditions that did not result in significant consequences, the scenario may be dismissed, even though a variant of it could pose serious consequences [33].

### 2.2.3 *The Team may have overlooked the accident*

There are various reasons for an overlook by a team of experts:
First of all, human nature plays a role. Expecting perfection from participants is unreasonable. Studies involve intense brainstorming sessions conducted over extended periods, often compounded by repetitive work. Fatigue and boredom must be combated, as participants can become jaded despite their desire to perform well [33].
Second, the distractions and demands of everyday life can also be a factor. Personal and work-related problems can influence the performance of team members in ways that are difficult to assess and may not even be known or recognized. Human performance can fluctuate from day to day, even under normal circumstances. These human factors decrease the likelihood of identifying accidents in a PHA, particularly the more complex scenarios [33].
In addition to that, it is important to remember that teams are understandably focused on identifying scenarios that are not readily apparent. They concentrate on the complexities of the process in an attempt to uncover such scenarios. However, this focus may lead to the oversight of simple scenarios that, in hindsight, might be obvious [33].
Also, the team may struggle to digest all process information. There are practical limits to how much process information can be read, understood, and applied in a PHA. Process drawings, such as P&IDs, are typically the standard reference for teams. Other documents, like electrical one-line diagrams, operating procedures, and equipment specification sheets, may be consulted, but teams usually cannot review every available document. It may be argued that numerous checklists are available on many topics and should all be used in PHA. However, there are practical limits to how many checklists a team can apply during a PHA. The repetition involved and the fatigue induced in the team members would quickly negate the benefits provided by the checklists [33].
Another criticality is the false sense of security. Whenever a serious, previously unknown potential accident is identified by a team, considerable discussion often follows, which can take a significant amount of time. In such circumstances, the team may move on to the next part of the process, believing they have sufficiently addressed the current part. This sense of mission

accomplished may not be justified. The satisfaction felt by the team in discovering the scenario can distract them from thoroughly continuing with the process [33].

The use of inappropriate analogies may also be a problem. Commonly, processes contain sections that are similar or even identical. Teams often conclude that the hazard scenarios for these sections should be the same, provide a cross-reference, and move on. However, seemingly minor differences can sometimes lead to the possibility of other types of accidents that may go unidentified [33].

To not forget is the possibility of having an accident sequence too complex for the team to identify. PHA relies on the team's ability to identify events that may result in accidents and to judge their likelihood to determine if the accidents are credible. The more events involved in an accident sequence, the harder it is for the team to conceptualize and identify the sequence, making it less likely to be judged as credible [33].

When hazard analysis teams consider scenarios composed of multiple events, there is a tendency to judge these scenarios as having a sufficiently low likelihood of occurring, thus deeming them not credible. Furthermore, identifying hazard scenarios is particularly challenging when accident contributors originate from different parts of the process. In a PHA study, the process is broken down into constituent pieces, called nodes in HAZOP analysis, to facilitate the examination. This, however, has the unfortunate disadvantage of complicating the identification of scenarios whose contributors originate within different nodes of the process [33].

Similarly, the process may be too complex for the team to identify a particular accident, since process complexity also means scenario identification complexity; the same is true for complicated control systems. Teams may be reluctant to admit or even be unaware that they do not fully understand the process [33].

In addition to what previously said, it is also important to consider that accident scenarios may be variants of that recorded in an analysis. There can be multiple ways in which an accident scenario develops, depending on the success or failure of process responses to the initiating event. The various combinations of events define different variants of an accident scenario. Usually, the variant with the worst-case consequences is recorded in an analysis. Unfortunately, a team may mistakenly identify the wrong worst-case scenario. Another variant of the scenario could pose even worse consequences. Additionally, corrective actions taken for a worst-case scenario may not effectively protect against accidents with lesser consequences [33].

Last, but not least, new phenomena and/or failure mechanisms are periodically discovered. Consequently, by definition, they cannot be addressed in a traditional HAZOP analysis [33]

# Chapter 3: Methodology

This chapter presents the theory and methodology behind this dissertation. Section 3.1 outlines the framework for developing the HAZOP automation system, highlighting key processes and decisions. Section 3.2 describes the phenomenological approach that underpins the system representation, ensuring accurate behavior under deviations. Section 3.3 explains the use of graphs in modeling the system, and Section 3.4 introduces the preHAZOP table generator, detailing its core functionality.

## 3.1 The framework

The primary objective of this methodology is to facilitate a detailed comparison between the results of a traditional HAZOP analysis and those generated through the partially automated approach. This comparison represents a pivotal step in the thesis, serving as an initial validation of the phenomenological-based HAZOP automation framework, which will be discussed in greater detail in subsequent sections. Ultimately, this comparison aims to demonstrate the effectiveness and reliability of the automated system, establishing a foundation for further exploration and development of the approach in relation to conventional methods.

Before going forward, it is important to point out that such a comparison will be conducted considering the specific scenario of a preHAZOP analysis. The preHAZOP represents an early-stage hazard and risk assessment technique used to identify potential hazards and operational issues in the design phase of a process or system. It is performed before a full HAZOP (Hazard and Operability Analysis) study and serves as a preparatory step, ensuring that potential major risks are identified and addressed early in the design of a process (Figure 12).

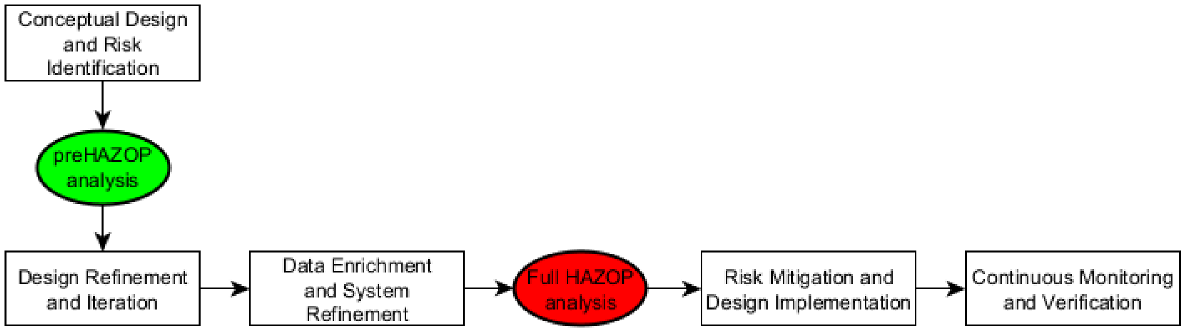



*Figure 12: preHAZOP and Full HAZOP within the flowchart representing the development of a process or project.*

It has been deemed the ideal scenario for the comparison mainly because of the early stage of the project, with many features required for a full HAZOP analysis that had not yet been implemented.

The methodology is structured into three main sections:

- *The Phenomenological Approach*. This is one of the foundational pillars of the project, adding scientific rigor by offering a detailed, quantitative framework for analyzing mass and energy flows within the system. This approach enables more accurate hazard identification by evaluating deviations based on actual physical and chemical properties, ensuring the analysis is grounded in observable phenomena rather than qualitative assumptions. It also enhances decision-making by providing a more reliable and adaptive methodology that aligns with industry standards.
- *Use of Graphs*. As this is an automated approach to HAZOP, the underlying phenomenology is implemented in a software environment. The system is modelled using graphs which allow efficient manipulation, visualization and analysis of system components and their interactions. For this project, the .graphml format was chosen as the most appropriate tool for representing these balances and interactions because of several key advantages. Firstly, it ensures compatibility with a wide range of software tools supported by specific Python libraries that allow easy manipulation of graph data. This allows the automation process to efficiently read, modify and analyze the graph structure. This compatibility is critical in the context of HAZOP automation, where different software may be used for analysis, data processing and reporting. The open and flexible nature of the .graphml format also enables smooth data exchange and interoperability across different platforms, making it a robust

choice for this project. Graphs provide a simplified way to track the propagation of a variation (i.e. an identified HAZOP deviation), identify critical paths and detect potential hazards. Their visual clarity, combined with the flexibility to integrate across multiple software platforms, makes them an ideal tool for both automated risk analysis and team collaboration.

- *Python Code Development*. The final pillar of this project involves the creation of Python code. This code extracts data from the .graphml file, calculates possible deviations, and generates detailed deviation propagation paths. The code offers an efficient and accurate preliminary HAZOP analysis (preHAZOP) by automating these steps. Additionally, it generates visualizations of the system that highlight potential risks, making the process more transparent and actionable.

The starting point for this methodology is the Process Flow Diagram (PFD), which has been chosen over a Block Flow Diagram (BFD) due to the greater amount of essential information it provides. A PFD includes key data such as major equipment, process flows, operating conditions (e.g., temperature and pressure), and material balances - all of which are critical for performing a HAZOP analysis. While a Piping and Instrumentation Diagram (P&ID) offers more detailed information, it is typically unavailable or not yet ready during the early stages of plant design, when preHAZOP analysis is expected. Therefore, the PFD serves as the optimal tool for this phase of the methodology.

The core of this project is structured according to the framework reported in Figure 12.

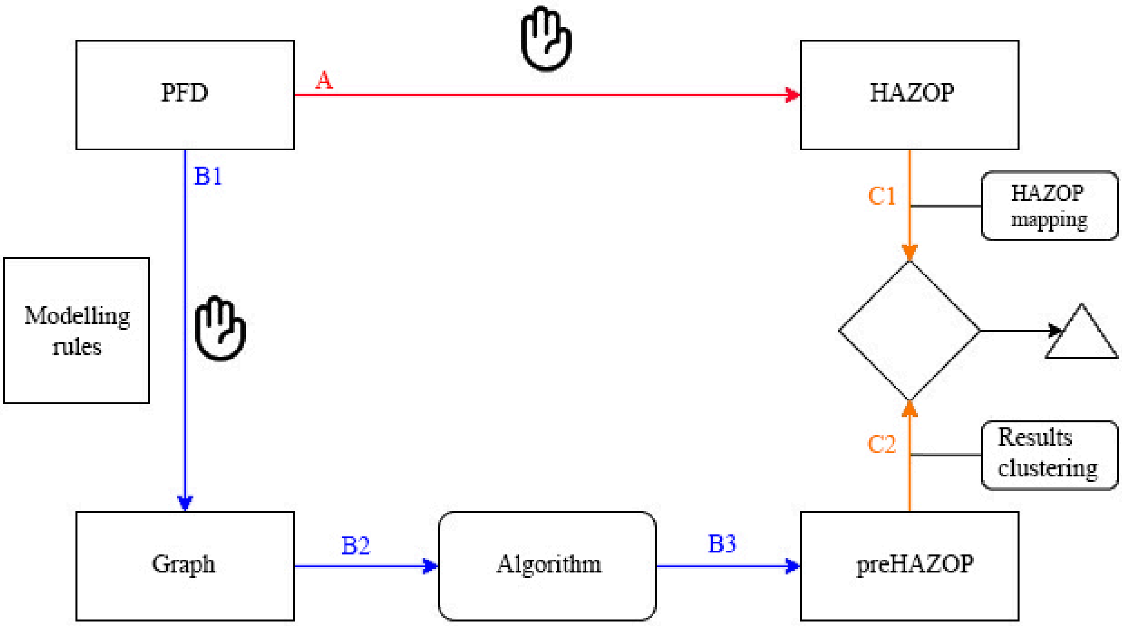



*Figure 13: Approach developed in this thesis to compare the results between traditional and automated HAZOP. The Traditional HAZOP pathway is highlighted in red, the Automated HAZOP pathway in blue, and the comparison between the two pathways is shown in orange. The current work aims to contribute to the Automated HAZOP pathway and the comparison strategy.*

From there, two possible pathways have been considered:

1. *Traditional HAZOP (A)*. The first step in a traditional HAZOP process is gathering the necessary documentation, with the Process Flow Diagram (PFD) serving as the primary reference [23] (Figure 14). The PFD provides an overview of the process, detailing essential aspects such as material flows, major equipment data, and primary operating conditions, including temperatures, pressures, and flow rates. The expert team or user begins by reviewing the PFD to obtain the overall structure and flow of the process, ensuring the diagram accurately represents the current state and includes all relevant components. Critical preliminary tasks include verifying the scope of the study and identifying the core process units.

   Once the PFD has been reviewed, the team will examine the critical process parameters displayed in the diagram. This involves noting specific flow rates, pressure points, temperatures, and the positions of key equipment. The goal at this stage is to ensure a detailed baseline understanding of the process. Sub-tasks may include comparing operating conditions with design specifications and creating a checklist of key equipment and their functions to ensure thorough preparation for further analysis.

   The next phase involves applying expert judgment to identify potential deviations from the design intent, such as deviations of process variables (e.g., "more flow" or "less pressure"). Using predefined HAZOP guidewords (e.g., "more", "less", "no", and "reverse"), the team systematically explores what could go wrong at various points in the process. This step is typically broken down by examining individual system components - such as valves and pumps - and considering how deviations might arise [21]. Sub-tasks include brainstorming sessions to cover all possible deviations, drawing on historical data and team experience to validate findings [27].

For each identified deviation, the team explores possible causes and consequences. At this early stage, the analysis remains generalized, focusing on identifying high-level risks such as safety or operability concerns. These risks are documented, though the precision of later-stage analyses is not yet required. Both internal design issues (e.g., potential equipment failure) and external influences (e.g., raw material availability, environmental factors) are considered, albeit with less granularity. The focus here is on flagging major risks rather than producing detailed cause-consequence diagrams. The team also anticipates potential design changes and highlights areas needing further development to address concerns identified during this phase. While the team may consult available documentation, such as preliminary design specifications or early design data, they rely heavily on expert judgment rather than detailed operational data.

The expected output of this preHAZOP phase is a high-level list of potential risk scenarios based on the conceptual design. Rather than detailing causes and consequences, this output identifies broad categories of risks that require further investigation. The findings are compiled into a preliminary report or worksheet, outlining key risks and areas for deeper analysis as the design evolves. While more detailed risk classification and prioritization (e.g., severity and likelihood) are reserved for subsequent HAZOP studies, basic prioritization of critical risks may be undertaken at this point. Recommendations are typically more general, such as reconsidering certain design aspects, identifying areas needing enhanced safety measures, or flagging sections for further analysis in later design phases.

Given that the design is still in the conceptual stages, detailed documents - such as equipment specifications and operating procedures - are often unavailable or not yet established. As a result, the team must rely on initial design assumptions, early-stage PFDs, and general safety guidelines to conduct the analysis. While the review of relevant regulations and safety standards remains essential, detailed vendor manuals and operational procedures are typically consulted later once more information becomes available. A critical final task is to ensure that all referenced design assumptions and early-stage documents are well-documented so they can be incorporated into subsequent, more detailed analyses.

The final output is a preHAZOP worksheet or summary report, capturing all identified high-level hazards and potential risks. Although this document may not yet contain specific causes or detailed control measures, it serves as a critical early-stage tool for influencing design decisions. The worksheet should accurately reflect the limitations of the current design and highlight areas for further investigation. Before finalizing the preHAZOP analysis, a review by peers or stakeholders is often conducted to ensure the analysis is sufficiently thorough for this early stage. The review focuses on verifying that the high-level hazards have been identified, assessing whether each major design assumption has been questioned using guidewords, and ensuring that potential issues related to process conditions (e.g., pressure, flow) have been considered. The team also evaluates whether key design documents, such as process flow diagrams (PFDs), were effectively used to identify risks and if any high-priority areas have been flagged for further, more detailed analysis during the subsequent full HAZOP. This process ensures that any significant gaps or overlooked early-stage risks are documented and highlighted for future study.

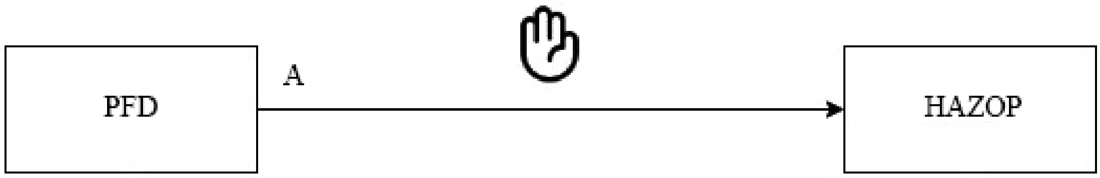



*Figure 14: Starting from the available documentation (e.g., a process flow diagram), a traditional HAZOP analysis (preHAZOP in this case) is performed (Scenario 1).*

2. *Automated HAZOP (**B1-B3**)*. In this approach, outlined in Figure 15, the human team manually converts the Process Flow Diagram (PFD) into a graph using appropriate modeling software (B1). This graph is structured based on predefined modeling rules to ensure it accurately reflects the system components and their interactions. Once created, the graph is fed into purpose-built software (B2), which processes the data and generates a preHAZOP table (B3). The preHAZOP table is produced by Python code, which loads the .graphml file containing the graph and uses it as the data source for the table generation. The following paragraphs will explain the details of this process.

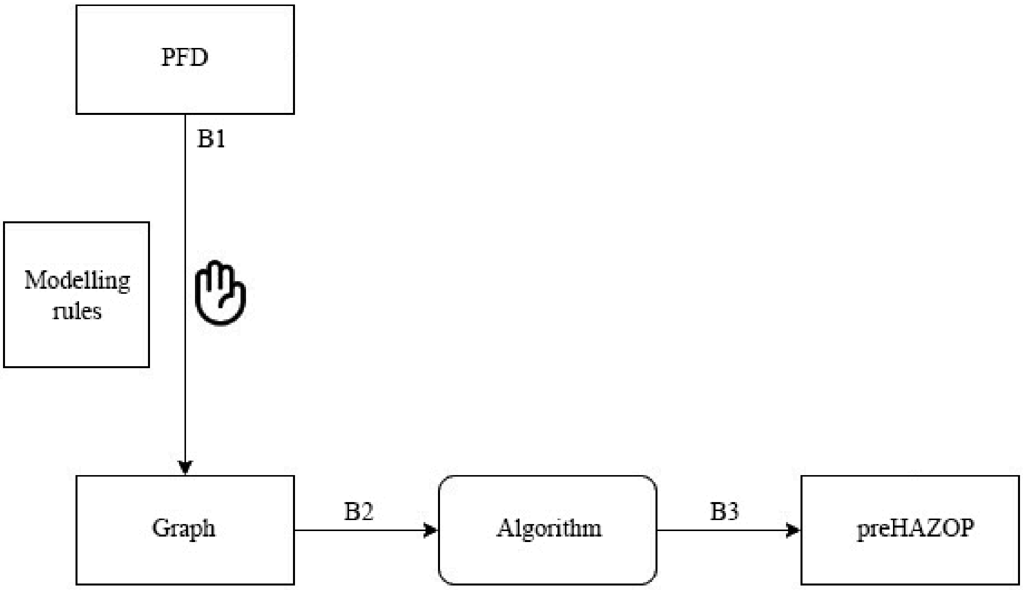



*Figure 15: Automated HAZOP approach. Using modelling software, the human team converts the Process Flow Diagram (PFD) into a graph. This graph, following predefined rules, is processed by custom software to generate the preHAZOP table, enabling the automated identification of deviations and risks. This approach is compared with traditional HAZOP methods (Scenario 2).*

To evaluate the effectiveness of the automated approach, a comparison between the results of the algorithm and a traditional HAZOP output was performed. The algorithm generates the preHAZOP table using a phenomenological approach, which differs significantly from the traditional HAZOP methodology. To assess the accuracy and validity of the algorithm's results, its output was compared with a traditional HAZOP table derived from the international standard BSI EN 16882:2016, which offers a rigorous and well-established framework for HAZOP analysis. This standard was chosen as a reference point due to its widespread industry acceptance and comprehensive guidelines.

The comparison aimed to determine how closely the algorithm's preHAZOP results align with those expected from the traditional HAZOP process.

It also sought to identify any differences or advantages of the automated approach. The differences, referred to as the "delta" (Δ), quantify the discrepancies between the two approaches by comparing the number of results produced and the depth of HAZOP-related information those results provide. The "delta" is manually calculated by comparing the total number of deviations identified in each approach and measuring the differences in the details provided, such as causes, consequences, and equipment involved. Software tools assist with tasks such as data formatting to ensure the accuracy and efficiency of the comparison.

A larger delta indicates that one approach detects more variances or provides more detailed descriptions for each variance than the other or that this approach produces erroneous results.

While this comparison remains manual for now, automation of the delta evaluation is being considered for future project phases, especially as the system grows in complexity, where manual comparison may become impractical. This comparison criterion helps to assess the completeness and effectiveness of each approach in capturing potential risks.

At this project stage, the human team compares and evaluates the discrepancies. Given that the number of results is automatically reported by the algorithm and is reported in the case study based on the BSI HAZOP table, while the information provided is easily manageable, developing an automated comparison algorithm at this stage was not considered necessary. The team manually analyses the differences between the traditional and automated HAZOP outputs to ensure an accurate and thorough evaluation of both approaches.

The criterion for comparison was based on the completeness and level of detail provided in each table. The unit of measurement used was the number of variances or types of information included in each output. No specific threshold was established, but the focus was on identifying significant differences in the comprehensiveness of reporting.

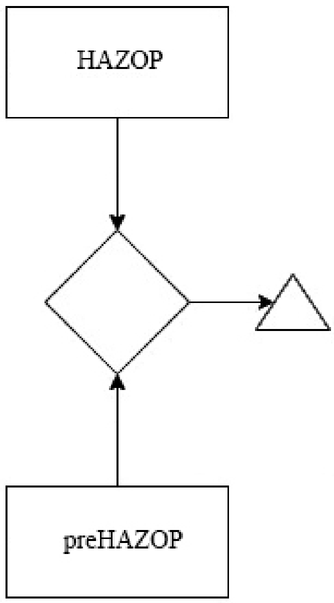



*Figure 16: Approach for comparing traditional and automated HAZOP pathways. The criterion is based on the measure of the differences in the number of deviations and the level of detail between the conventional and automated HAZOP.*

Both outputs required modifications to enable a meaningful comparison, as the initial review revealed significant structural differences. These adjustments were made to align the tables' formats as closely as possible without altering their core content, ensuring the integrity of the comparison was maintained. The specific modifications are detailed in the following paragraphs.

### 3.1.1 *Results (de)-clusterization*

Starting from the structure of the results, two approaches have been developed to facilitate the comparison between the traditional HAZOP table and the algorithm-generated table (Figure 17).

The first approach is to de-cluster the traditional HAZOP table derived, in the current case, from the BSI standard example. During the initial review, it was observed that specific cells in the BSI table contained multiple elements, such as multiple statements, causes or consequences. De-clustering separates these elements into individual entries, resulting in a structure where each row contains only one cause, one consequence, and one deviation - similar to the output format produced by the algorithm.

The second approach focuses on clustering the algorithm-generated table, where each deviation, cause, and consequence is initially treated as a separate entry. By clustering related entries, this approach attempts to mimic the traditional HAZOP table format by grouping multiple causes or consequences together when appropriate. Both approaches aim to make the tables more consistent and directly comparable while preserving the integrity of the original data. The goal is to simplify the comparison process, and these steps are intended to be performed before detailed analysis.

**Table B.2 – Example HAZOP worksheet for introductory example**

| | | |
|---|---|---|
| **STUDY TITLE:** PROCESS EXAMPLE | | **SHEET:** 1 of 4 |
| **Drawing No.:** | **REV. No.:** | **DATE:** December 17, 1998 |
| **TEAM COMPOSITION:** | LB, DH, EK, NE, MG, JK | **MEETING DATE:** December 15, 1998 |
| **PART CONSIDERED:** | **Transfer line from supply tank A to reactor** | |
| **DESIGN INTENT:** | **Material:** A **Activity:** Transfer continuously at a rate greater than B<br>**Source:** Tank for A **Destination:** Reactor | |

| No. | Guide word | Element | Deviation | Possible causes | Consequences | Existing controls | Comments | Actions required | Action allocated to |
|---|---|---|---|---|---|---|---|---|---|
| 1 | NO | Material A | No material A | Supply tank A is empty | No flow of A into reactor<br>Explosion | None shown | Situation not acceptable | Consider installation on tank A of a low-level alarm plus a low-level trip to stop pump B | MG |
| 2 | NO | Transfer A (at a rate > B) | No transfer of A takes place | Pump A stopped, line blocked | Explosion | None shown | Situation not acceptable | Measurement of flow rate for material A plus a low flow alarm and a low flow which trips pump B | JK |
| 3 | MORE | Material A | More material A: supply tank over full | Filling of tank from tanker when insufficient capacity exists | Tank will overflow into bounded area | None shown | Remark: This would have been identified during examination of the tank | Consider high-level alarm if not previously identified | EK |
| 4 | MORE | Transfer A | More transfer of A<br><br>Increased flow rate of A | Wrong size impeller<br><br>Wrong pump fitted | Possible reduction in yield<br><br>Product will contain large excess A | None | | Check pump flows and characteristics during commis-sioning<br>Revise the commissioning procedure | JK |

*Figure 17: BSI HAZOP table used as the starting point for result de-clustering. Initially in PDF format, the table was processed by an AI-based model, allowing the output to be converted into the preferred format for further comparison [18].*

As shown in Figure 17, the column reporting the Consequences for each deviation in the traditional HAZOP table contains multiple elements, grouping multiple consequences under a single deviation. The de-clustering option involves mapping and expanding the traditional HAZOP table to match the format of the algorithm-generated table, where each row corresponds to a single deviation and its associated consequence. At this stage, each deviation is associated with only one consequence, ensuring that comparing the two approaches is more structured and more accessible to the process.
This shift is particularly beneficial for future project phases, as it allows the comparison process to be more easily automated. Treating each deviation and effect as a single entry makes the results more digestible for software, ensuring accuracy and reducing the likelihood of errors when handling large data sets.
While the traditional HAZOP approach often merges multiple consequences into a single cell, this can be seen as a weakness (Table 8). Merging consequences may improve the complexity when comparing and can hinder essential details about how each deviation affects the system. In contrast, the current approach, where each deviation has a single consequence, provides more clarity and allows for a straightforward evaluation of the results.

*Table 8: Example of a row extracted from a HAZOP table. Elements are clustered before the application of the de-clustering algorithm.*

| No. | Guide word | Element | Deviation | Potential causes | Consequences |
|---|---|---|---|---|---|
| 4 | MORE | Transfer A | More transfer of A<br><br>Increased flow rate of A | Wrong size impeller<br><br>Wrong pump fitted | Possible reduction in yield<br><br>Product will contain large excess of A |

In Table 8, the HAZOP table includes multiple entries, such as deviations, potential causes, and consequences. Columns beyond "Consequences" were not considered in the comparison due to the early stage of the project, which does not yet incorporate features like "Comments," "Actions Required," and "Action Assigned to." Although these columns were excluded from the direct comparison, their absence in the automated HAZOP approach was noted for the Δ evaluation, i.e. for comparing the results of the algorithm application. It is also important to mention the "Existing Controls" column. This project focuses on preHAZOP analysis, typically performed in the early design stages when control systems may not yet be fully defined or available. Additionally, the last column, which assigns actions to individuals or teams, is not included in the algorithm-generated table since the analysis is conducted by software, rendering such information unnecessary for this comparison.

The unclustered table is subsequently fed into an AI-based model for the de-clustering process. The result, applied to the example discussed, is shown in Table 9.

*Table 9: Example of a row from a HAZOP table after de-clustering. The original clustered row is presented in Table 8.*

| No. | Guide word | Element | Deviation | Possible causes | Consequences |
|---|---|---|---|---|---|
| 4.1 | MORE | Transfer A | More transfer of A | Wrong size impeller | Possible reduction in yield |
| 4.2 | MORE | Transfer A | More transfer of A | Wrong size impeller | Product will contain large excess A |
| 4.3 | MORE | Transfer A | More transfer of A | Wrong pump fitted | Possible reduction in yield |
| 4.4 | MORE | Transfer A | More transfer of A | Wrong pump fitted | Product will contain large excess A |
| 4.5 | MORE | Transfer A | Increased flow rate of A | Wrong size impeller | Possible reduction in yield |
| 4.6 | MORE | Transfer A | Increased flow rate of A | Wrong size impeller | Product will contain large excess A |
| 4.7 | MORE | Transfer A | Increased flow rate of A | Wrong pump fitted | Possible reduction in yield |
| 4.8 | MORE | Transfer A | Increased flow rate of A | Wrong pump fitted | Product will contain large excess A |

The de-clustered table contains significantly more rows than the original version (8 vs. 1), each representing a single deviation, cause, and consequence. This revised structure aligns more closely with the format used in the automated HAZOP table, facilitating a more consistent and accurate comparison. The approach discussed above is conceptualized in Figure 18 within the general framework discussed in Figure 13.

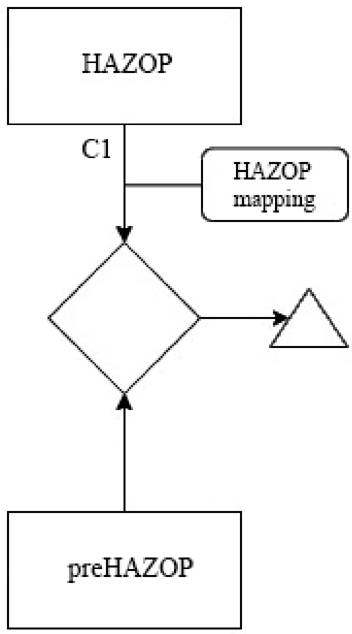



*Figure 18: Detail of the HAZOP mapping approach (C1) applied to the results.*

Alternatively, another approach is to cluster the algorithm-generated table (C2), reversing the de-clustering process abovementioned (Figure 19). In this method, the consequences associated with a common deviation are grouped into a single row, reducing the number of table entries. The purpose of this approach mirrors that of de-clustering: to align the structures of the tables and ensure a consistent basis for comparison.

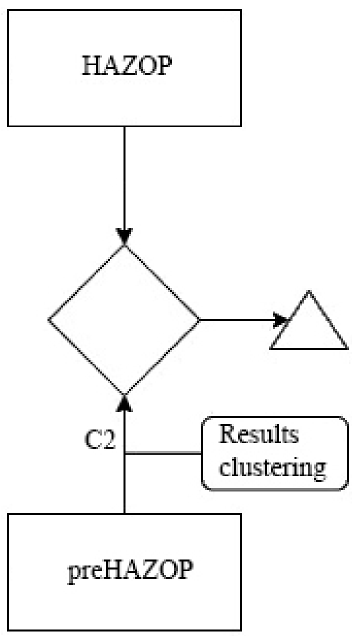



*Figure 19: Detail of the preHAZOP results clustering approach (C2) applied to the results.*

In the case study under consideration, the algorithm-generated unclustered table initially contains over twelve hundred results. Detailed analysis will be provided in the results chapter. After applying the AI-based clustering approach, the table is reduced to only sixty rows. Table 10 shows an example of a clustered row, with only the first four columns displayed for clearer visualization. In this example, the model has consolidated all rows with the same deviation.

*Table 10: Algorithm-generated table after clustering. PV: process variable. ID: identifier.*

| PV | ID | PV description | Keyword |
|---|---|---|---|
| PVx(y) | node1node2node3node4node5node6;<br>node1node2node3node4node5node7;<br>node1node2node8;<br>node1node2node9;<br>node1node2node9node10;<br>node1node2node11;<br>node1node2node12;<br>node1node2node13node14 | Process variable description (y) [Units of measure] | Keyword1;<br>Keyword2; |

The "PV" column contains the node label for the process variable used as the reference for clustering. In parentheses, the corresponding piece of equipment is indicated with one or more letters. The second column, labeled "ID," lists all the paths from the aforementioned process variable to downstream Risk Nodes. The "PV description" column describes the process variable, while the "Keyword" column includes all the keywords used for the paths The original implementation of the last column aimed to indicate which keywords were encountered but lacked specificity about their use along individual paths. This limitation reduced its usefulness for detailed analysis. To address this, the code was updated to display the full sequence of keywords used for each specific path. This enhancement not only facilitates human review, but also provides clearer insight into how process variables influence each other, improving the overall transparency and effectiveness of the analysis.

### 3.1.2 *Refining deviation analysis*

One challenge encountered was the difference in scope between the traditional HAZOP analysis and the algorithm-generated preHAZOP table. In the BSI example used for comparison, only deviations related to a specific plant section—the supply line for component A—were considered. This approach aligns with standard HAZOP practice, where separate tables are typically produced for each plant section. In contrast, the algorithm-generated preHAZOP table included deviations for the entire plant, resulting in inconsistencies in the comparison.

To resolve this issue, additional code was developed to filter the algorithm-generated results. A new dataframe was created to focus exclusively on deviations related to the supply line for component A. This filtering logic selects rows in the complete preHAZOP dataframe where the process variable (PV) or other relevant attributes directly correspond to the supply line section of component A. The filtered dataframe is then used to generate a more targeted table, which is exported as a spreadsheet (e.g. with extension .xlsx) for easier review and comparison.

### 3.1.2 *Explored and Discarded Approaches*

Throughout the development of this thesis project, various alternative approaches were considered. One significant proposal involved using an AI model to format the algorithm-generated table to resemble a traditional HAZOP table, aligning columns and formatting, converting it to PDF format, and then conducting a comparison between the two.

The rationale behind this proposal was to harness Artificial Intelligence to further automate the process. However, this approach was ultimately discarded due to the unreliability of AI models when comparing textual data. Their inability to fully comprehend the underlying meaning of words could result in inaccurate comparisons and create confusion for the human assessment team during the review phase.

Although this approach was set aside, it sparked the use of AI models for clustering and de-clustering the tables, where they proved effective. Additionally, with the rapid progress of AI technology, its potential role in supporting HAZOP analysis may grow significantly in the future.

## 3.2 The phenomenological approach

Another cornerstone of this thesis is the integration of a phenomenological-based approach to HAZOP analysis. This method focuses on understanding the fundamental behaviors and processes within a system and examining how deviations in these processes can lead to potential hazards. Every deviation in a system has a phenomenological basis, meaning it originates from physical or chemical phenomena. For example, a container explosion results from excessive pressure, which itself stems from the accumulation of mass in the gaseous phase within a closed space. Similarly, an overflow in a tank may occur due to either an increased mass inflow or a reduced outflow. In the first example, the deviation in the HAZOP analysis, such as “MORE MATERIAL” or “MORE ACCUMULATION OF MATERIAL,” is clearly linked to the underlying phenomena. In the second example, deviations like "MORE FLOW RATE OF MATERIAL" or "LESS FLOW RATE OF MATERIAL" reflect the phenomenological drivers behind the observed outcome.

By directly modelling and observing these physical and chemical interactions, the phenomenological approach goes beyond traditional guideline-based HAZOP and provides deeper insight into the root causes of hazards. Because each hazard is linked to observable or measurable phenomena, this approach allows for a more accurate and realistic identification of potential failures and their consequences. This leads to higher-quality results as the analysis is based on empirical evidence and simulations rather than purely qualitative assumptions.

It also improves the accuracy and efficiency of the HAZOP process. Traditional HAZOP studies often require lengthy discussions and iterative steps to hypothesize potential deviations. In contrast, the phenomenological approach can automate parts of the analysis through advanced modelling tools and simulations, allowing the HAZOP team to focus on critical decision-making rather than exhaustive manual hazard identification. This results in a more efficient process without compromising the depth of analysis.

In addition, the phenomenological approach helps to prioritize risks more effectively because the analysis is based on actual process behavior. This allows for more focused identification of high-risk areas and the development of accurate, targeted mitigation strategies. Overall, integrating phenomenology into HAZOP makes the analysis more robust, reliable and better suited to the complexity of processes.

