# Incorporating Resilience into HAZOP to Enhance Process Safety in Industrial Facilities

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**Abstract:** Despite the worldwide focus on safety and steady operations, process plants struggle with the inherent complexities of industrial conditions that can lead to unexpected problems. The continuing prevalence of accidents with different root causes underlines the critical need for more robust process safety and risk management approaches. Process plants currently depend on the traditional hazard and operability study (HAZOP) to pinpoint potential hazards. The existing approach to risk assessment often focuses on identifying potential vulnerabilities and neglects the system's ability to endure and bounce back from disruptions. Resilience focuses on a system's ability to survive the initial disruption, adapt and recover back to the normal operation. Integrating resilience into the early design phase and operation of process plants offers a solution to significantly enhance process safety. This paper proposes a novel approach to improve industrial safety by integrating resilience into HAZOP studies during the design and operation phases. The research advocates for a more robust risk assessment, emphasising the importance of resilience throughout the design and operational stages. The proposed method integrates resilience principles as an essential element throughout the entire HAZOP framework and flowchart, ensuring resilience is built into the system's design and operation.

Keywords: Hazard and operability (HAZOP), Resilience, avoidance, survivability, recoverability.

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## Acronyms

| | |
|---|---|
| HAZOP | Hazard and Operability Study |
| GW | Guideword |
| ETD | Error-tolerant design |
| ED | Early detection |
| P | Plasticity |
| R | Recoverability |
| PFD | Process Flow Diagram |

# 1. Introduction

The concept of resilience is garnering significant attention in academia and industry, driven by the possibility that resilience can mitigate the impacts of inevitable system disruptions [Carroll, 2012; Park et al., 2012]. Over the past six decades, process safety management has experienced a significant transformation. The focus has shifted from primarily relying on technical factors to strengthening systems ability to adjust and recover from disruptions. This shift can be traced back to Holling's book in 1973, that introduced the concepts of resilience and stability for an ecological system [Bhamra et al. 2011; Holling, 1973].

Despite the enhancement in risk assessment approaches and growing public concern. Industries continue to face challenges, highlighting the need for robust risk management strategies. Process plants utilise Hazard and Operability (HAZOP) analysis extensively to identify and manage risks related to equipment, processes, and systems. HAZOP studies prevent accidents and ensure safe operations in modern industries by systematically examining potential risks in the designs and operations that could harm people, damage equipment, or cause disasters [Jain et al., 2017; Zhang et al., 2023]. The success of a HAZOP study depends on the expertise of the team, who thoroughly understands the process, which involves breaking down the plant's systems into smaller sections called nodes.

Process industries, which are economic drivers for many nations, operate in inherently risky environments [Ab Rahim et al., 2024]. In addition to the risks inherent to processes and operations, there are also environmental factors and human error, which was identified as a causal factor in industrial accidents such as the Flixborough disaster [Jenson et al., 2019; Moreno-Sader, et al., 2019]. To proactively manage these threats and ensure safe, steady plant operations, industrial plants prioritise frequent risk assessments such as HAZOP [Amin et al., 2022]. Process plants use the HAZOP method to actively identify potential risks and develop safeguards to counter these threats [Chastain et al., 2016].

Resilience surpasses the scope of traditional risk assessments. It focuses on a system’s ability to withstand and recover from disruptions, incorporates strategies to minimise risks and restore normal operations [Hosseini et al., 2016; Woods, 2015]. In contrast to HAZOP, which primarily identifies potential problems, resilience prioritises early detection and rapid recovery [CCPS, 2007; Dinh et al., 2012]. While both aim to ensure normal operations, their approaches differ: HAZOP focuses on process-based deviations, while resilience ensures system preparedness for unforeseen challenges.

Resilience focuses on a system's ability to withstand and recover from unexpected disruptions. Unlike traditional risk assessments that aim to prevent incidents. A common drawback of HAZOP, particularly when relying on brainstorming techniques, is an excessive focus on equipment-related issues, which can lead to an underestimation of the human causes of incidents [Dunjó et al., 2010]. To enhance

HAZOP's resilience, it is essential to recognise the complex interactions between humans and systems and proactively pinpoint potential human error [Baybutt, 2002; Hassall et al., 2014].

Resilience is a cornerstone of industrial success. As depicted in Table 1, it encompasses business continuity, risk management, asset protection, survivability, and recovery capabilities [Haimes, 2009; Park et al., 2012]. By ensuring steady operations, proactively managing risks, adapting to change, safeguarding assets and personnel, and enabling swift recovery, organisations can enhance their performance and safety [Madni & Jackson, 2009].

Table 1: Key elements driving the importance of incorporating resilience.

| | |
|---|---|
| **Business continuity** | The developing of business continuity plans helps to maintain continuous production to minimise downtime caused by equipment malfunctions or process disruptions. |
| **Risk management** | Industries can effectively manage risks by recognising vulnerabilities and risk mitigation plans to reduce the effects of potential disruptions. |
| **Survivability** | Enable industries to adjust and change circumstances, such as process upsets, plant trips, or environmental impacts such as flooding. |
| **Personnel and physical assets** | Resilience safeguards personnel and physical assets by prioritising on the employee safety and swift restoration after an incident. |
| **Recoverability** | Resilience supports the recoverability of industrial operations by ensuring that processes are efficient and can handle disruptions after undesired incidents or upsets [Madni and Jackson, 2009]. |

Industrial plants operate under high-risk conditions that demand an ongoing commitment to safety and reliability [Cagno et al., 2002]. Therefore, it is vital to incorporate resilience into HAZOP to enhance the robustness of HAZOP studies and overcome their limitations. The global drive to improve safety and operational reliability in process plants is hindered by the complex, hazardous nature of industrial settings, which are prone to unexpected disturbances. This research paper outlines a novel methodology for integrating resilience principles into HAZOP studies to enhance the process safety in industrial plants. It identifies resilience as a multi-phase process. This integration can be achieved by incorporating resilience principles such as error-tolerant design, early detection, plasticity, and recoverability into the HAZOP framework. Furthermore, this research provides a novel approach for integrating resilience implementation action into the HAZOP flowchart, ensuring an effective HAZOP implementation.

The case study shown in (Appendix I) was conducted in a petrochemical facility and focused on the distillation column as crucial equipment for separating feed mixtures. The integrated resilience and HAZOP assessment was used to identify potential hazards and operational challenges in the distillation process, such as feed line, rectifying column, reboiler, reflex pump and condenser. These critical equipment’s posed risks such as blockages, equipment failures, and process disturbances. To enhance the system's resilience, this study proposes a comprehensive approach that incorporates avoidance strategies, survivability control measures, and recovery capabilities.

A recent development is the emergence of risk assessment methodologies that are embedded in risk governance frameworks [IRGC, 2018; Renn, 2008]. However, these frameworks acknowledge the limitations of only identifying and addressing risks. Hollnagel et al. [2008], Jackson [2009], and Jain et al. [2016] advocate a three-stage framework for incorporating resilience into HAZOP studies. This methodology focuses on incident prevention (avoidance), system robustness (survivability), and efficient restoration (recoverability).

HAZOP is a systematic methodology for identifying potential issues within a process or system that originated at Imperial Chemical Industries (ICI) in the late 1960s, as documented by Elliot and Owen in 1968 [Swann & Preston, 1995]. HAZOP has evolved into a formalised approach [ICI, 1977] that involves a multidisciplinary team analysing potential deviations from design intent to uncover hazards, causes, and consequences. HAZOP is inherently a design review tool rather than a design tool. Positioning this study as a resilience study aligns with this distinction, as it aims to enhance system robustness while maintaining the established role and intent of HAZOP. This perspective neither contradicts nor challenges the fundamental purpose of HAZOP but rather serves as a complementary approach

The term ‘resilience’ originates from the Latin word ‘*resiliere*’, meaning ‘to rebound’ [Hosseini et al., 2016]. In recent decades, process safety management has evolved to emphasise a system’s ability to withstand and recover from disruptions and has shifted from a purely technical focus to a more adaptive approach [Fei et al., 2018]. C.S. Holling's 1973 book, Resilience and Stability of Ecological Systems, introduced the concept of resilience to a wider audience and is considered one of the pioneering works in establishing resilience concepts and principles. This seminal work laid the foundation for exploring resilience across diverse fields.

Holling [1973] defined resilience as a system's capacity to absorb disturbance, in terms of the magnitude of disruption that it can withstand, and distinguished between resilience and stability, concepts that later evolved into 'ecological resilience' and 'engineering resilience' [Bhamra et al., 2011]. Pimm [1984] subsequently characterised resilience as the time necessary for a system to return to its equilibrium state following a disturbance. Building on these concepts, Johnsen [2010] described resilience as a system's ability to endure and adapt to unexpected challenges while maintaining functionality. Finally, Caputo et al. [2023] and Pasman, as cited by Jain et al. [2016] defined resilience as a system's capacity to withstand initial disruptions and its ability to efficiently recover to normal operations.

Resilience is generally categorised into three phases: Avoidance aims to prevent disruptions, survivability focuses on mitigating the impacts of disruptions, and recoverability seeks to restore normal operations [Jain et al., 2016; Vesey et al., 2023]. Although studies use a variety of terms such as reliability, restoration, absorption, and adaptation to describe resilience phases, the fundamental goal is consistent: improving a system's capacity to handle and recover from disruptions.

## 1.1 Aims and objectives.

This research aims to enhance industrial process safety by incorporating resilience principles into HAZOP methodology.

The research study focuses on following six objectives:

1. Defining and understanding HAZOP and resilience principles.
2. Determine the limitation in traditional HAZOP studies and resilience.
3. Comparing HAZOP and resilience aspect.
4. Determining key resilience phases.
5. Integrating resilience principles into the HAZOP framework.
6. Develop a comprehensive HAZOP worksheet that incorporates resilience principles and phases.