The phenomenological approach leverages material and energy balances to evaluate the effects of deviations within a system.

These balances are fundamental tools in chemical engineering, providing a rigorous framework to understand how mass and energy flow through different parts of a process.

Leveraging a phenomenological approach allows for a rigorous reconstruction of the cause-deviation-consequence chain grounded in physical laws. This goes beyond the current HAZOP methodology, where this reconstruction is often, if not always, done without detailed investigation or without incorporating the knowledge derived from material and energy balances, which remain intact and unchallenged. By basing the analysis on fundamental scientific principles, the phenomenological approach provides a more structured and scientifically sound understanding of how failures propagate through a system, ensuring that the assessment is not only qualitative but quantitatively rooted in the actual dynamics of the process.

For example, consider a deviation involving a sudden increase in pressure (identified in HAZOP analysis as "MORE pressure") in a closed vessel. In a traditional HAZOP analysis, this deviation might highlight the risk of equipment damage or even explosion, but it may not delve deeply into the physical mechanisms driving the pressure increase. With a phenomenological approach, however, material and energy balances would reveal how factors like heat transfer or a chemical reaction are contributing to the pressure build-up. This deeper analysis would show that the pressure increase is due to the system's inability to expand within its fixed volume and could also clarify how other variables, such as temperature or reaction rates, impact the system's behavior. This understanding enables more accurate predictions of system outcomes and supports the development of more precise and effective mitigation strategies.

At its core, the phenomenological approach is qualitative, aiming to relate balance terms – such as mass or energy accumulation – to deviations in a qualitative way, highlighting a departure from the design intent or operating conditions.

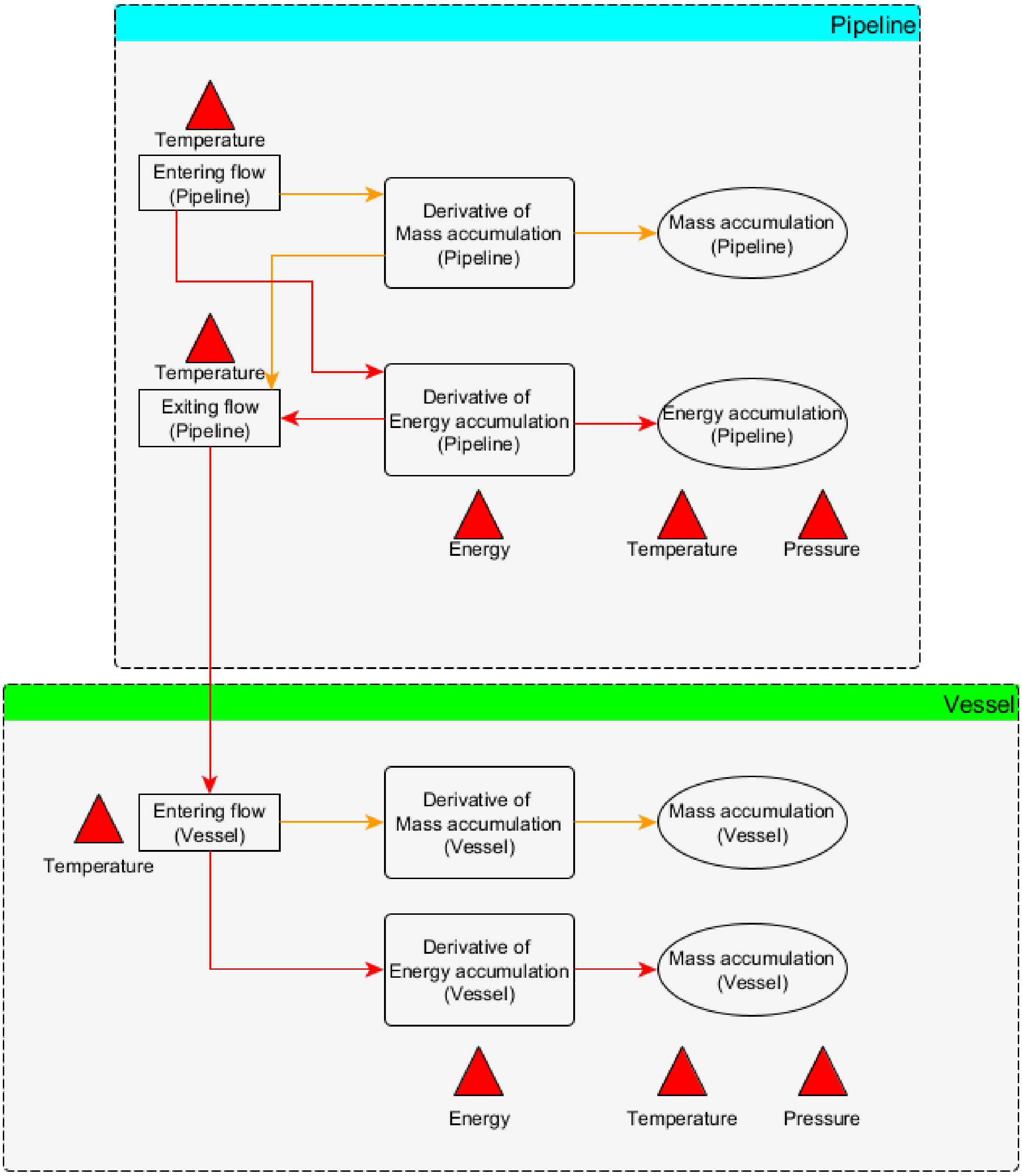



*Figure 20: From a phenomenological perspective, an increase in temperature results in a pressure rise in a system where mass accumulation occurs. Additionally, the terms considered in the balance—accumulation, inlet, outlet, and generation or consumption due to reactions—indicate the direction of the HAZOP deviation.*

As illustrated in Figure 20, a temperature rise in a closed system may qualitatively indicate an increase in pressure. While the current focus is on identifying qualitative deviations, future developments could enable the quantification of these deviations, offering deeper insights into the system's behavior and providing more detailed predictions of potential outcomes.

By systematically applying these principles, this approach enables a more thorough assessment of how deviations from normal operating conditions—such as changes in flow rates, temperature, or pressure—affect the overall system.

For each piece of equipment in the system, material and energy balances are conducted, accounting for inputs, outputs, and any accumulation of mass and energy. The accumulation term is crucial in understanding the system's behavior, as its magnitude could provide insights or be used to assess the deviation scale. By examining accumulation, the severity of the deviation can be more accurately assessed, and a probability of occurrence function can eventually be developed. This relationship enables a more informed evaluation of the deviation's potential impact, supporting more precise risk assessment and decision-making.

Component-specific balances have been introduced to refine the analysis by capturing how individual substances within a mixture respond to deviations. This enhancement is particularly important for identifying risks such as product contamination, yield reduction, and changes in flammability or explosivity limits within the container. These balances provide a more detailed understanding of system behavior by isolating the accumulation terms of each component in the liquid phase, which are represented as separate nodes in the graph structure. For the gas phase, a single node is used to represent the total accumulation under the assumption that reactions occur only in the liquid phase. On the other hand, phase-specific balances are essential in systems with multiple phases, such as liquid and vapor, ensuring that phase transitions and interactions are considered to understand the full impact of variations.

This approach surpasses traditional qualitative methods by more accurately interpreting observed behavior. The structural relationships within these balances bridge the gap between theory and practice, allowing experts to apply their scientific knowledge more effectively. Using tools fundamental to chemical engineering, the analysis becomes more precise, better aligned with industry standards and methodologies, and more easily replicable. This robust framework enhances decision-making capabilities, identifying potential hazards and implementing solutions grounded in a comprehensive understanding of process dynamics.

## 3.3 Use of graphs

To fully leverage material and energy balances in this HAZOP automation project, representing them through graphs has been deemed essential. Graphs provide an intuitive and structured way to visualize the relationships between different process units and how mass and energy flow through the system (Figure 21). By using graphs, it becomes easier to track the propagation of deviations across the system and ensure that all interactions are considered. For this project, the .graphml format has been selected as the most suitable tool for representing these balances and interactions.

The .graphml format offers several key advantages. Firstly, it ensures compatibility with a wide range of software tools, thanks to the support provided by specific Python libraries. These libraries allow for easy manipulation of graph data, enabling the automation process to efficiently read, modify, and analyze the graph structure. This compatibility is critical in a HAZOP automation context, where different software may be involved in the analysis, data processing, and reporting stages. The open and flexible nature of the .graphml format ensures smooth data exchange and interoperability across various platforms, making it a robust choice for this project.

Another significant advantage of using graphs is the visual clarity they provide. By representing the system as a graph, the HAZOP team can more easily visualize how deviations propagate through the process, greatly enhancing their ability to verify and validate the results. This graphical representation simplifies understanding of the flow of material and energy in the system and helps identify potential bottlenecks or vulnerabilities where deviations could escalate into more significant hazards. The visual format also aids in communication within the team, fostering a more collaborative and transparent approach to safety analysis.

Furthermore, graph-based representation supports advanced automation by allowing algorithms to operate more efficiently on structured data. Tracing the propagation of deviations becomes more straightforward when the relationships between system components are clearly mapped out. This structured approach not only helps identify and mitigate potential hazards but also reduces the likelihood of oversight or error by making system interactions explicit. Overall, the .graphml format combines technical compatibility for automation with visual clarity, which helps expert teams ensure the accuracy and thoroughness of the HAZOP analysis.

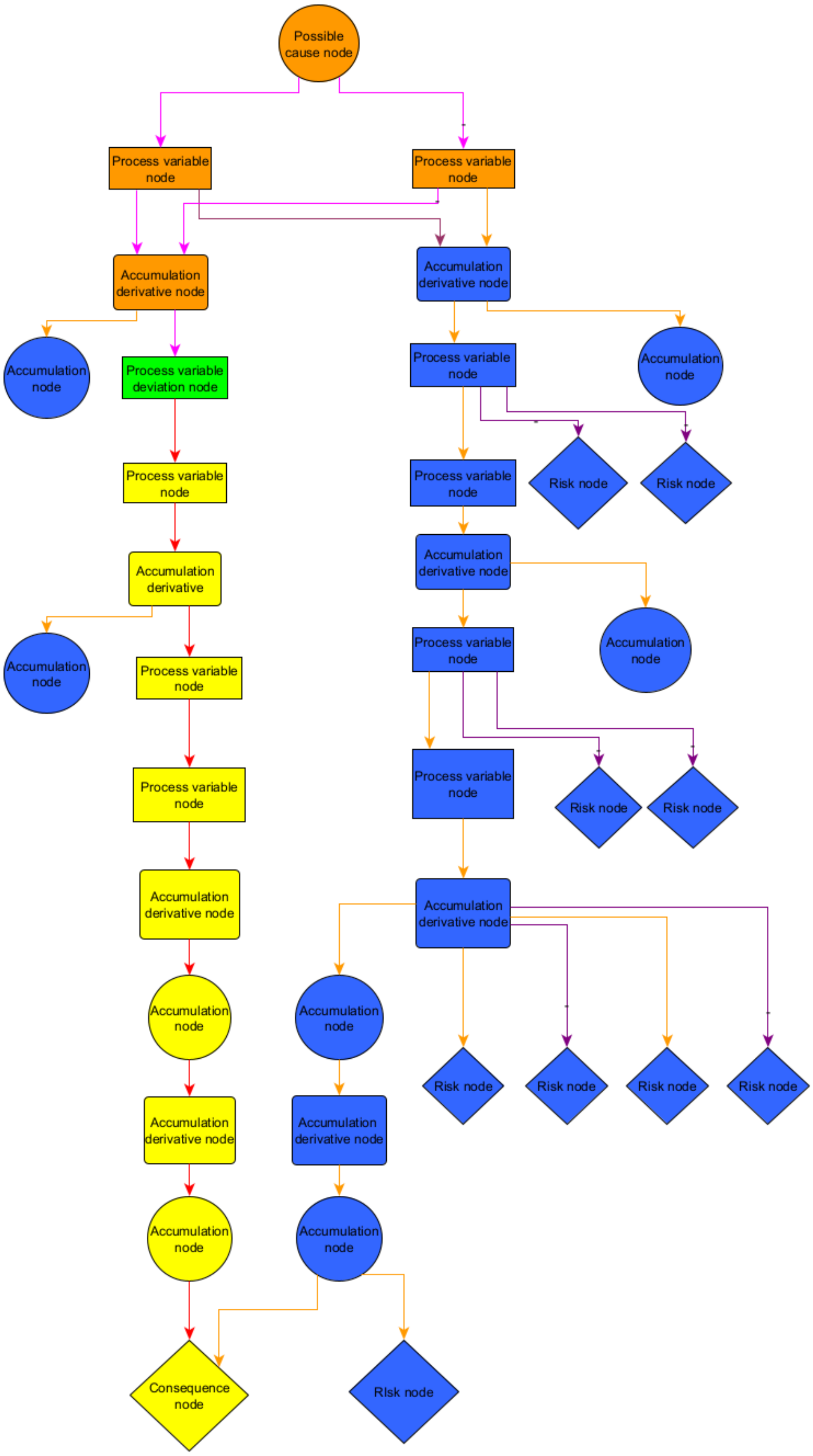



*Figure 21: Zoomed view of the cause-deviation-consequence chain, showing upstream accumulation nodes (orange) as potential causes and downstream paths through accumulation and derivative nodes, ending with risk probability nodes (blue) representing potential consequences of the deviation (green).*

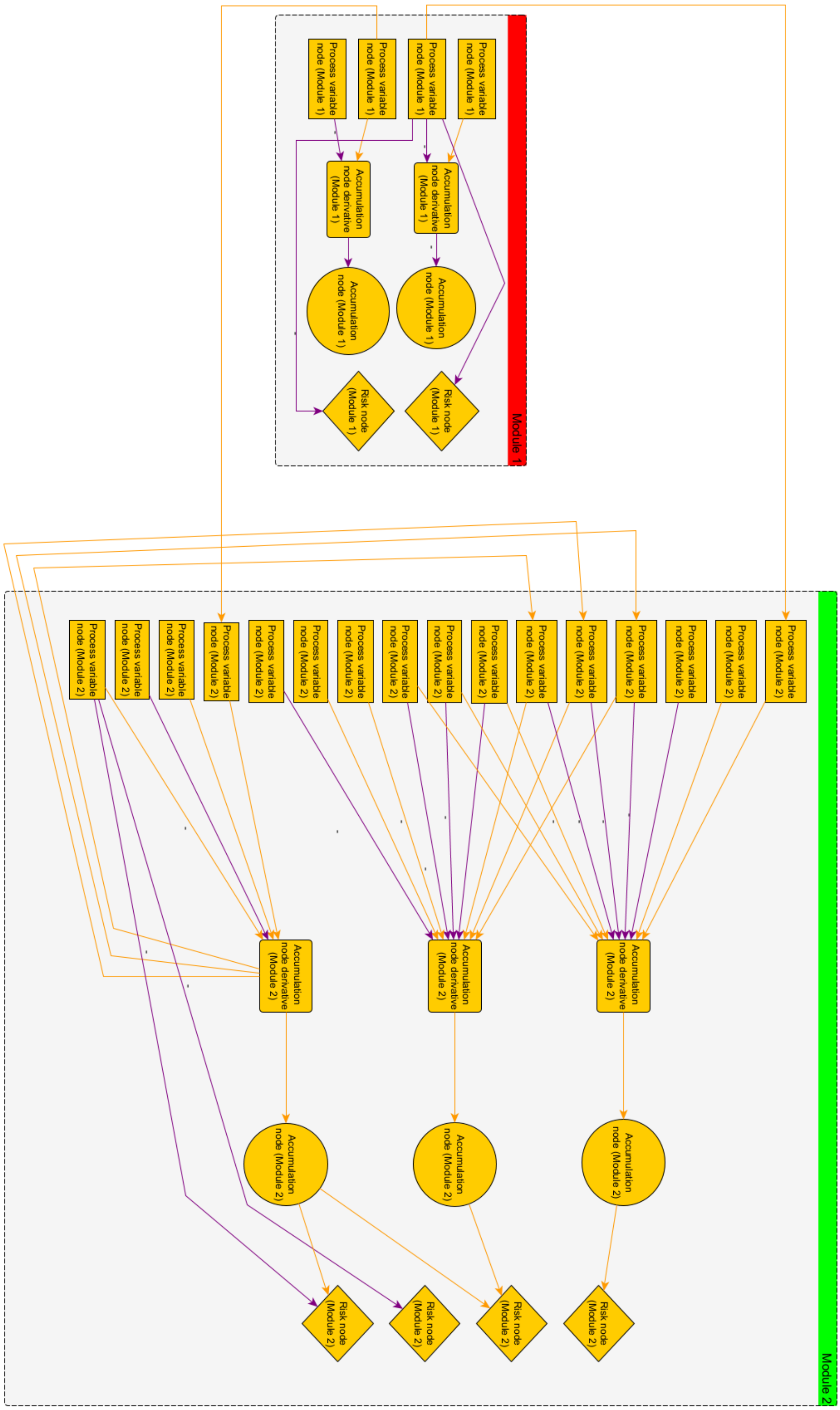



*Figure 22: Simplified representation of a complete system in graph form.*

The figure illustrates a cause-effect chain within a graph-based representation, demonstrating the visual accessibility of the connections between nodes. By organizing elements into a network of nodes connected by clear paths, the graph format allows users to intuitively follow the flow of influence from potential causes to final consequences. This format provides an efficient and structured way to observe the relationships between process variables, deviations, and potential risks, which is particularly beneficial for understanding complex systems where multiple factors influence outcomes.

In this example, we start with an accumulation node that represents a potential cause, such as an excessive buildup of material in a section of the system. This accumulation node is connected to a downstream process variable node where the variation begins to propagate. Moving along the highlighted path, we encounter an "Accumulation Derivative Node" and subsequent process variable nodes, each representing incremental changes in the state of the system as the deviation develops. Finally, the path leads to a "Risk Node" (representing a consequence) where the deviation could manifest itself as an operational risk, such as equipment failure or process instability. This structured sequence of nodes makes it easy to track how an initial accumulation can escalate into a dangerous deviation, with clear visibility into each step of the process.

The graph-based format used here not only enhances the visual accessibility of the cause-deviation-consequence chain, but also allows for better integration with the software's phenomenological approach. By representing each element of the process as an individual node with defined connections, the system can interpret these relationships programmatically, enabling automated identification of cause-effect chains. This automated approach ensures a more thorough exploration of possible risks and deviations, while allowing the HAZOP team to quickly assess the impact of deviations on overall process safety.

### 3.3.1 Modelling rules

To maintain rigor and consistency, specific modeling rules were established for system representation. These rules guide the structuring and organization of the system's components within the graph, ensuring that the analysis remains both comprehensive and adaptable.
These rules guide specifically the following categories: subgraphs, nodes and arcs.

*Table 11: Modelling rules of the categories subgraphs, nodes and arcs.*

| Category | Rules |
|---|---|
| *Subgraphs* | Every unit operation is provided with a separate subgraph. |
| | Every subgraph contains the process variable nodes and accumulation term nodes related to the accumulation terms of material and energy balances. |
| *Nodes* | Nodes are categorized based on the associated representation, i.e. Process Variable, Accumulation Term, Deviation Probability. |
| | Every node has the following attributes: Label, Shape, Description. |
| | Every node has a unique shape and the associated label and description. |
| *Arcs* | Arcs are of two types and represent a direct or reverse correlation. |
| | Arcs representing a reverse correlation has the attribute "Label". |
| | Label of an arc representing a reverse correlation is indicated with a sign " - ". |

Figure 21 shows an example of a graph representation, where subgraphs, nodes, and arcs are clearly visible. These elements will be explained in the following subparagraphs.

### 3.3.1.1 Subgraphs associated with a unit operation

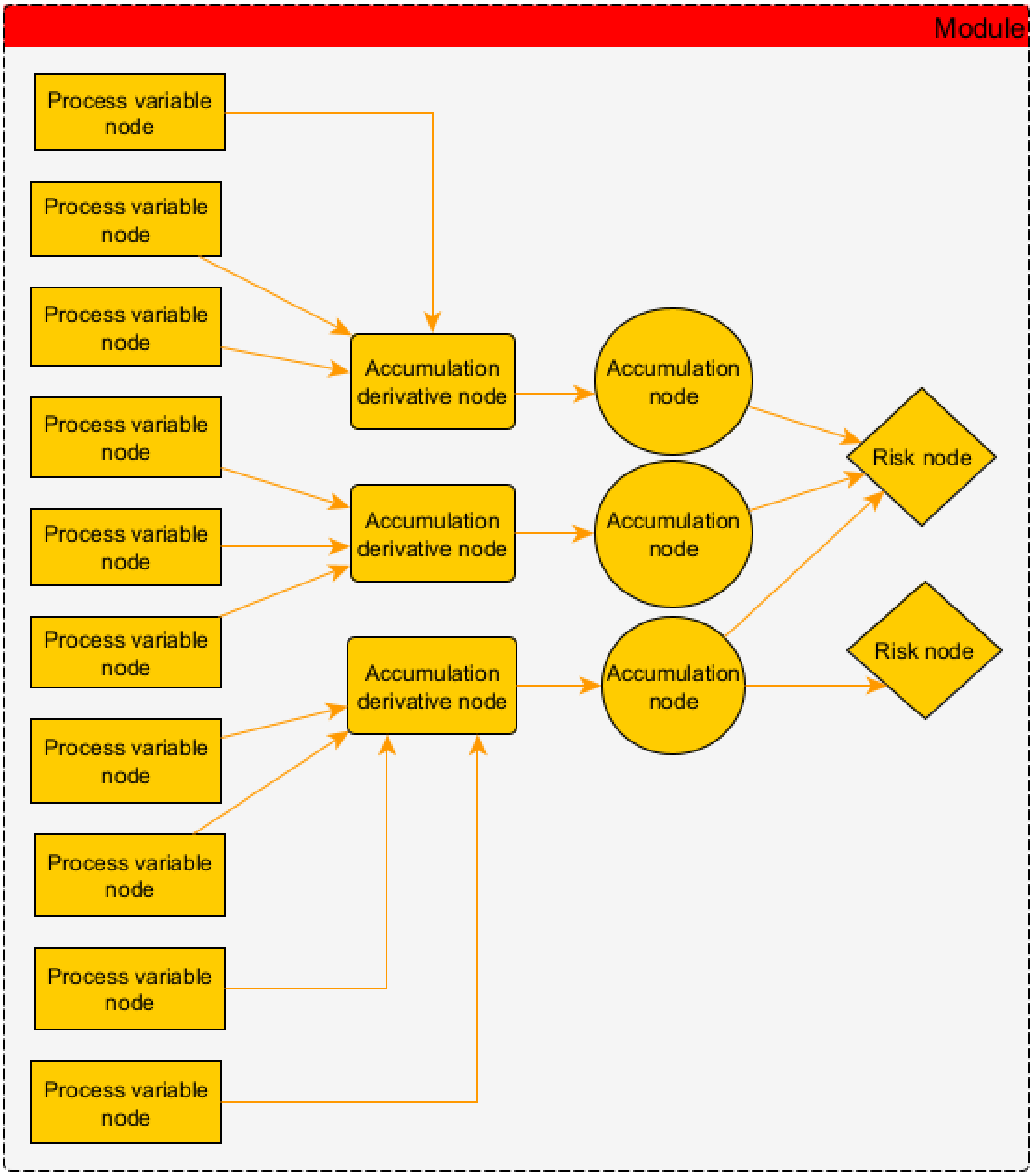



*Figure 23: Example of subgraph associated with a unit operation.*

Each unit operation is represented by its own dedicated subgraph. This modular approach, where each unit operation is mapped separately and then integrated into the overall system graph, offers two key advantages essential for both visualization and system updates:

- *Visual Accessibility*: Clearly defined subgraphs enhance the overall system visualization. By isolating units of operation into distinct subgraphs, it becomes easier to identify specific graph nodes associated with each component. This improves clarity, especially when tracking variables or troubleshooting specific sections of the system during the HAZOP process. In complex systems, these distinct subgraphs help the team quickly locate critical areas without being overwhelmed by excessive information.

- *Modifiability and modularity*: A modular graph structure greatly simplifies system modifications, providing flexibility and efficiency throughout the life cycle of a process or plant. When reviewing or updating an existing system, modular subgraphs allow for quick and efficient changes without disrupting the overall layout. This approach is particularly beneficial in industries where frequent updates occur due to operational adjustments, equipment upgrades, or design phase iterations. Modularity enables specific parts of a system—such as individual equipment or operational units—to be adapted or refined without requiring a complete model overhaul, preserving the integrity of the larger system.

During the design phase, when iterative changes are common, modularity allows the engineering team to adjust individual components (such as equipment configurations or process parameters) without impacting other system parts, resulting in a faster design process. Similarly, in an existing system, upgrades or changes to process conditions require updating only the relevant subgraph, streamlining the review process and maintaining alignment with the overall design.

Modularity also enhances the automation process by providing a structured data format that is easier for software to process. With a modular approach, the algorithm can efficiently focus on specific system parts, resulting in faster computation and analysis. Additionally, modularity saves significant time and resources: by representing the system in a digital format, changes can be implemented quickly, enabling the team to concentrate on critical decision-making rather than time-consuming manual updates. This speeds up the overall process and reduces the risk of error when integrating new changes. The ability to isolate modifications to specific subgraphs ensures system consistency and minimizes disruption, making modularity a key advantage in both the design and operational phases of complex systems.

#### 3.3.1.2 Nodes and arc representation

In the graph, nodes representing different process variables and arcs corresponding to various types of influences between these variables are visually differentiated.

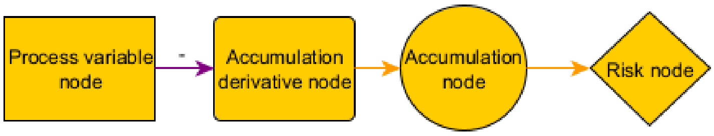



*Figure 24:Example of usage of nodes and arcs. This example illustrates a process variable with a reverse correlation to the derivative of the accumulation term(the instant variation on the value of the accumulation). This derivative directly influences the integral accumulation term, which, in turn, has the same type of correlation with a risk node.*

This visual distinction is essential because node shapes, labels, and descriptions serve as recognized attributes within the software, allowing for effective node classification and enabling the software to gather additional data from the graph.. The following parameters have been established:

- *Node Shape*: Different shapes are assigned to nodes to enable accurate identification and sorting of variables into appropriate categories upon import. Unlike labels, which may sometimes overlap in meaning, shapes act as unique identifiers, preventing misinterpretation by the system. This distinction is crucial for both the software automation and the team.

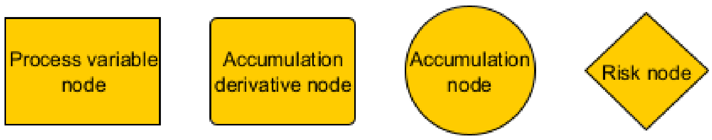



*Figure 25: Examples of each node shape adopted. Distinct node shapes also help quickly differentiate between variable types, facilitating the tracking of key variables throughout the graph and ensuring that information flow is easily understood.*

- *Node and Arc Labels*: Labels on nodes and arcs serve a dual purpose. For nodes, labels provide concise summaries of the variables they represent, often using abbreviations or short descriptions, allowing for quick identification of data types or conditions at each node. For arcs, labels clarify the type of influence between nodes—such as material flow, heat transfer, or control signals—providing immediate insight into interactions and ensuring that relationships between components are clearly understood both visually and computationally.
- *Description*: Each node and arc includes a detailed description, providing a deeper understanding of the variable or interaction. This description specifies whether a variable is an input or output and identifies the associated equipment. Additionally, the description field allows for the inclusion of relevant details, such as the unit of measure for a variable or any specific properties necessary for the analysis. This extra layer of detail ensures that both the software and the human team have all the information required to interpret the graph

accurately. Such thoroughness is essential for verifying the HAZOP analysis and for ensuring that all aspects of the system are fully considered.

Adhering to these modeling rules ensures that the graph accurately represents the system's components and interactions. The combination of visual and data-driven attributes enhances both the automation and expert validation of the HAZOP process, making the analysis more efficient and reducing the likelihood of errors.

#### 3.3.1.3 Type of nodes

After establishing the representation rules, nodes were categorized based on their content to improve clarity and functionality in the HAZOP analysis. Each category is designed to represent key system aspects, such as process variables, accumulation terms, or the probability of risk. This organization enables both the HAZOP software and human operators to track and analyze variables, deviations, and interactions effectively within the system.

- *Process variable nodes*: These nodes represent the process variables in the system. Positioned upstream of the accumulation derivative nodes, their influence following a deviation ultimately determines changes in the risk downstream.
- *Accumulation derivative nodes*: Representing the instant variation of the accumulation term in the material or energy balance for each process unit, these nodes are typically connected to process variable nodes upstream and to the integral accumulation node downstream.
- *(Integral) Accumulation nodes*: These nodes represent the integral variation of the accumulation term. At this stage of the project, they primarily aid in identifying possible deviation sources, as will be detailed later. In future stages, they will serve as a quantitative measure of deviation impact on the system; specifically, they will help determine if a deviation surpasses a predetermined threshold, enabling specific hazardous scenarios.
- *Risk nodes*: Positioned at the end of each deviation propagation path, these nodes assess the likelihood of a hazardous consequence resulting from a deviation. They provide a qualitative risk assessment by reflecting how the probability of a hazardous event changes as deviations propagate through the system. These nodes dynamically adjust based on the direction and impact of deviations: if a deviation intensifies the effects of previous deviations, the risk increases; conversely, if system safeguards mitigate the deviation’s effects, the risk decreases.

This dynamic adjustment enables the model to capture the evolving risk profile as deviations interact with various system elements, offering a comprehensive view of potential hazards.

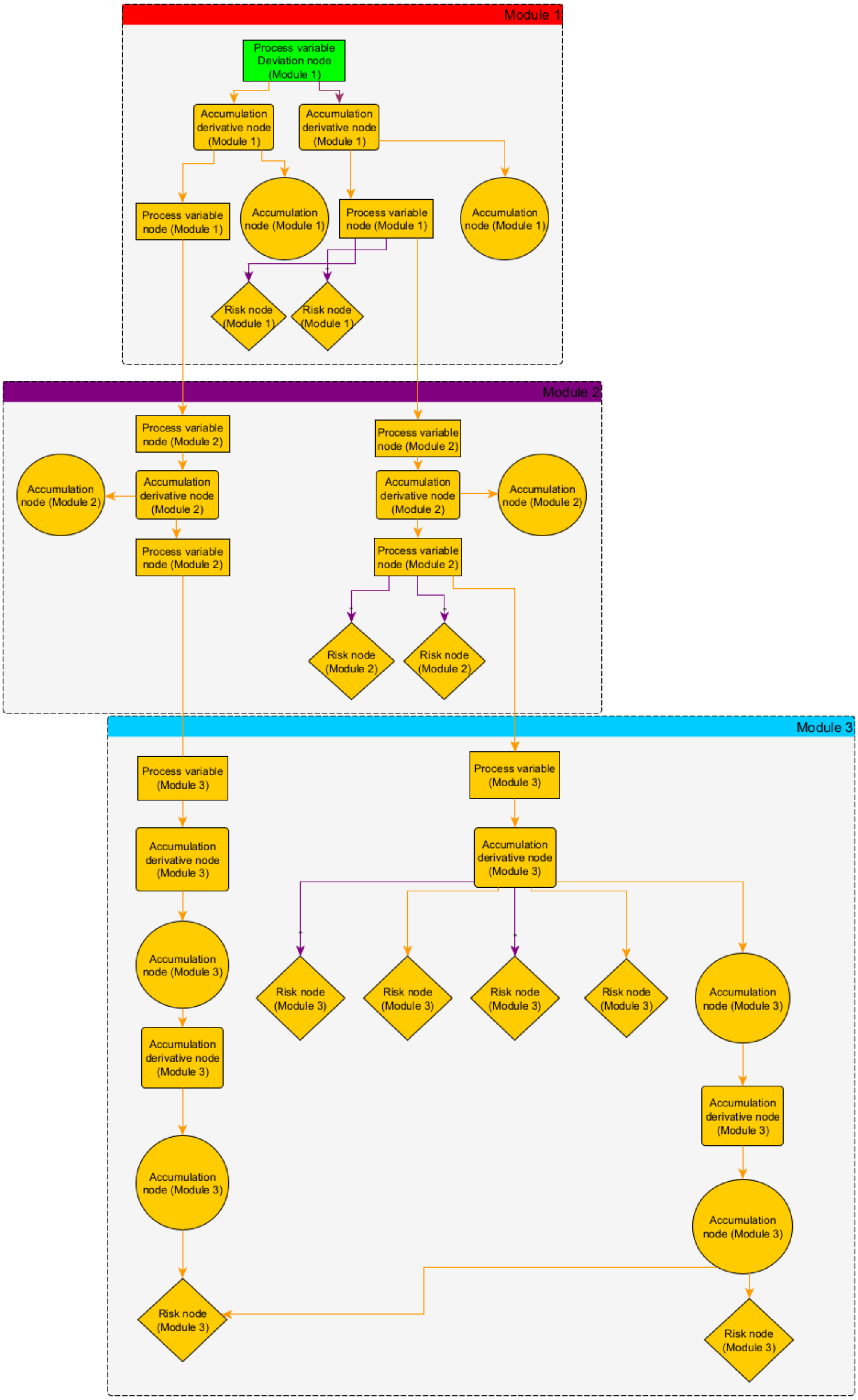



*Figure 26: Graph portion showing deviation propagation across three modules, with nodes representing process variables, accumulation terms, and risk points. The modular layout aids in visualizing how deviations move through each stage, highlighting interactions and potential risk.*

Figure 26 illustrates a segment of the system as a graph, divided into labeled modules for visual clarity. This modular labeling is purely for graphical clarity, as it allows the reader to follow the progression of deviations through different sections. Each type of node-Process Variable, Accumulation Derivative, Accumulation, and Risk-plays an equally important role in representing different stages of the variation propagation chain. Starting with an initial process variable deviation, this graph shows how the deviation propagates through the connected nodes to reach the risk nodes where potential hazards can be assessed.

In this representation, a generic deviation in a process variable node in Module 1 could propagate downstream, triggering changes in accumulation nodes and eventually influencing risk nodes. These Risk nodes provide a qualitative risk assessment that shows how the probability of a hazardous event evolves as deviations affect the system. This chain of interactions, captured visually, allows for quick and structured identification of critical pathways.

The arcs connecting the nodes are labeled and color-coded to help trace the paths and influences within the graph. Although the color coding is purely visual in this example, these arcs are discussed further in the following section, where their specific roles and classifications are elaborated.

Importantly, this structure supports automated HAZOP analysis by allowing the system to systematically interpret the attributes of each node. The classification of each node (via shapes, labels, and descriptions) allows for efficient data extraction, automated risk assessment, and ultimately a more streamlined, objective HAZOP process.

By incorporating probability nodes, the model enables both the HAZOP software and experts to assess potential consequences of a deviation with greater precision and scientific rigor. The dynamic nature of these nodes allows them to continuously adjust as new information is introduced, enabling the HAZOP analysis to remain relevant over time. As deviations propagate and interact within the system, the evolving risk profile provides a more accurate and responsive risk assessment. This continuous adjustment not only keeps the analysis current but also supports data-driven, risk-informed decision-making, enabling the HAZOP team to make safety and operational choices based on real-time insights. By transforming HAZOP analysis from a static review into a dynamic tool, the approach enhances risk management effectiveness as conditions change.

In summary, risk nodes serve as the final checkpoint in deviation propagation, dynamically encapsulating the likelihood of hazardous outcomes. These nodes not only assess individual risks but also consider potential chains of subsequent events triggered by a deviation. By capturing how one event can lead to another, they offer a more comprehensive understanding of the system's vulnerabilities. This adaptability provides a robust framework for risk prioritization, ensuring that HAZOP analysis is thorough, actionable, and focused on managing cascading risks to prevent escalation.

#### 3.3.1.4 Arcs

As previously mentioned, arcs in the graph represent the influence one variable exerts on another. These arcs are essential for modeling the interdependencies and interactions between process variables, making the graph a powerful tool for tracing deviation propagation throughout the system. To maintain simplicity and clarity, this project focuses on two fundamental types of correlations between variables: direct and reverse correlations.

- *Direct Correlation:* This occurs when a change in one variable causes a corresponding change in another variable in the same direction.

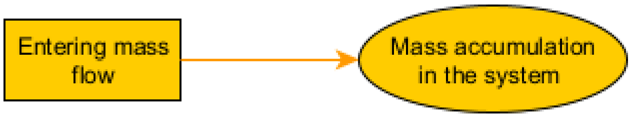



*Figure 27: Direct correlation between two nodes of the graph.*

For instance, an increase in the mass flow entering a unit of operation is directly correlated with an increase in the accumulated mass within that unit. From a phenomenological perspective, this relationship aligns with the principles of mass conservation, where the accumulation term in a material balance equation reflects the net effect of inflows and outflows. By capturing these physical dependencies, the model provides a deeper understanding of how deviations propagate, reinforcing the phenomenological approach's focus on representing system behavior based on fundamental physical laws. This allows for a more accurate assessment of how changes in one part of the system can lead to cascading effects, enhancing the precision of risk analysis.

- *Reverse Correlation:* This occurs when a change in one variable leads to an opposite change in another.

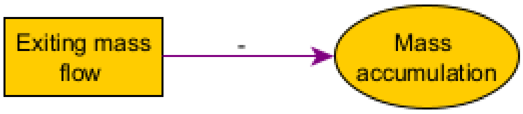



*Figure 28: Reverse correlation between two nodes of the graph.*

Using a similar example, if an increase in the exiting flow from a unit leads to a decrease in mass accumulation within that unit, this inverse relationship would be represented by a reverse arc. From a phenomenological perspective, this illustrates mass balance principles, where increased outflow reduces accumulated mass.

By limiting correlations to direct and reverse, this project simplifies the graph-building process without compromising model accuracy or effectiveness. This approach, supported by data in the following chapter, along with the advantages of a software-assisted phenomenological approach, keeps the graph manageable even in large, complex systems while providing a robust representation of key variable interactions. These two arc types offer a clear and concise framework for modeling deviation propagation, making it easier for both the HAZOP software and the team to understand and interpret system behavior under abnormal conditions.

This simplification also allows the project to focus on automating the analysis of critical relationships, ensuring that generated insights are both actionable and reliable. Future stages of the project may introduce additional arc types, including one for each HAZOP keyword, or to indicate correlation magnitudes. Such refinements could provide more detailed results, allow for a broader range of scenarios, and offer quantitative measures of deviation impact on system behavior and the probability of hazardous events.

### *3.3.2 Enhancement of graph-based representation*

After a series of tests and evaluations, modifications to the graph were deemed necessary. This section will provide a detailed explanation of the additions, including the piping system, the dual-phase hypothesis, and the incorporation of mass and energy losses due to leakages. These are discussed in the following sections.

### 3.3.2.1 Pipings

The inclusion of piping as individual modules in the system model enhances its ability to capture the complexity of real-world processes. By representing each pipeline as a separate subgraph, the model accurately reflects actual flow paths and the dependencies between devices typically connected by piping. This structure allows for a more comprehensive analysis of how deviations could propagate throughout the system. In addition, this development highlights the benefits of a modular approach where each piece of equipment or subsystem, including piping, is represented as an independent subgraph. These subgraphs are connected by process variable nodes, allowing seamless integration between different modules. Implementing pipelines as dedicated modules not only maintains the modularity of the system, but also improves the accuracy of the analysis by pinpointing specific sources of variation along different pipeline segments.

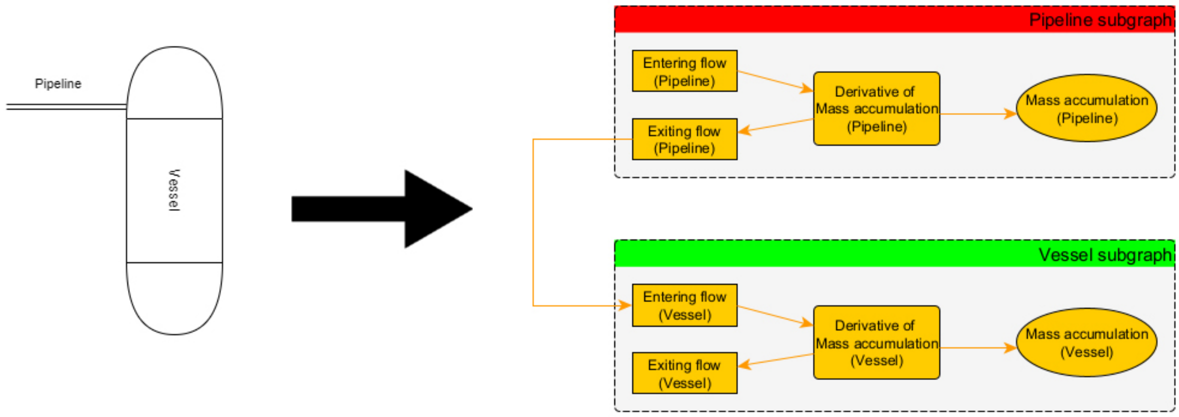



*Figure 29: Illustrative graph representation showing how pipelines are integrated as distinct modules, alongside vessels and other units of operation. Each module, whether pipeline or vessel, is represented with its own flows and accumulation terms, facilitating modularity in the graph structure.*

Nodes representing the exiting flow of a pipe can be connected to the corresponding incoming flow of the vessel at the pipe's endpoint. This interconnected structure ensures cohesive system functioning, enabling deviations to propagate accurately through the network and enhancing the overall effectiveness of the analysis.

The integration of the piping network highlights the flexibility of this method, requiring only a few straightforward steps:

- Copying and pasting a standard template that includes input and output flows for both mass and energy balances.
- Writing the appropriate labels for each node.
- Ensuring that the subgraphs are correctly connected.

This modular approach allows for rapid changes while maintaining the accuracy of the system representation. Modularity is especially valuable when scaling complex, real-world systems, as it allows for efficient updates and adjustments within the graph representation. By organizing each component or subsystem as a separate module, it becomes easier to visualize and track potential propagation paths of deviations, supporting both the expert team's review of software-generated results and the overall analysis process. This modular structure not only reduces the time and effort required to update the model, but also minimizes complexity and error potential during the design and commissioning phases, ensuring that changes can be implemented without disrupting the integrity of the system.

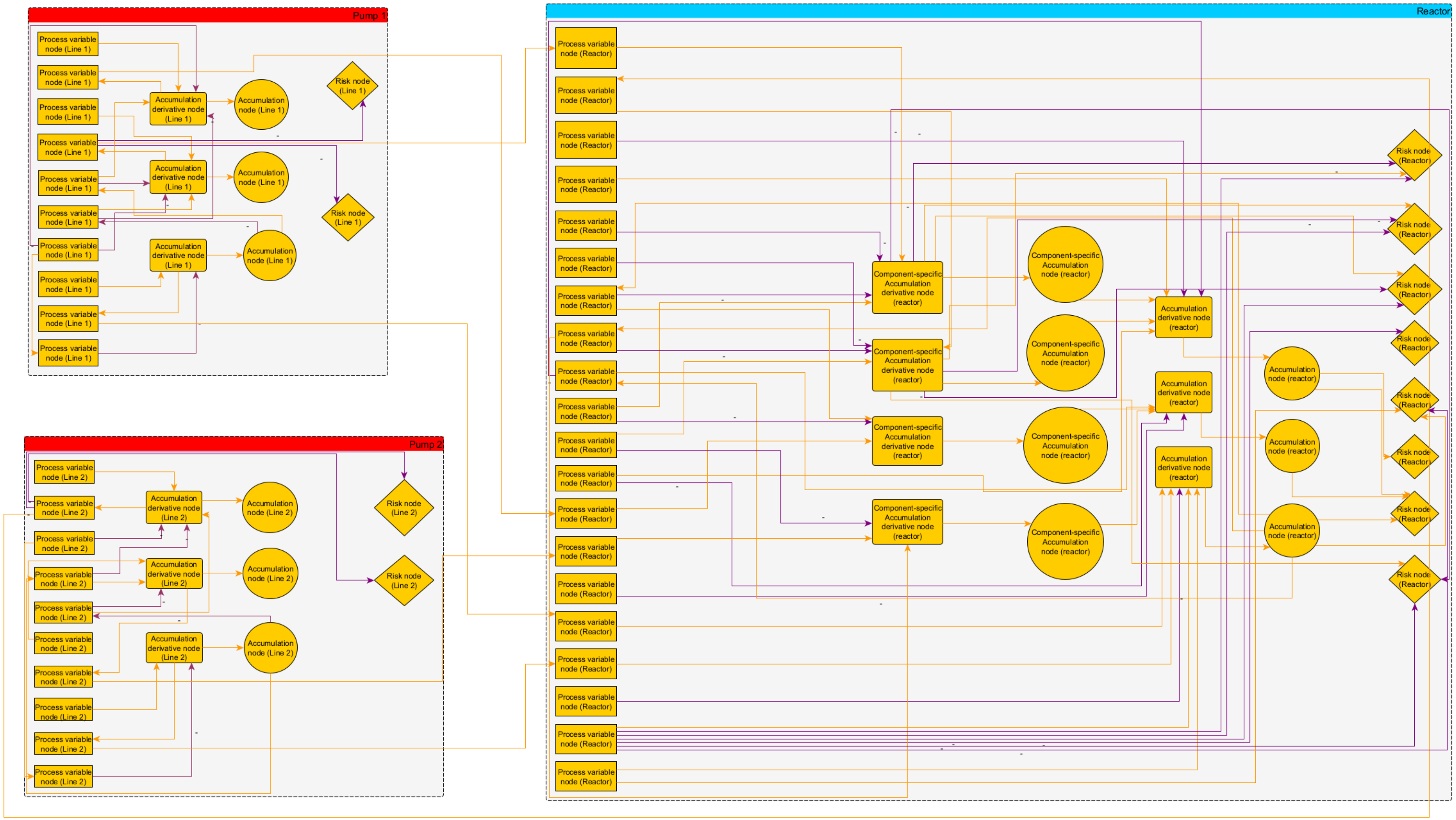



*Figure 30: System graph before the integration of the piping module.*

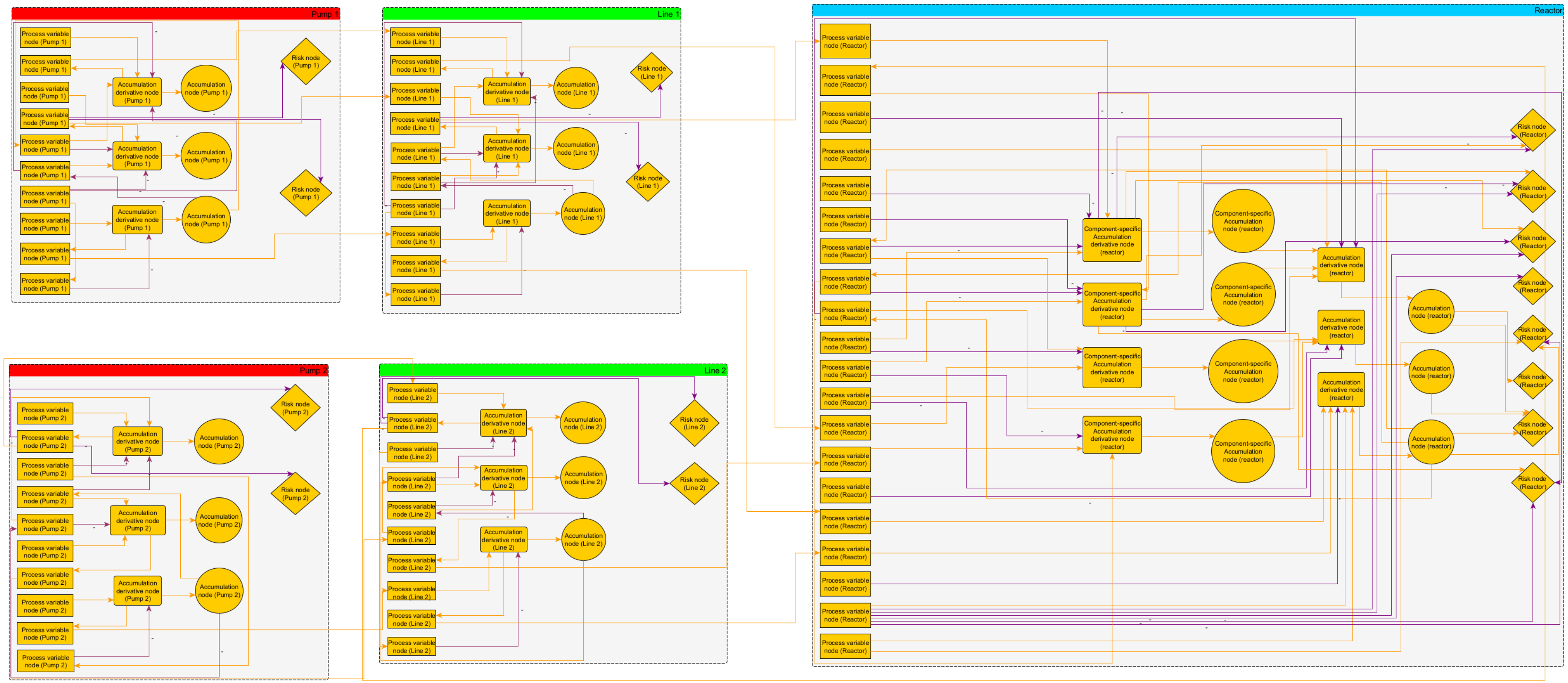



*Figure 31: System graph after the integration of the piping module.*

### 3.3.2.2 Dual-phase representation

To further enhance the precision of the system model, a dual-phase representation has been integrated into the graph, capturing both liquid and gas phases. In complex chemical processes, phases often coexist or transition between each other, especially in systems involving heating, cooling, or depressurization. Distinctly representing these phases within the graph enables a more realistic and nuanced depiction of process behavior under varying conditions, providing an accurate account of mass and energy flow throughout the system.

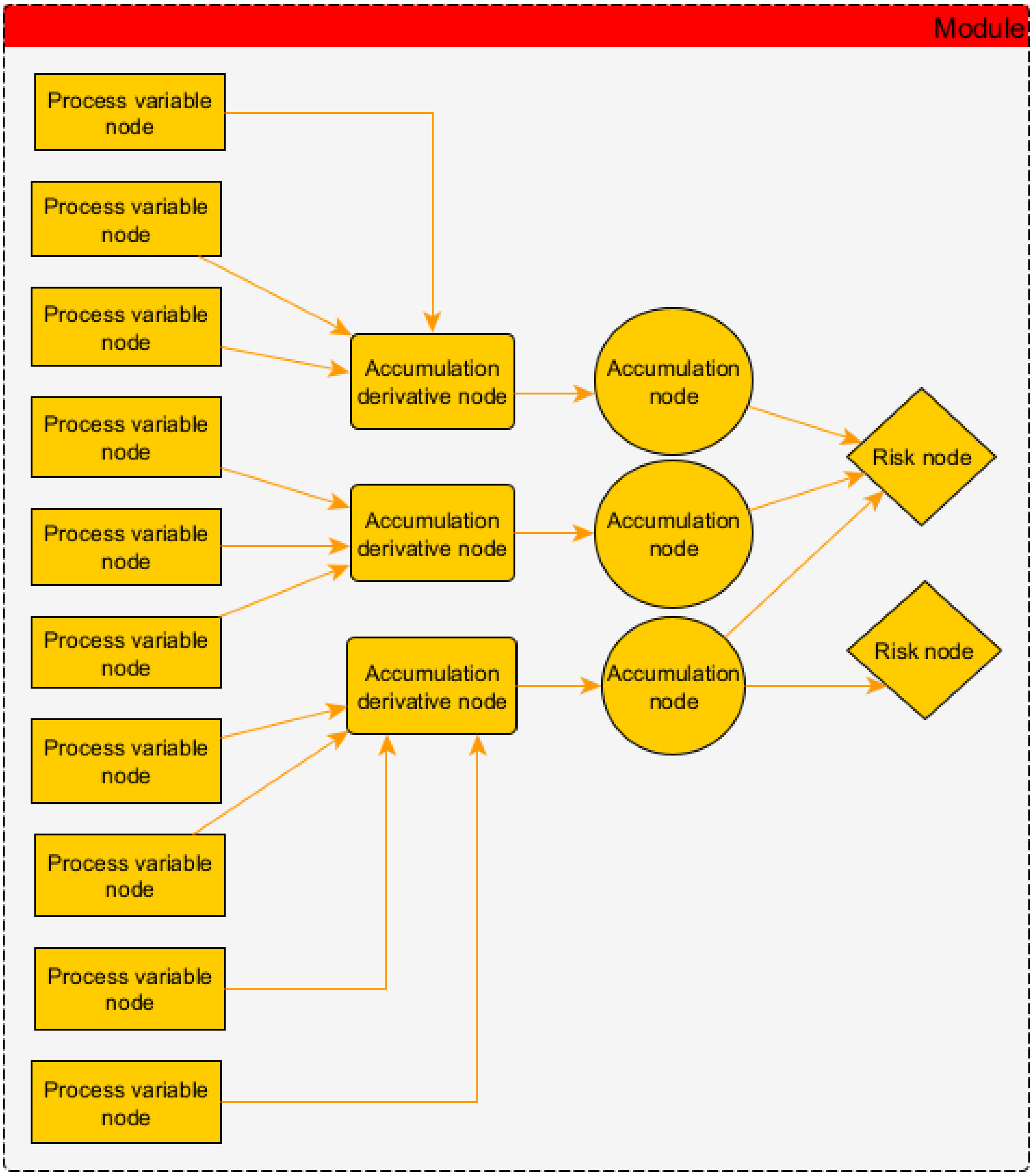



*Figure 32: Example of a subgraph with additional nodes and arcs for a dual-phase condition. Two of the three accumulation and accumulation derivative nodes are dedicated to the mass balance for liquid and gas phases. These two nodes are connected differently in the graph as the phases influence the system in different ways.*

The graph now includes separate process variables for the mass flow of liquid and gas entering and exiting each component. This distinction allows the model to track the behavior of different phases as they move through the system, enabling a more detailed assessment of potential deviations in phase behavior, such as flash evaporation or condensation. Additionally, new variables have been introduced to account for phase transitions, such as liquid vaporization or gas condensation. These transitions are critical for accurately modeling equipment like heat exchangers or reactors, where energy input can cause phase changes that significantly influence safety outcomes.

To complement these changes, arcs in the graph have been adjusted to reflect energy exchange between phases. For instance, the influence of temperature on phase transitions is now captured, demonstrating how energy input or removal directly impacts the system's state of matter. These enhancements not only improve the physical realism of the model but also increase its predictive power, particularly when analyzing potential deviations during HAZOP studies.

Additionally, the accumulation terms for mass balances within each piece of equipment have been divided into separate terms for gas and liquid phases. This separation ensures the model can more accurately calculate the system's response to changes in flow or energy input. In real-world applications, liquid and gas phases often exhibit distinct behaviors due to their differing physical properties (e.g., density, viscosity, compressibility factor, etc.). Combining them into a single accumulation term could lead to oversimplifications or inaccuracies. By splitting these terms, the graph provides greater granularity in representing phase-specific accumulations, thereby improving the reliability and precision of the system analysis.

The mass balance for each phase can be generally expressed as:

$$Accumulation = Inflow - Outflow + Generation - Consumption$$

For the liquid phase, the mass balance is:

$$Accumulation_{liquid} = Inflow_{liquid} - Outflow_{liquid} + Generation_{liquid} - Consumption_{liquid}$$

Similarly, for the gas phase, the mass balance is:

$$Accumulation_{gas} = Inflow_{gas} - Outflow_{gas} + Generation_{gas} - Consumption_{gas}$$

By separating the mass balances into two distinct equations—one for the gas phase and one for the liquid phase—the model can track the behavior of each phase individually. This separation offers a more accurate representation of the system's dynamics, as each phase can accumulate or deplete mass differently depending on phase-specific factors such as flow rates, reactions, or physical properties.

In the graph representation, this separation is depicted through distinct nodes for liquid and gas accumulation, with each node accounting for phase-specific inflows, outflows, and internal reactions. This modular approach allows for precise tracking of deviations and phase-specific risks, enhancing the model's overall accuracy and flexibility.

To simplify the model, generation and consumption terms have been considered only for the liquid phase. This assumption is based on the observation that significant reactions and material transformations primarily occur in the liquid phase, where chemical reactions, phase changes, or mass transfer significantly influence system dynamics. By contrast, the gas phase is treated mainly as a transport medium, without substantial generative or consumptive contributions. This approach reduces model complexity while capturing the most critical aspects of phase-specific behavior.

This two-phase representation not only improves the accuracy of the system model, but also increases its flexibility and scalability. It is particularly well-suited for processes involving multiphase flow and heat transfer, such as those found in petrochemical plants, refineries, and chemical manufacturing facilities. It is also invaluable for closed systems where vapor evolution poses a risk of pressure buildup. By accurately representing the accumulation and interactions of liquid and vapor phases, this approach helps identify potential hazards associated with pressure build-up in closed environments, providing deeper insight into fault propagation and risk assessment..

After comparing the traditional HAZOP-generated table with the algorithm-driven one, it became evident that mass and energy losses due to leakages cannot be overlooked. The traditional HAZOP analysis highlighted numerous hazardous scenarios directly linked to leakages, such as pressure drops, material losses, and energy inefficiencies. Given the frequency and impact of these scenarios, coupled with the relatively straightforward integration of leakage effects into the algorithm, it was determined that incorporating leakages is essential.

This decision not only enhances the comprehensiveness of the results but also accommodates the integration of leakage-related risk scenarios in future project phases. By accounting for these losses, the model provides a more realistic representation of potential hazards, particularly those affecting process safety and performance deviations caused by leaks.

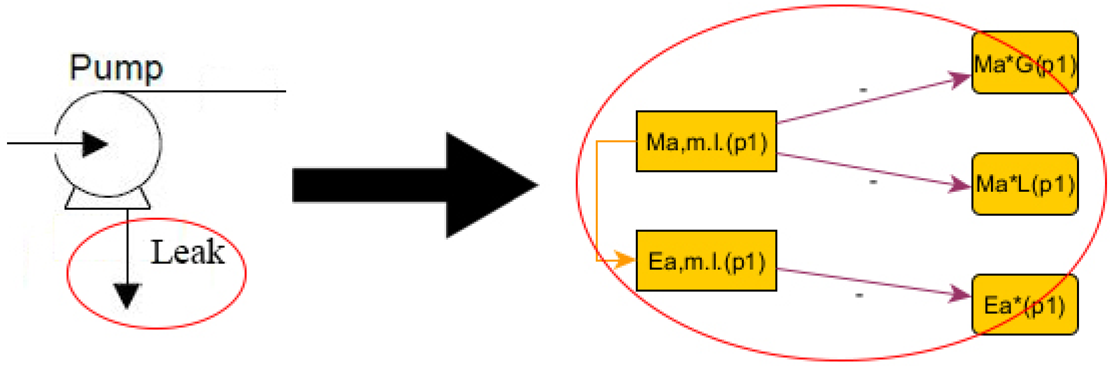



*Figure 33: An example of additional nodes for mass and energy losses within the Pump 1 subgraph is illustrated. Nodes labeled with "M" represent volumes of mass, while "a" specifies Component A, and "m.l." indicates mass loss due to leakage. An asterisk (*) denotes accumulation derivative nodes, and the letters in parentheses identify the specific submodule to which each node belongs.*

To implement this, additional terms for mass and energy losses due to leakages were introduced for each subgraph representing a piece of equipment or system component, as showed in figure 33. Since leakages impact both the mass and energy balances, these losses are represented by dedicated nodes within the graph. Instead of generating separate nodes for liquid and gas losses, a single node was designed to represent both phases, streamlining the model while maintaining its effectiveness.

This simplification is appropriate for the current stage of the project, where relationships between variables are being treated qualitatively rather than quantitatively. The primary objective at this stage is to track the potential influence of leakage without introducing unnecessary complexity.

Arcs originating from the mass loss node interact with the system in two key ways. First, they connect to the derivative of the mass accumulation nodes with an inverse relationship. This reflects that mass leakage reduces overall mass accumulation within the system, which can result in lower pressure, flow rates, or other critical variables, depending on the scenario. Second, the mass loss node is linked to the energy loss node, recognizing that material lost from the system also carries energy.

Similarly, the energy loss node connects to the derivative of the energy accumulation term, again with an inverse relationship. As with mass, fluid leakage reduces the energy retained within the system, which may manifest as a temperature drop, decreased heat transfer efficiency, or diminished energy availability for downstream processes.

The inclusion of leakage-related losses lays a solid foundation for future expansions of the project. Specifically, it enables the easier integration of leakage-specific risk assessments, which are essential in real-world HAZOP analyses. Leakages not only lead to immediate operational inefficiencies but also pose significant safety hazards, such as the release of toxic, flammable, or corrosive substances. By embedding this framework into the graph at an early stage, the model becomes more adaptable to detailed quantitative risk assessments in later phases of development.

Incorporating these leakage terms ensures that the model provides a more accurate and comprehensive representation of real-world process systems. By addressing inevitable mass and energy losses, the model enhances the rigor of safety and performance evaluations, offering a robust tool for managing both operational and safety risks.

## 3.4 preHAZOP table generation through software

The final step of this project is the development of Python code specifically designed to extract data from the .graphml file and calculate how every possible deviation in each process variable could impact the system. This Python script serves as the core computational engine of the project, automating deviation propagation analysis and offering detailed insights into the system's behavior under abnormal conditions.

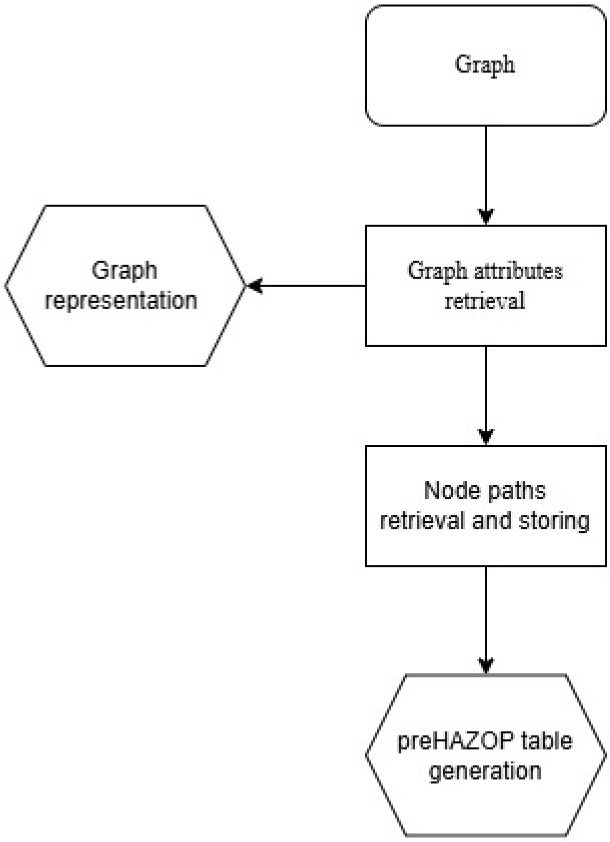



*Figure 34: preHAZOP table generation and flowchart illustrating the key actions performed by the software.*

The Python script utilizes a specialized library, called NetworkX, to enable seamless interaction with the .graphml file. These libraries are essential for importing and interpreting graph data, ensuring that the system's components, interactions, and variables are accurately represented. One of the primary functions of the code is to visualize the graph as an image, leveraging the benefits outlined in earlier sections.

This visualization provides the HAZOP team with a powerful tool to track deviations and understand their propagation through different nodes in the system. By providing a clear and intuitive representation, it highlights the relationships between process variables, causes and effects, enabling the team to quickly identify critical paths and potential failure points. This is particularly valuable during human review of automated results, as it serves as a guide to ensure the accuracy and relevance of the system's output.

The practical impact is significant: the visual layout makes complex systems easier to understand, reducing the cognitive load on the HAZOP team. It helps pinpoint deviations that span multiple modules, helping to identify areas that may require deeper analysis or intervention. For example, in a scenario where a deviation propagates across modules, the visualization clearly marks the affected paths, allowing the team to effectively assess the risk and its potential impact.

In the future, this capability could be further enhanced by incorporating a dynamic visualization feature. This future enhancement would allow the software to generate interactive images that highlight specific paths or nodes on demand, speeding up the review process and making it easier for the team to focus on areas of high concern. By providing both a static and potentially dynamic representation of the system, this visualization bridges the gap between automated analysis and expert validation, ensuring a comprehensive and reliable HAZOP process..

In addition to supporting human analysis, the graphical output acts as a validation tool, helping experts verify that the system has been accurately modeled. By allowing experts to review the system's construction visually, the graph representation ensures that nodes are correctly connected and no paths are overlooked during the graph creation process.

This comprehensive visualization enhances the HAZOP team's ability to validate the model's accuracy and completeness, providing an intuitive overview of system interactions and ensuring that potential deviations are fully accounted for.

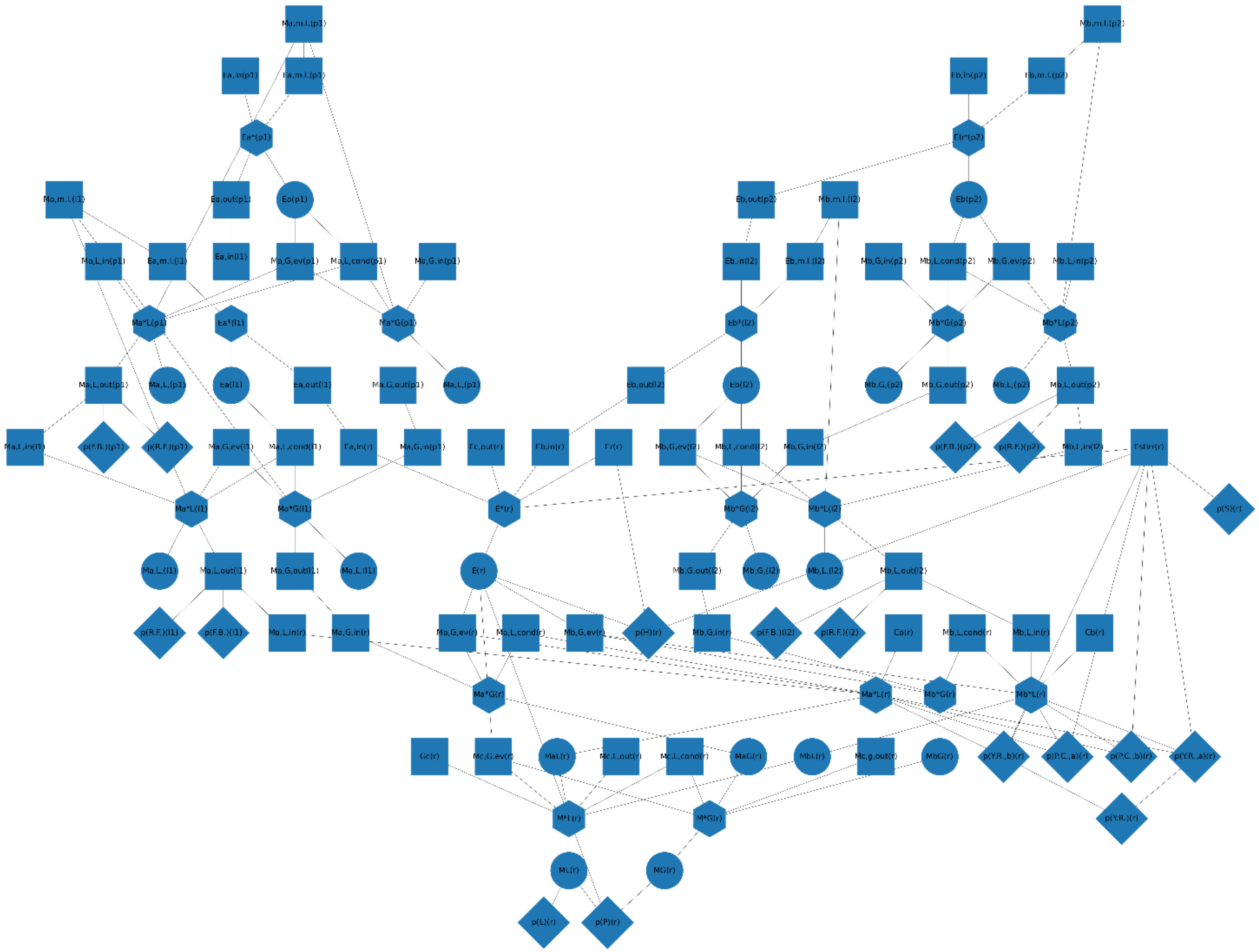


*Figure 35:Software representation of the imported graph, using the "Graphviz dot layout"*

Beyond visualization, the Python code utilizes the imported data to generate all possible paths from each process variable to its associated risk nodes.

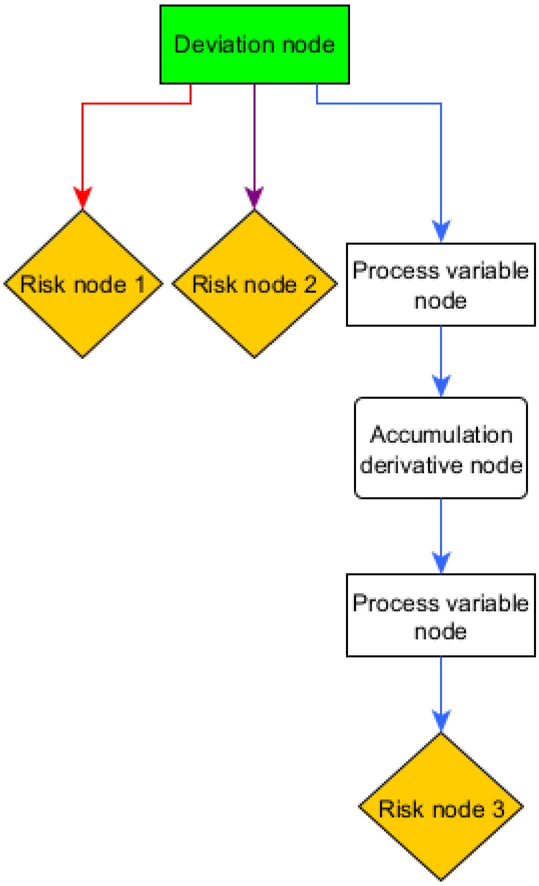



*Figure 36: Example of possible paths from a single process variable node. The red, purple and blue arrows shows the three possible paths to three different risk nodes from the same process variable as a result of a deviation.*

This step is essential as it enables the software to map how deviations in one part of the system can propagate through downstream processes, potentially leading to hazardous conditions.