The literature offers diverse interpretations of the attributes of resilience, as shown in Table 2. Reliability and restoration emerged as foundational dimensions [Youn et al., 2011], where reliability signifies the system's ability to sustain performance under stress and restoration is its capacity to fully recover [Hu, 2011]. However, the terminology differs across journals; 'avoidance' is sometimes termed 'reliability' or 'absorption', and 'survivability' termed 'adaption' or 'vulnerability' [Hosseini et al., 2016; Jain et al., 2016; Baroud et al., 2014]. While various journals define the term 'recoverability' as 'restoration' [Youn et al., 2011; Hosseini et al., 2016; Hoseyni, and Cordiner, 2024; Abbasnejadfard et al., 2022; Duchek, 2019]. Further resilience dimensions include anticipation, monitoring, response, and learning [Hollnagel et al., 2008], absorption, adaptation, and restoration [Hosseini et al., 2016], and reliability, vulnerability, survivability, and recoverability [Baroud et al., 2014]. These terms aim to identify and mitigate threats to safeguard personnel and the plant disruption [Jackson, 2009; Jain et al., 2016]

Table 2: Diverse terminology employed across different studies.

| Reference | Key Resilience Dimensions Discussed |
|---|---|
| Youn et al., 2011 | Reliability, Restoration |
| Jain et al., 2016; Jackson, 2009 | Avoidance, Survivability, Recoverability |
| Hollnagel et al., 2008 | Anticipation, Monitoring, Response, Learning |
| Baroud et al., 2014 | Reliability, Vulnerability, Survivability, Recoverability |

| | |
|---|---|
| Hosseini et al., 2016 ; Abbasnejadfard et al., 2022 ; Hoseyni, and Cordiner, 2024 | Absorption, Adaptation, Restoration |
| Duchek, 2019 | Anticipation/Adaptation, Exposure, Recovery/Restoration |

In conclusion, traditional HAZOP studies rely on a structured, multidisciplinary approach to identify hazards in chemical processes, assessing deviations while avoiding complexities like multiple failures and consequences [Mokhtarname, R. et al. 2020]. Incorporating resilience into traditional HAZOP studies marks a significant enhancement in process safety management. In this approach, the focus can be shifted from identifying hazards to improving a system's capacity to withstand, survive, and recover from disruptions. The literature highlights how resilience is a vital concept that is commonly divided into three phases: avoidance, survivability, and recoverability. These phases are supported by principles such as error-tolerant design, early detection, plasticity, and recoverability, which are essential for developing resilience concept. Additionally, employing guidewords from different plant layers, equipment, personnel, and management systems can enhance the integration of resilience into HAZOP studies. Some may view the incorporation of resilience into HAZOP as making the brainstorming process overly complex and less effective. However, the proposed approach offers a different perspective. Rather than treating resilience as an additional burden, we emphasize its integration into the HAZOP study to enhance its effectiveness. While HAZOP traditionally focuses on identifying hazards and mitigating risks, it often overlooks the ability of systems to adapt and recover from disruptions. Thoughtfully embedding resilience within HAZOP encourages teams to consider both safety and system robustness without adding unnecessary complexity. A practical way to achieve this is by introducing resilience-oriented guidewords or prompts at key stages of HAZOP analysis. These prompts naturally steer discussions toward system adaptability and recovery strategies while maintaining the structured flow of HAZOP. This approach ensures that resilience considerations complement safety evaluations, enriching the process without compromising efficiency.

## 2. Research methodology

### 2.1 Identification of resilience phases

The successful integration of resilience into HAZOP studies requires a thorough understanding of resilience phases and principles. Resilience is often conceptualised as a multi-phased process. According to Jain et al [2016], resilience can be simplified into three key phases: avoidance, survivability, and recoverability. Although different models exist, Figure 1 depicts a commonly used framework.

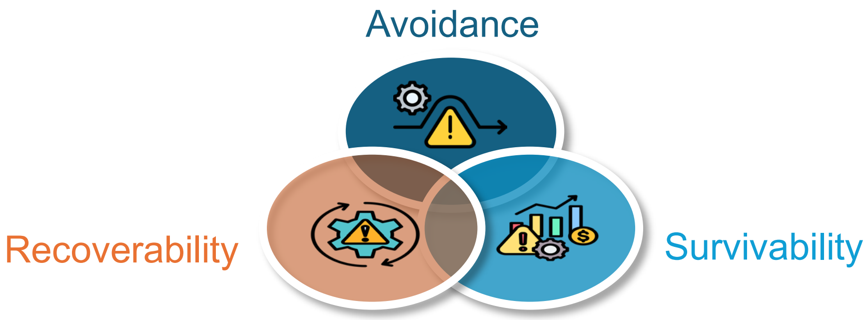


Figure 1: An illustration of the resilience phases.

Resilience goes beyond hazard identification, and its phases of avoidance, survivability, and recoverability can be proactively integrated into HAZOP [Jackson, 2009; Jain et al., 2016]. This approach identifies potential hazards, mitigates their impact, and ensures efficient system recovery.

**Avoidance**: This phase identifies the potential hazards and outcomes to avoid or stop them from causing process interruptions or harming people or the facility [Jain et al., 2016].

**Survivability**: This phase determines the factors that could lead to incidents and suggests safety control measures to reduce the chance of events occurrence [Jain et al., 2016].

**Recoverability**: This phase aims to ensure that the system can rapidly return to normal operations after an incident [Jain et al., 2016].

Figure 1 depicts the three key phases of resilience: avoidance, survivability, and recoverability. It also demonstrates how these key phases can function in relation to the transition sequence from normal operations to upset conditions and incidents. The concept of avoidance aims to use proactive avoid disruption and mitigate the risks to prevent upset conditions. However, if the system does enter an upset condition, the focus shifts to survivability. This involves maintaining critical functions and preventing the upset from escalating to an incident [Pu et al. 2023]. In the event of an incident, recoverability becomes a primary focus, including restoring the system to normal operation condition in order to minimising damage and learn from the incident.

The careful alignment of resilience phases highlights the critical magnitude of resilience principles in the development of robust systems. Therefore, embedding these principles at every phase, organisations can significantly enhance system reliability and foster adaptability to address unforeseen challenges. Figure 2 shows a comprehensive analysis of the resilience phases and principles that require a focus on avoiding disruptions and detect potential failures. During the survivability phase, the focus shifts to maintaining system function despite adverse conditions, as the system has already shifted from normal operations. The final phase focused on restoring the system to its normal state after a disturbance [Namvar and Bamdad, 2021].

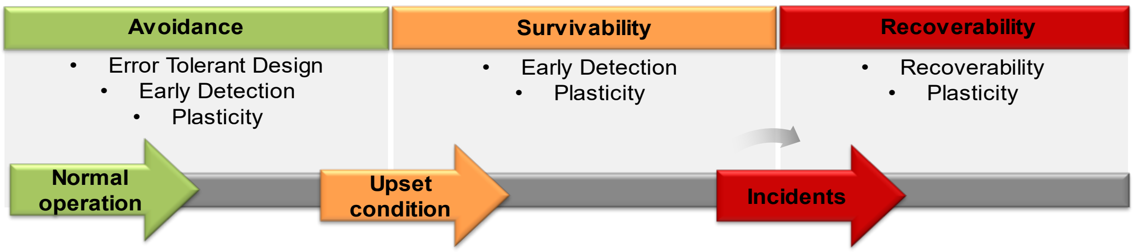


Figure 2: Phases of resilience and resilience principles [Jain et al., 2017].

## 2.2 Identification of resilience principles

Building on Hollnagel's [2008] concept of resilience, Jain et al. [2016] suggest following four core strategies for enhancing system resilience (Figure 3):

1. Designing systems that tolerate errors.
2. Detecting the early warning signs of potential deviations or issues.
3. The ability of the system to adapt and control distribution.
4. The ability of the system to recover back from disruptions.

The effective integration of resilience principles into the HAZOP process depends upon the incorporation of these four resilience strategies, which are essential for enhancing system reliability and operational efficiency.

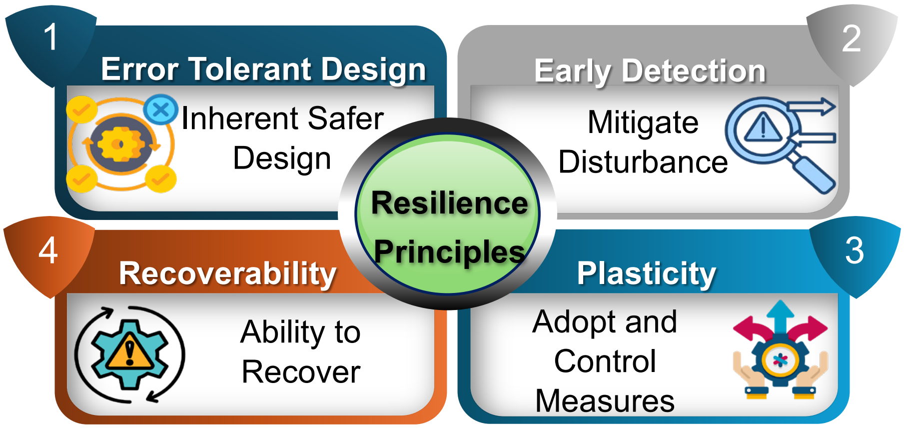


Figure 3: An overview of the resilience principles [Jain et al., 2016].

Table 3 presents four fundamental principles for constructing resilient systems: error-tolerant design, early detection, plasticity, and recoverability. These principles justify why resilience is important and offer guide models of how they can be used to safeguard systems from unexpected disruptions.

Table 3: Resilience principles and their applications.

| Resilience Principles | Rationale | Example |
|---|---|---|
| **Error-tolerant design** | Incorporating an error-tolerant design offers a more effective way to identify these errors [Kidam et al. 2015]. This will create a more robust system to handle unexpected issues. | Installing a pressure relief valve can protect the system from interruption by releasing excess pressure. |
| **Early detection** | Identifying the system weak signals and early indicators of potential issues can enable timely interventions. | Process alarms and safety culture issues can be early signs of the potential weak signals. Alarms are essential for detecting process abnormalities [Le Coze, 2008; Goel et al., 2017]. |
| **Plasticity (resistive flexibility)** | The ability of an organisation to adapt, change circumstances and maintain control during disruptions can be improved the system performance. | Knowledge sharing between experienced personnel and newcomers. Also, the communication of the shift turnover [Jain et al., 2016; Jain et al., 2018]. |
| **Recoverability** | The ability of the system to bounce back to the normal operation after disruption or incidents. | Emergency response plans and critical spare parts inventories can foster a swift recovery [Jain et al., 2018]. |

## 2.3 Integrating resilience principles into the HAZOP framework.

One effective approach to prevent catastrophic incidents is through a comprehensive risk assessment process that integrates resilience principles into both the design and operational phases. This is to proactively consider how a system might respond to unforeseen challenges, which enables process plants to enhance their ability to withstand and recover from disruptions [Jain et al., 2017a]. While the advantages of incorporating resilience into HAZOP studies are widely acknowledged, it is crucial to extend this approach to a broader risk assessment framework for optimal results. To effectively incorporate resilience into the HAZOP process, it is essential to expand HAZOP's focus to include resilience assessments, develop specific resilience guidewords, evaluate resilience throughout various stages, assess the consequences of resilience, and foster a resilience culture (Table 4).