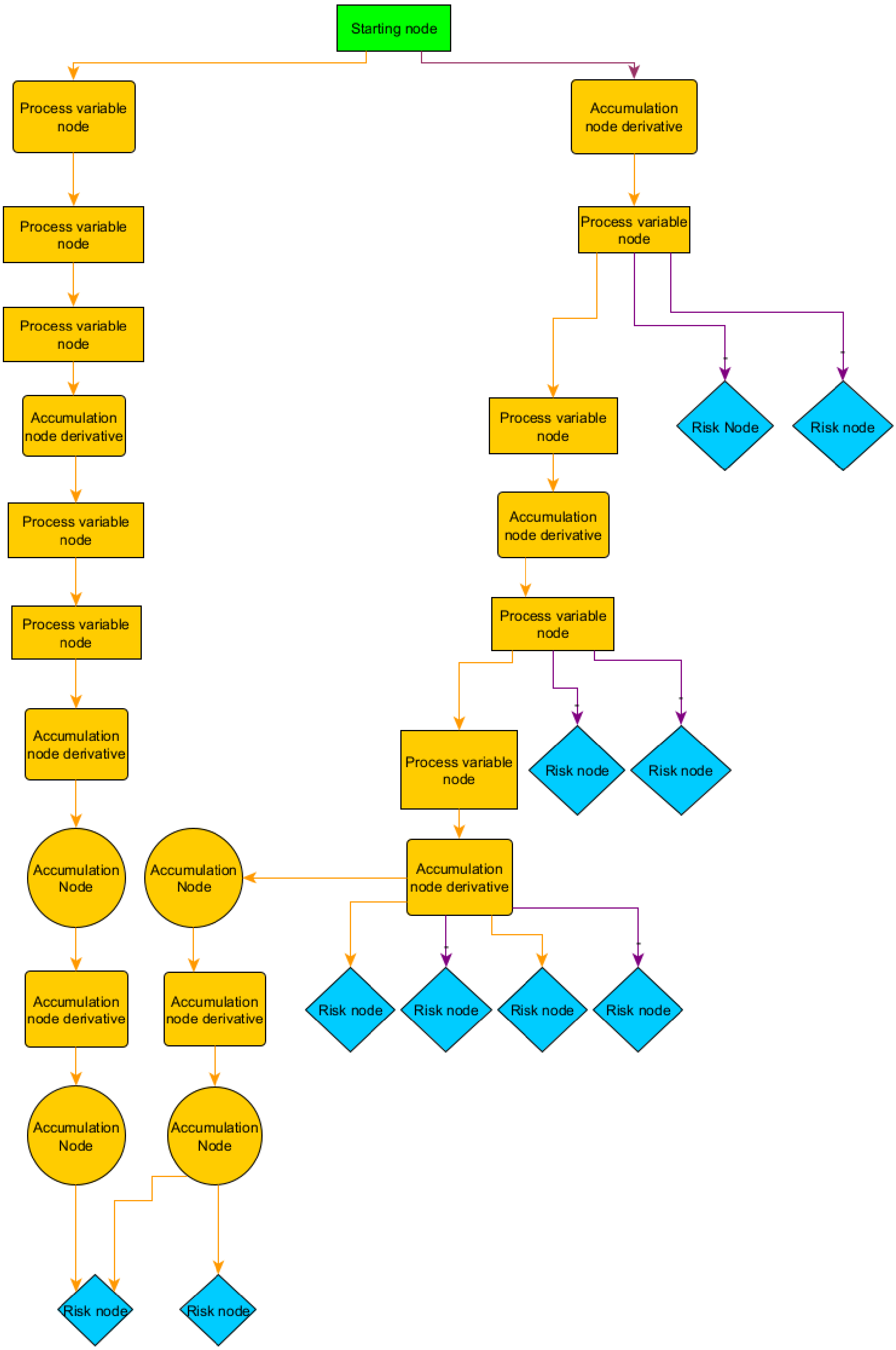



*Figure 37: Visual representation of all possible paths from a starting node (green) to all connected risk nodes (cyan). This portion of the graph represents how, from a single starting node, the software can track all the possible consequences thanks to the calculated paths.*

Using data imported from the graph, the software generates and stores all possible paths from each process variable node. This ensures that no scenario is overlooked and provides a comprehensive view of how failures interact and propagate through the system. Automated path generation significantly increases the speed and accuracy of HAZOP analysis, minimizing the risk of human error while providing detailed insight into system weaknesses. In addition, this capability ensures consistent and comprehensive identification of potential hazard scenarios, which is critical for complex systems.

The uploaded image illustrates the results of this automated path tracing. The green colored node represents the "starting node" where the hypothetical deviation occurs. The cyan-colored nodes represent all possible risk probabilities affected by this deviation, effectively showing the range of potential consequences. Each path connecting these nodes represents a different propagation path, demonstrating how deviations cascade through the system.
Once all paths are generated, the Python code uses this information to populate the preHAZOP table. This table serves as a preliminary version of the full HAZOP analysis, systematically documenting every possible deviation, its potential consequences, and associated risks. The preHAZOP table provides a structured and organized overview of the system's risk profile, enabling the HAZOP team to prioritize hazards effectively and identify where additional safeguards or mitigations are needed.
This automation ensures that the preHAZOP table remains comprehensive and up to date, accurately reflecting all potential deviation scenarios derived from the graph data.

| **HAZOP Analysis** | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| No. | Item | Function/ Purpose | Parameter | Guide Word | Consequence | Cause | Hazard | Risk | Recommendation | Comments |
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |

*Figure 38: Suggested HAZOP worksheet table used in traditional HAZOP analysis*

| No. | ID | PV | PV description | Keyword | Cause | Cause description | Last PV before Effect | Last PV description | Effect | Effect description |
|---|---|---|---|---|---|---|---|---|---|---|
| ① | ② | ③ | ④ | ⑤ | ⑥ | ⑦ | ⑧ | ⑨ | ⑩ | ⑪ |

*Figure 39: Automated HAZOP table*

Figure 38 and Figure 39 show a suggested HAZOP table template for traditional HAZOP analysis and a template for the automated HAZOP analysis proposed in this thesis project.

| No. | ID | PV | PV description | Keyword | Cause | Cause description |
|---|---|---|---|---|---|---|
| 1 | n0n4n1n8 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | low | Not Found | No accumulation nodes identified as sources |
| 2 | n0n4n1n9 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | low | Not Found | No accumulation nodes identified as sources |
| 3 | n0n4n1n89n93n90n97 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | low | Not Found | No accumulation nodes identified as sources |
| 4 | n0n4n1n89n93n90n98 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | low | Not Found | No accumulation nodes identified as sources |
| 5 | n0n4n1n89n93n90n24n54n56n45n48n52 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | high | Not Found | No accumulation nodes identified as sources |
| 6 | n0n4n1n89n93n90n24n54n56n45n48n53 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | high | Not Found | No accumulation nodes identified as sources |
| 7 | n0n4n1n89n93n90n24n54n63 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | high | Not Found | No accumulation nodes identified as sources |
| 8 | n0n4n1n89n93n90n24n54n63n66 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | high | Not Found | No accumulation nodes identified as sources |
| 9 | n0n4n1n89n93n90n24n54n65 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | low | Not Found | No accumulation nodes identified as sources |
| 10 | n0n4n1n89n93n90n24n54n65n66 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | low | Not Found | No accumulation nodes identified as sources |
| 11 | n0n4n1n89n93n90n24n54n62 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | high | Not Found | No accumulation nodes identified as sources |
| 12 | n0n4n1n89n93n90n24n54n64 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | low | Not Found | No accumulation nodes identified as sources |
| 13 | n1n8 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 14 | n1n9 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 15 | n1n89n93n90n97 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 16 | n1n89n93n90n98 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 17 | n1n89n93n90n24n54n56n45n48n52 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 18 | n1n89n93n90n24n54n56n45n48n53 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 19 | n1n89n93n90n24n54n63 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 20 | n1n89n93n90n24n54n63n66 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 21 | n1n89n93n90n24n54n65 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 22 | n1n89n93n90n24n54n65n66 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 23 | n1n89n93n90n24n54n62 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 24 | n1n89n93n90n24n54n64 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[kg/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1)[kg/s] |
| 25 | n2n5n7n67n75n73n107n111n109n36n58n60n44n47n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1)[J/s] | high | Not Found | No accumulation nodes identified as sources |
| 26 | n2n5n7n67n4n1n8 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1)[J/s] | low | Not Found | No accumulation nodes identified as sources |
| 27 | n2n5n7n67n4n1n9 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1)[J/s] | low | Not Found | No accumulation nodes identified as sources |
| 28 | n2n5n7n67n4n1n89n93n90n97 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1)[J/s] | low | Not Found | No accumulation nodes identified as sources |
| 29 | n2n5n7n67n4n1n89n93n90n98 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1)[J/s] | low | Not Found | No accumulation nodes identified as sources |
| 30 | n2n5n7n67n4n1n89n93n90n24n54n56n45n48n52 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1)[J/s] | high | Not Found | No accumulation nodes identified as sources |

| Last PV before Effect | Last PV description | Effect | Effect description |
|---|---|---|---|
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r)□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r)□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r)□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r)□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b□ |
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r)□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r)□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r)□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r)□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a□ |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b□ |
| Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r)[□g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)[□g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r)[□g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |

*Figure 40:preHAZOP table, software generated*

In summary, the Python code serves as the technological backbone of this project, automating both the graphical representation of the system and the generation of deviation propagation paths. By leveraging Python libraries and the structured data within the .graphml file, the code ensures seamless integration of the graph into the software, allowing for accurate and comprehensive analysis. This automation replaces the most time-consuming aspect of traditional HAZOP analysis: manual scenario generation and results tabulation, significantly reducing the time required for the process.

This approach increases the accuracy of the analysis by eliminating common pitfalls associated with manual efforts, such as errors due to fatigue, overconfidence, or biases. Instead, the software's reliance on a phenomenological approach ensures that each scenario is analyzed objectively, free from subjective human influence. In addition, the modular design of the code allows for scalability, making it adaptable to complex and large-scale systems, such as those commonly found in industrial applications.

Beyond its technical capabilities, this automated methodology allows the HAZOP team to focus on high-level decision making and risk prioritization. With the labor-intensive tasks handled by the software, experts can focus their attention on interpreting results, developing mitigation strategies, and ensuring alignment with safety goals.

Looking ahead, this technology framework provides a solid foundation for future enhancements. The code can evolve to include more sophisticated analyses, such as real-time data integration, dynamic scenario visualization, or enhanced probabilistic assessments. These developments would further enhance the system's ability to support the HAZOP process and ensure that safety assessments remain rigorous, efficient, and adaptable to ever-increasing industrial complexity.

### 3.4.1 Code structure and evolution

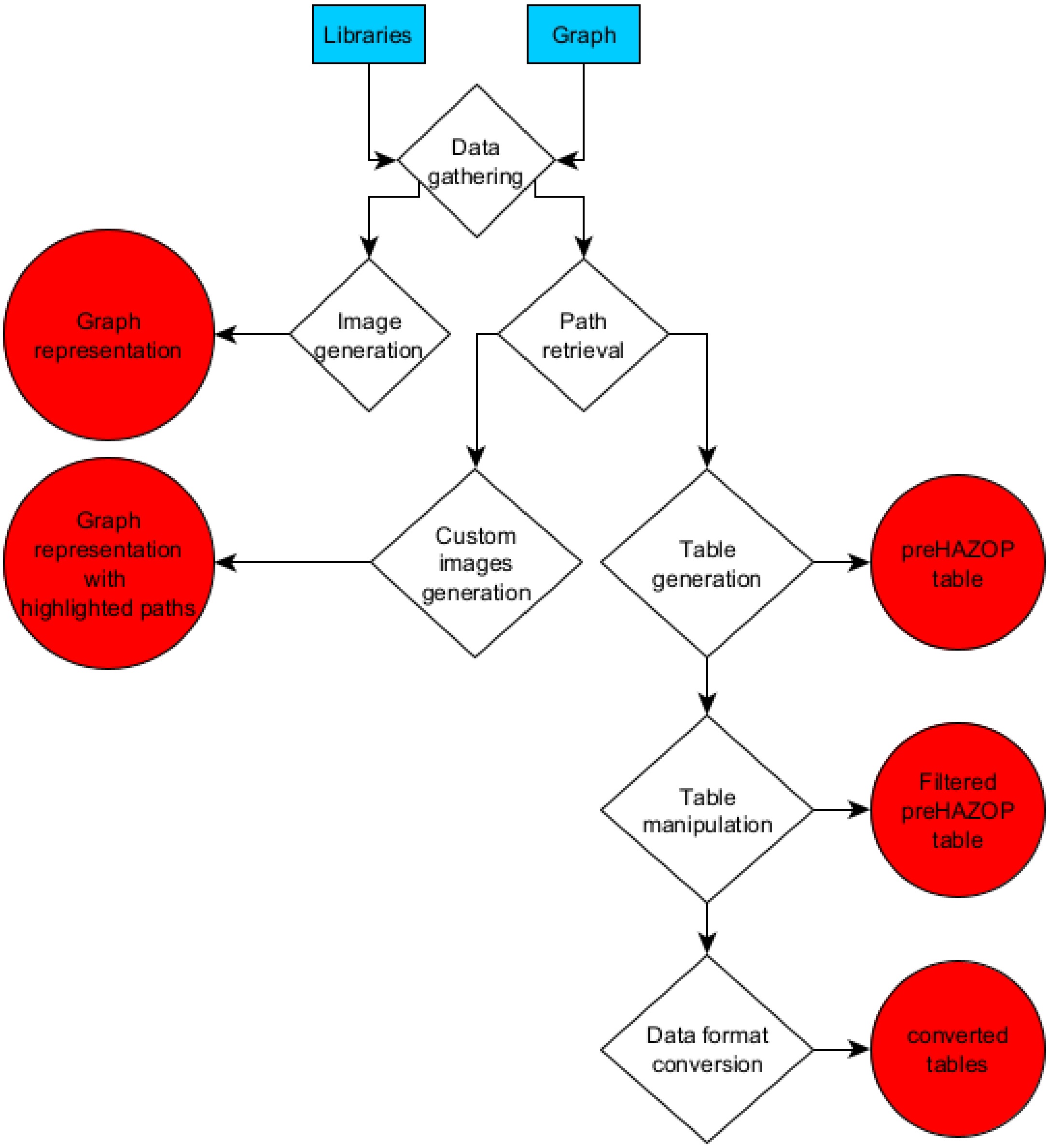



*Figure 41: Code structure diagram. Cyan rectangles represent the required inputs, white diamonds the processing steps and, finally, red circles are the outputs produced by the software program.*

Essentially, the abovementioned Python code structure can be divided into four parts:

#### 3.4.1.1 Libraries and data import

In this initial section, the required Python libraries are imported to enable graph manipulation, data storage, and file management. Said libraries include:

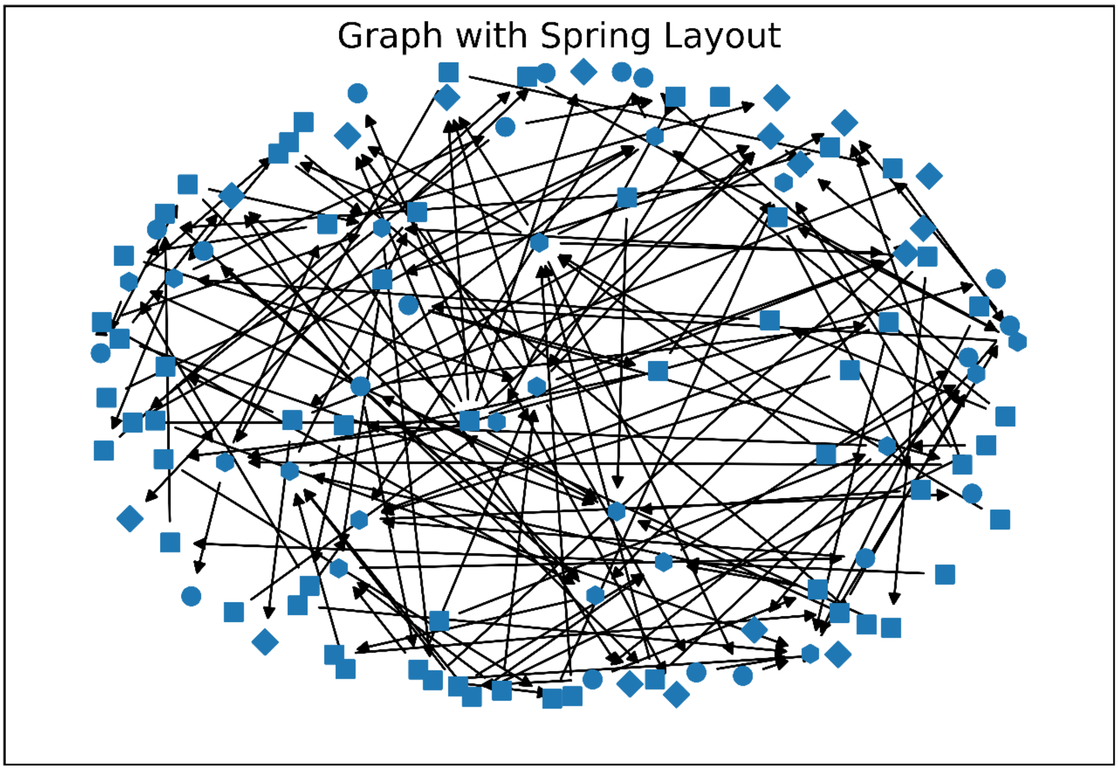
- *NetworkX*: Used for graph-based operations, enabling manipulation of the imported graph and retrieval of its attributes.

- *Pandas*: Essential for handling tabular data, facilitating the generation and manipulation of the preHAZOP table.
- *Matplotlib*: Used for rendering graphical output, allowing the creation of images necessary for visualizing the graph.
- *Openpyxl*: Enables saving and manipulating results in the widely used .xlsx format, which can be easily opened and understood by the human team using Microsoft Excel.

Once the libraries are loaded, the graph data—typically in .graphml format—is imported and parsed. Nodes, arcs, and their associated attributes are extracted from the graph file and stored in arrays or data structures like dictionaries for further processing.

This step is critical, as it transforms the graph's raw structure into a format that the code can efficiently manipulate and analyze. During this process, essential information such as variable types, node labels, and connections is mapped, laying the foundation for an accurate and systematic analysis of the system.

### 3.4.1.2 Graph representation



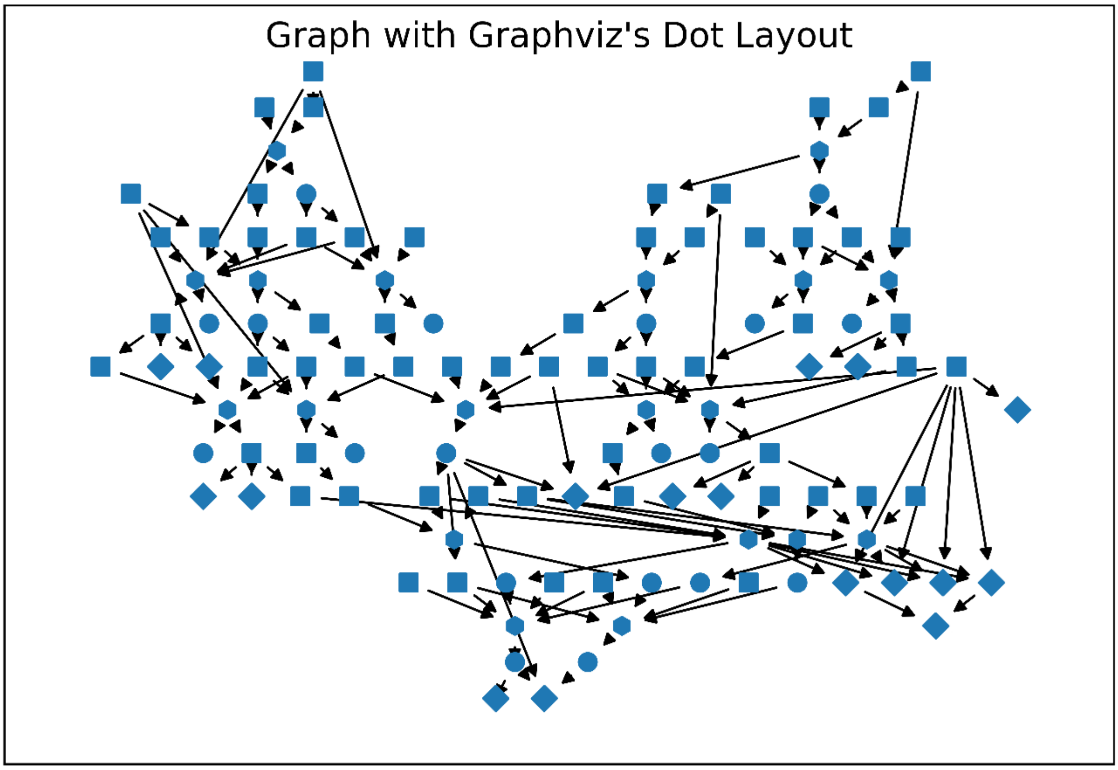




*Figure 42: Graph representation used in this project. The top one uses a Spring layout and has been deemed not clear enough for a helpful visualization of the graph. The bottom one improves on this side by using Graphviz's layout.*

This section focuses on visually representing the imported graph. Depending on the system's complexity, various layout algorithms can be applied to enhance visual clarity. Common approaches include:

- *Spring Layout*: A force-directed layout that provides a natural and intuitive representation of relationships.
- *Circular Layout*: Ideal for visualizing interactions within the graph.
- *Hierarchical Layout*: Useful for emphasizing top-down structures, particularly in systems with clear dependencies.

These graphical representations are not merely static images; they form the basis for dynamic manipulations in subsequent stages of the code. Each node and arc is labeled with detailed information, including descriptions and shapes, ensuring accurate identification and tracking of variables for the HAZOP analysis. This visual clarity helps both the automated process and the human team verify the graph's correctness and completeness.

#### 3.4.1.3 preHAZOP table generation

This section is the core of the Python code, where the algorithm executes the deviation analysis. Using the stored graph data, the code generates all possible paths from process variables (e.g., flow rate, temperature) to their associated risk nodes (e.g., hazards, failures, or abnormal conditions).

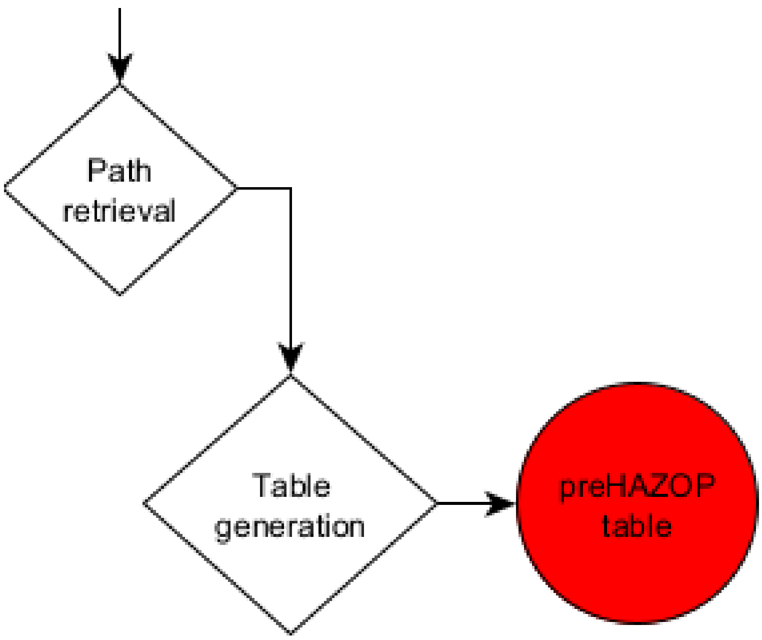



*Figure 43: Zoomed code structure, highlighting the preHAZOP table generation part.*

These paths represent the chains of influence and deviation propagation, illustrating how disturbances in the system can spread and interact. This automated pathway generation is pivotal for ensuring a comprehensive understanding of the system's vulnerabilities, forming the foundation for the preHAZOP table and enabling a systematic evaluation of potential risks.

Once these paths are identified, the code leverages this information to populate the preHAZOP table. Acting as a preliminary risk analysis tool, the table systematically maps potential hazards arising from deviations from normal operating conditions, along with their propagated effects throughout the system.

| No. | ID | PV | PV description | Keyword | Cause | Cause description |
|---|---|---|---|---|---|---|
| 1 | n0n4n1n8 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [kg/s] | high -> high -> low | Not Found | No accumulation nodes identified as sources |

| Last PV before Effect | Last PV description | Effect | Effect description |
|---|---|---|---|
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [kg/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |

*Figure 44: Table representation of the identified path.*

Figure 43 shows an example row from the generated preHAZOP table, illustrating the structured organization of data for each scenario. The "ID" column identifies the specific path associated with the scenario being analyzed. The "PV" and "PV Description" columns detail the process variable where the deviation is hypothesized to occur. The Keyword column lists the complete sequence of keywords along the path. The "Cause" and "Cause Description" columns highlight a possible cause for the identified deviation. The "Last PV before Effect" and its corresponding description indicate the last process variable affected by the deviation before reaching the "Effect", which represents the final consequence. This effect is captured as a risk node in the graph and is further detailed in the last two columns of the table.

#### 3.4.1.4 Output manipulation and recording

This final section of the Python code's structure represents a critical addition that enhances its functionality and adaptability to address the specific needs of this thesis project. It includes supplementary code developed to manipulate the output for specialized tasks such as results filtering, enhanced visualization, and alignment with traditional HAZOP analysis requirements.

*Results filtering*

One of the primary additions is the results filtering functionality, which focuses on producing output relevant to specific submodules or deviations. This feature is particularly important for comparing the algorithm-generated table with the traditional HAZOP table. For example, the table derived from the BSI standard focuses exclusively on deviations related to the supply line A leading to the reactor. To ensure consistency in the comparison, the results from the algorithm were filtered to align with this narrower scope.

This filtering process operates by selecting rows within the preHAZOP table that correspond specifically to the targeted process variable or system component. By doing so, the analysis remains focused and avoids the inclusion of irrelevant data that could complicate or skew the comparison. This filtered output can also be sorted for improved navigation, allowing the team to quickly identify and prioritize key deviations. These refinements not only make the comparison more consistent but also enhance the usability of the results for both automated and manual review processes.

*Enhanced visualization*

Recognizing the importance of clear and accessible presentation, two major features were added to improve the visualization of results:

- Excel File Export: The filtered preHAZOP tables are exported into separate Excel files with pre-determined formatting. This formatting ensures that the data is presented in a structured and readable manner, facilitating its interpretation by the HAZOP team. The Excel export feature also provides a practical way to document and share results, enabling team members to review the findings in a familiar and user-friendly format.
- Deviation Propagation Graphs: To offer deeper insights into how deviations propagate through the system, the Python code regenerates system graphs with specific paths highlighted. These paths represent the propagation of deviations through different nodes and modules, providing a visual narrative of how a disturbance can affect downstream or upstream elements. This graphical representation is particularly valuable for identifying critical points within the system where deviations may escalate into hazards, as well as for validating the connections and relationships modeled in the graph.

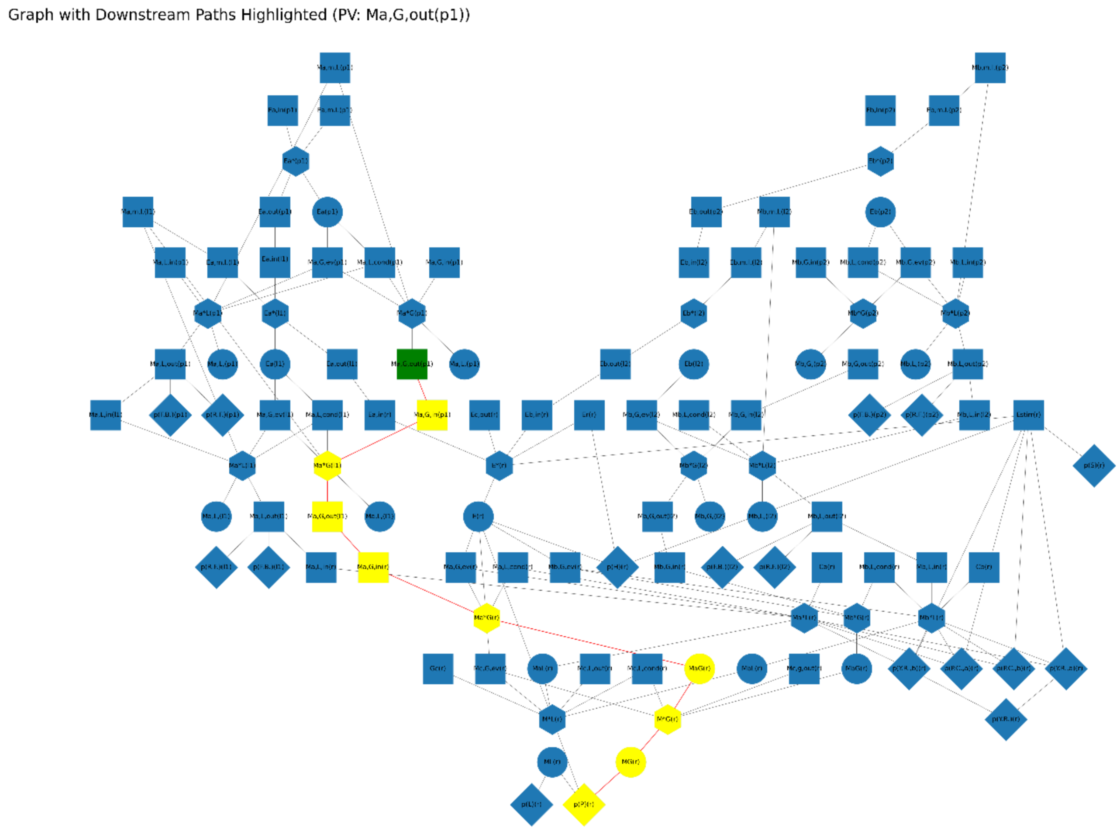



*Figure 45: Python representation of a process variable (Green) deviation propagation into the system*

Two distinct use cases illustrate the importance of these visualization features:

- *Downstream Propagation Paths*: The code highlights paths from a process variable to risk nodes downstream, illustrating how a deviation could cascade through the system. This visual tool helps the team anticipate potential hazards and develop mitigation strategies.
- *Upstream Deviation Sources*: Instead of identifying every possible upstream node relative to a process variable, the code uses accumulation nodes as indicators of potential deviation sources. This approach simplifies the analysis by focusing on key points within each module, ensuring that the investigation remains targeted and manageable without compromising accuracy.

Figure 40 and Figure 41 demonstrate these features, showing how propagation and source paths are visualized for clearer understanding and analysis. These visualizations are instrumental in both consequence identification and source tracing, providing a holistic view of how deviations interact within the system.

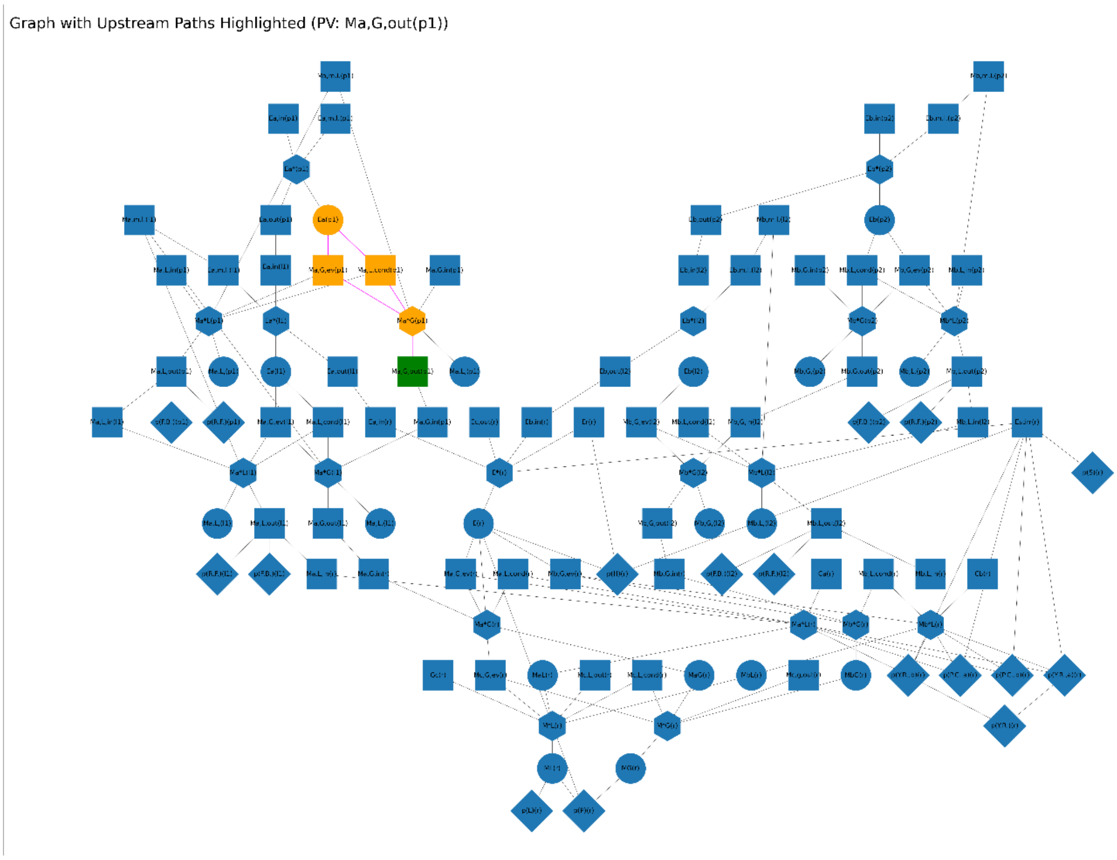



*Figure 46: Python representation of a process variable (Green) upstream path to the module where the deviation may have originated*

The enhanced graph representation introduced in this study offers significant advantages for the preHAZOP process. Using this approach, the software can automatically identify both potential causes and potential consequences of deviations and comprehensively document them in the preHAZOP table. In addition, the ability to generate visual representations of these paths provides a powerful tool for the human team during the review phase. This visual aid not only facilitates the identification of critical paths and interactions, but also ensures that no potential scenario is overlooked.

As the complexity and size of the system increases, the benefits of this approach become even more apparent. Manually tracking error propagation paths and potential sources in large systems can be both error-prone and time-consuming. The automated process, however, performs this task in seconds while maintaining high accuracy and significantly reducing the risk of oversight. The ability to integrate these enhanced representations into both tabular and graphical outputs exemplifies the potential of this tool to transform traditional preHAZOP workflows, making them more efficient and reliable.

# Chapter 4: Results and case study

## 4.1 Case study description

To assess the performance of the phenomenological approach when applied to automation techniques, a comparison was made with a table generated by a traditional HAZOP analysis. This reference table conforms to the international standard for HAZOP analysis, BS EN 61882:2016, ensuring a robust and industry-recognized benchmark. The case study selected for this comparison was intentionally simple, allowing for a focused evaluation of the capabilities of the approach:

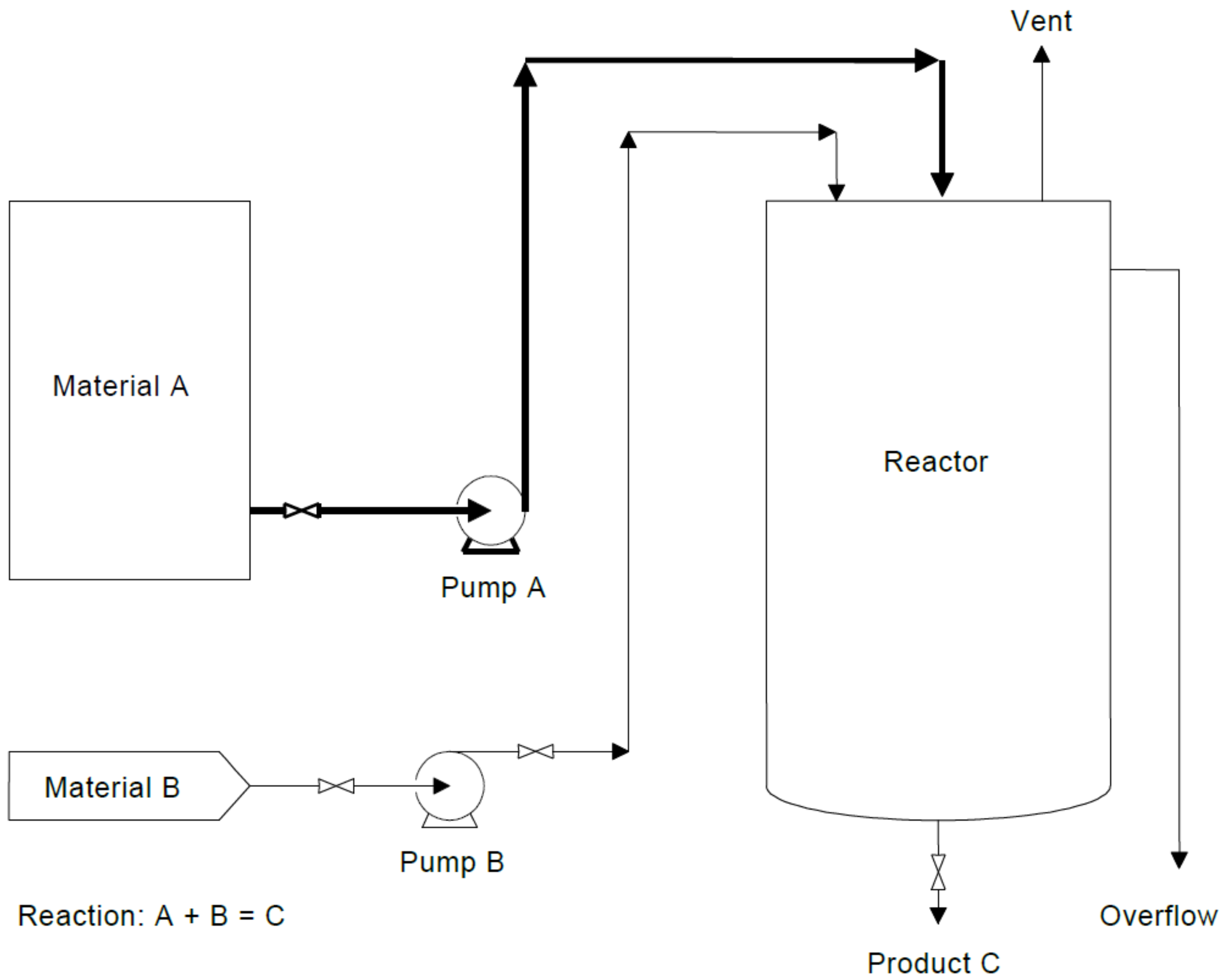



*Figure 47: Case study template utilized in this thesis project. The system features two pump-fitted lines delivering pure components A and B into a well-mixed reactor.*

As illustrated in Figure 47, the system comprises two pump-fitted lines responsible for delivering pure components to a mixed reactor. For component A, an upstream tank is also present; however, for the sake of simplicity, it was treated in the same manner as line B. Both the traditional HAZOP analysis and the automated approach were carried out under the assumption that the reaction in the reactor must operate with an excess of component A, a requirement attributed to unspecified safety considerations. In alignment with the pre-HAZOP framework, overflow and vent components were excluded from the analysis. Figure 48 depicts a graphical representation of the actual system utilized for the automated analysis.

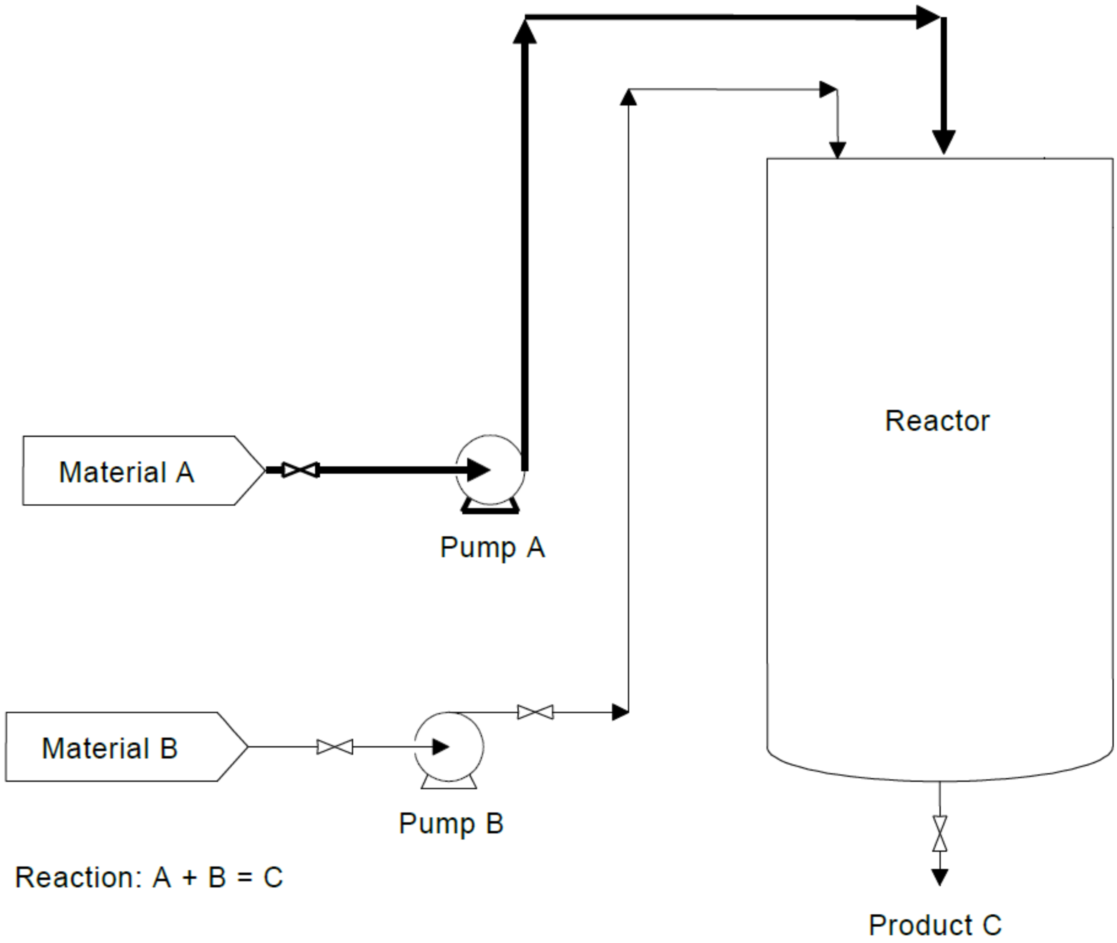



*Figure 48: Adapted template from the BSI case study. The overflow prevention system, air vent, and the upstream tank for component A have been removed to align with the simplified analysis approach.*

### *4.1.1 Table description*

In the international standard used for the comparison, the abovementioned case study is subjected to a traditional HAZOP analysis. However, the table shown in the document only addresses a small part of the overall system, specifically the transfer line for component A to the reactor.

**Table B.2 – Example HAZOP worksheet for introductory example**

| | | | |
|---|---|---|---|
| **STUDY TITLE:** PROCESS EXAMPLE | | | **SHEET:** 1 of 4 |
| **Drawing No.:** | **REV. No.:** | | **DATE:** December 17, 1998 |
| **TEAM COMPOSITION:** | LB, DH, EK, NE, MG, JK | | **MEETING DATE:** December 15, 1998 |
| **PART CONSIDERED:** | **Transfer line from supply tank A to reactor** | | |
| **DESIGN INTENT:** | **Material:** A<br>**Source:** Tank for A | **Activity:** Transfer continuously at a rate greater than B<br>**Destination:** Reactor | |

| No. | Guide word | Element | Deviation | Possible causes | Consequences | Existing controls | Comments | Actions required | Action allocated to |
|---|---|---|---|---|---|---|---|---|---|
| 1 | NO | Material A | No material A | Supply tank A is empty | No flow of A into reactor<br>Explosion | None shown | Situation not acceptable | Consider installation on tank A of a low-level alarm plus a low-level trip to stop pump B | MG |
| 2 | NO | Transfer A (at a rate > B) | No transfer of A takes place | Pump A stopped, line blocked | Explosion | None shown | Situation not acceptable | Measurement of flow rate for material A plus a low flow alarm and a low flow which trips pump B | JK |
| 3 | MORE | Material A | More material A: supply tank over full | Filling of tank from tanker when insufficient capacity exists | Tank will overflow into bounded area | None shown | Remark: This would have been identified during examination of the tank | Consider high-level alarm if not previously identified | EK |
| 4 | MORE | Transfer A | More transfer of A<br>Increased flow rate of A | Wrong size impeller<br>Wrong pump fitted | Possible reduction in yield<br>Product will contain large excess A | None | | Check pump flows and characteristics during commis-sioning<br>Revise the commissioning procedure | JK |

*Figure 49: HAZOP table for the transfer line for component A from the BSI standard. First page.*

| No. | Guide word | Element | Deviation | Possible causes | Consequences | Existing controls | Comments | Actions required | Action allocated to |
|---|---|---|---|---|---|---|---|---|---|
| 5 | LESS | Material A | Less A | Low level in tank | Inadequate net positive suction head<br>Possible vortexing and leading to an explosion<br>Inadequate flow | None | Unacceptable<br>Same as 1 | Low-level alarm in tank<br>Same as 1 | MG |
| 6 | LESS | Transfer A (at rate > B) | Reduced flow rate of A | Line partially blocked, leakage, pump under-performing, etc. | Explosion | None shown | Not acceptable | Same as 2 | JK |
| 7 | AS WELL AS | Material A | As well as A there is other fluid material also present in the supply tank | Contaminated supply to tank | Not known | Contents of all tankers checked and analysed prior to discharge into tank | Considered acceptable | Check operating procedure | LB |
| 8 | AS WELL AS | Transfer A | As well as transferring A, something else happens such as corrosion, erosion, crystallization or decomposition | The potential for each would need to be considered in the light of more specific details | | | | | NE |
| 9 | AS WELL AS | Destination reactor | As well as to reactor<br>External leaks | Line, valve or gland leaks | Environmental contamination<br>Possible explosion | Use of accepted piping code/ standard | Qualified acceptance | Locate flow sensor for trip as close as possible to the reactor | DH |
| 10 | REVERSE | Transfer A | Reverse direction of flow<br>Material flows from reactor to supply tank | Pressure in reactor higher than pump discharge pressure | Back contamination of supply tank with reaction material | None shown | Position not satisfactory | Consider installing a non-return valve in the line | MG |

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BS EN 61882:2016
IEC 61882:2016 © IEC 2016

*Figure 50:HAZOP table for the transfer line for component A from the BSI standard. Second page.*

| No. | Guide word | Element | Deviation | Possible causes | Consequences | Existing controls | Comments | Actions required | Action allocated to |
|---|---|---|---|---|---|---|---|---|---|
| 11 | OTHER THAN | Material A | Other than A<br>Material other than A in supply tank | Wrong material in supply tank | Unknown<br>Would depend on material | Tanker contents identity checked and analysed prior to discharge | Position acceptable | | |
| 12 | OTHER THAN | Destination reactor | External leak<br>Nothing reaches reactor | Line fracture | Environmental contamination and possible explosion | Integrity of piping | Check piping design | Specify that proposed flow trip should have a sufficiently rapid response to prevent an explosion | MG |





*Figure 51: HAZOP table for the transfer line for component A from the BSI standard. Third page.*

Upon further review of the HAZOP table included in the BSI EN 16882:2016 international standard example, certain aspects raise questions about the depth and thoroughness of the analysis. It is important to note, however, that the HAZOP provided in the standard is intended as an excerpt and may not fully reflect the complete assessment. Notably, the consequences column tended to focus exclusively on worst-case scenarios—such as listing 'explosion' as the outcome for a supply line blockage—while neglecting other potential, and perhaps more probable, consequences. This oversimplification could compromise the comprehensive nature expected of a HAZOP analysis.

Moreover, the scope of the analysis, encompassing only 12 lines of data for an entire chemical plant supply line, appears to differ significantly from the depth and comprehensiveness typically observed in exemplary HAZOP studies. While this approach may serve as a simplified excerpt for illustrative purposes, it raises questions about the ability of the assessment to capture the full spectrum of potential hazards and operational challenges, despite utilizing up to three times the number of keywords compared to the algorithm-generated table.

### *4.1.2 Comparison with a complete HAZOP table.*

After acknowledging the shortcomings of the proposed table, it has been decided to do an additional comparison between it and a manual HAZOP conducted by the team.

Table 12 presents the results of a manual HAZOP analysis, formatted to align with the same table structure used in the BSI standard. The methodology applied in this analysis mirrors the approach outlined in the international standard, with a particular emphasis on considering existing control instrumentation. This consistency ensures a comparable framework for evaluating the results.

*Table 12: HAZOP Table Generated from the Manual Traditional HAZOP Analysis.*

| No. | Guide Word | Element | Deviation | Possible Causes | Consequences | Existing Controls | Comments | Actions Required | Action Allocated To |
|---|---|---|---|---|---|---|---|---|---|
| 1 | NO | Material A | No material A supply | Empty tank | Reaction stops | Low-level alarm | Critical failure | Replenish tank | Assigned to [Name] |
| 2 | MORE | Material B | Excess material B | Pump failure | Imbalance | Pump monitor | Monitor closely | Repair pump | Assigned to [Name] |
| 3 | LESS | Reactor Pressure | Pressure too low | Leakage | Incomplete reaction | Pressure alarm | Moderate risk | Seal leaks | Assigned to [Name] |
| 4 | AS WELL AS | Flow to Reactor | Blockage in flow | Blockage in line | No product flow | Flow meter | Routine issue | Clear blockage | Assigned to [Name] |
| 5 | OTHER THAN | Product Quality | Contaminated product | Contamination during processing | Product recall | Quality checks | Requires investigation | Investigate contamination | Assigned to [Name] |
| 6 | REVERSE | Temperature | Temperature too high | Heater malfunction | Overheating | Temperature sensors | Urgent issue | Fix heater | Assigned to [Name] |
| 7 | EARLY | Reactor Output | Output delay | Slow reaction | Delayed output | Output monitoring | Delay management | Increase monitoring | Assigned to [Name] |
| 8 | LATE | Material B Feed | Delayed material feed | Delayed input | Underperformance | Input timing controls | Critical to address | Adjust timing | Assigned to [Name] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 9 | BEFORE | Valve Operation | Valve stuck open | Valve malfunction | Leakage | Valve maintenance | Routine inspection | Replace valve | Assigned to [Name] |
| 10 | AFTER | Sensor Response | Sensor not responding | Wiring issue | No feedback | Sensor calibration | Upgrade needed | Repair wiring | Assigned to [Name] |
| 11 | NO | Material A Feed | Material feed failure | Tank empty | Shutdown | Tank alarms | Check supplies | Refill tank | Assigned to [Name] |
| 12 | MORE | Material B Temperature | Temperature spike | Heater overrun | Damage to product | Heater controls | Emergency controls required | Inspect heater | Assigned to [Name] |
| 13 | LESS | Flow Sensor | Sensor calibration off | Calibration drift | System errors | Regular calibration checks | Routine maintenance needed | Recalibrate sensor | Assigned to [Name] |
| 14 | AS WELL AS | Reactor Contents | Incorrect reactor contents | Operator error | Safety breach | Standard operating procedures | High risk of failure | Retrain operator | Assigned to [Name] |
| 15 | OTHER THAN | Product Release | Premature product release | Pump malfunction | Quality issue | Output release control | Delicate operation | Review pump settings | Assigned to [Name] |
| 16 | EARLY | Product Release | Released too soon | Operator error | Premature delivery | Release monitoring | Critical | Review process | Assigned to [Name] |
| 17 | LATE | Sensor Calibration | Calibration delayed | Sensor fault | Data inaccuracy | Calibration schedules | Moderate risk | Fix sensor | Assigned to [Name] |
| 18 | BEFORE | Heater Control | Heater stopped | Power outage | System shutdown | Backup power | High priority | Restore power | Assigned to [Name] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 19 | AFTER | Tank Level | Tank level dropped | Leakage | Supply failure | Level alarms | Urgent | Seal leaks | Assigned to [Name] |
| 20 | NO | Material B | No material B feed | Empty tank | Reaction stops | Low-level alarm | Critical | Replenish tank | Assigned to [Name] |
| 21 | MORE | Reactor Pressure | Excess pressure | Valve failure | Explosion risk | Pressure alarm | Urgent issue | Replace valve | Assigned to [Name] |
| 22 | LESS | Flow to Reactor | Reduced flow | Pump underperformance | Insufficient reaction | Flow sensors | Monitor closely | Repair pump | Assigned to [Name] |
| 23 | AS WELL AS | Material A | Additional substance present | Contamination | Adverse reaction | Quality checks | Requires investigation | Investigate contamination | Assigned to [Name] |
| 24 | OTHER THAN | Reactor Output | Different product output | Incorrect mixing | Off-spec product | Output monitoring | Routine issue | Check ratios | Assigned to [Name] |
| 25 | REVERSE | Flow to Reactor | Reverse flow | Pump failure | Contamination | Non-return valve | High risk | Inspect pump | Assigned to [Name] |
| 26 | EARLY | Heater Control | Heater activated prematurely | Timing error | Overheating | Automation controls | Critical issue | Recalibrate timing | Assigned to [Name] |
| 27 | LATE | Valve Operation | Valve delayed in closing | Manual operation delay | Overflow risk | Automation system | Monitor closely | Replace manual valve | Assigned to [Name] |
| 28 | BEFORE | Tank Level | Level reading inaccurate | Faulty sensor | Overflow | Sensor calibration | Critical risk | Inspect sensor | Assigned to [Name] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 29 | AFTER | Flow Sensor | Data delay | Communication error | System delay | Redundant system | High priority | Replace wiring | Assigned to [Name] |
| 30 | NO | Temperature | Heater not activated | Power failure | Reaction stops | Backup power system | Urgent | Repair power supply | Assigned to [Name] |
| 31 | MORE | Sensor Calibration | Excessive frequency of calibration | System misalignment | Maintenance delay | Updated schedules | Low priority | Adjust schedule | Assigned to [Name] |
| 32 | LESS | Tank Level | Insufficient level detected | Sensor failure | Misread supply | Backup sensor | Critical | Replace sensor | Assigned to [Name] |
| 33 | AS WELL AS | Reactor Pressure | Excess pressure detected | Sensor miscalibration | False alarm | Routine checks | Routine | Recalibrate sensor | Assigned to [Name] |
| 34 | OTHER THAN | Material B | Different feedstock detected | Supply contamination | Off-spec reaction | Material checks | Critical issue | Inspect source | Assigned to [Name] |
| 35 | REVERSE | Material A | Flow reversed | Pressure imbalance | Contamination | Non-return valve | High priority | Repair piping | Assigned to [Name] |
| 36 | EARLY | Flow Sensor | Sensor activated prematurely | Control error | False alarm | System calibration | Moderate risk | Check timing | Assigned to [Name] |
| 37 | LATE | Material A Feed | Material delayed | Operator error | Reaction delay | Automation controls | Critical issue | Automate feed | Assigned to [Name] |
| 38 | BEFORE | Reactor Output | Output detected prematurely | Operator error | Yield loss | Output monitor | Critical | Train staff | Assigned to [Name] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 39 | AFTER | Product Release | Release delayed | Valve malfunction | Delivery delay | Routine inspection | High risk | Replace valve | Assigned to [Name] |
| 40 | NO | Tank Level | No level detected | Faulty sensor | Overflow risk | Level alarms | Critical | Repair sensor | Assigned to [Name] |
| 41 | MORE | Heater Control | Excess heating | Control error | Overheating | Temperature sensors | High risk | Inspect heater | Assigned to [Name] |
| 42 | LESS | Reactor Contents | Insufficient contents | Valve underperforming | Incomplete reaction | Flow monitoring | Routine | Inspect valve | Assigned to [Name] |
| 43 | AS WELL AS | Product Quality | Unexpected property | Contamination | Product rejection | Routine quality checks | Moderate | Reinspect batch | Assigned to [Name] |
| 44 | OTHER THAN | Sensor Response | Incorrect reading | Wiring fault | Control failure | Routine inspection | Critical | Fix wiring | Assigned to [Name] |
| 45 | REVERSE | Flow to Reactor | Flow reversed | Pump failure | Contamination | Non-return valve | Critical | Inspect pump | Assigned to [Name] |
| 46 | EARLY | Valve Operation | Valve opened prematurely | Timing error | Overflow | Automation controls | Critical | Recalibrate timing | Assigned to [Name] |
| 47 | LATE | Material B Feed | Feed delayed | Blockage | Reaction delay | Flow monitor | High risk | Remove blockage | Assigned to [Name] |
| 48 | BEFORE | Temperature | Heater activated before required | Automation error | Overheating | System calibration | Moderate | Recalibrate heater | Assigned to [Name] |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 49 | AFTER | Reactor Pressure | Pressure detected after reaction | Sensor error | Safety delay | Backup sensor | Critical | Replace sensor | Assigned to [Name] |
| 50 | NO | Product Release | No release detected | Valve malfunction | Delivery halt | Routine inspection | Critical | Repair valve | Assigned to [Name] |

## 4.2 Graph modelling

The first phase of the project was dedicated to graph building. Initially, the subgraph modules had been built individually.

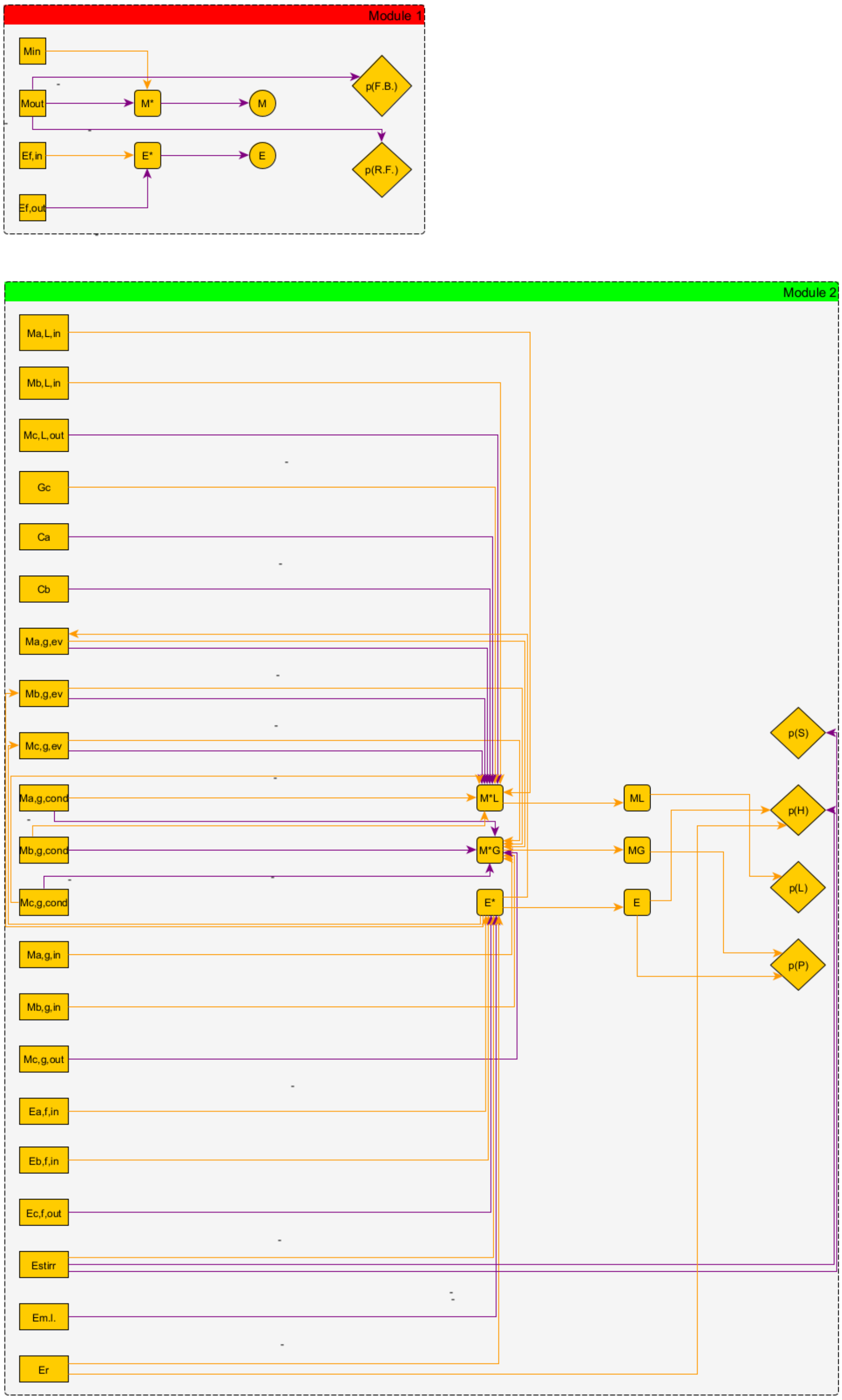


*Figure 52: Graph first build. The two types of modules that will be used in the project are observable. The first from the top will be used as template for both pumps and pipelines, and the second represents the reactor.*

As depicted in Figure 52, the initial graph build lacks component-specific nodes for the accumulation and accumulation derivative, while phase-specific nodes are included solely in the reactor's subgraph. Additionally, since the modules in this initial build serve as templates for future iterations, the node labels do not yet specify the individual unit of operation or module to which they belong.

In the second iteration, two submodules representing the pumps for lines A and B were implemented and connected to the reactor's subgraph. To prevent label duplication and streamline the review process, module-specific references were introduced using a combination of letters and numbers in parentheses. This enhancement not only reduced the risk of misinterpretation but also laid the foundation for future software upgrades that could leverage this feature.

Figure 53 illustrates the results of this second iteration, showcasing the advancements in the graph's structure and functionality.

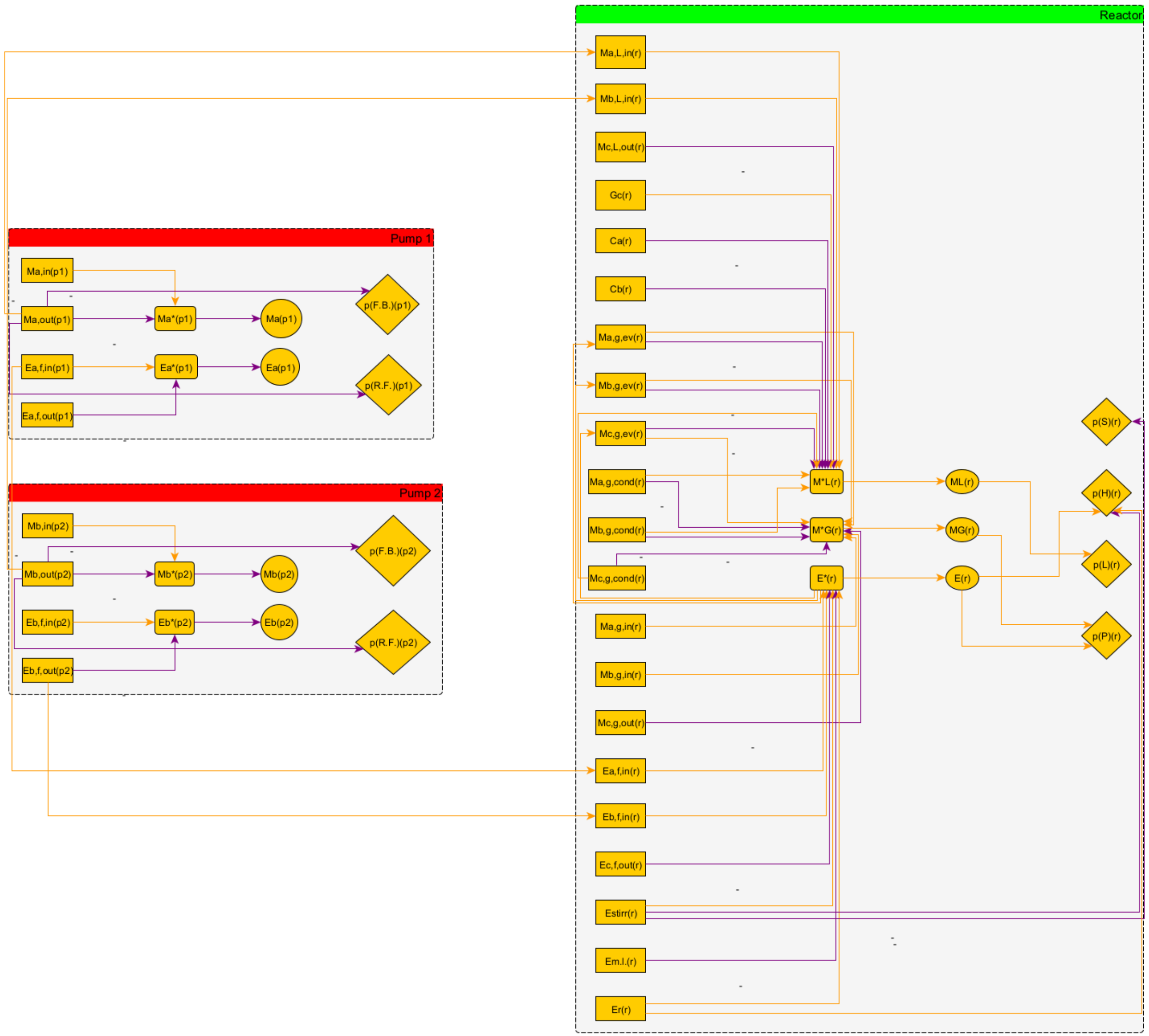


*Figure 53: Second iteration for generating the graph. Submodules have been connected, with node labels now including module-specific references enclosed in parentheses. Pump modules are identified by red labels, while the reactor module is highlighted with a green label.*

For the third and final build, more extensive modifications had been made to the graph. For starters, two additional modules for the two pipelines connecting the pumps and the reactor had been implemented. Additionally, in each module section related to accumulations and accumulation derivatives nodes for component specific accumulation had been added. The last update to the graph structure allowed for the introduction of additional risk nodes, related to product contamination and reduction in yield due to variations in the component ratios.

One, last, improvement to the graph consists in exploiting the "Description" attribute available in the graph builder to attach additional information for each node. This will prove to be very useful in the software implementation of the graph, as said information will be used to provide a clear description of every node involved in the preHAZOP analysis.

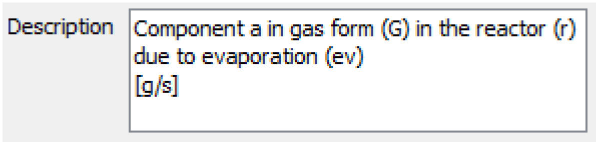


*Figure 54: Example of the "Description" feature available in the graph builder, properly filled with information according to predetermined rules*

As it can be observed from Figure 54, it has been decided that, for every node, a description of the label and the unit of measures will be provided.

Figure 55 shows the last graph iteration of this thesis project:

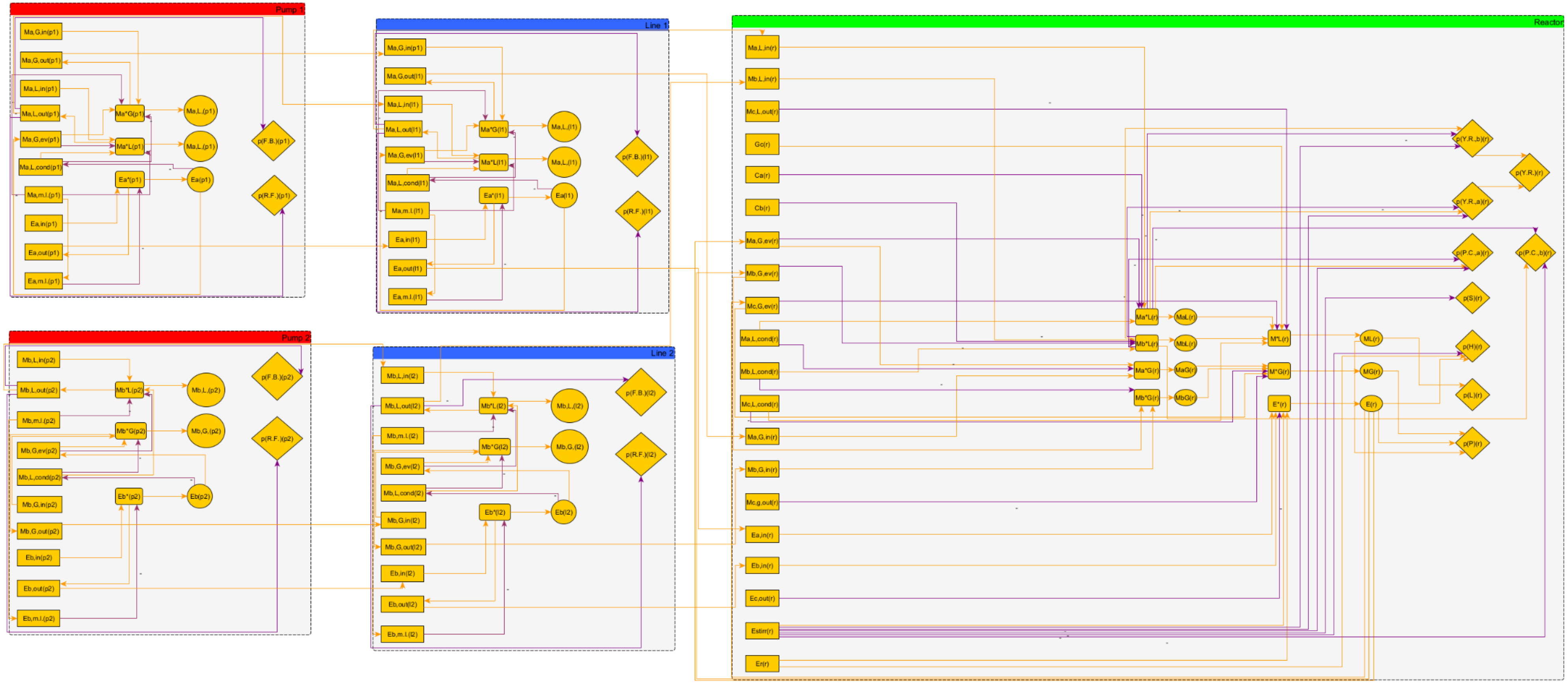


*Figure 55: Graph third and final iteration. Pump modules are marked with red labels, pipeline modules with blue labels, and the reactor module is highlighted in green. Component-specific accumulation and accumulation derivative nodes are visible at the center of each module*

## 4.3 Software implementation

The software code was developed with the assistance of an AI model, emphasizing modularity as a core design principle. The code was divided into distinct chunks, each dedicated to a specific task, which streamlined the development process. This modular approach not only simplified debugging but also reduced the computational load on the machine executing the code, ensuring greater efficiency and maintainability.