Accordingly, the below Table 4 demonstrate a step-by-step approach to incorporate resilience into the HAZOP process. These steps will aid in implementing the integration of resilience into the HAZOP study.

Table 4: Resilience principles and their applications

| No. | Description | Incorporation details |
|---|---|---|
| **1** | **Expansion of HAZOP scope** | **Hazard identification**<br>- Traditional HAZOP focuses on identifying the hazards associated with plant operation, processes or equipment. The expansion of the HAZOP scope to include the system ability to withstand disruption,<br>**Integrating resilience principles**<br>- Integrate the resilience principles into the HAZOP framework. This will enhance the system's ability to withstand, adapt and recover after disruption. |
| **2** | **Development of resilience guidewords** | **Resilience guidewords**<br>- Create specific guidewords that address the resilience concept.<br>**Integrate Resilience Principles**<br>- Integrate the resilience principles into the HAZOP framework by developing comprehensive guidewords that address the resilience concept. |
| **3** | **Determine resilience phases** | **Avoidance phase**<br>- Incorporate the resilience principles into the design and operation stages to avoid potential threats. This will build a more robust system that can withstand distribution.<br>**Survivability phase**<br>- Evaluate the ability of the system to determine factors that could lead to incidents and propose safety measures to control them.<br>**Recoverability phase**<br>- Evaluate the ability of the system to rebound to the normal operation after incidents/distribution. |
| **4** | **Assess resilience consequences** | **Consequences**<br>- Assess the disruption impact on the system, including but not limited to production loss or environmental.<br>**Resilience measurement**<br>- Measure the consequences of the system disruption and the effectiveness of resilience implementation. |
| **5** | **Foster resilience culture** | **Training Program**<br>- Provide a training program for the HAZOP team to enhance their understanding of resilience principles and phases.<br>**Continuous enhancement**<br>- Foster a resilience culture to continuously learn and enhance the understanding of resilience aspects. |

The implementation of these incorporation steps enables organisation to enhance the effectiveness of the HAZOP studies and build a more robust risk assessment method to identify vulnerabilities. It's crucial to understand that integrating resilience principles into the HAZOP study requires a mindset shift to proactively identify risk and enhance the risk management strategies.

A visual representation of comprehensively incorporating resilience principles into the HAZOP framework (Figure 4) aims to ensure that all phases of the HAZOP assessment are considered when integrating resilience into the HAZOP framework [Penelas & Pires, 2021]. The integration of resilience principles into the HAZOP framework will enable organisation to foster error tolerance during design and operation stages, detect the system's weak signals, adaptability and facilitate a swift recovery. The rationale behind embedding these principles into the HAZOP framework is to overcome the HAZOP's limitations in terms of physical infrastructure (plant, equipment and system), human intervention and management systems (procedure, safety culture and leadership).


Figure 4: A combined HAZOP and resilience framework [Penelas, and Pires, 2021].

Table 5 illustrates the integration of resilience principles into the HAZOP framework. It outlines the key HAZOP phases and resilience principles that can enhance system resilience and mitigate risks.

Table 5: Integrated HAZOP stages and resilience concepts.

| No. | HAZOP phase | Resilience principle | Rationale |
|---|---|---|---|
| **1** | Definition (scope and objective) | Error-tolerant design | Building systems that are inherently robust to withstand unexpected events and align with HAZOP's focus on identifying deviations from design and operational intent. |
| **2** | Examination of the process/system (causes, consequences, and safeguards) | Early warning signs | Including early indicators of potential problems during this phase can enhance the system resilience. |
| **3** | | Plasticity | The ability to adapt and changing circumstances between normal and abnormal operations is emphasised in the HAZOP examination phase. |
| **4** | Recommendations and HAZOP documentation | Recoverability | The final HAZOP phase aligns with resilience principles to quickly return to normal operations after disruptions. |

## 2.4 Resilience and HAZOP process integrated flowchart

A comprehensive examination of resilience principles was undertaken to effectively integrate them into the HAZOP flowchart [Mokhtarname, et al. 2024; Zinetullina et al., 2021]. Figure 5 illustrates this integrated approach and provides a comprehensive guide for incorporating resilience considerations into HAZOP studies. This flowchart offers a clear roadmap for enhancing system robustness and survivability.

The HAZOP and resilience analysis is a systematic approach to identify and mitigate potential hazards within a system. It begins by defining the system's operational boundaries and breaking it down into key stages or nodes [Rossing et al., 2010]. The analysis extends to assessing the system's resilience by identifying early warning indicators and evaluating its ability to maintain control and recover from disruptions.

The integration of resilience into HAZOP is a novel and complex approach that requires a structured explanation to ensure clarity and usability. While the current study thoroughly addresses the concept, its logical flow can be refined to enhance comprehension. To improve readability, the methodology could benefit from a clearer step-by-step breakdown of how resilience principles such as avoidance, survivability, and recoverability are incorporated into HAZOP at different stages (Figure 5). Additionally, using structured flowcharts and tables to illustrate the integration process would provide a more intuitive understanding. The resilience guidewords stipulated in (Table 6) and their application within HAZOP could be explicitly mapped to traditional HAZOP elements, ensuring a seamless connection between the two concepts. Furthermore, a more detailed explanation of the resilience and HAZOP integrated flowchart, with real-world examples from the case study (shown in Appendix I).

The methodology of combining resilience principles into HAZOP, aims to enhance the overall system safety and reliability. The flowchart demonstrates the overall process for conducting the resilience and HAZOP study. It aims to identify potential hazards and develop resilience strategies to eliminate risks while enhancing the system's ability to withstand and recover from disruptions. The HAZOP and resilience flowchart (Figure 5) outlines a structured approach to integrating resilience principles into traditional HAZOP. The process begins with plant, unit, or system selection, followed by defining the scope and objectives. The HAZOP analysis identifies operational nodes, selects parameters, and determines possible deviations along with their causes and consequences. If deviations exist, additional safety and recovery measures are proposed.

The resilience implementation phase assesses the system's ability to tolerate errors, detect early warning signs, maintain control, and recover from disruptions. If gaps are identified, safety enhancements, early warning mechanisms, or recovery strategies are recommended. The process is iterative, ensuring continuous improvement through the evaluation of additional nodes and parameters before finalising the assessment. This integrated approach strengthens risk management by embedding resilience strategies into hazard identification and mitigation.

The flowchart can be broken down into steps that comprehensively cover the integration process.

**Step-by-Step Breakdown**

1. **HAZOP assessment (start point):**
- **Plant/unit/system selection:** Selection of plant, unit, or system to analyse.
- **Definition of scope and objective:** Clearly define the objective and scope of the integrated resilience and HAZOP study.
2. **HAZOP analysis:**
- **Determine the plant operation nodes**: identify the selected elements (nodes) within the plant operation.
- **Define and select parameter:** Determine which parameters will be assess and evaluated during the integrated process.
- **Determine possible deviations:** Evaluate the possible deviation to examinate the potential causes and consequences.
- **Investigate other deviations (if applicable):** evaluate the possibility of additional deviations if the selected deviation doesn't exist.
- **Purpose additional safety and recovery measures:** Utilise existing safeguards or propose additional ones to mitigate the identified risks and hazards.
3. **Resilience implementation actions:**
- **Node selection assessment:** Evaluate the selected node based on the inherently safer design aspect and resilience principles.
- **Detection of early signs:** Identify early warning signs and weak signals of potential risks which can facilitate timely interventions.
- **Determine control measures:** Determine the control measure to reduce the impact for unexpected distribution.
- **Determine the capability of recovery:** Determine and assess the system ability to recover.
4. **Repetitive process and action:**
- Propose additional system, equipment, and parameters to address additional hazards associated with the selected nodes.
- Propose additional safety measures to enhance the system's resilience.
5. **Integrated resilience and HAZOP assessment (end):**
- After assessing and evaluating all selected nodes, the process of integrating resilience into HAZOP concludes.

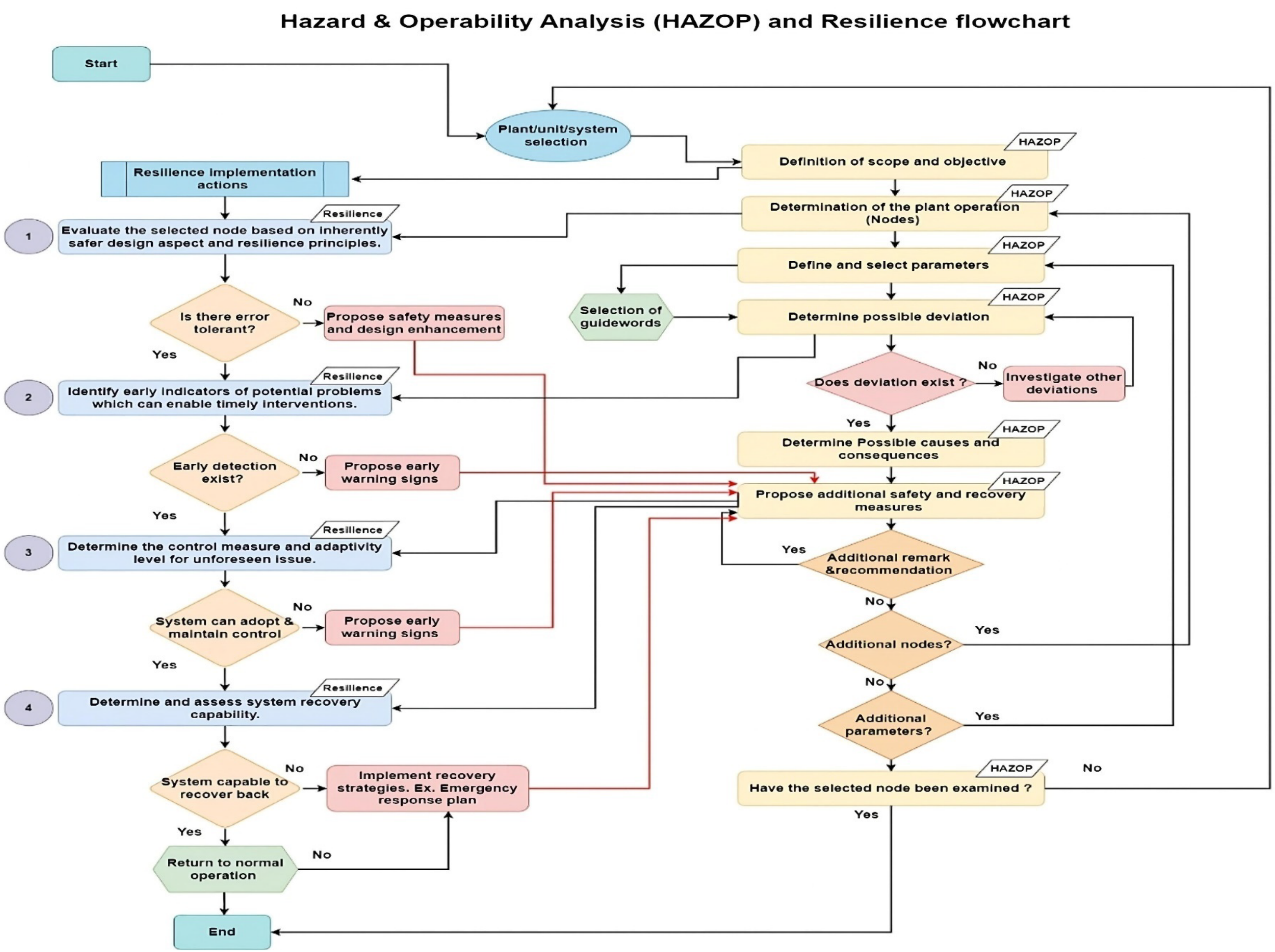


Figure 5: The integrated resilience and HAZOP flowchart.

## 2.5 Resilience guidewords

Process plants are complex systems that involve facilities, equipment, personnel, and management systems. Breaking down these components into separate elements helps to seamlessly incorporate resilience planning into hazard and operability (HAZOP) studies and enhances the effectiveness of implementing resilience measures. Recognising the significance of resilience, researchers Gentile et al. [2003] and Khan et al. [2005] introduced a unified inherent safety index. This index employs standardised guidelines to identify core safety principles, which are essential for building resilience. The suggested guidewords were adapted from the human factor's principles outlined by Crowl in 2007. To effectively integrate resilience into HAZOP, it is crucial to develop guidewords that align with traditional HAZOP methods and clearly define facility, equipment, human intervention, safety culture and procedures, as illustrated in Table 6. The suggested guidewords were categorised into three primary pillars to simplify comprehension and facilitate the integration of resilience:

1. **Physical infrastructure (facility and equipment)**

- Traditionally, HAZOP analysis identifies potential hazards arising from equipment malfunctions (equipment reliability) or fluctuations in process parameters such as temperature, pressure, and flow rate (process maintainability). These studies rely heavily on guidewords like 'more', 'less', and 'no' to explore different scenarios. The absence of this focus can contribute to major incidents, as seen in the 2017 Kawasaki Tennessee Aluminium Dust Fire [Okoh, 2019].

2. **Human factors (People)**

- Human actions are the driving force behind an organisation's success or downfall. Recognising the crucial role of human performance, organisations prioritise process safety [Crowl, 2007]. Employees are the cornerstone of any organisation, and their actions and decisions contribute to achieving safety goals. They are accountable for identifying potential risks and following established protocols to operate and maintain facilities [Baybutt, 2013].

3. **Organisational factors (management systems; safety culture and leadership; procedures)**

- A safety management system consists of four key components: leadership and safety culture, procedures, and project design and execution [Crowl, 2007]. Safety culture is a blend of values, attitudes, and perceptions [HSE, 2014]. A strong safety culture can positively influence the implementation of resilience [Olive et al., 2006]. Procedures act as a roadmap for routine and abnormal operations to help organisations maintain safe and reliable operations. Design and execution are crucial for any project to minimise risk and ensure inherently safer designs [Taylor, 2017].

Within each pillar, numerous works were included to address resilience aspects concerning both people and plant assets (systems, facilities, and equipment). This categorisation is crucial for identifying hazards and ranking risks consistently using the HAZOP methodology.

Table 6 presents guidewords organised by the three resilience pillars: physical infrastructure (facilities and equipment), human factors (people), and organisational factors (safety culture, leadership, and procedures).

Table 6: Resilience guidewords for facilities and equipment, human, and plant management systems.

| **Facilities and equipment guidewords** | | | |
|---|---|---|---|
| **Resilience Principle** | **Guidewords** | **Abbreviations** | **Parameters** |
| Error-tolerant design | More, Less, No | ETD (1) | Relief Valves (RV), Emergency Shutdown Devices (ESD), Safety Instrument Function (SIF) |
| Early detection | More, Less, No | ED (1) | Leaks/Release, Corrosion, Vibration |
| Early detection | Missed, Inadequate, Incomplete | ED (2) | Activation of Alarm, Trips, Pressure Relief |
| Early detection | Actioned, Adequate, Complete | ED (3) | Activation of Alarm, trips, Pressure relief |
| Plasticity | Inadequate, Incomplete | P (1) | Maintenance, Inspection |
| Plasticity | Planned, Unplanned | P (2) | Maintenance, Inspection |
| Recoverability | Unavailable, Incomplete | R (3) | Emergency Shutdown valve |
| **People guidewords** | | | |
| **Resilience Principle** | **Guidewords** | **Abbreviations** | **Parameters** |
| Plasticity | Lack | P (3) | Supervision, Training, Procedures |
| Plasticity | Overlook, Missing | P (4) | Action |
| Early detection | Missed, Mistimed | ED (4) | Alarm |
| Plasticity | Not Actioned, Inadequate, Incomplete | P (5) | Communication |
| Plasticity | Inadequate, Incomplete | P (6) | Maintenance, Inspection |
| Plasticity | Planned, Unplanned | P (7) | Maintenance, Inspection |
| Plasticity | Wrong, Inadequate | P(13) | Sample Collection |
| **Safety culture and leadership' guidewords** | | | |

| Resilience Principle | Guidewords | Abbreviations | Parameters |
|---|---|---|---|
| Plasticity | Missing, Incomplete | P (8) | Safety, Training |
| Plasticity | Missing | P (9) | Security Threats |
| Early detection | Missing, Inadequate | ED (5) | Metrics, Reporting |
| Recoverability | Unavailable, Incomplete | R (1) | Process Emergency Response Plan |
| **Procedure guidewords** | | | |
| **Resilience Principle** | **Guidewords** | **Abbreviations** | **Parameters** |
| Early detection | Unavailable, Incomplete | ED (6) | Inspections, Procedures |
| Plasticity | Unavailable, Incomplete | P (10) | Maintenance, Procedures |
| Plasticity | Wrong, Inadequate | P (11) | Isolation |
| Recoverability | Unavailable, Missing | R (2) | Blind List, ESD Locations |
| Plasticity | Unavailable, Missing | P (12) | Sample Collection, Procedures |

## 2.6 HAZOP and resilience integrated worksheet

Resilience concepts can be integrated into the HAZOP analysis worksheet (See Figure 6). The integration of resilience principles (previously listed in Table 4) into the HAZOP study can expand the focus of traditional risk assessment by identifying potential operational and design hazards. This integration aims to enhance the overall plant's safety performance, enabling the plant system to withstand, adapt to, and recover from unexpected disruptions. This holistic approach promotes a more robust risk assessment strategies and enhance the overall system resilience. The integrated resilience and HAZOP worksheet was designed to incorporate resilience principles and phases.

## 2.7 Integrated worksheet risk matrix

A risk matrix is a key tool in HAZOP studies for evaluating and prioritising potential risks. It visually ranks risks based on the severity of potential harm and the likelihood of occurrence (Figure 7). This facilitates identifying control measures and high-priority risks that require immediate action [Crawley & Tyler, 2015; Marhavilas, et al. 2019]. The risk matrix provides a clear, structured way to manage risks in complex systems [Musthafa, 2023].

The risk matrix is a crucial tool for integrating resilience concepts into HAZOP studies. It provides a structured framework to assess the likelihood and severity of risks alongside the system's ability to withstand, adapt to, and recover. By categorising risks based on their potential impact and frequency, the risk matrix helps teams prioritise critical hazards while also evaluating the system's resilience [Pramoth et al., 2020]. For example, when using the risk matrix, resilience principles like error-tolerant design can assess the system's ability to handle unexpected disruption without escalating the consequences.

Similarly, the early detection principle can be evaluated to ensure the system can detect weak signals. The matrix also allows for an assessment of the system's plasticity to ensure that high-priority risks can be maintained and controlled [Qureshi, 2022]. Finally, the recoverability aspect can be evaluated to ensure swift recovery to normal operations after a disruption. This comprehensive approach enables organisations to establish risk-based approaches, including resilience principles.

| HAZOP & RESILIENCE STUDY REPORT | | | |
|---|---|---|---|
| DATE: | | P & ID NUMBER: | |
| NODE: | | | |
| DESIGN INTENT OF THE SYSTEM: | | | |
| HAZOP CHAIRMAN: | | | |
| HAZOP TEAM MEMBERS | 1) | | |
| | 2) | | |
| | 3) | | |
| | 4) | | |

| Guide Word (HAZOP) | Deviation | Possible Cause | Consequences | Existing Safeguards | Severity | Likelihood | Risk | Recommendation | Action taken |
|---|---|---|---|---|---|---|---|---|---|
| NO | NO FLOW | | | | | | | | |
| MORE | MORE FLOW | | | | | | | | |
| | MORE PRESSURE | | | | | | | | |
| | MORE TEMPERATURE | | | | | | | | |
| LESS | LESS FLOW | | | | | | | | |
| | LESS PRESSURE | | | | | | | | |
| | LESS TEMPERATURE | | | | | | | | |

| Guide Word (Resilience - Human scheme) | Deviation | Resilience aspects | Possible Cause | Consequences | Existing Safeguards | Severity | Likelihood | Risk | Recommendation | Resilience Phases |
|---|---|---|---|---|---|---|---|---|---|---|
| Inadequate | Inadequate inspection | Plasticity (P-4) | | | | | | | | |
| Mistimed | Missing alarm action | Early detection (ED-4) | | | | | | | | |
| Unavailable, incomplete | Unavailable emergency Response Plan | Recoverability (R-1) | | | | | | | | |
| More, Less, No | No safety instrument function (SIF) | Error-tolerant design (ETD-1) | | | | | | | | |
| Lack | Luck of supervision, training, procedure | Plasticity (P-1) | | | | | | | | |
| Overlook/missing | Action | Plasticity (P-2) | | | | | | | | |
| Not Actioned, inadequate, incomplete | Communication | Plasticity (P-3) | | | | | | | | |
| Planned, unplanned | Maintenance, inspection | Plasticity (P-5) | | | | | | | | |
| Unavailable, incomplete | Unavailable inspection procedure | Early detection (ED-6) | | | | | | | | |

Figure 6: A combined worksheet for resilience and HAZOP analysis.