### *4.3.1 Data gathering and graph representation*

In the initial code build, the primary focus was on data gathering, specifically importing and extracting information from the graph. The NetworkX library played a crucial role in enabling these operations. However, additional effort was required in prompt engineering to refine the AI-generated code, as the initial version defaulted to assigning shapes instead of accurately retrieving them from the graph's attributes. Another challenge stemmed from shape compatibility: certain shapes used in the graph-building program were not included in the Matplotlib library's database, which was utilized for graphical representation. This issue was addressed by introducing a shape-mapping step immediately after the importing process, showed in Figure 56, ensuring proper integration and visualization.

```
# Map node shapes to Matplotlib node shapes
shape_mapping = {
    "rectangle": "s",          # Square
    "roundrectangle": "h",     # Hexagon (closest to round rectangle)
    "ellipse": "o",            # Circle
    "diamond": "D",            # Diamond
}
```

*Figure 56: Code section dedicated to the shape mapping process. The rectangle with rounded corners has been associated with the hexagon shape from the Matplotlib database*

As an initial step to verify that the data import process was successfully completed, the next section of the code focused on generating a visual representation of the imported graph. A key parameter for this task is the node layout, which is the algorithm used to determine the position of each node in the graph representation. In the first iteration, the Spring layout algorithm was selected, with all other parameters left at their default settings. The results of this first attempt are shown in the following figure:

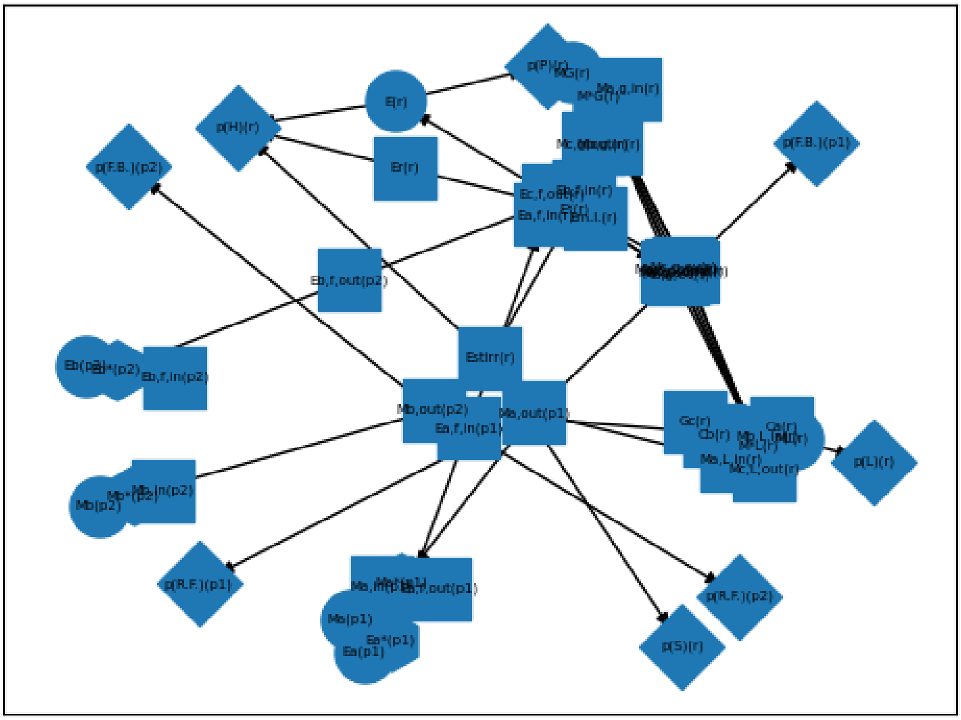


*Figure 57:First attempt of graph representation. Spring layout algorithm with default settings used.*

Results had been deemed unsatisfactory for multiple reasons. First, and most important, a serious case of node overlapping has been identified. Second, the graph occupies only a small portion of the image and third, the node positioning does not clearly represents the paths connecting the nodes.

After adjusting the parameters of the spring layout algorithm, the observed changes in node positioning were found to be consistent, as will be shown in Figure 58.

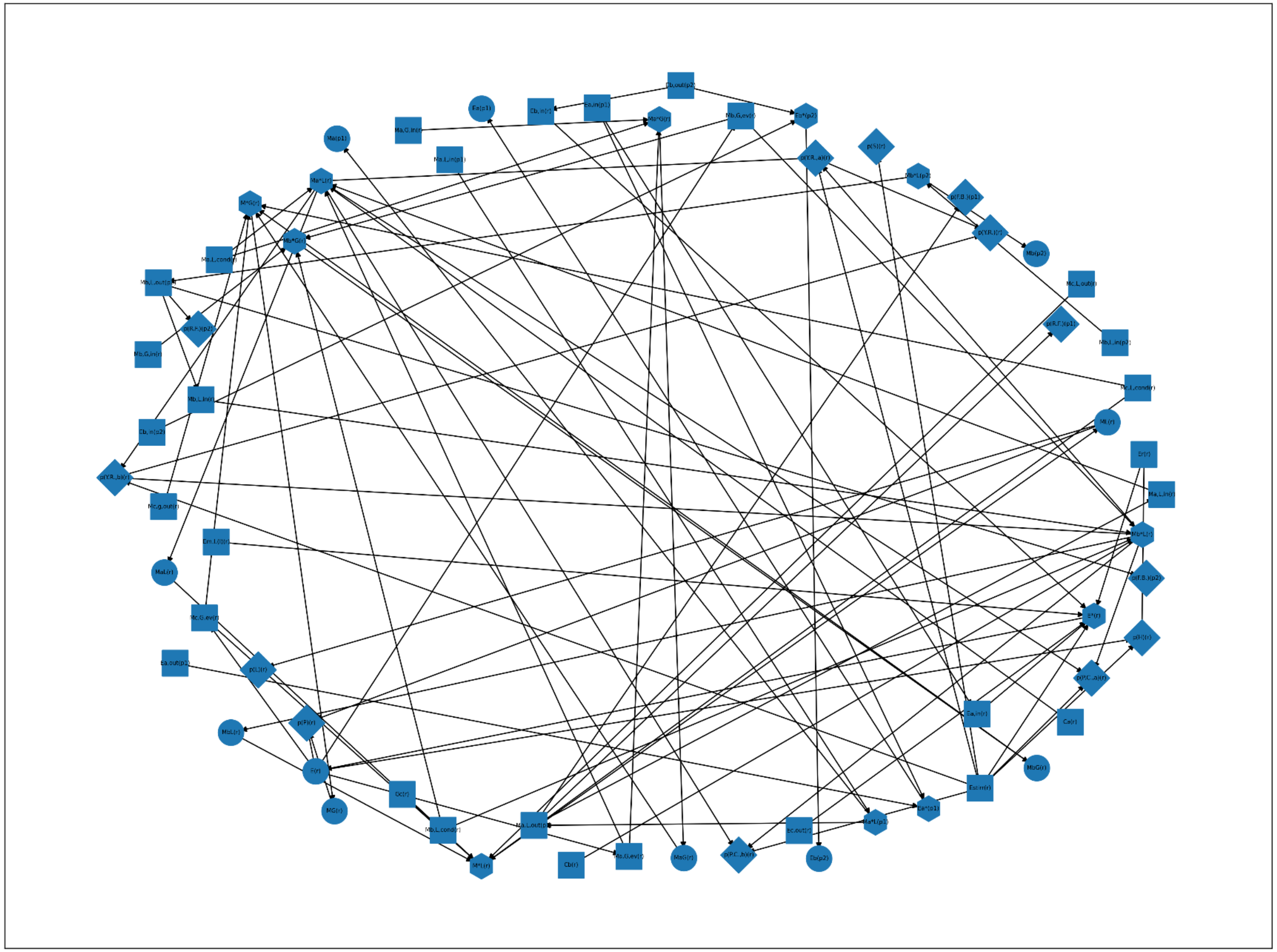

*Figure 58:Second attempt at graph representation. Spring layout algorithm with tweaked settings used.*

Although the overlapping problem has been solved, the image still does not show clearly the paths between nodes. To solve this issue, another algorithm was picked for the task. Specifically, after some try and error the Graphviz's layout, that has to be imported from a separated library, showed satisfactory results, as it is shown in Figure 59. It's worth mentioning that , as for the previous layout algorithm, settings had been tuned to achieve the desired result; in addition to that , additional code had been implemented to show the figure essential information in the image as a title.

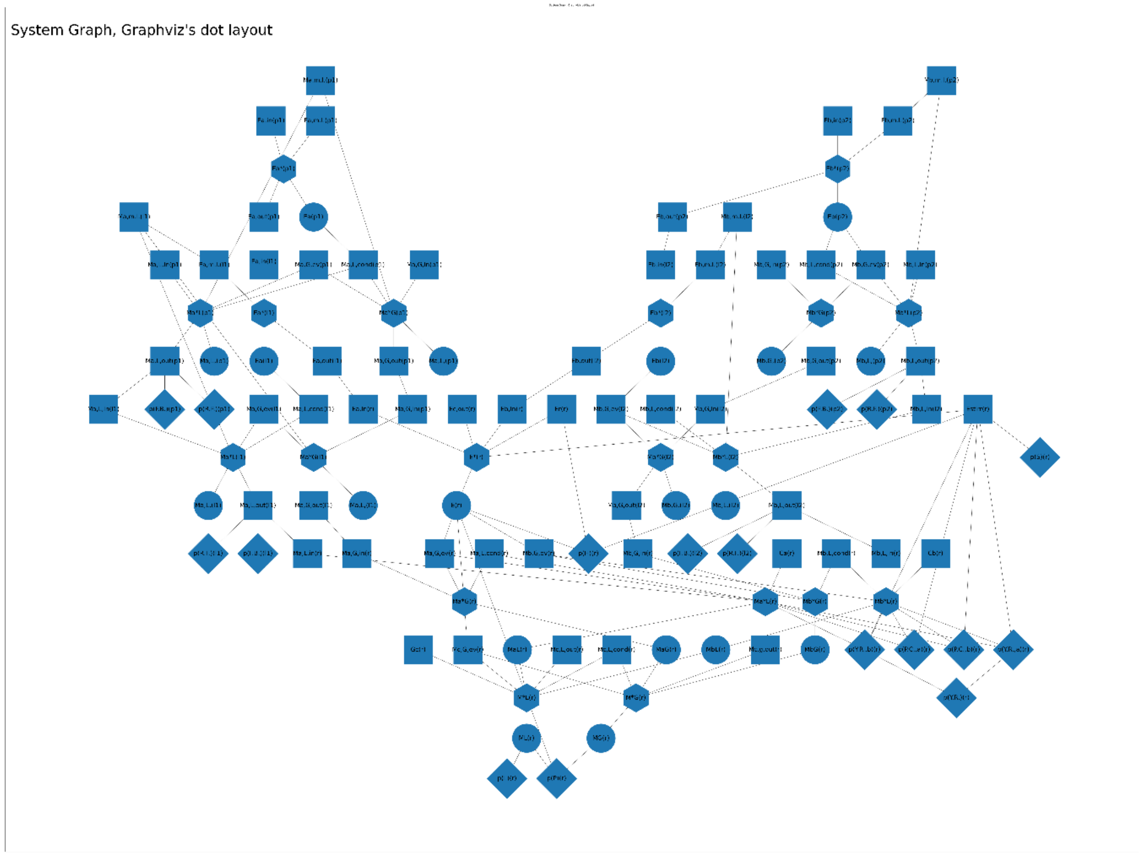


*Figure 59: Third attempt at graph representation. Graphviz's layout algorithm with tweaked settings used*

This part of the code will prove valuable in the final section, serving as the foundation for implementing additional features and enhancing the overall functionality of the tool.

### *4.3.2 preHAZOP table generation*

Two key code modules have been developed for the core functionality. The first generates and stores data for all possible paths starting from each process variable node and reaching all connected downstream risk nodes. The second module uses these paths to systematically calculate all possible scenarios based on the cause-deviation-consequence chain, ensuring comprehensive coverage of potential outcomes.

```
#Graph paths retrieval
paths = []
for n in PV_nodes:
    for p in nx.all_simple_paths(G,source=n,target=Risk_nodes):
        paths.append(p)
print(paths)
```

*Figure 60: Code dedicated to paths retrieval from the graph in the first iteration of the code*

It is important to mention that the path retrieval process, showed in Figure 60, has been coupled from the beginning with additional lines of code that determine the correlation coefficient between the process variable subjected to the deviation and the risk node downstream for every stored path.

```
for p in paths:
    # determine overall correlation coefficient
    d = 1;
    for i in range(1,len(p)):
        if 'label' in G[p[i-1]][p[i]] and G[p[i-1]][p[i]]['label'] == '-':
            d = d * -1

    HT[''.join(p)] = [PV[p[0]], ds[d+1], PV[p[-2]], PV[p[-1]]]
```

*Figure 61: Code chunk dedicated to correlation coefficient determination for every calculated path*

The code leverages the label function in the graph builder for arcs, associating a minus sign with the "low" keyword to indicate an inverse correlation and the absence of a label with the "high" keyword to represent a direct correlation. By means of a simple multiplication by one or minus one for every arc in the path, the final correlation coefficient is calculated and stored, as showed in Figure 61.

After completing the path retrieval, all stored information are used to populate the table.

```
#Pre-HAZOP table generation
ds = ["low", "?", "high"]

HT = {}
PV = nx.get_node_attributes(G,"label")

for p in paths:
    # determine overall correlation coefficient
    d = 1;
    for i in range(1,len(p)):
        if 'label' in G[p[i-1]][p[i]] and G[p[i-1]][p[i]]['label'] == '-':
            d = d * -1

    HT[''.join(p)] = [PV[p[0]], ds[d+1], PV[p[-2]], PV[p[-1]]]

# print(HT)
df = pd.DataFrame([[key] + list(value) for key, value in HT.items()], columns=['ID','PV', 'Keyword', 'Cause', 'Effect']);
print(tabulate(df, headers='keys', tablefmt='psql'))
```

*Figure 62: preHAZOP generation code chunk, first code iteration*

As it is observable from Figure 62, the overall correlation coefficient determination code is embedded in the one for the table generation. All previously obtained data, properly stored in a dataframe, is used to populate the table. Results of the first draft of the code can be seen in the following figure:

| | ID | PV | Keyword | Cause | Effect |
|---|---|---|---|---|---|
| 0 | n1n8 | Mb,out(p2) | low | Mb,out(p2) | p(F.B.)(p2) |
| 1 | n1n9 | Mb,out(p2) | low | Mb,out(p2) | p(R.F.)(p2) |
| 2 | n1n11n32n35n39 | Mb,out(p2) | high | ML(r) | p(L)(r) |
| 3 | n3n26n33n16n32n35n39 | Eb,f,out(p2) | low | ML(r) | p(L)(r) |
| 4 | n3n26n33n16n31n34n40 | Eb,f,out(p2) | high | MG(r) | p(P)(r) |
| 5 | n3n26n33n17n32n35n39 | Eb,f,out(p2) | low | ML(r) | p(L)(r) |
| 6 | n3n26n33n17n31n34n40 | Eb,f,out(p2) | high | MG(r) | p(P)(r) |
| 7 | n3n26n33n18n32n35n39 | Eb,f,out(p2) | low | ML(r) | p(L)(r) |
| 8 | n3n26n33n18n31n34n40 | Eb,f,out(p2) | high | MG(r) | p(P)(r) |
| 9 | n3n26n33n36n38 | Eb,f,out(p2) | high | E(r) | p(H)(r) |
| 10 | n3n26n33n36n40 | Eb,f,out(p2) | high | E(r) | p(P)(r) |

*Figure 63: First ten rows of the preHAZOP table produced by the first code draft. Results are reported in the terminal windows of the code editor.*

Figure 63 displays the populated table generated by the software and shown within the Code Editor terminal. In this initial iteration, the table includes the following elements:

- *Path* (ID): Presented as a sequence of node indices, illustrating the propagation of the deviation.
- *Process Variable* (PV): The label of the process variable subjected to the deviation.
- *Correlation coefficient* (Keyword): The overall correlation coefficient associated with the deviation path.

- *Cause:* The last process variable impacted by the deviation, referred to as the "cause" in this version.
- *Effect*: The associated risk node representing the "effect" or outcome of the deviation.

This table provides a structured summary of the deviation paths and their implications within the system. As an example, scenario number 2 will be considered:

For this scenario, the node sequence n1-n11-n32-n35-n39 in the "ID" column represents the deviation-to-consequence path within the graph. The label of the first node in the sequence (n1) is listed in the "PV" column, as this is where the deviation is hypothesized to originate. The "Keyword" column displays "low," indicating a reverse correlation between the deviation node (n1) and the risk node that concludes the sequence (n39). The final node (n39) and the preceding node (n35) are recorded in the table's last two columns, "Effect" and "Cause," respectively.

After evaluating the results, adjustments were made to the table structure to address identified issues and enhance its usability for the expert review team:

- *Node Descriptions*: It was determined that merely reporting the node label in the table did not provide sufficient context for a thorough review. To address this, an additional column was introduced for every node label column. This new column includes a detailed description of the corresponding node, utilizing the "Description feature" demonstrated in Figure 54. This improvement ensures that the table conveys essential information about each node, enhancing clarity and aiding the expert team in their analysis. A portion of the updated table, containing the first ten rows, is shown Figure 54.

| | ID | PV | PV description |
|---|---|---|---|
| 0 | n0n4n1n8 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 1 | n0n4n1n9 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 2 | n0n4n1n89n93n90n97 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 3 | n0n4n1n89n93n90n98 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 4 | n0n4n1n89n93n90n24n54n56n45n48n52 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 5 | n0n4n1n89n93n90n24n54n56n45n48n53 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 6 | n0n4n1n89n93n90n24n54n63 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 7 | n0n4n1n89n93n90n24n54n63n66 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 8 | n0n4n1n89n93n90n24n54n65 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 9 | n0n4n1n89n93n90n24n54n65n66 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |
| 10 | n0n4n1n89n93n90n24n54n62 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] |

*Figure 64: Portion of the improved table, showing the first ten rows with an additional description column for the process variable nodes subjected to deviation.*

- *Renaming and Expanding the "Cause" Column*: The original "Cause" column title created potential confusion, as the term was already used in the project to refer to the possible source of a deviation. To resolve this, the column was renamed "Last PV before effect" to indicate its purpose clearly, with an accompanying "Last PV description" column providing detailed node information. Additionally, two new columns were introduced to display the actual potential causes of the deviation.
- *Coding Challenges for Cause Identification*: Implementing the feature for identifying and displaying possible causes proved to be the most complex coding challenge. Initially, the AI model tasked with writing the code attempted to reverse the graph to calculate new downstream paths to the accumulation nodes, designated as indicators of possible deviation sources. However, this approach was deemed ineffective. Reversing the graph altered the indices of all nodes, leading to errors in the table generation process.

The resulting table, as shown in Figure 65 highlights the shortcomings of the reversed graph approach. This method proved to be ineffective because reversing the graph altered the indices of all nodes, leading to inconsistencies and errors in the table generation process.

```
+--------------+-------------------------------------------------------------------------------
| Cause        | Cause description
+--------------+-------------------------------------------------------------------------------
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)
|              | [g/s]
| Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)
|              | [g/s]
| Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)
|              | [g/s]
| Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1)
|              | [g/s]
| ML(r)        | Liquid (L) overall accumulation in the reactor (r)
|              | [g/s]
| ML(r)        | Liquid (L) overall accumulation in the reactor (r)
|              | [g/s]
| Ma*L(r)      | Derivative (*) of liquid (L) accumulation of component a in the reactor (r)
|              | [g/(s^2)]
| p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r)
|              |
| Ma*L(r)      | Derivative (*) of liquid (L) accumulation of component a in the reactor (r)
|              | [g/(s^2)]
| p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r)
|              |
| Ma*L(r)      | Derivative (*) of liquid (L) accumulation of component a in the reactor (r)
|              | [g/(s^2)]

|              | [g/s]
| MG(r)        | Gas (G) overall accumulation in the reactor (r)
|              | [g/s]
+--------------+-------------------------------------------------------------------------------
```

*Figure 65: Illustration of the resulting table from the reversed graph approach, demonstrating the errors caused by the altered node indices.*

To illustrate this point, consider the first four rows of the table, where the nodes listed in the "Cause" column include two process variable nodes: one from the pump and one from the pipeline in Component A's transfer line. In the original, non-reversed graph, these nodes are indexed as n1 and n90. However, after the software inverts the graph, these indices now correspond to two accumulation nodes that the software is programmed to identify. While the software correctly stores these indices and attempts to retrieve the required attributes, it performs this action on the non-reversed graph. As a result, the attributes retrieved and subsequently used in the table are incorrect, resulting in inconsistencies in the reported data.
After providing clearer context, the A.I. model successfully implemented code lines to track all possible accumulation nodes upstream for each process variable subjected to deviation and store the data accurately.

| Cause | Cause description |
|---|---|
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Not Found | No accumulation nodes identified as sources |
| Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] |

*Figure 66: Portion of the improved table, showing the new "Cause" and "Cause description" column implemented*

Figure 66 shows the results of the updated code and highlights an essential addition: if no accumulation node is identified upstream, the software automatically inserts a placeholder string in its place and in the corresponding description column.

### 4.3.3 Data and results manipulation

After completing the coding part related to the preHAZOP table generation, the focus shifted on results manipulation. This section was added to better fit the automated HAZOP results for confrontation and as a way to facilitate the manual review of them.

The first modification was related to results filtering: As already mentioned, the HAZOP analysis extent of the BSI table only covers the transfer line of material A to the reactor. Because of that, in order to facilitate the comparison between the two approaches, a chunk of code dedicated to deviation filtering has been implemented.

Specifically, it has been decided to filter out all deviations not related to the module p1, the one related to the pump for the component A transfer line to the reactor.

```
filtered_df = df[df['PV'].str.contains(r'\(p1\)', na=False)]

# Reset the index of the filtered DataFrame and start numbering from 1
filtered_df = filtered_df.reset_index(drop=True)
filtered_df.index = filtered_df.index + 1  # Start numbering from 1

# Print the filtered table with row numbering
print("\nFiltered table, only p1 considered")
print(tabulate(filtered_df, headers='keys', tablefmt='psql'))
```

*Figure 67: Code section related to results filtering. The first line executes the filtering following the parameters contained inside the purple parenthesis. The remaining lines are for dataframe visual tuning and printing the output on the code editor terminal.*

Figure 67 shows how such result had been achieved: the node label part between parenthesis, meant to indicate to which module the node belongs to had been exploited to isolate the nodes belonging to the module of interest. The filtering is applied to the dataframe containing all the results for the full preHAZOP table and stored to a separated one. After writing a line for resetting the index numbering for the table rows the following code instructs the program to show the output in the terminal window of the code editor.

In addition to that, for the sake of an easier result visualization, the following code chunks contain code lines to export both the full table and the filtered one in the .xlsx Excel format.

```python
# Save the table to an Excel file
output_file = "Pre_HAZOP_table_full.xlsx"
with pd.ExcelWriter(output_file, engine='openpyxl') as writer:
    df.to_excel(writer, index=False, startrow=1, startcol=1)  # Start from cell B2 (row 2, column 2)

# Open the saved Excel file for formatting
wb = load_workbook(output_file)
ws = wb.active

# Set the column width to auto-adjust based on the content
for col in ws.columns:
    max_length = 0
    column = col[0].column_letter  # Get the column letter
    for cell in col:
        if cell.value:
            max_length = max(max_length, len(str(cell.value)))
    ws.column_dimensions[column].width = max_length + 2  # Add extra space for readability

# Define border styles
thin_border = Border(
    left=Side(style='thin'), right=Side(style='thin'),
    top=Side(style='thin'), bottom=Side(style='thin')
)
thick_border = Border(
    left=Side(style='thick'), right=Side(style='thick'),
    top=Side(style='thick'), bottom=Side(style='thick')
)

# Apply thin borders to the entire table
for row in ws.iter_rows(min_row=2, min_col=2, max_row=ws.max_row, max_col=ws.max_column):
    for cell in row:
        cell.border = thin_border

# Apply thick border to the outside of the first row (headers)
for cell in ws[2]:  # Header is now in the second row
    cell.border = thick_border

# Save the changes to the Excel file
wb.save(output_file)

print(f"Table saved with formatting as '{output_file}'")
```

*Figure 68: One of the code chunks containing instructions for data exporting. This specific chunk is for exporting the full preHAZOP table.*

Figure 68 demonstrates an example of the aforementioned code sections. This specific block of code is responsible for exporting the complete HAZOP table into an Excel format. As illustrated, additional lines of code were included to customize the exported table, enhancing the visualization and readability of the results.

The final feature implemented in this section, and the overall code, focused on image manipulation. Building upon the graph representation using the Graphviz layout algorithm, the code groups results from the filtered dataframe by their shared value in the "PV" column (representing scenarios with the same deviation). Once the grouping is completed and data is organized, the software is programmed to generate three images for each group: one highlighting all downstream paths, one showing only upstream paths, and a third combining both. Examples of these visualizations are provided in Figure 69, Figure 70 and Figure 71.

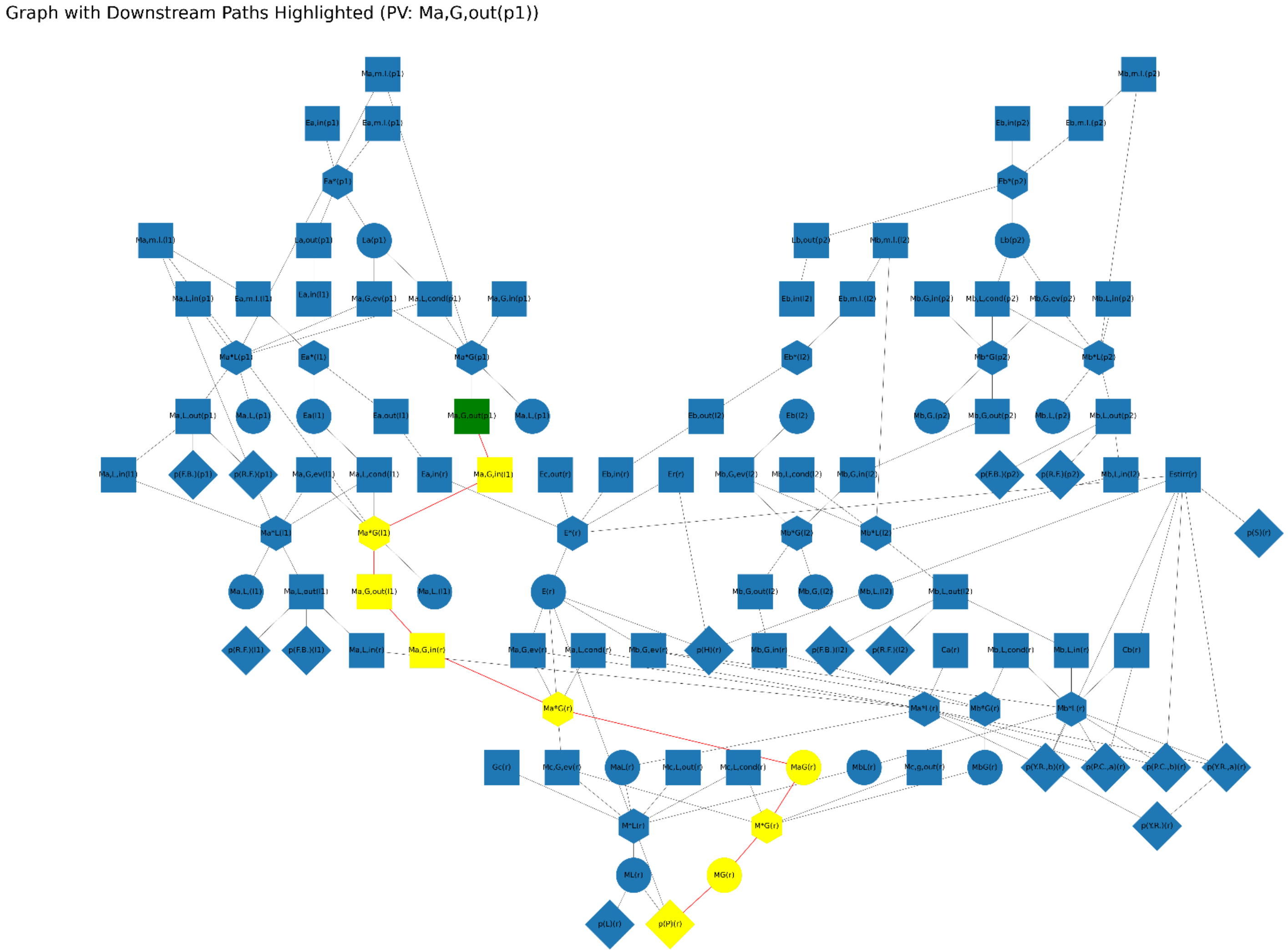


*Figure 69: Modified graph representation illustrating the downstream paths for the process variable corresponding to the exiting flow of component A in gas form from the pump. The process variable node subjected to deviation is highlighted in green, while the nodes within the paths of interest are marked in yellow. The connecting arcs between these nodes are emphasized in red.*

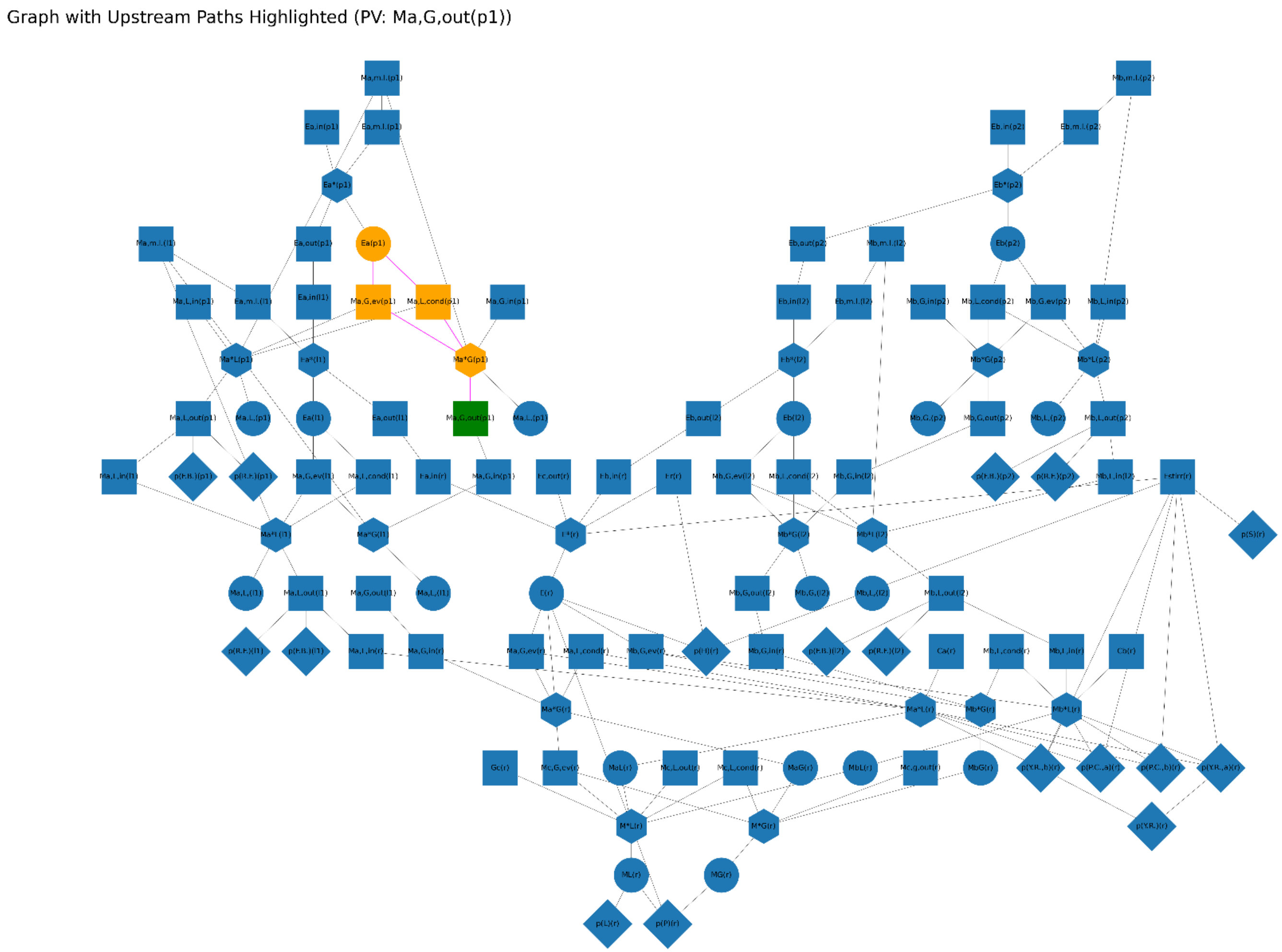


*Figure 70: Modified graph representation illustrating the upstream paths for the process variable corresponding to the exiting flow of component A in gas form from the pump. The process variable node subjected to deviation is highlighted in green, while the nodes within the paths of interest are marked in orange. The connecting arcs between these nodes are emphasized in purple.*

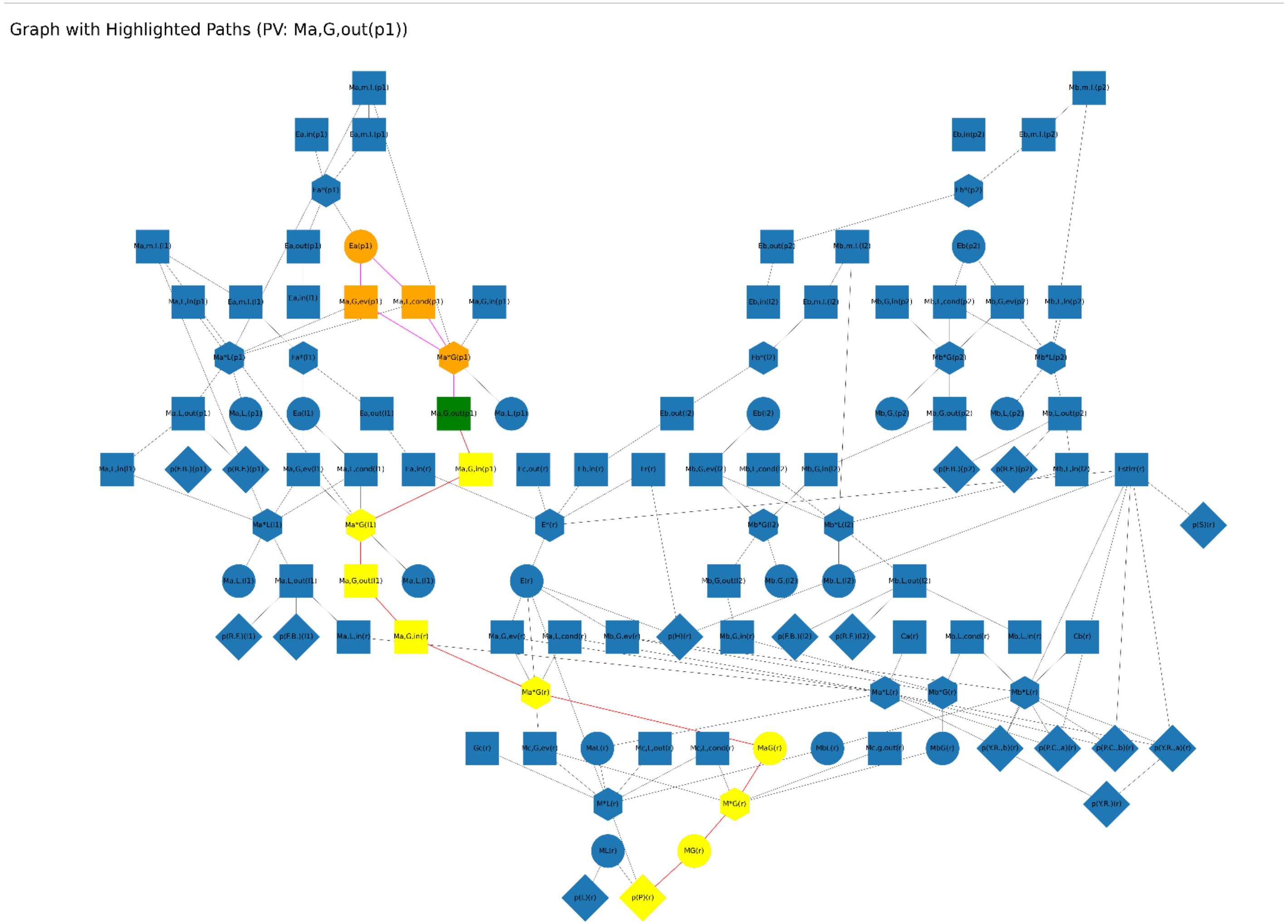


*Figure 71: Modified graph representation displaying both downstream and upstream paths for the process variable corresponding to the exiting flow of component A in gas form from the pump. The coloring schemes are consistent with the previous images, with the process variable node subjected to deviation highlighted in green, downstream nodes and arcs in yellow and red, and upstream nodes and arcs in orange and purple.*

Figure 69, Figure 70, and Figure 71 illustrate three examples of modified images for the same process variable: the exiting flow of component A in gas form from the pump in the transfer line. Adjustments to the code were necessary to achieve proper node highlighting, as the highlighting process involved overlaying a colored node on top of the original. To ensure accurate representation, it was essential to specify the shape and size of the overlaying node. Fortunately, since the shape attribute for each node had already been stored during the initial data gathering process, these updates were implemented seamlessly.

The graph in Figure 69 illustrates the propagation of a deviation starting from the process variable node highlighted in green and labeled "Ma,G,out(p1)". This node represents the gas outflow of Component A from the pump and serves as the starting point for the downstream paths considered in this example. The propagation of the deviation from this starting node is shown by highlighted paths that connect to various downstream nodes.

Each yellow-highlighted node represents a significant point along the deviation propagation path, ultimately leading to potential risk or accumulation nodes. The red arcs between these nodes trace the exact connections in the graph, making the deviation path visually intuitive. For example, starting from "Ma,G,out(p1)", the deviation propagates first to Ma,G,in(l1), and from there to Ma*G(l1), ultimately resulting in the risk node(s) at the end of the path.

This visual representation helps the reader understand how deviations propagate through the system, linking process variables to potential consequences. The green node marks the origin of the deviation, while the yellow nodes indicate critical nodes or endpoints affected by the deviation. This clear mapping of deviation paths underscores the value of the algorithm in systematically identifying all possible propagation scenarios and visualizing them for HAZOP analysis.

The highlighted arcs, selected based on their connection to two highlighted nodes, further enhance clarity by focusing only on the relevant relationships that are critical to the propagation of the deviation. This approach provides an accurate and actionable understanding of how risks could evolve from a single deviation within the system.

## 4.4 Selected approach for table comparison

After carefully assessing the available approaches described in section 3.1, the de-clustering of the table results provided by the British Standards Institution (BSI) was identified as the most suitable method. This approach offered simplicity in implementation while enabling more consistent comparisons of the differences (Δ) between the generated results.

Although the AI model demonstrated the capability to perform both clustering and de-clustering with similar levels of prompt engineering, clustering presented additional challenges in terms of software compatibility. Specifically, the presence of multiple elements within a single cell—especially when these elements included text in the form of statements or acronyms with punctuation, as in this case study—complicated the process and hindered the generation of consistent results.

## 4.5 First comparison results

From the outset, a notable difference in the number of results emerged, even after applying de-clustering and deviation filtering.

Specifically, the de-clustered BSI table contains twenty-eight rows, whereas the filtered algorithm-generated table produces more than three hundred. This stark contrast highlights a significant divergence in the level of detail captured by the two approaches.

In terms of system details and deviations, the algorithm-generated table lacks certain key elements present in the BSI table. For instance, it does not provide information about actions that may be required to address deviations, additional comments on hypothetical scenarios, or, in its initial iteration, possible causes for the deviations.

This discrepancy between the two tables prompted a thorough investigation into potential errors and inconsistencies in both approaches to better understand the root of the differences.

### *4.5.1 Algorithm-produced table analysis*

A detailed analysis of the table generated by the Python algorithm was conducted to identify key features present in the BSI EN 16882:2016 standard HAZOP table that were absent in the algorithm-generated version. The primary limitation identified was the lack of a dedicated column for reporting potential causes of deviations—a critical element in the BSI standard. Addressing this gap became a priority to enhance the completeness and quality of the algorithm's output by ensuring all essential information, such as possible causes, was adequately documented.

To resolve this issue, the Python code was updated to include new functionality for capturing and storing potential causes of deviations. Additional lines of code were implemented to trace all possible paths from each process variable node to upstream nodes. These paths were then stored in arrays and integrated into the data frame used to construct the table, ensuring potential causes of variations are now clearly represented.

Given the significant volume of results initially produced by the algorithm, refining the scope of causal analysis became essential to prevent information overload. Initially, the algorithm considered all potential causes prior to each anomaly, which resulted in a large and unwieldy dataset. To streamline the analysis and focus on the most relevant data, the algorithm was adjusted to prioritize specific points in the system where material or energy accumulates. By concentrating on these critical areas, the algorithm narrowed down the likely sources of variation, providing a more concise and manageable dataset while maintaining accuracy and depth of analysis.

An example of the results after implementing these modifications is shown in Table 13.

*Table 13:Example of the Algorithm-Produced preHAZOP Table After Modification. This table showcases an updated version of the algorithm-generated preHAZOP table following the inclusion of modifications to capture potential causes. For clarity and enhanced visualization, some columns irrelevant to the explanation have been omitted.*

| ID | PV | PV description | Cause | Cause description |
|---|---|---|---|---|
| node1node8 | Process variable | Process variable description (label of the node representing the unit of operation associated with the process variable) [Units of measure] | Possible cause | Possible cause description (label of the node representing the unit of operation associated with the process variable) [Units of measure] |
| node0node4node1node8 | Process variable | Process variable description (label of the node representing the unit of operation associated with the process variable) [Units of measure] | Not Found | No accumulation nodes identified as sources |

Two rows were selected to illustrate the possible outcomes of the path retrieval operation:

- Successful Path Retrieval: When the operation succeeds, the accumulation node and its description are correctly identified and stored, populating the relevant columns in the preHAZOP table with accurate information.
- Unsuccessful Path Retrieval: If no accumulation node is found upstream, predefined placeholder text is used to populate the columns. This ensures software compatibility and prevents errors caused by empty cells.

This refined and comprehensive approach enhances practical efficiency, minimizing the time and effort required during the review process. By streamlining the analysis, it reduces repetitive tasks for the human assessment team and ensures consistency across the results.

## 4.6 Second comparison

Following the implementation of the modifications, a second comparison was conducted, and the delta recalculated (Figure 16). The number of results remained unchanged, with the algorithm-produced table still generating hundreds more potential scenarios than the BSI table. Regarding the level of detail and types of information provided, the BSI table includes additional columns not present in the algorithm-produced version. These columns cover aspects such as existing system controls, comments on identified scenarios, actions required to address deviations, and the team member responsible for each specific table entry. These elements remain absent in the algorithm-produced table, highlighting key areas where further development could align the automated results more closely with traditional HAZOP outputs.

*Table 14: Comparative Analysis of the BSI and Algorithm-Generated Tables. A summary of the differences between the traditional HAZOP table from the BSI standard and the algorithm-generated table after modifications. Key aspects compared include the number of results and the inclusion of columns for system controls, scenario comments, required actions, and responsible team members*

| | **Number of results** | **Information reported with the deviation** |
|---|---|---|
| *BSI original HAZOP table* | **28** identified output rows | Guideword<br>Element involved<br>Deviation<br>Possible cause<br>Consequence<br>Existing control<br>Comment<br>Actions required<br>Action allocated to |
| PreHAZOP table produced by the algorithm | **1275** identified output rows | Specific path in the graph<br>Process variable subjected to deviation<br>Description of process variable subjected to deviation<br>Keyword<br>Possible cause<br>Description of possible cause<br>Last downstream process variable influenced by the deviation.<br>Description of the last process variable influenced by the deviation<br>Possible consequence of the deviation<br>Description of the possible deviation consequence |

After careful consideration, it was determined that only the “Comments” and “Action Required” columns are relevant for the comparison. Since this thesis project focuses on the preHAZOP analysis stage, the presence or absence of control systems is not significant, as such analysis is typically conducted during the early stages of design, when detailed information about controls is often unavailable. Additionally, the "Responsible Team Member" column is not relevant in this context, as the algorithm-generated table assigns responsibility for all outputs to the software itself, rendering this information unnecessary.

*Table 15: Four Example Rows from the Algorithm-Produced preHAZOP Table.*

| No. | ID | PV | PV Description | Keyword | Cause | Cause Description | Last PV Before Effect | Last PV Description | Effect | Effect Description |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | n0n4n1n8 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 2 | n0n4n1n9 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 3 | n0n4n1n89n93n90n97 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 4 | n0n4n1n89n93n90n98 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |

All four rows have $M_{a,L,in}(p1)$ as the hypothetical deviation, so Figure 72 can be used to better understand the paths reported in the "ID" column.

More in detail, row no. 1 outlines the propagation of the deviation leading to the risk node $P(F.B.)(p1)$, which represents the risk of flow blockage in the transfer line pump for pure component A. The analysis reveals no upstream accumulation nodes associated with this path, and the combination of keywords yields "low," indicating an inverse correlation between the process variable node and the risk node. This means that as the input flow to the pump decreases, the likelihood of a flow blockage increases. In addition, the "Last PV before effect" column highlights $M_{a,L,out}(p1)$ (the flow exiting the pump) as the last process variable affected by the initial deviation, providing additional clarity on the relationship between the deviation and the identified risk.

For the remaining rows, they all share the same "Last PV before Effect" process variable, and no accumulation nodes have been identified as potential sources for any of the scenarios. In each case, the resulting keyword is "low", indicating an inverse correlation between the deviation and the associated risk node. The risk nodes shown are $p(R.F.)(p1)$, $p(F.B.)(l1)$, and $p(R.F.)(l1)$, corresponding to the probability of reverse flow in the pump, the probability of flow blockage, and the reverse flow in the pipeline for the transfer of Component A to the reactor, respectively.

Compared to the BSI table, the algorithm-generated table compensates for the lack of "Comments" and "Action Required" columns by providing a more precise and scientifically based description of the cause-deviation-consequence chain. In addition, the integration of the phenomenological approach into the software significantly increases the number of identified outcomes, demonstrating the enhanced comprehensiveness of the automated methodology.

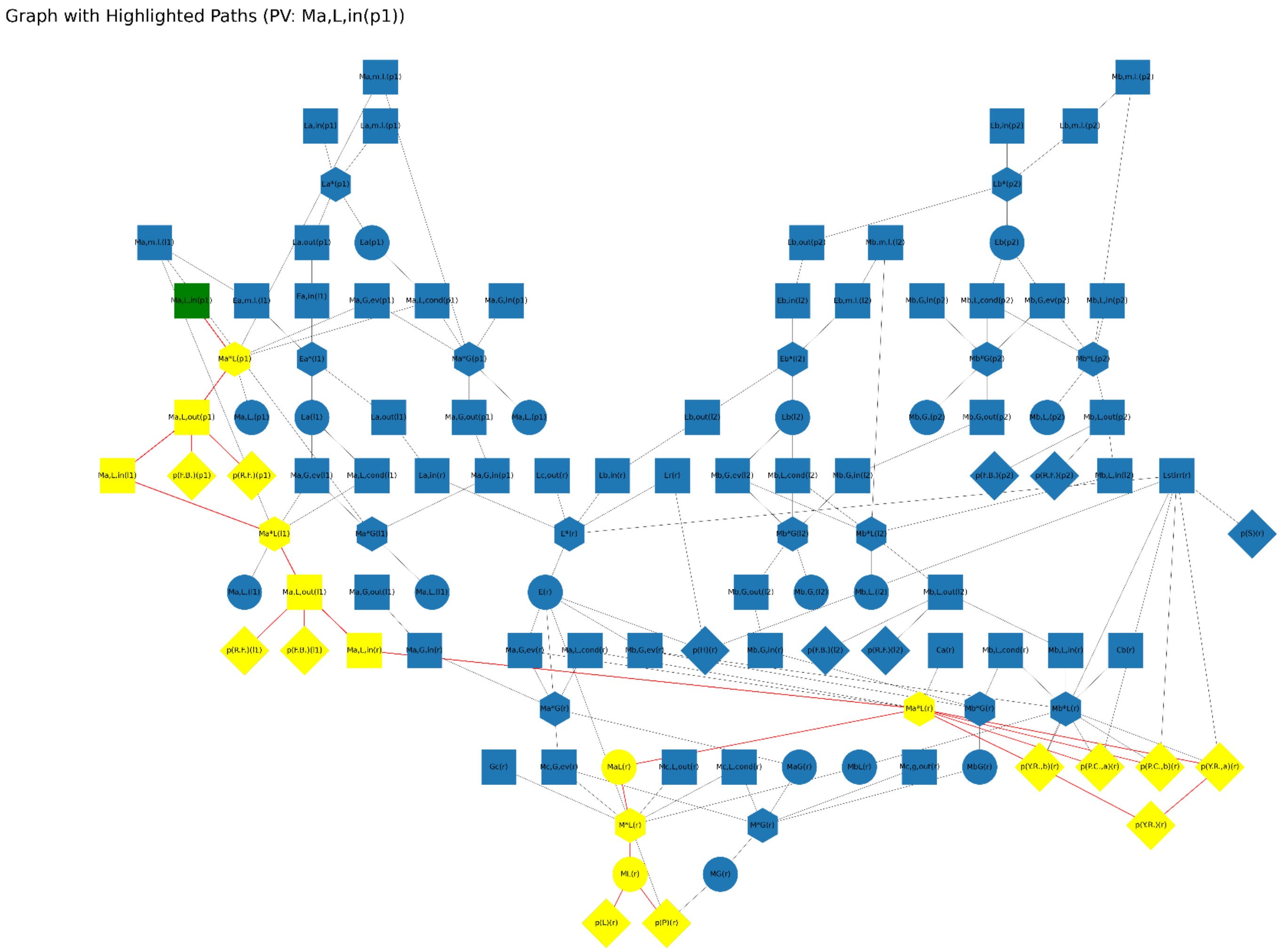


*Figure 72: Graph representation of the cause-deviationi-consequence chain for the Process variable Ma,L,in(p1), the massive flow of pure component A entering the pump in the transfer line to the reactor of component A. The process variable node has been highlighted in green, the other nodes of the paths are highlighted in yellow and the arcs connecting them in red*

## 4.7 Algorithm performances evaluation

As a final section of the results chapter, this paragraph is dedicated to evaluating the algorithm developed during the course of this thesis project. It also provides a detailed description of its functionality and highlights the advantages brought by incorporating the phenomenological approach into HAZOP analysis.

As emphasized in earlier sections, the algorithm demonstrates the capability to identify a significantly larger number of scenarios compared to traditional methods. This improvement stems from the combination of a phenomenological approach, which focuses on the fundamental behaviors and interactions within the system, and the efficiency provided by automation through software implementation.

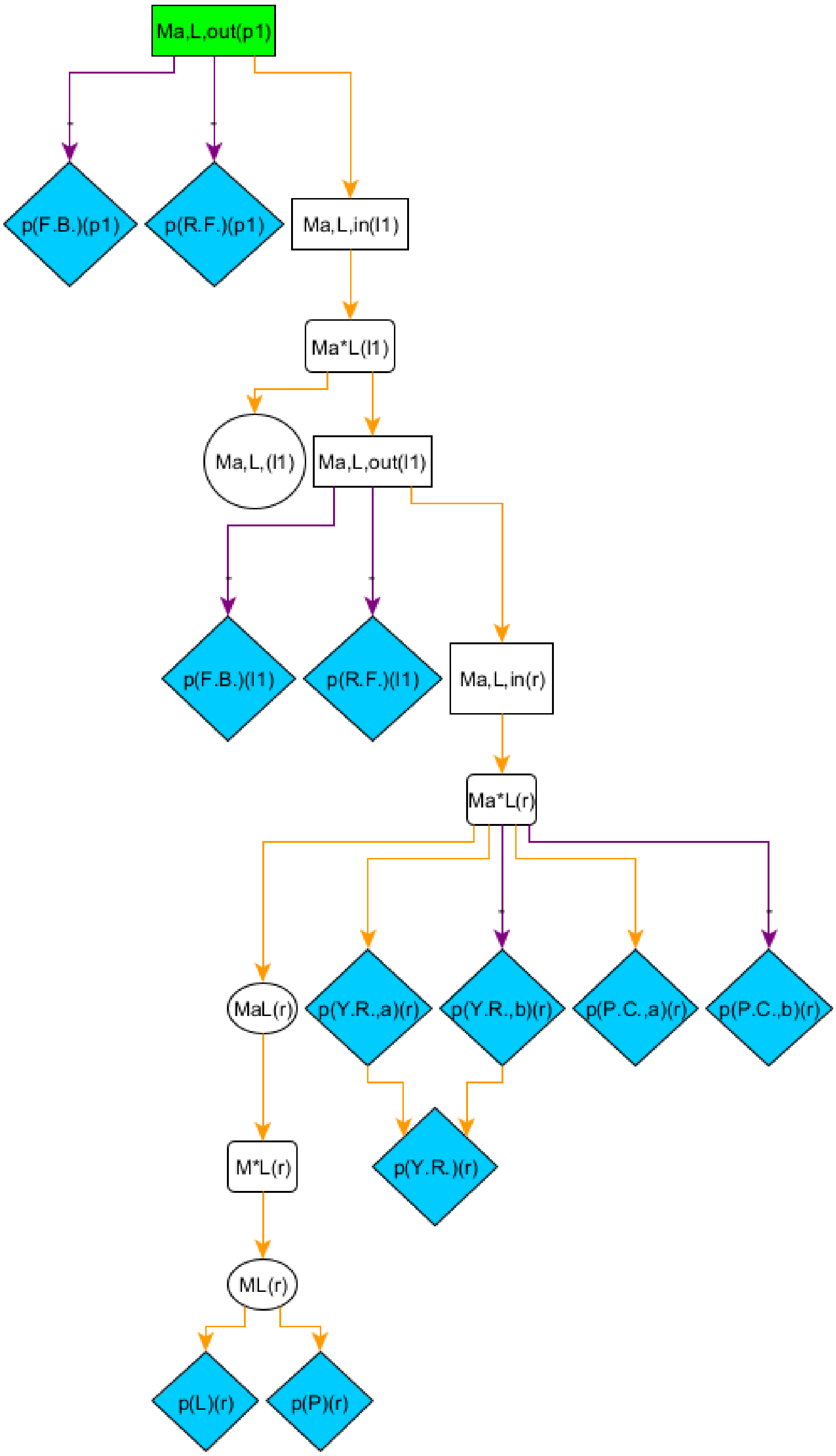


*Figure 73: Illustration of the algorithm's capability to trace every possible consequence (cyan) originating from every relevant process variable node (green).*

As shown in Figure 73, the phenomenological approach, implemented through a graph-based structure, ensures that each process variable is scientifically related to all potential consequences, which is a major advantage of the automated HAZOP method over traditional approaches. For example, starting from the process variable node Ma,L,out(p1), which represents the output flow of pump 1 for pure component A, the arcs of the graph allow direct connections to the cyan-colored risk nodes to be easily identified by both the software and the expert team. In addition, as the algorithm analyzes the other paths, it follows downstream connections through the modules of the graph, reaching additional risk nodes while evaluating the final correlation coefficient for each path. By systematically calculating and documenting every possible cause and effect for each process variable node, the automated system identifies significantly more scenarios than a human team typically uncovers during a traditional analysis. This capability minimizes the risk of overlooking potentially hazardous scenarios and ensures a more complete and detailed evaluation of system risks, thereby increasing the overall reliability and thoroughness of the analysis.

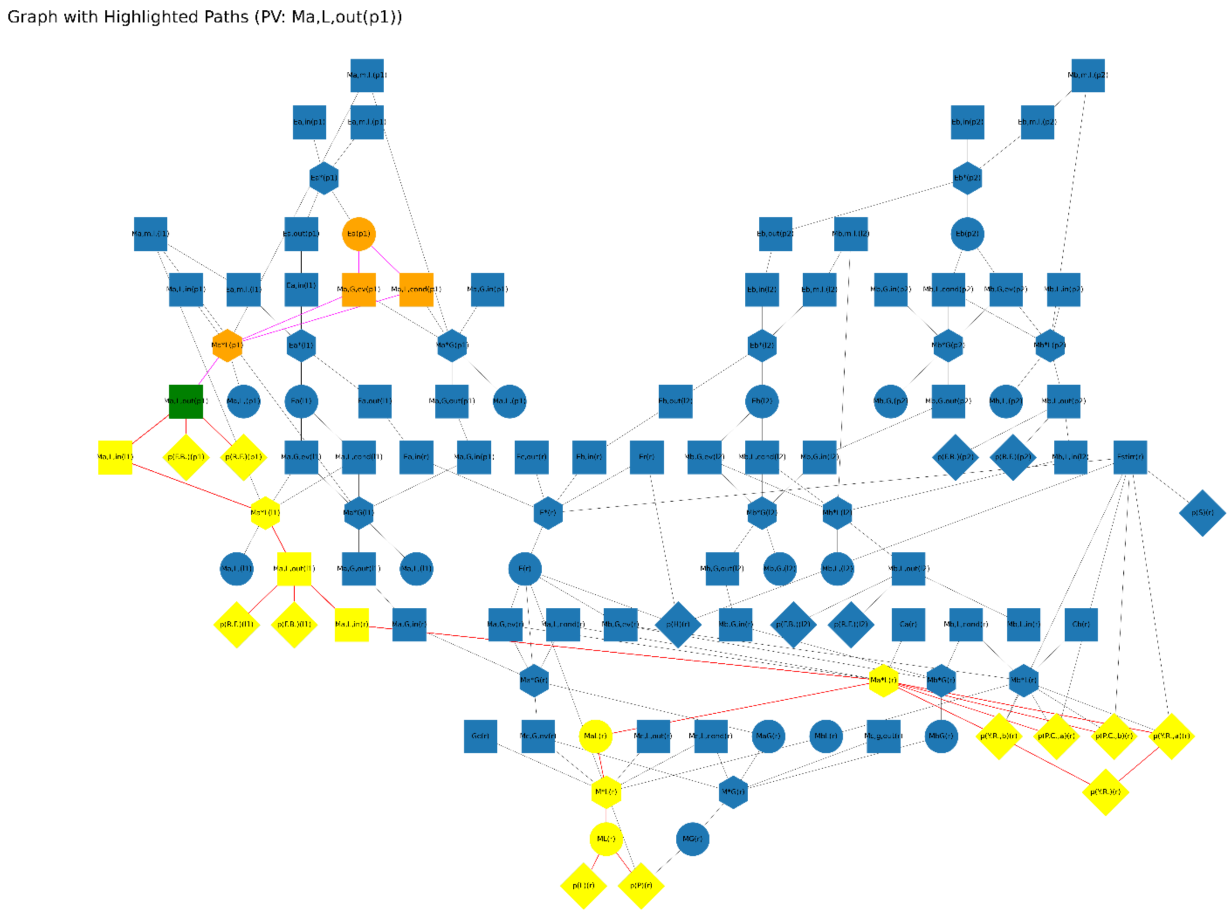


*Figure 74: Cause-Deviation-Consequence chain generated by the algorithm and visualized through the software in graphical form. Nodes representing causes, deviations, and consequences are distinctly highlighted, offering a clear depiction of the propagation paths within the system.*

Additionally, the algorithm employs the same scientific principles to trace potential sources for each deviation, starting from the process variable node where it occurs. This capability allows for a precise and thorough evaluation of the complete cause-deviation-consequence chain, providing a level of depth and rigor in hazard analysis that surpasses traditional methods.

Figure 74 illustrates this methodology in practice. Starting from the same node as in Figure 73, the paths to the risk nodes are represented by the yellow-highlighted nodes connected by red-colored arcs. Additionally, orange-colored nodes connected by light purple arcs are included in the graph. These nodes represent upstream accumulation nodes that the algorithm tracks to identify potential causes for the deviation under consideration. In this specific instance, starting from the node Ma,L,out(p1), which corresponds to the mass flow exiting the pump module, the algorithm identifies the upstream accumulation node Ea(p1), associated with energy accumulation within the same module.

The developed algorithm has proven to be a highly effective support tool for HAZOP analysis, but its performance heavily depends on the quality of the system's digital twin. A detailed digital twin is essential, particularly in terms of capturing a comprehensive set of process variables. These variables serve as the foundational data for the algorithm to generate scenarios. A more detailed representation minimizes the risk of overlooking scenarios, ensuring a thorough and reliable analysis. Conversely, a lack of detail in the digital twin can result in significant analytical gaps. Without adequate information about process variables and the physical phenomena they represent, the algorithm cannot fully explore the potential cause-deviation-consequence chains inherent in the system.

For instance, during the graph development process, the absence of component-specific nodes initially prevented the algorithm from addressing critical scenarios such as product contamination or yield reduction. These scenarios were omitted because the algorithm lacked the necessary data to incorporate them, underscoring the importance of a robust and detailed digital twin to enhance the algorithm's effectiveness.

While the algorithm offers considerable advantages, human expertise remains indispensable in the process. Experts are essential for verifying the completeness of the digital twin and reviewing the algorithm’s outputs. Their knowledge ensures the accuracy and reliability of the HAZOP analysis by identifying and addressing any gaps that may arise due to limitations in the digital representation of the system. This collaborative approach between automation and expert oversight maximizes the robustness of the hazard analysis

# Chapter 5: Conclusions

The increasing complexity of modern process industries has highlighted the critical need for efficient, reliable, and early-stage hazard identification methods. While traditional Hazard and Operability (HAZOP) analyses remain a cornerstone of process risk assessment, they are often time-intensive and labor-intensive, particularly for large-scale systems. In response to these challenges, recent research has focused on the automation of HAZOP analyses to improve efficiency and accuracy.

This thesis was driven by the industry's demand for faster and more accurate safety evaluations and by the potential of automation to transform HAZOP methodologies. Specifically, the project focused on automating preliminary HAZOP (preHAZOP) analysis, an early-stage design tool that identifies potential hazards before detailed design decisions are made. By addressing risks at this stage, preHAZOP facilitates proactive safety management, allowing designers to implement safeguards earlier in the design process.

The main objective of this project was to design and implement an automated preHAZOP approach using Python, built around a phenomenological framework. This methodology combined traditional HAZOP principles with automated processes, relying on a modular, graph-based system representation to systematically process, analyze, and visualize deviations. Python libraries played a central role in supporting data manipulation, graph-based modeling, and visualization, enabling a structured and streamlined analysis. The automation aimed to reduce manual effort while maintaining the depth and rigor of traditional HAZOP studies.

To evaluate the effectiveness of this approach, the project conducted a comparative analysis of traditional and automated methods. This comparison provided valuable insights into the strengths and limitations of each approach, particularly regarding their ability to capture and document deviations and associated risks. The findings underscore the potential of automation to enhance the scope, speed, and precision of HAZOP analyses, while also identifying areas where manual expertise remains indispensable

This work has resulted in several notable advances:

- *Enhanced Efficiency and Accuracy in Deviation Identification*. By automating the initial stages of the preHAZOP process, this approach can potentially reduce the time and effort traditionally required for identifying deviations, a task that is often resource-intensive. Automation ensured the consistent application of HAZOP guidelines and facilitated the efficient documentation of deviation patterns. This streamlined method enhances the accessibility of early hazard identification, even for highly complex systems.

- *Phenomenological Grounding for Analytical Depth*. The automated preHAZOP process incorporated a phenomenological approach, emphasizing fundamental physical and chemical behaviors to identify deviations and their underlying causes. By grounding the analysis in scientific principles (i.e. balances), the methodology provided a realistic and nuanced understanding of system behavior. This approach enabled analysts to explore root causes beyond predefined categories, establishing a robust framework for early deviation and risk identification.
- *Graph-Based Visualization for Improved System Transparency*. A cornerstone of this methodology was the graph-based representation of system interactions, which offered a clear and intuitive overview of the system's dynamic behavior. The graphical output allowed users to trace deviation propagation and identify critical risk pathways with ease. This enhanced transparency was instrumental in validating the automated analysis, ensuring that key process pathways were accurately represented. Additionally, the visual format facilitated peer review and effective communication with stakeholders.
- *Modular structure for flexibility and scalability*. The graph-based approach's modular design significantly enhanced the flexibility and scalability of the automated preHAZOP methodology. By representing individual units as modular subgraphs, the system can seamlessly adapt to design changes with minimal reconfiguration. This modularity allows for a highly customizable and user-friendly HAZOP framework that responds effectively to evolving design specifications. Such adaptability is particularly valuable in industries where systems are routinely upgraded, expanded, or redesigned, ensuring that hazard analyses remain relevant and robust throughout the lifecycle of the process

Significant validation of the developed methodology was achieved through a comparative case study using an example from the BS EN 61882:2016 standard. This example focused on a simple system consisting of two transfer lines supplying pure components to a reactor where a reaction takes place. The HAZOP analysis for the transfer line of component A served as the basis for the comparison between the traditional approach and the automated preHAZOP methodology. The results showed notable differences: the traditional HAZOP table presented in the standard lacked both the comprehensiveness and detail provided by the algorithm-generated table. Specifically, the automated approach identified a significantly greater number of scenarios, ensuring that no potential deviations were overlooked. In addition, the algorithm provided a more scientifically sound and detailed description of the cause-deviation-consequence chains, offering insights based on the phenomenological framework. This comparative analysis, detailed in Sections 4.6 and 4.7, underscores the effectiveness of the developed methodology in addressing the limitations of traditional HAZOP analyses. By integrating computational precision and a rigorous scientific approach, the automated system has demonstrated its ability to enhance both the depth and breadth of hazard identification, confirming its potential as a transformative tool for process safety.

The developed approach presents several promising directions for future development. One important area is the enhancement of automation to cover a broader range of processes and provide more objective analyses. Expanding the current system to capture a wider array of deviations, particularly in complex multi-phase processes, would greatly increase its versatility. The integration of real-time data could enable continuous adaptation to operational changes, supporting ongoing hazard analysis. As systems become more intricate, automating the comparison between traditional and automated HAZOP results, which is currently performed manually, would ensure consistent and objective assessments. The implementation of automated tools for delta calculations could streamline monitoring and maintain high-quality hazard identification, allowing for rapid and reliable assessments without overwhelming human reviewers.

Another promising avenue is the quantitative estimation of deviation impacts through advanced correlations. Future developments could extend the current qualitative approach to include a quantitative assessment of how deviations affect the system. By quantifying the physical effects of deviations on process variables, the methodology would support more accurate risk probability estimates, improving the understanding of the likelihood and severity of potential hazards. For instance, determining how a temperature increase influences downstream pressure changes would enable the system to adjust risk probabilities based on actual process conditions. Achieving this goal requires developing complex correlations beyond simple binary relationships, potentially using graded correlation coefficients to represent the magnitude of influence between variables. This quantitative approach would allow for a more comprehensive analysis of how variations propagate across interconnected variables, encompassing all aspects of the process rather than focusing on isolated sections.

In conclusion, the automated preHAZOP methodology developed in this project represents a significant contribution to the field of process safety and risk analysis. By combining computational precision with a phenomenological foundation, it achieves a high degree of rigor while maintaining efficiency, transparency, and scalability. With continued development, this methodology has the potential to set a new standard for early hazard identification, enabling safer, more reliable, and adaptable industrial processes.