**Consequences**

| | | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|---|
| | **Risk Matrix** | | **Negligible** | **Minor** | **Moderate** | **Major** | **Catastrophic** |
| **Li kel iho od** | **5** | **Almost Certain** | (5) Moderate | (10) High | (15) Very High | (20) Extreme | (25) Extreme |
| | **4** | **Likely** | (4) Moderate | (8) Moderate | (12) High | (16) Very High | (20) Extreme |
| | **3** | **Possible** | (3) Low | (6) Moderate | (9) Moderate | (12) High | (15) Very High |
| | **2** | **Unlikely** | (2) Low | (4) Low | (6) Moderate | (8) Moderate | (10) High |
| | **1** | **Rare** | (1) Low | (2) Low | (3) Low | (4) Moderate | (5) Moderate |

Figure 7: The 5x5 risk matrix [Musthafa, 2023].

# 3. Project Results

## 3.1 Case Study: Distillation column in the petrochemical industry

The case study demonstrates the process of distillation column, as it's an essential process in the petrochemical industry for separating substances. For example, one distillation process separates components of a feed mixture into top and bottom products, as demonstrated by the process flow diagram below (Figure 8) [Tan and Cong, 2023]. This process is used in various industries, including the chemical, petrochemical, and refining industries. A Hazard and Operability (HAZOP) study was conducted to identify potential hazards and operability risks within this distillation process.

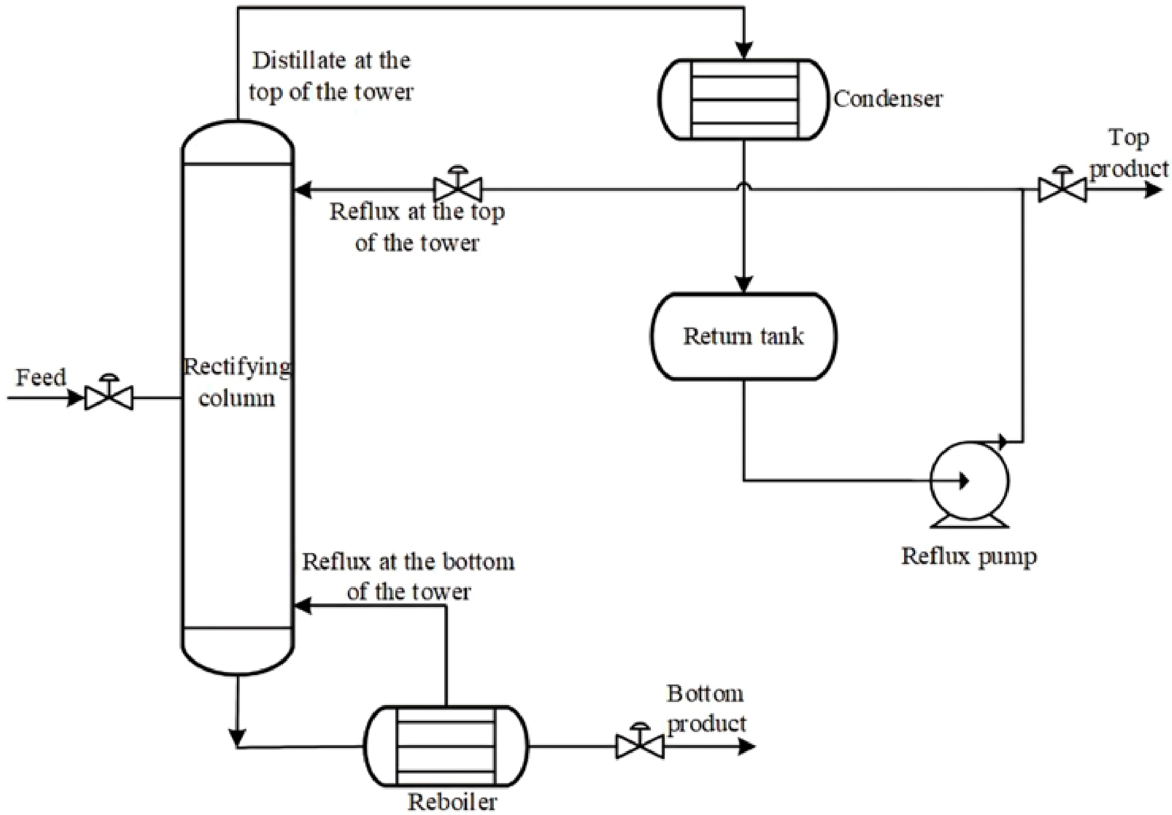


Figure 8: Process flow diagram (PFD) of a distillation column in petrochemical industries [Tan and Cong, 2023].

### 3.1.1 Detailed process description of the distillation column system

A typical distillation column setup, such as the one depicted in Figure 8, separates a feed mixture into two products: a distillate (top product) and bottoms (bottom product). The following section provides a detailed explanation of each component and its role in the process [Tan and Cong, 2023]. The process involves the feed entering the rectifying column, which is where the separation occurs. The top product is condensed, and then part of it is returned as reflux. Similarly, part of the bottom product is collected, and part of it is reboiled and returned to the column.

The main parts of the system are:

**1- Feed line:**

The feed mixture enters the distillation column through the feed line.

**2- Rectifying column:**

The rectifying column is the key equipment to separate the feed mixture. The mixture inside the column is subjected to a cycle of vaporisation and condensation to separate the components based on their boiling points.

**3- Reboiler:**

The reboiler heats and vaporises the liquid at the bottom of the column and rises back up through the column. This provides sufficient energy for the distillation and the separation processes. The bottom product, which contains the feed components with the high boiling points, is discharged from the reboiler.

**4- Condenser:**

The condenser cools the vapour that rises to the top of the rectifying column and condenses it back into a liquid known as the distillate.

**5- Return tank:**

The return tank stores the condensed distillate and returns it to the top of the rectifying column as reflux to improve the separation efficiency.

**6- Reflux pump:**

The reflux pump circulates the liquid from the return tank and returns it to the top of the rectifying column.

**7- Top product valve and bottom product valve:**

The top and bottom product valves control the removal of the distillate from the system.

### 3.1.2 Nodes

A key step in an effective HAZOP analysis is breaking down the process into smaller sections (called nodes) for detailed review. Each selected node is examined using the integrated resilience and HAZOP methodology to consider factors such as process conditions, operating parameters, and design goals [Dunjó et al., 2011].

The case study's HAZOP study was conducted by examining nodes at key points in the process. Each node was analysed for deviations using HAZOP guidewords ('no', 'more', 'low', and 'high') and resilience guidewords . The integrated resilience and HAZOP case study included seven nodes as shown in Table 7.

Table 7: Description of nodes based on the process flow diagram of the case study

| Node | Equipment description | Element |
|---|---|---|
| 1 | Feed line | Flow |
| 2 | Rectifying column | Pressure |
| 3 | Condenser | Cooling |
| 4 | Return tank | Level |
| 5 | Reflux pump | Flow |
| 6 | Reboiler | Temperature |
| 7 | Top and bottom product outlets | Composition |

### 3.2 Case Study 1 Results: Distillation column in the petrochemical industry

The integrated resilience and HAZOP analysis for the distillation column in the petrochemical industry identified critical safety and operational risks. The feed line node (shown in Appendix I) was evaluated based on risk ranking of potential impacts such as blockages in feed line, control valve malfunction and pump failure. These possible causes could compromise the overall plant safety. The integrated study recommends installing a backup feed pump, a bypass to divert the flow, and a dual flow control valve. These measures align with resilience concepts and principles to avoid, adapt to, and recover from disruptions.

The integrated resilience and HAZOP study also identified pressure and cooling as potential critical issues in the rectifying column and condenser. High pressure, caused by a blockage, could damage equipment, while low pressure from leaks could disrupt operations in the rectifying column. Insufficient cooling and excessive cooling were identified as deviations for the condenser. In order to mitigate the risks associated with cooling deviations, the integrated study recommended installing a redundant cooling system to address insufficient cooling and temperature control monitor to address excessive cooling cause. These recommendations will enhance the system's ability to withstand and bounce back after cooling disruptions. The generated recommendations contribute to maintaining ideal process conditions for a stable and efficient distillation process.

The integrated study emphasised the criticality of maintaining stable levels and flow rates within the return tank and reflux pump. Abnormal conditions, such as excessive or insufficient tank levels due to equipment failure, could lead to operational distribution such as control valve failure or pump failure. Similarly, reflux pump malfunctions could significantly disrupt the process. In order to overcome these potential hazards, the study recommended installing redundant level sensors, low-level shutoff valve, and backup pump. These safety measures align with the resilience principles of survivability and recoverability since they enable the system to withstand disturbances and swiftly return to normal operations. Moreover, high and low temperatures were identified as potential threats to the reboiler process. To address these hazards, the study recommended installing a temperature sensor along with a backup reboiler to overcome the low temperature scenarios.

Furthermore, maintaining product quality by adhering to specifications for top and bottom product outlets was identified as essential. The study recommended the installation of a product composition analyser and the implementation of periodic maintenance to prevent off-spec product. These recommendations align with the resilience principle of avoidance by proactively preventing issues.

To further explore each application and the methodology used for specific nodes, Table 8 provides a detailed analysis of the case study outcomes. It is worth mentioning that the deviations highlighted there are illustrative examples to comprehensively showcase the potential benefits. Additional deviations can be found in Table 9 and Appendix I (Integrated resilience and HAZOP worksheet) for further reference.

The integrated resilience and HAZOP worksheet was applied to selected nodes of the distillation column to demonstrate the rationale and benefits of this combined approach. After node selection, a HAZOP study was conducted to identify risks associated with the feed line (Node 1). Subsequently, the three phases of resilience (avoidance, survivability, and recoverability) were incorporated and translated into specific recommendations. The intention was to avoid deviations that could lead to catastrophic incidents. The risk evaluation was conducted based on typical risk assessment methods, using the risk matrix as shown in Figure 7. The integration of resilience extends beyond the implementation of resilience phases; it also integrates resilience principles such as human factors, organisation, and plant management systems. Multiple rows were developed and added to the worksheet to add on the resilience principles based on the causes. Table 8 showcases the results for Node 1 (feed line) based on the example issue of flow deviation (Node 1 – Feed line – More flow deviation).

Table 8: Integrated resilience and HAZOP process examining flow deviation at Node 1.

| **Deviation** | **Consequences** | **Resilience phases** | **Resilience principles** | **Possible cause** | **Recommendation** |
|---|---|---|---|---|---|
| More flow | Column overload and potential overfilling, which could lead to reduced separation efficiency. | Survivability and recoverability | Error-tolerant design (ETD-1). | Error-tolerant design was not considered in the early design stage leading to pump malfunction. | - Install dual flow control valve and a bypass to divert the flow.<br>- Install a relief valve in the distillation column |

| | | | | | |
|---|---|---|---|---|---|
| More flow | Potential for a pump malfunction, resulting in a more flow scenario | Survivability and recoverability | Plasticity (P-6) | Inadequate operator maintenance on the pump | - Site supervisor to monitor critical activity.<br>- Implement operator development program |

Table 9 presents the entire methodology employed to integrate resilience into the HAZOP study and showcases the outcomes of this approach.

Table 9: The outcomes of integrating resilience into HAZOP

| **Node 1:** Feed Line **- Element:** Flow | | |
|---|---|---|
| **Deviation** | **Result and recommendation based on resilience phases** | **Resilience principles** |
| - More flow<br>- Low flow<br>- No flow | **Avoidance**<br>- Install a standby feed pump.<br>- Conduct periodic inspection.<br>**Survivability**<br>- Install dual flow control valve.<br>- Install a bypass to divert the flow.<br>**Recoverability**<br>- Install additional relief valve in the distillation column.<br>- Site supervisor to monitor critical activities.<br>- Implement operator development program. | - Error-tolerant design (ETD-1) (related to design issue).<br>- Plasticity (P-6) (related to human error). |
| **Node 2:** Rectifying Column - **Element**: Pressure | | |
| **Deviation** | **Result and recommendation based on resilience phases** | **Resilience principles** |
| - High pressure<br>- Low pressure | **Avoidance**<br>- Schedule periodic inspections.<br>- Install additional pressure-monitoring sensors.<br>**Survivability**<br>- Install additional vacuum breakers.<br>- Conduct regular leak tests.<br>**Recoverability**<br>cal alarm rationalisation program.<br>ng and awareness.<br>nt drills that simulate leak scenarios. | - Early detection (ED-4) (related to human error-missed alarm)<br>- Plasticity (P-5) (related to human error – no action taken) |
| **Node 3**: Condenser - **Element**: Cooling | | |
| **Deviation** | **Result and recommendation based on resilience phases** | **Resilience principles** |

| | | |
|---|---|---|
| - No cooling<br>- Low cooling | **Avoidance**<br>- Install redundant temperature controls.<br>- Review condenser cooling performance.<br>**Survivability**<br>- Install backup cooling systems.<br>- Regular maintenance of condenser tubes.<br>**Recoverability**<br>- Install emergency isolation valve to shutdown column feed.<br>- Develop a critical alarm rationalisation program.<br>- Operator training and awareness. | - Plasticity (P-1) (related to inadequate maintenance)<br>- Recoverability (R-3) |
| **Node 4**: Level Controls - **Element**: Level | | |
| **Deviation** | **Result and recommendation based on resilience phases** | **Resilience principles** |
| - High level<br>- Low level | **Avoidance**<br>- Install redundant level sensors.<br>- Install high-level shutoff systems.<br>- Regular maintenance of control valves.<br>**Survivability**<br>- Install redundant temperature controls.<br>- Install low-level shutoff systems.<br>**Recoverability**<br>- Develop a maintenance plan, including a critical equipment list.<br>- Implement site supervision. | - Plasticity (P-1) (related to inadequate maintenance)<br>- Plasticity (P-4) (related to inadequate maintenance) |
| **Node 5**: Reflux Pump - **Element**: Flow | | |
| **Deviation** | **Result and recommendation based on resilience phases** | **Resilience principles** |
| - No flow<br>- High flow | **Avoidance**<br>- Install flow restrictors.<br>- Conduct periodic flow calibration.<br>**Survivability**<br>- Install a standby pump.<br>- Install flow controls on the pump outlet.<br>**Recoverability**<br>- Develop a maintenance plan, including a critical equipment list.<br>- Operator training and awareness.<br>- Implement site supervision. | - Plasticity (P-1)<br>- Plasticity (P-4) |
| **Node 6**: Reboiler - **Element**: Temperature | | |
| **Deviation** | **Result and recommendation based on resilience phases** | **Resilience principles** |

| Deviation | Result and recommendation based on resilience phases | Resilience principles |
|---|---|---|
| - High temperature<br>- Low temperature | **Avoidance**<br>- Install temperature sensors.<br>- Conduct periodic maintenance.<br>**Survivability**<br>- Develop a maintenance plan, including a critical equipment list.<br>- Implement an assets integrity program.<br>- Install a standby pump.<br>- Install a backup reboiler to avoid process upset.<br>**Recoverability**<br>- Operator training and awareness.<br>- Implement site supervision. | - Plasticity (P-1)<br>- Plasticity (P-4) |
| **Node 7:** Top and Bottom Product Outlets - **Element**: Composition | | |
| **Deviation** | **Result and recommendation based on resilience phases** | **Resilience principles** |
| - High composition<br>- Low composition | **Avoidance**<br>- Install a product composition analyser.<br>- Conduct periodic maintenance on the sample points.<br>**Survivability**<br>- Product quality monitoring program.<br>**Recoverability**<br>- Standardised sampling procedure.<br>- Operator training and awareness. | - Plasticity (P-13) (sample collection) |

### 3.3 Summary of case study results

The integrated resilience and HAZOP methodology applied to all selected nodes resulted in recommendations that go beyond traditional hazard identification methodologies like HAZOP. The incorporation of resilience principles such as error tolerance, early detection, plasticity, and recoverability, aids in identifying and mitigating risks and enhances the system's overall robustness. This comprehensive approach ensures the system's ability to avoid disruptions, survive incidents, and recover quickly, thus improving operational reliability and safety.

## 4. Discussion

The integrated resilience and HAZOP study conducted on distillation columns in the petrochemical industry identified several critical hazards that could potentially compromise the safety and efficiency of the process. The results revealed that the feed line node, rectifying column, condenser, return tank, reflux pump, and product outlets are particularly vulnerable to disruptions.

The study's findings highlight the importance of implementing a robust resilience strategy. By incorporating the recommended actions, the distillation process can be protected against potential hazards, enhancing its overall safety and reliability (Table 10). The emphasis on avoidance, survivability, and recoverability is crucial for maintaining ideal process conditions and minimising the impacts of unforeseen events.

Table 10: Recommended actions for the distillation column nodes identified in Table 7

| Node | Element | Deviation | Resilience Principle | Resilience Phase | Purpose | Recommended Action |
|---|---|---|---|---|---|---|
| 1 | Flow | No flow | Error-tolerant design | Avoidance | Prevent disruptions from blockages and sustain continuous production. | Install a backup feed pump and implement periodic inspection. |
| | | Low flow | Early warning signs | Survivability | Maintain flow control during control valve malfunctions. | Install a bypass to divert the flow. |
| | | More flow | Plasticity | | Prevent overfilling and ensure adequate separation efficiency. | Install dual flow control valve. |
| 2 | Pressure | High pressure | Early warning signs | Avoidance | Prevent overpressure and potential damage to the column through effective detection signals. | Install additional pressure control monitoring sensors and conduct periodic inspections. |
| | | Low pressure | Recoverability | Recoverability | Enable swift recovery from upset | Install additional vacuum breakers and conduct regular leak tests. |
| 3 | Cooling | No cooling | Error-tolerant design | Avoidance | Ensure efficient condensation process to prevent overpressure which increase the | Install backup cooling systems and perform regular maintenance for condenser tubes. |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | | | | tolerance of cooling failures. | |
| | | More cooling | Plasticity | Survivability | Avoid inadequate condensation process by maintaining column stability. | Implement redundant temperature controls and review cooling performance periodically. |
| 4 | Level | High level | Early warning signs | Avoidance | Prevent overflow scenario and process disruptions through effective detection intervention. | Install redundant level sensors and high-level shutoff systems and maintain control valves regularly. |
| | | Low level | Recoverability | Recoverability | Maintain adequate reflux process and recover after pump failure. | Install low-level shutoff systems and ensure the availability of backup pumps. |
| 5 | Flow | No flow | Error-tolerant design | Avoidance | Prevent temperature fluctuations and ensure consistent flow | Install flow restrictors and conduct periodic flow calibration. |
| | | High flow | Plasticity | Survivability | Avoid overfilling of the column. | Install flow controls on the pump outlet and calibrate regularly. |
| 6 | Temperature | High temperature | Error-tolerant design | Avoidance | Prevent thermal degradation and decrease fire risks by building tolerance for control failure. | Install temperature sensors and perform periodic maintenance. |
| | | Low temperature | Recoverability | Recoverability | Ensure separation efficiency and recovery after mechanical failures. | Install a backup reboiler and implement temperature monitoring program. |
| 7 | Composition | Off-spec product | Early warning signs | Avoidance | Ensure product quality | Install a product analyser and conduct periodic maintenance on plant sample points. |

The study effectively demonstrates the integration of resilience into HAZOP but could be further strengthened by incorporating more practical industrial examples. Certain equipment, such as screw compressors, inherently exhibit resilience due to their design flexibility and operational adaptability. Additionally, surge control mechanisms in compressors enhance system stability by preventing operational disturbances, while mechanical systems like surge relief valves and bladders ensure the resilience of piping networks by mitigating pressure fluctuations. To further illustrate how the resilience approach can be assessed across different equipment, the following (Table 11) provides practical examples of various industrial systems, their associated deviations, and the resilience strategies used to enhance their avoidance, survivability, and recoverability. This structured approach helps demonstrate how resilience principles can be systematically incorporated into industrial safety frameworks.

Table 11: Recommended actions for enhancing resilience in various industrial equipment.

| Element | Equipment | Deviation | Resilience Principle | Resilience Phase | Recommended Action |
|---|---|---|---|---|---|
| Pressure | Surge Relief Valve | High Pressure Surge | Plasticity | Recoverability | Install surge relief valves and conduct periodic maintenance. |
| Flow | Screw Compressor | Overloading | Error-tolerant design | Avoidance | Install overload protection and continuous monitoring. |
| Flow | Surge Control System (Compressor) | Surge Event | Early detection | Survivability | Implement surge control mechanisms and alarm systems. |
| Piping System | Bladder System | Pressure Fluctuation | Recoverability | Recoverability | Use bladder surge tanks to dampen pressure variations. |
| Control System | Process Safety Control System | Instrumentation Failure | Early detection | Avoidance | Implement redundant control loops and fail-safe mechanisms. |

It is essential to note that while this study provides a comprehensive overview of potential hazards and resilience concept strategies, the effectiveness of these recommendations will depend on their effective implementation. Audits and risk assessments are crucial for identifying potential risks and achieving necessary modifications to the resilience strategy. The study's findings emphasise on the importance of a holistic approach to the process safety. The overall system resilience will be enhanced by addressing these potential hazards and integrating resilience principles within the distillation column. The implementation of the recommended actions depends upon the criticality of the selected system.