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# Appendix A

## Overall system graph

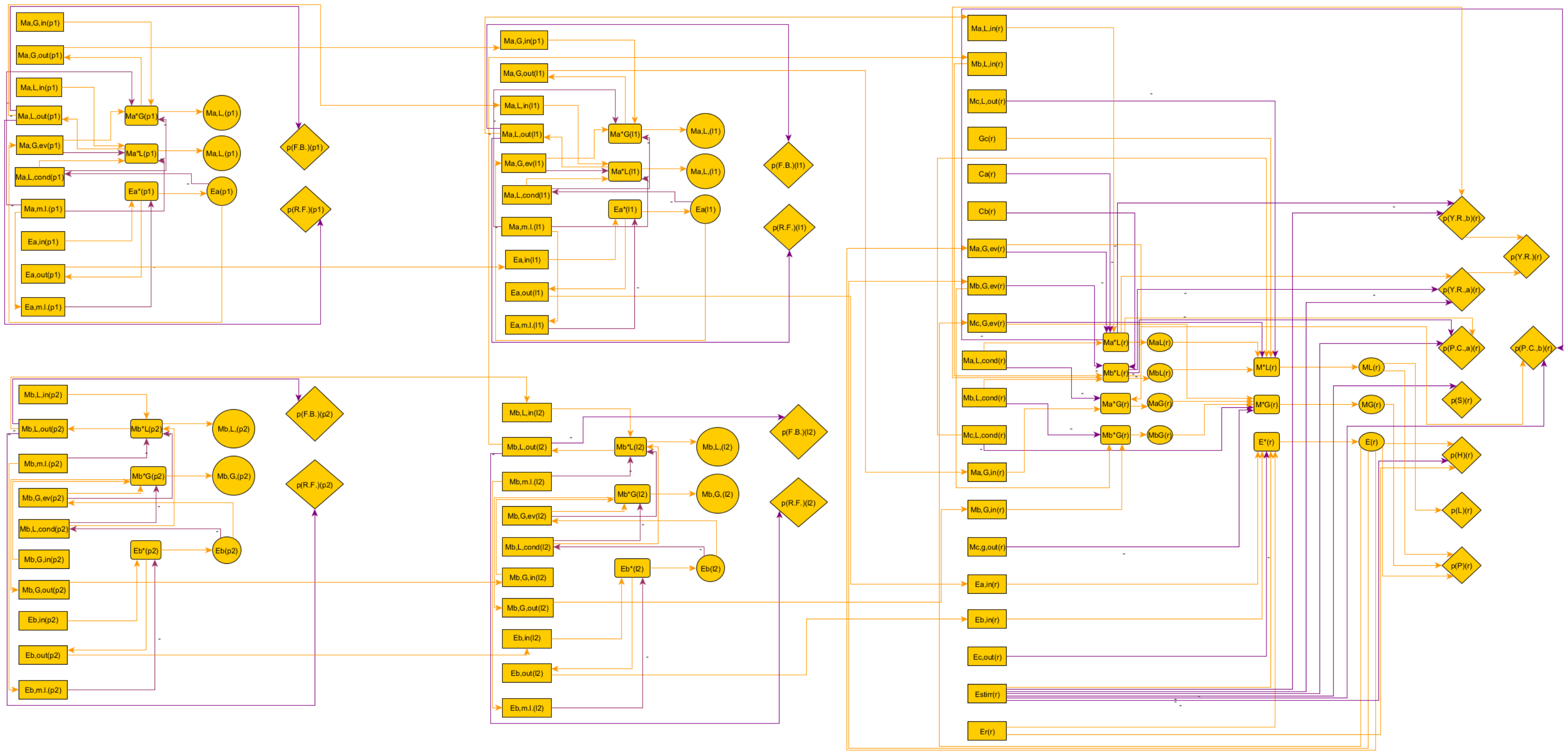

*Figure 75: Graph of the complete system used in this thesis project. No grouping has been applied  to ease the visualization of the modules, as with the objective of this figure is representing how the team of experts saw the graph for the duration of the project*

## Filtered preHAZOP table

*Table 16: Filtered preHAZOP table produced by the software*

| No | ID | PV | PV description | Keyword | Cause | Cause description | Last PV before Effect | Last PV description | Effect | Effect description |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | n0n4n1n8 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 2 | n0n4n1n9 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 3 | n0n4n1n89n93n90n97 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 4 | n0n4n1n89n93n90n98 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 5 | n0n4n1n89n93n90n24n54n56n45n48n52 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 6 | n0n4n1n89n93n90n24n54n56n45n48n53 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | high | Not Found | No accumulation | Ma,L,in(r) | Liquid (L) Input flow | p(P)(r) | Probability of excessive |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | nodes identified as sources | | (in) of component a to the reactor (r) [g/s] | | pressure (P) buildup in the reactor (r) |
| 7 | n0n4n1n89n93n90n24n54n63 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 8 | n0n4n1n89n93n90n24n54n63n66 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 9 | n0n4n1n89n93n90n24n54n65 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 1 | n0n4n1n89n93n90n24n54n65n66 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 11 | n0n4n1n89n93n90n24n54n62 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 12 | n0n4n1n89n93n90n24n54n64 | Ma,L,in(p1) | Liquid (L) Input flow (in) of component a to pump 1 (p1) [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | reactor (r) [g/s] | | |
| 13 | n1n8 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 14 | n1n9 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 15 | n1n89n93n90n97 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 16 | n1n89n93n90n98 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 17 | n1n89n93n90n24n54n56n45 n48n52 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 18 | n1n89n93n90n24n54n56n45 n48n53 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 19 | n1n89n93n90n24n54n63 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 2 | n1n89n93n90n24n54n63n66 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 21 | n1n89n93n90n24n54n65 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 22 | n1n89n93n90n24n54n65n66 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 23 | n1n89n93n90n24n54n62 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 24 | n1n89n93n90n24n54n64 | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 25 | n2n5n7n67n75n73n107n111n109n36n58n60n44n47n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes | Ma,G,in(r) | Gas (G) Input flow (in) of component | p(P)(r) | Probability of excessive pressure (P) |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | identified as sources | | a to the reactor (r) [g/s] | | buildup in the reactor (r) |
| 26 | n2n5n7n67n4n1n8 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 27 | n2n5n7n67n4n1n9 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 28 | n2n5n7n67n4n1n89n93n90n97 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 29 | n2n5n7n67n4n1n89n93n90n98 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 3 | n2n5n7n67n4n1n89n93n90n24n54n56n45n48n52 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 31 | n2n5n7n67n4n1n89n93n90n24n54n56n45n48n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |

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| | | | | | | | | reactor (r) [g/s] | | |
| 32 | n2n5n7n67n4n1n89n93n90n24n54n63 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 33 | n2n5n7n67n4n1n89n93n90n24n54n63n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 34 | n2n5n7n67n4n1n89n93n90n24n54n65 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 35 | n2n5n7n67n4n1n89n93n90n24n54n65n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 36 | n2n5n7n67n4n1n89n93n90n24n54n62 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 37 | n2n5n7n67n4n1n89n93n90n24n54n64 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 38 | n2n5n7n69n4n1n8 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation | Ma,L,out(p1) | Liquid (L) Output | p(F.B.)(p1) | Probability of Flow |

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| | | | | | nodes identified as sources | | flow (out) of component a from pump 1 (p1) [g/s] | | Blockage (F.B.) in pump 1 (p1) |
| 39 | n2n5n7n69n4n1n9 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 4 | n2n5n7n69n4n1n89n93n90n97 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 41 | n2n5n7n69n4n1n89n93n90n98 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 42 | n2n5n7n69n4n1n89n93n90n24n54n56n45n48n52 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 43 | n2n5n7n69n4n1n89n93n90n24n54n56n45n48n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 44 | n2n5n7n69n4n1n89n93n90n24n54n63 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes | Ma,L,in(r) | Liquid (L) Input flow (in) of component | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to |

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| | | | | | identified as sources | | a to the reactor (r) [g/s] | | excess of component a in the reactor (r) |
| 45 | n2n5n7n69n4n1n89n93n90n24n54n63n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 46 | n2n5n7n69n4n1n89n93n90n24n54n65 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 47 | n2n5n7n69n4n1n89n93n90n24n54n65n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 48 | n2n5n7n69n4n1n89n93n90n24n54n62 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 49 | n2n5n7n69n4n1n89n93n90n24n54n64 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 5 | n2n5n7n69n75n73n107n111n109n36n58n60n44n47n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |

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| 51 | n2n5n3n91n94n96n103n111n109n36n58n60n44n47n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 52 | n2n5n3n91n94n96n103n93n90n97 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 53 | n2n5n3n91n94n96n103n93n90n98 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 54 | n2n5n3n91n94n96n103n93n90n24n54n56n45n48n52 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 55 | n2n5n3n91n94n96n103n93n90n24n54n56n45n48n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 56 | n2n5n3n91n94n96n103n93n90n24n54n63 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 57 | n2n5n3n91n94n96n103n93n90n24n54n63n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes | Ma,L,in(r) | Liquid (L) Input flow (in) of | p(Y.R.)(r) | Probability of yield reduction |

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| | | | | | | identified as sources | | component a to the reactor (r) [g/s] | | (Y.R.) in the reactor (r) |
| 58 | n2n5n3n91n94n96n103n93n90n24n54n65 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 59 | n2n5n3n91n94n96n103n93n90n24n54n65n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 6 | n2n5n3n91n94n96n103n93n90n24n54n62 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 61 | n2n5n3n91n94n96n103n93n90n24n54n64 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 62 | n2n5n3n91n94n96n105n93n90n97 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 63 | n2n5n3n91n94n96n105n93n90n98 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |

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| | | | | | | | | pump 1 (p1) [g/s] | | |
| 64 | n2n5n3n91n94n96n105n93n90n24n54n56n45n48n52 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 65 | n2n5n3n91n94n96n105n93n90n24n54n56n45n48n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 66 | n2n5n3n91n94n96n105n93n90n24n54n63 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 67 | n2n5n3n91n94n96n105n93n90n24n54n63n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 68 | n2n5n3n91n94n96n105n93n90n24n54n65 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 69 | n2n5n3n91n94n96n105n93n90n24n54n65n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 7 | n2n5n3n91n94n96n105n93n90n24n54n62 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation | Ma,L,in(r) | Liquid (L) Input flow | p(P.C.,a)(r) | Probability of final product |

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| | | | | | | nodes identified as sources | | (in) of component a to the reactor (r) [g/s] | | contamination (P.C.) of component a |
| 71 | n2n5n3n91n94n96n105n93n90n24n54n64 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 72 | n2n5n3n91n94n96n105n111n109n36n58n60n44n47n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 73 | n2n5n3n91n94n92n39n46n49n30n54n56n45n48n52 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 74 | n2n5n3n91n94n92n39n46n49n30n54n56n45n48n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 75 | n2n5n3n91n94n92n39n46n49n30n54n63 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 76 | n2n5n3n91n94n92n39n46n49n30n54n63n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |

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| 77 | n2n5n3n91n94n92n39n46n49n30n54n65 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 78 | n2n5n3n91n94n92n39n46n49n30n54n65n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 79 | n2n5n3n91n94n92n39n46n49n30n54n62 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 8 | n2n5n3n91n94n92n39n46n49n30n54n64 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 81 | n2n5n3n91n94n92n39n46n49n30n58n60n44n47n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 82 | n2n5n3n91n94n92n39n46n49n31n55n57n45n48n52 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 83 | n2n5n3n91n94n92n39n46n49n31n55n57n45n48n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |

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| | | | | | | | | evaporation (ev) [g/s] | | |
| 84 | n2n5n3n91n94n92n39n46n49n31n55n63 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 85 | n2n5n3n91n94n92n39n46n49n31n55n63n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 86 | n2n5n3n91n94n92n39n46n49n31n55n65 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 87 | n2n5n3n91n94n92n39n46n49n31n55n65n66 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 88 | n2n5n3n91n94n92n39n46n49n31n55n62 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 89 | n2n5n3n91n94n92n39n46n49n31n55n64 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 9 | n2n5n3n91n94n92n39n46n49n31n59n61n44n47n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation | Mb,G,ev(r) | Component b in gas | p(P)(r) | Probability of excessive |

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| | | | | | | nodes identified as sources | | form (g) in the reactor (r) due to evaporation (ev) [g/s] | | pressure (P) buildup in the reactor (r) |
| 91 | n2n5n3n91n94n92n39n46n49n32n45n48n52 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 92 | n2n5n3n91n94n92n39n46n49n32n45n48n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 93 | n2n5n3n91n94n92n39n46n49n32n44n47n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 94 | n2n5n3n91n94n92n39n46n49n51 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ea,in(r) | Energy Input flow (in) related to component a in the reactor (r) [J/s] | p(H)(r) | Probability of Hot spots (H) formation in the reactor (r) |
| 95 | n2n5n3n91n94n92n39n46n49n53 | Ea,in(p1) | Energy Input flow (in) related to component a in pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ea,in(r) | Energy Input flow (in) related to component a in the reactor (r) [J/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 96 | n3n91n94n96n103n111n109n36n58n60n44n47n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |

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| | | | | | | | | reactor (r) [g/s] | | |
| 97 | n3n91n94n96n103n93n90n97 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 98 | n3n91n94n96n103n93n90n98 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 99 | n3n91n94n96n103n93n90n24n54n56n45n48n52 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 1 | n3n91n94n96n103n93n90n24n54n56n45n48n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 101 | n3n91n94n96n103n93n90n24n54n63 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 102 | n3n91n94n96n103n93n90n24n54n63n66 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |

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| 103 | n3n91n94n96n103n93n90n24n54n65 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 104 | n3n91n94n96n103n93n90n24n54n65n66 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 105 | n3n91n94n96n103n93n90n24n54n62 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 106 | n3n91n94n96n103n93n90n24n54n64 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 107 | n3n91n94n96n105n93n90n97 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 108 | n3n91n94n96n105n93n90n98 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 109 | n3n91n94n96n105n93n90n24n54n56n45n48n52 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes | Ma,L,in(r) | Liquid (L) Input flow (in) of | p(L)(r) | Probability of reaching excessive |

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| | | | | | | identified as sources | | component a to the reactor (r) [g/s] | | level (L) value in the reactor (r) (possible overflow) |
| 11 | n3n91n94n96n105n93n90n24n54n56n45n48n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 111 | n3n91n94n96n105n93n90n24n54n63 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 112 | n3n91n94n96n105n93n90n24n54n63n66 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 113 | n3n91n94n96n105n93n90n24n54n65 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 114 | n3n91n94n96n105n93n90n24n54n65n66 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 115 | n3n91n94n96n105n93n90n24n54n62 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |

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| 116 | n3n91n94n96n105n93n90n24n54n64 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 117 | n3n91n94n96n105n111n109n36n58n60n44n47n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 118 | n3n91n94n92n39n46n49n30n54n56n45n48n52 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 119 | n3n91n94n92n39n46n49n30n54n56n45n48n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 12 | n3n91n94n92n39n46n49n30n54n63 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 121 | n3n91n94n92n39n46n49n30n54n63n66 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 122 | n3n91n94n92n39n46n49n30n54n65 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of |

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| | | | | | | | | evaporation (ev) [g/s] | | component b in the reactor (r) |
| 123 | n3n91n94n92n39n46n49n30 n54n65n66 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 124 | n3n91n94n92n39n46n49n30 n54n62 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 125 | n3n91n94n92n39n46n49n30 n54n64 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 126 | n3n91n94n92n39n46n49n30 n58n60n44n47n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 127 | n3n91n94n92n39n46n49n31 n55n57n45n48n52 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 128 | n3n91n94n92n39n46n49n31 n55n57n45n48n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 129 | n3n91n94n92n39n46n49n31 n55n63 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes | Mb,G,ev(r) | Component b in gas form (g) in | p(Y.R.,a)(r) | Probability of yield reduction |

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| | | | | | | identified as sources | | the reactor (r) due to evaporation (ev) [g/s] | | (Y.R.) due to excess of component a in the reactor (r) |
| 13 | n3n91n94n92n39n46n49n31 n55n63n66 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 131 | n3n91n94n92n39n46n49n31 n55n65 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 132 | n3n91n94n92n39n46n49n31 n55n65n66 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 133 | n3n91n94n92n39n46n49n31 n55n62 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 134 | n3n91n94n92n39n46n49n31 n55n64 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 135 | n3n91n94n92n39n46n49n31 n59n61n44n47n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |

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| 136 | n3n91n94n92n39n46n49n32 n45n48n52 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 137 | n3n91n94n92n39n46n49n32 n45n48n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | low | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 138 | n3n91n94n92n39n46n49n32 n44n47n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 139 | n3n91n94n92n39n46n49n51 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ea,in(r) | Energy Input flow (in) related to component a in the reactor (r) [J/s] | p(H)(r) | Probability of Hot spots (H) formation in the reactor (r) |
| 14 | n3n91n94n92n39n46n49n53 | Ea,out(p1) | Energy Output flow (out) related to component a to pump 1 (p1) [J/s] | high | Not Found | No accumulation nodes identified as sources | Ea,in(r) | Energy Input flow (in) related to component a in the reactor (r) [J/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 141 | n10n4n1n8 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 142 | n10n4n1n9 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself | high | Not Found | No accumulation nodes | Ma,L,out(p1) | Liquid (L) Output flow (out) | p(R.F.)(p1) | Probability of Reverse Flow |

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| | | | or pipings inside the equipment control volume [g/s] | | | identified as sources | | of component a from pump 1 (p1) [g/s] | | (R.F.) in pump 1 (p1) |
| 143 | n10n4n1n89n93n90n97 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 144 | n10n4n1n89n93n90n98 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 145 | n10n4n1n89n93n90n24n54n56n45n48n52 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 146 | n10n4n1n89n93n90n24n54n56n45n48n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 147 | n10n4n1n89n93n90n24n54n63 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 148 | n10n4n1n89n93n90n24n54n63n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |

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| | | | | | | | | reactor (r) [g/s] | | |
| 149 | n10n4n1n89n93n90n24n54n65 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 15 | n10n4n1n89n93n90n24n54n65n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 151 | n10n4n1n89n93n90n24n54n62 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 152 | n10n4n1n89n93n90n24n54n64 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 153 | n10n11n5n7n67n75n73n107n111n109n36n58n60n44n47n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 154 | n10n11n5n7n67n4n1n8 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 155 | n10n11n5n7n67n4n1n9 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by | high | Not Found | No accumulation | Ma,L,out(p1) | Liquid (L) Output | p(R.F.)(p1) | Probability of Reverse Flow |

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| | | | leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | | | nodes identified as sources | | flow (out) of component a from pump 1 (p1) [g/s] | | (R.F.) in pump 1 (p1) |
| 156 | n10n11n5n7n67n4n1n89n93 n90n97 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 157 | n10n11n5n7n67n4n1n89n93 n90n98 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 158 | n10n11n5n7n67n4n1n89n93 n90n24n54n56n45n48n52 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 159 | n10n11n5n7n67n4n1n89n93 n90n24n54n56n45n48n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 16 | n10n11n5n7n67n4n1n89n93 n90n24n54n63 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 161 | n10n11n5n7n67n4n1n89n93 n90n24n54n63n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself | low | Not Found | No accumulation nodes | Ma,L,in(r) | Liquid (L) Input flow (in) of component | p(Y.R.)(r) | Probability of yield reduction |

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| | | | or pipings inside the equipment control volume [g/s] | | | identified as sources | | a to the reactor (r) [g/s] | | (Y.R.) in the reactor (r) |
| 162 | n10n11n5n7n67n4n1n89n93 n90n24n54n65 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 163 | n10n11n5n7n67n4n1n89n93 n90n24n54n65n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 164 | n10n11n5n7n67n4n1n89n93 n90n24n54n62 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 165 | n10n11n5n7n67n4n1n89n93 n90n24n54n64 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 166 | n10n11n5n7n69n4n1n8 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 167 | n10n11n5n7n69n4n1n9 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |

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| 168 | n10n11n5n7n69n4n1n89n93 n90n97 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 169 | n10n11n5n7n69n4n1n89n93 n90n98 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 17 | n10n11n5n7n69n4n1n89n93 n90n24n54n56n45n48n52 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 171 | n10n11n5n7n69n4n1n89n93 n90n24n54n56n45n48n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 172 | n10n11n5n7n69n4n1n89n93 n90n24n54n63 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 173 | n10n11n5n7n69n4n1n89n93 n90n24n54n63n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 174 | n10n11n5n7n69n4n1n89n93 n90n24n54n65 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself | low | Not Found | No accumulation nodes | Ma,L,in(r) | Liquid (L) Input flow (in) of | p(Y.R.,b)(r) | Probability of yield reduction |

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| | | | or pipings inside the equipment control volume [g/s] | | | identified as sources | | component a to the reactor (r) [g/s] | | (Y.R.) due to excess of component b in the reactor (r) |
| 175 | n10n11n5n7n69n4n1n89n93 n90n24n54n65n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 176 | n10n11n5n7n69n4n1n89n93 n90n24n54n62 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 177 | n10n11n5n7n69n4n1n89n93 n90n24n54n64 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 178 | n10n11n5n7n69n75n73n107 n111n109n36n58n60n44n47n 53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 179 | n10n11n5n3n91n94n96n103 n111n109n36n58n60n44n47n 53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 18 | n10n11n5n3n91n94n96n103 n93n90n97 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |

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| 181 | n10n11n5n3n91n94n96n103 n93n90n98 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 182 | n10n11n5n3n91n94n96n103 n93n90n24n54n56n45n48n5 2 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 183 | n10n11n5n3n91n94n96n103 n93n90n24n54n56n45n48n5 3 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 184 | n10n11n5n3n91n94n96n103 n93n90n24n54n63 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 185 | n10n11n5n3n91n94n96n103 n93n90n24n54n63n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 186 | n10n11n5n3n91n94n96n103 n93n90n24n54n65 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 187 | n10n11n5n3n91n94n96n103 n93n90n24n54n65n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself | high | Not Found | No accumulation nodes | Ma,L,in(r) | Liquid (L) Input flow (in) of | p(Y.R.)(r) | Probability of yield reduction |

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| | | | or pipings inside the equipment control volume [g/s] | | | identified as sources | | component a to the reactor (r) [g/s] | | (Y.R.) in the reactor (r) |
| 188 | n10n11n5n3n91n94n96n103 n93n90n24n54n62 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 189 | n10n11n5n3n91n94n96n103 n93n90n24n54n64 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 19 | n10n11n5n3n91n94n96n105 n93n90n97 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 191 | n10n11n5n3n91n94n96n105 n93n90n98 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 192 | n10n11n5n3n91n94n96n105 n93n90n24n54n56n45n48n5 2 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 193 | n10n11n5n3n91n94n96n105 n93n90n24n54n56n45n48n5 3 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |

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| 194 | n10n11n5n3n91n94n96n105 n93n90n24n54n63 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 195 | n10n11n5n3n91n94n96n105 n93n90n24n54n63n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 196 | n10n11n5n3n91n94n96n105 n93n90n24n54n65 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 197 | n10n11n5n3n91n94n96n105 n93n90n24n54n65n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 198 | n10n11n5n3n91n94n96n105 n93n90n24n54n62 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 199 | n10n11n5n3n91n94n96n105 n93n90n24n54n64 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 2 | n10n11n5n3n91n94n96n105 n111n109n36n58n60n44n47n 53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself | low | Not Found | No accumulation nodes | Ma,G,in(r) | Gas (G) Input flow (in) of component | p(P)(r) | Probability of excessive pressure (P) |

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| | | | or pipings inside the equipment control volume [g/s] | | | identified as sources | | a to the reactor (r) [g/s] | | buildup in the reactor (r) |
| 201 | n10n11n5n3n91n94n92n39n46n49n30n54n56n45n48n52 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 202 | n10n11n5n3n91n94n92n39n46n49n30n54n56n45n48n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 203 | n10n11n5n3n91n94n92n39n46n49n30n54n63 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 204 | n10n11n5n3n91n94n92n39n46n49n30n54n63n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 205 | n10n11n5n3n91n94n92n39n46n49n30n54n65 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 206 | n10n11n5n3n91n94n92n39n46n49n30n54n65n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |

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| 207 | n10n11n5n3n91n94n92n39n46n49n30n54n62 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 208 | n10n11n5n3n91n94n92n39n46n49n30n54n64 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 209 | n10n11n5n3n91n94n92n39n46n49n30n58n60n44n47n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 21 | n10n11n5n3n91n94n92n39n46n49n31n55n57n45n48n52 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 211 | n10n11n5n3n91n94n92n39n46n49n31n55n57n45n48n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 212 | n10n11n5n3n91n94n92n39n46n49n31n55n63 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 213 | n10n11n5n3n91n94n92n39n46n49n31n55n63n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |

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| | | | | | | | | evaporation (ev) [g/s] | | |
| 214 | n10n11n5n3n91n94n92n39n46n49n31n55n65 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 215 | n10n11n5n3n91n94n92n39n46n49n31n55n65n66 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 216 | n10n11n5n3n91n94n92n39n46n49n31n55n62 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 217 | n10n11n5n3n91n94n92n39n46n49n31n55n64 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 218 | n10n11n5n3n91n94n92n39n46n49n31n59n61n44n47n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 219 | n10n11n5n3n91n94n92n39n46n49n32n45n48n52 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | high | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 22 | n10n11n5n3n91n94n92n39n46n49n32n45n48n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself | high | Not Found | No accumulation nodes | Mc,G,ev(r) | Component c in gas form (g) in | p(P)(r) | Probability of excessive pressure (P) |

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| | | | or pipings inside the equipment control volume [g/s] | | | identified as sources | | the reactor (r) due to evaporation (ev) [g/s] | | buildup in the reactor (r) |
| 221 | n10n11n5n3n91n94n92n39n46n49n32n44n47n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 222 | n10n11n5n3n91n94n92n39n46n49n51 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ea,in(r) | Energy Input flow (in) related to component a in the reactor (r) [J/s] | p(H)(r) | Probability of Hot spots (H) formation in the reactor (r) |
| 223 | n10n11n5n3n91n94n92n39n46n49n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ea,in(r) | Energy Input flow (in) related to component a in the reactor (r) [J/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 224 | n10n75n73n107n111n109n36n58n60n44n47n53 | Ma,m.l.(p1) | Node related to mass (M) losses (m.l.) of component a in pump 1 (p1), caused by leakage in the piece of equipment itself or pipings inside the equipment control volume [g/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 225 | n11n5n7n67n75n73n107n111n109n36n58n60n44n47n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 226 | n11n5n7n67n4n1n8 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |

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| | | | | | | | | pump 1 (p1) [g/s] | | |
| 227 | n11n5n7n67n4n1n9 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 228 | n11n5n7n67n4n1n89n93n90 n97 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 229 | n11n5n7n67n4n1n89n93n90 n98 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 23 | n11n5n7n67n4n1n89n93n90 n24n54n56n45n48n52 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 231 | n11n5n7n67n4n1n89n93n90 n24n54n56n45n48n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 232 | n11n5n7n67n4n1n89n93n90 n24n54n63 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |

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| 233 | n11n5n7n67n4n1n89n93n90 n24n54n63n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 234 | n11n5n7n67n4n1n89n93n90 n24n54n65 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 235 | n11n5n7n67n4n1n89n93n90 n24n54n65n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 236 | n11n5n7n67n4n1n89n93n90 n24n54n62 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 237 | n11n5n7n67n4n1n89n93n90 n24n54n64 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 238 | n11n5n7n69n4n1n8 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 239 | n11n5n7n69n4n1n9 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes | Ma,L,out(p1) | Liquid (L) Output flow (out) of | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |

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| | | | | | | identified as sources | | component a from pump 1 (p1) [g/s] | | |
| 24 | n11n5n7n69n4n1n89n93n90 n97 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 241 | n11n5n7n69n4n1n89n93n90 n98 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 242 | n11n5n7n69n4n1n89n93n90 n24n54n56n45n48n52 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 243 | n11n5n7n69n4n1n89n93n90 n24n54n56n45n48n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 244 | n11n5n7n69n4n1n89n93n90 n24n54n63 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 245 | n11n5n7n69n4n1n89n93n90 n24n54n63n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |

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| | | | | | | | | reactor (r) [g/s] | | |
| 246 | n11n5n7n69n4n1n89n93n90 n24n54n65 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 247 | n11n5n7n69n4n1n89n93n90 n24n54n65n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 248 | n11n5n7n69n4n1n89n93n90 n24n54n62 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 249 | n11n5n7n69n4n1n89n93n90 n24n54n64 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 250 | n11n5n7n69n75n73n107n111 n109n36n58n60n44n47n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 251 | n11n5n3n91n94n96n103n111 n109n36n58n60n44n47n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 252 | n11n5n3n91n94n96n103n93 n90n97 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of | high | Not Found | No accumulation nodes | Ma,L,out(l1) | Liquid (L) Output flow (out) | p(F.B.)(l1) | Probability of Flow Blockage |

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| | | | equipment itself (p1) or pipings inside the equipment control volume [J/s] | | | identified as sources | | of component a from pump 1 (p1) [g/s] | | (F.B.) in pump 1 (p1) |
| 253 | n11n5n3n91n94n96n103n93 n90n98 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 254 | n11n5n3n91n94n96n103n93 n90n24n54n56n45n48n52 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 255 | n11n5n3n91n94n96n103n93 n90n24n54n56n45n48n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 256 | n11n5n3n91n94n96n103n93 n90n24n54n63 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 257 | n11n5n3n91n94n96n103n93 n90n24n54n63n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 258 | n11n5n3n91n94n96n103n93 n90n24n54n65 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b |

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| | | | | | | | reactor (r) [g/s] | | in the reactor (r) |
| 259 | n11n5n3n91n94n96n103n93 n90n24n54n65n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 260 | n11n5n3n91n94n96n103n93 n90n24n54n62 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 261 | n11n5n3n91n94n96n103n93 n90n24n54n64 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 262 | n11n5n3n91n94n96n105n93 n90n97 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 263 | n11n5n3n91n94n96n105n93 n90n98 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 264 | n11n5n3n91n94n96n105n93 n90n24n54n56n45n48n52 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 265 | n11n5n3n91n94n96n105n93 n90n24n54n56n45n48n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of | high | Not Found | No accumulation | Ma,L,in(r) | Liquid (L) Input flow | p(P)(r) | Probability of excessive |

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| | | | equipment itself (p1) or pipings inside the equipment control volume [J/s] | | | nodes identified as sources | | (in) of component a to the reactor (r) [g/s] | | pressure (P) buildup in the reactor (r) |
| 266 | n11n5n3n91n94n96n105n93 n90n24n54n63 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 267 | n11n5n3n91n94n96n105n93 n90n24n54n63n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 268 | n11n5n3n91n94n96n105n93 n90n24n54n65 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 269 | n11n5n3n91n94n96n105n93 n90n24n54n65n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 27 | n11n5n3n91n94n96n105n93 n90n24n54n62 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 271 | n11n5n3n91n94n96n105n93 n90n24n54n64 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |

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| | | | | | | | reactor (r) [g/s] | | |
| 272 | n11n5n3n91n94n96n105n111 n109n36n58n60n44n47n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 273 | n11n5n3n91n94n92n39n46n 49n30n54n56n45n48n52 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 274 | n11n5n3n91n94n92n39n46n 49n30n54n56n45n48n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 275 | n11n5n3n91n94n92n39n46n 49n30n54n63 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 276 | n11n5n3n91n94n92n39n46n 49n30n54n63n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 277 | n11n5n3n91n94n92n39n46n 49n30n54n65 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 278 | n11n5n3n91n94n92n39n46n 49n30n54n65n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of | low | Not Found | No accumulation | Ma,G,ev(r) | Component a in gas | p(Y.R.)(r) | Probability of yield |

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| | | | equipment itself (p1) or pipings inside the equipment control volume [J/s] | | | nodes identified as sources | | form (G) in the reactor (r) due to evaporation (ev) [g/s] | | reduction (Y.R.) in the reactor (r) |
| 279 | n11n5n3n91n94n92n39n46n49n30n54n62 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 28 | n11n5n3n91n94n92n39n46n49n30n54n64 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 281 | n11n5n3n91n94n92n39n46n49n30n58n60n44n47n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ma,G,ev(r) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 282 | n11n5n3n91n94n92n39n46n49n31n55n57n45n48n52 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 283 | n11n5n3n91n94n92n39n46n49n31n55n57n45n48n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 284 | n11n5n3n91n94n92n39n46n49n31n55n63 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |

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| 285 | n11n5n3n91n94n92n39n46n49n31n55n63n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 286 | n11n5n3n91n94n92n39n46n49n31n55n65 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 287 | n11n5n3n91n94n92n39n46n49n31n55n65n66 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 288 | n11n5n3n91n94n92n39n46n49n31n55n62 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 289 | n11n5n3n91n94n92n39n46n49n31n55n64 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 29 | n11n5n3n91n94n92n39n46n49n31n59n61n44n47n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Mb,G,ev(r) | Component b in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 291 | n11n5n3n91n94n92n39n46n49n32n45n48n52 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to | p(L)(r) | Probability of reaching excessive level (L) value in the reactor |

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| | | | | | | | | evaporation (ev) [g/s] | | (r) (possible overflow) |
| 292 | n11n5n3n91n94n92n39n46n49n32n45n48n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | high | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 293 | n11n5n3n91n94n92n39n46n49n32n44n47n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Mc,G,ev(r) | Component c in gas form (g) in the reactor (r) due to evaporation (ev) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 294 | n11n5n3n91n94n92n39n46n49n51 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ea,in(r) | Energy Input flow (in) related to component a in the reactor (r) [J/s] | p(H)(r) | Probability of Hot spots (H) formation in the reactor (r) |
| 295 | n11n5n3n91n94n92n39n46n49n53 | Ea,m.l.(p1) | Node related to energy losses (E) caused by component leakage from the piece of equipment itself (p1) or pipings inside the equipment control volume [J/s] | low | Not Found | No accumulation nodes identified as sources | Ea,in(r) | Energy Input flow (in) related to component a in the reactor (r) [J/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 296 | n67n75n73n107n111n109n36n58n60n44n47n53 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 297 | n67n4n1n8 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |

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| 298 | n67n4n1n9 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 299 | n67n4n1n89n93n90n97 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 300 | n67n4n1n89n93n90n98 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 301 | n67n4n1n89n93n90n24n54n56n45n48n52 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 302 | n67n4n1n89n93n90n24n54n56n45n48n53 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 303 | n67n4n1n89n93n90n24n54n63 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 304 | n67n4n1n89n93n90n24n54n63n66 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | high | Ea(p1) | Energy accumulation | Ma,L,in(r) | Liquid (L) Input flow | p(Y.R.)(r) | Probability of yield |

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| | | | | | | related to component a in pump 1 (p1) [g/s] | | (in) of component a to the reactor (r) [g/s] | | reduction (Y.R.) in the reactor (r) |
| 305 | n67n4n1n89n93n90n24n54n65 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 306 | n67n4n1n89n93n90n24n54n65n66 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 307 | n67n4n1n89n93n90n24n54n62 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 308 | n67n4n1n89n93n90n24n54n64 | Ma,G,ev(p1) | Component a in gas form (G) in the reactor (r) due to evaporation (ev) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 309 | n69n4n1n8 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(p1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 31 | n69n4n1n9 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(p1) | Liquid (L) Output flow (out) of component a from | p(R.F.)(p1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |

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| | | | | | | | | pump 1 (p1) [g/s] | | |
| 311 | n69n4n1n89n93n90n97 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(F.B.)(l1) | Probability of Flow Blockage (F.B.) in pump 1 (p1) |
| 312 | n69n4n1n89n93n90n98 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,out(l1) | Liquid (L) Output flow (out) of component a from pump 1 (p1) [g/s] | p(R.F.)(l1) | Probability of Reverse Flow (R.F.) in pump 1 (p1) |
| 313 | n69n4n1n89n93n90n24n54n56n45n48n52 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(L)(r) | Probability of reaching excessive level (L) value in the reactor (r) (possible overflow) |
| 314 | n69n4n1n89n93n90n24n54n56n45n48n53 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 315 | n69n4n1n89n93n90n24n54n63 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,a)(r) | Probability of yield reduction (Y.R.) due to excess of component a in the reactor (r) |
| 316 | n69n4n1n89n93n90n24n54n63n66 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |

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| 317 | n69n4n1n89n93n90n24n54n65 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.,b)(r) | Probability of yield reduction (Y.R.) due to excess of component b in the reactor (r) |
| 318 | n69n4n1n89n93n90n24n54n65n66 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(Y.R.)(r) | Probability of yield reduction (Y.R.) in the reactor (r) |
| 319 | n69n4n1n89n93n90n24n54n62 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | high | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,a)(r) | Probability of final product contamination (P.C.) of component a |
| 32 | n69n4n1n89n93n90n24n54n64 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,L,in(r) | Liquid (L) Input flow (in) of component a to the reactor (r) [g/s] | p(P.C.,b)(r) | Probability of final product contamination (P.C.) of component b |
| 321 | n69n75n73n107n111n109n36n58n60n44n47n53 | Ma,L,cond(p1) | Component a in liquid form (L) in the reactor (r) due to condensation (cond) [g/s] | low | Ea(p1) | Energy accumulation related to component a in pump 1 (p1) [g/s] | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 322 | n71n75n73n107n111n109n36n58n60n44n47n53 | Ma,G,in(p1) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | high | Not Found | No accumulation nodes identified as sources | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |
| 323 | n73n107n111n109n36n58n60n44n47n53 | Ma,G,out(p1) | Gas (G) Input flow (in) of component a to the reactor (r) [g/s] | high | Ea(p1) | Energy accumulation related to component a | Ma,G,in(r) | Gas (G) Input flow (in) of component a to the | p(P)(r) | Probability of excessive pressure (P) buildup in the reactor (r) |

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| | in pump 1 (p1) [g/s] | reactor (r) [g/s] |