In conclusion, the integrated resilience and HAZOP study provided comprehensive insights into the potential risks associated with the distillation process. The petrochemical industry can significantly improve the safety, reliability, and efficiency of its operations by implementing the resilience principles and phases. Constant monitoring and evaluation of the resilience strategy will be essential to ensure the long-term sustainability of this integration.

## 5. Recommendations

To facilitate the integration of resilience into the HAZOP process, organisations should systematically incorporate resilience principles into the HAZOP frameworks. This can be executed by modifying existing HAZOP frameworks to include specific criteria that evaluate the resilience of systems. By embedding resilience principles into the HAZOP framework, organisations can better prepare to respond and recover from unexpected disruptions to ensure business continuity.

One important factor of implementing this integration is allocating resources to train HAZOP teams on resilience concepts. This highlights the significance of proactive risk management strategies that extend beyond traditional hazard identification. The training should encompass practical guidance on evaluating the system performance in line with resilience principles during design and operational stages. Furthermore, a value versus cost analysis is essential to assure the effective implementation of the integrated framework. The benefits of incorporating resilience measures, like risk reduction, need to be assessed against the expenses associated with their implementation.

By incorporating resilience into HAZOP studies, organisations can significantly minimise the likelihood of operational disruptions and improve their capacity to swiftly recover from any incidents that do occur [Shirali et al., 2012]. This approach enhances safety and reliability and ensures long-term operational sustainability in an increasingly complex and risky industrial environment. Continuous monitoring, frequent audits, and fostering an organisational resilience culture are essential to maintain the effectiveness of this integration approach.

## 6. Conclusion and Future work

This dissertation effectively demonstrates the importance of integrating resilience principles into HAZOP methodology to enhance the safety and reliability of industrial processes, especially in high-risk environments like the petrochemical industry. By expanding the traditional focus of HAZOP beyond hazard identification to encompass resilience aspects such as error-tolerant design, early detection, plasticity, and recoverability, this study presents a more comprehensive approach to risk management. The case study on distillation columns in the petrochemical industry identified several potential risks and demonstrated how the incorporation of resilience principles can proactively mitigate these risks to ensure the system's ability to withstand, adapt and recover from disruptions. The result findings underscore the importance of adopting resilience strategies for improving process safety. This contributes to the long-term operational sustainability by minimising the impact of unforeseen events and facilitate swift recovery.

The integration of resilience into HAZOP studies enables organisations to proactively mitigate risks and promote a culture of continuous improvement. This will enhance their ability to adapt and recover from disruptions. Integrating resilience into risk management prepares process industries to anticipate and respond to emerging challenges such as incidents or upsets. Finally, the integrated risk assessment proposes a novel approach to bolster safety in industrial sectors and enhance the system's ability to withstand, adapt to, and recover from disruptions. This groundwork proactively prepares plants for any disruption that could jeopardise plant, personnel, or environmental safety. Building on the foundation established by this research, further research is required to enhance and expand the proposed methodology for integrating resilience into HAZOP studies. Future studies should prioritise the following areas:

1. **Development of quantitative or semi- quantitative metrics:** To improve the practical utility of resilience principles, future research should focus on creating and validating quantitative or semi-quantitative metrics that can be incorporated into the HAZOP process.
2. **Applicable to various industrial sector:** While this study focused on the petrochemical industry, the resilience methodology should be evaluated and modified to be used in other high-risk sectors such as nuclear energy, pharmaceuticals, and aerospace. This would contribute to the findings and validating the benefit of the resilience integrated HAZOP framework.
3. **Automation and digitalisation:** Exploring the potential of automation and digitising tools to streamlining the integration of resilience into HAZOP studies. This automation is a promising avenue for future research.
4. **Tracking resilience implementation:** To monitor the implementation of resilience principles in HAZOP over time would be valuable for assessing the ongoing impact of these strategies on process safety and operational continuity. These studies could provide realistic evidence to support the widespread adoption of resilience-integrated HAZOP methodologies.

5. **Environmental impact:** To enhance the plant's overall safety, it's crucial to prioritise natural hazards such as flooding, earthquakes and sandstorms in risk assessment. Although these events are low probability but high-risk impact, the potential consequences can significantly disrupt the plant operations.
6. **Multivariate dynamic modelling:** The integration of resilience into HAZOP aligns with multivariate dynamic modelling, which enhances early detection and system adaptability through predictive analytics. Integrating such techniques can further improve hazard identification and risk mitigation by forecasting process deviations over long time horizons. As a future research direction, multivariate dynamic modelling can be explored to strengthen resilience assessment, providing a data-driven approach for proactive risk management in complex industrial processes [Shokry, A. et al., 2020].
7. **Alarm management**: The integration of alarm management into resilience-based HAZOP enhances system reliability by preventing alarm flooding, which can overwhelm operators and delay critical responses. By optimizing alarm prioritisation and reducing false alarms, this approach strengthens early detection, survivability, and recoverability, ensuring timely intervention and minimizing system disruptions [Mustafa, F.E. et al., 2023].

Future research can build on this dissertation's findings by exploring these avenues to further enhance the effectiveness of resilience principles in industrial sectors.

# 7. Study limitation

While the study presents a valuable framework for integrating resilience into HAZOP, certain limitations should be recognised to provide a balanced perspective and guide future research. These constraints primarily relate to the qualitative nature of the analysis, industry-specific focus, and the need for broader validation. Acknowledging these challenges can help refine the methodology, enhance its applicability across various sectors, and explore opportunities for automation and digitalisation in resilience-based risk assessments.

The study has the following limitations:

1. The study primarily uses qualitative resilience principles integrated into HAZOP, lacking quantitative or semi-quantitative metrics to objectively measure resilience effectiveness.
2. The methodology is applied to a petrochemical distillation column, limiting generalisability to other industries like pharmaceuticals, nuclear, or aerospace without further validation.
3. The effectiveness of resilience integration in HAZOP relies on the experience and expertise of the HAZOP team, introducing subjectivity in risk assessment.

4. The integration of resilience into HAZOP remains manual, without leveraging digital tools, AI, or automated systems to streamline analysis and improve decision-making.
5. The study does not account for external disruptions such as natural disasters, cyber threats, or supply chain failures, which can significantly impact industrial resilience.

# Appendix I

Table A-1: Node 1: Feed line - Element: Flow

| Node | 1 | Element | Flow |
|---|---|---|---|

| No. | HAZOP GW | Deviation | Possible Cause | Consequences | Existing Safeguards | Risk Matrix S | L | R | Recommendations | Resilience Phases |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | No | No flow | Blockage in feed line. | Disruptions to the distillation process.<br>Potential damage to internal parts of column due to temperature imbalances. | Feed flow alarms.<br>Regular inspection of feed pumps and lines. | 3 | 2 | (6) Moderate | - Install a backup feed pump for redundancy.<br>- Periodic inspection schedules. | **Avoidance**<br>**6.** Install a backup feed pump for redundancy.<br>**7.** Periodic inspection schedules. |
| 2 | Low | Low flow | Control valve shut (malfunction). | Reduced separation efficiency, leading to an off-spec product. | Emergency shutdown. | 3 | 3 | (9) Moderate | Install a bypass to divert the flow. | **Survivability**<br>**8.** Dual flow control valve.<br>**9.** Install a bypass to divert the flow. |
| 3 | More | More flow | Pump malfunction. | Overloading or potential overfilling of the column.<br>Potential for reduced separation efficiency. | Flow control valves.<br>Level indicators in the column. | 4 | 3 | (12) High | - Install dual flow control valve.<br>- Install a bypass to divert the flow. | |

| Node | Resilience GW | Deviation (More flow) | Resilience principles | Possible Cause | Consequences | Existing Safeguards | Risk Matrix S | L | R | Recommendation | Resilience Phases |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | No | No existing relief valve on the column | Error-tolerant design (ETD-1). | Error-tolerant design was not considered in the early design stage | Potential for overfilling in the column | Refer to more flow scenario (item 3). | **3** | **3** | (9) Moderate | Install a relief valve in the distillation column. | **Recoverability**<br>**10.** Install a relief valve in the distillation column.<br>**11.** Site supervisor to monitor critical activity.<br>**12.** Implement operator development program |
| 3 | Inadequate | Inadequate maintenance | Plasticity (P-6). | Inadequate operator maintenance on the pump | Potential for a pump malfunction, resulting in a more flow scenario | Maintenance plan and record. | **2** | **3** | (5) Moderate | Site supervisor to monitor critical activity. | |

Table A-2: Node 2: Rectifying Column - Element: Pressure

| **No.** | **Node No.** | 2 | **Element** | Pressure | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **HAZOP GW** | **Deviation** | **Possible Cause** | **Consequences** | **Existing Safeguards** | **Risk Matrix S** | **L** | **R** | **Recommendation** | **Resilience Phases** |
| 4 | High | High pressure | Blockage in the feed line. | Potential for overpressure and damage to the column's internal parts. | High and H.High pressure alarms<br>Pressure control valve.<br>Leak detectors | 3 | 3 | (9) moderate | - Conduct periodic inspections.<br>- Install additional pressure-monitoring sensors. | **Avoidance**<br>**13.** Conduct periodic inspections.<br>**14.** Install additional pressure-monitoring sensors |
| | | | Leak downstream from the control valve. | Damage to the column could lead to asset loss. | | 3 | 3 | (9) moderate | | |
| 5 | Low | Low Pressure | Leak from the bottom of the column. | A drop in pressure that could lead to operation upset. | Low-pressure alarms<br>Leak detectors | 3 | 3 | (9) moderate | - Conduct regular leak tests.<br>- Install additional vacuum breakers. | **Survivability**<br>**15.** Install additional vacuum breakers.<br>**16.** Conduct regular leak tests. |

| **No.** | **Resilience GW** | **Deviation (High/low Pressure)** | **Resilience principles** | **Possible Cause** | **Consequences** | **Existing Safeguards** | **Risk Matrix S** | **L** | **R** | **Recommendation** | **Resilience Phases** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 4 | Missed | Operator missed H.High alarm | Error-tolerant design (ETD-4) | Operator missed critical high alarm due to workload | Potential for a pressure build-up in the distillation column. | Refer to high pressure scenario (item 4) | **3** | **3** | (9) moderate | - Develop a critical alarm rationalisation program.<br>- Operator training and awareness. | **Recoverability**<br>**17.** Develop a critical alarm rationalisation program.<br>**18.** Operator training and awareness.<br>**19.** Conduct frequent drills that simulate leak scenarios. |
| 5 | No | No action | Plasticity (P-5) | No action was taken from field operator to communicate the leak to CCR | Potential for a fire. | Refer to low pressure scenario (item 5) | 4 | 3 | (12) High | - Conduct frequent drills that simulate leak scenarios.<br>- Training and awareness | |

Table A-3: Node 3: Condenser - Element: Cooling

| No. | Node No. | 3 | Element | Cooling | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **HAZOP GW** | **Deviation** | **Possible Cause** | **Consequences** | **Existing Safeguards** | **Risk Matrix S** | **L** | **R** | **Recommendation** | **Resilience Phases** |
| 6 | No | No cooling | Condenser tube blockage | Inefficient condensation leading to potential overpressure. | Cooling water flow alarms condenser | 4 | 3 | (12) high | - Install backup cooling systems.<br>- Regular maintenance of condenser tubes. | **Avoidance**<br>**20.** Install redundant temperature controls.<br>**21.** Review condenser cooling performance. |
| 7 | More | More cooling | Control water failure | More vapor to condense than intended leading to higher liquid load returning to rectifying column. | Temperature control system<br>Cooling system alarms | 3 | 3 | (9) moderate | - Implement redundant temperature controls.<br>- Periodically review condenser cooling performance. | **Survivability**<br>- Install backup cooling systems.<br>- Regular maintenance of condenser tubes. |

| No. | Resilience GW | Deviation from HAZOP (No/more cooling) | Resilience principles | Possible Cause | Consequences | Existing Safeguards | Risk Matrix S | L | R | Recommendation | Recoverability |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 6 | Inadequate | Inadequate maintenance | Plasticity (P-1) | Condenser tube wasn't part of the planned maintenance | Pressure builds up due to inefficient condensation | Refer to no cooling scenario (item 6) | 3 | 3 | (9) moderate | - Develop a critical alarm rationalisation program.<br>- Operator training and awareness. | - Install emergency isolation valve to shutdown column feed.<br>- Develop a critical alarm rationalisation program.<br>- Operator training and awareness. |
| 7 | Unavailable | Unavailable shutdown valve | Recoverability (R-3) | Emergency shutdown valve not installed | Increased vapour can lead to a high liquid load carried out to the column. | Refer to more cooling scenario (item 7) | 4 | 3 | (12) High | - Install an emergency isolation valve to shut down the feed to the column and implement recoverability measures. | |

Table A-4: Node 4: Return tank - Element: Level

| No. | HAZOP GW | Deviation | Possible Cause | Consequences | Existing Safeguards | Risk Matrix S | Risk Matrix L | Risk Matrix R | Recommendation | Resilience Phases |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Node No.** | 4 | **Element** | Level | | | | | | |
| 8 | High | High level | Control valve failure | A tank overflow due to control valve failure could lead to a process upset | Level sensors.<br>Overflow alarms. | 4 | 3 | (12) high | - Install redundant level sensors.<br>- Regular maintenance of control valves.<br>- Install high-level shutoff systems. | **Avoidance**<br>- Install redundant level sensors.<br>- Install high-level shutoff systems.<br>- Regular maintenance of control valves. |
| 9 | Low | Low level | Pump failure | Pump cavitation could lead to inadequate reflux | Level sensors.<br>Low-level alarms | 3 | 3 | (9) moderate | - Install redundant temperature controls.<br>- Install low-level shutoff systems.<br>- Ensure backup pumps are available. | **Survivability**<br>- Install redundant temperature controls.<br>- Install low-level shutoff systems. |
| | | | | Temperature fluctuations could lead to process upset | Temperature sensors and control | 3 | 3 | (9) moderate | | |

| No. | Resilience GW | Deviation from (High/low level) | Resilience principles | Possible Cause | Consequences | Existing Safeguards | Risk Matrix S | Risk Matrix L | Risk Matrix R | Recommendation | Resilience Phases |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 8 | Inadequate | Inadequate maintenance | Plasticity (P-1) | Control valve failure due to inadequate maintenance | Tank overflow due to control valve failure. | Refer to high level scenario (item 8) | 3 | 3 | (9) moderate | - Develop a maintenance plan, including a critical equipment list.<br>- Implement an assets integrity program. | **Recoverability**<br>- Develop a maintenance plan, including a critical equipment list.<br>- Implement site supervision. |
| 9 | Inadequate | Inadequate maintenance | Plasticity (P-4) | Inadequate maintenance due to operator error | Potential for inefficient process separation and process upset. | Refer to low level scenario (item 9) | 3 | 2 | (6) moderate | - Operator training and awareness.<br>- Implement site supervision. | |

Table A-5: Node 5: Reflux pump - Element: Flow

| **No.** | **Node No.** | 5 | **Element** | | Flow | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **HAZOP GW** | **Deviation** | **Possible Cause** | | **Consequences** | **Existing Safeguards** | **Risk Matrix** | | | **Recommendation** | **Resilience Phases** |
| | | | | | | | **S** | **L** | **R** | | |
| 10 | No | No flow | Power loss | | Pump trip leading to temperature fluctuations. | Flow control valves.<br>Flow alarms | 3 | 3 | (9) moderate | - Install flow restrictors.<br>- Conduct periodic flow calibration.<br>- Install a standby pump. | **Avoidance**<br>- Install flow restrictors.<br>- Conduct periodic flow calibration. |
| 11 | High | High flow | Pump overruns | | Potential overfilling of the distillation column | Flow control valves.<br>High flow alarms | 3 | 3 | (9) moderate | - Install flow control on the pump outlet.<br>- Conduct regular flow calibration. | **Survivability**<br>- Install a standby pump.<br>- Install flow controls on the pump outlet. |
| **No.** | **Resilience GW** | **Deviation from HAZOP (No/high flow)** | **Resilience principles** | **Possible Cause** | **Consequences** | **Existing Safeguards** | **Risk Matrix** | | | **Recommendation** | |
| | | | | | | | **S** | **L** | **R** | | |
| 10 | Inadequate | Inadequate maintenance | Plasticity (P-1) | Power failure | Reflux pump trip could lead to process upset. | Refer to more flow scenario (item 10) | 3 | 3 | (9) moderate | Develop a maintenance plan, including a critical equipment list.<br>Implement an assets integrity program.<br>Install a standby pump. | **Recoverability**<br>- Develop a maintenance plan, including a critical equipment list.<br>- Operator training and awareness.<br>- Implement site supervision. |
| 11 | Inadequate | Inadequate maintenance | Plasticity (P-4) | Inadequate maintenance due to operator error leading to pump overruns | Increased pressure drops. | Refer to high flow scenario (item 11) | 3 | 2 | (6) moderate | Operator training and awareness.<br>Implement site supervision. | |

Table A-6: Node 6: Reboiler - Element: Temperature

| No. | Node No. | 6 | Element | | Temperature | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | HAZOP GW | Deviation | Possible Cause | | Consequences | Existing Safeguards | Risk Matrix S | L | R | Recommendation | Resilience Phases |
| 12 | High | High temperature | Excessive heating due to control failure | | Thermal degradation of products.<br>Potential for a fire. | Temperature control system<br>High temperature alarms | 3 | 3 | (9) moderate | - Install temperature sensors.<br>- Conduct periodic maintenance. | **Avoidance**<br>- Install temperature sensors.<br>- Conduct periodic maintenance. |
| 13 | Low | Low temperature | Insufficient heating due to reboiler mechanical failure | | Reduced separation efficiency. | Temperature control system<br>Low temperature alarms | 4 | 3 | (12) High | - Install a backup reboiler to avoid process upset.<br>- Implement temperature monitoring systems. | **Survivability**<br>- Develop a maintenance plan, including a critical equipment list.<br>- Implement an assets integrity program.<br>- Install a standby pump.<br>- Install a backup reboiler to avoid process upset. |
| **No.** | **Resilience GW** | **Deviation (High/low temp.)** | **Resilience principles** | **Possible Cause** | **Consequences** | **Existing Safeguards** | **Risk Matrix S** | **L** | **R** | **Recommendation** | |
| 12 | Inadequate | Inadequate maintenance | Plasticity (P-1) | Damage to internal heater components. | A heater trip could lead to process upset. | Refer to more flow scenario (item 12) | 3 | 3 | (9) moderate | - Develop a maintenance plan, including a critical equipment list.<br>- Implement an assets integrity program. | **Recoverability**<br>- Operator training and awareness.<br>- Implement site supervision. |
| 13 | Inadequate | Inadequate maintenance | Plasticity (P-4) | Inadequate maintenance due to operator error leads to a reboiler trip | Process upset. | Refer to low temperature scenario (item 13) | 3 | 2 | (6) moderate | - Operator training and awareness.<br>- Implement site supervision. | |

Table A-7: Node 7: Top and bottom product outlets - Element: Composition

| **No.** | **Node No.** | 7 | **Element** | | Composition | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **HAZOP GW** | **Deviation** | **Possible Cause** | | **Consequences** | **Existing Safeguards** | **Risk Matrix** | | | **Recommendation** | **Resilience phases** |
| | | | | | | | **S** | **L** | **R** | | |
| 14 | High | Off-spec Product | An incorrect reflux ratio could lead to temperature or pressure abnormalities | | The product will not meet specifications and may require reprocessing. | Product quality monitoring program<br>Periodic sampling | 4 | 3 | (12) High | - Install a product composition analyser.<br>- Conduct periodic maintenance on the sample points. | **Avoidance**<br>- Install a product composition analyser.<br>- Conduct periodic maintenance on the sample points. |
| **No.** | **Resilience GW** | **Deviation from HAZOP (composition)** | **Resilience principles** | **Possible Cause** | **Consequences** | **Existing Safeguards** | **Risk Matrix** | | | **Recommendation** | **Survivability**<br>Product quality monitoring program. |
| | | | | | | | **S** | **L** | **R** | | |
| 14 | Wrong | Wrong sample collection | Plasticity (P-13) | Incorrect sample collection due to operator error could lead to off-spec products | Off-spec product | Refer to off-spec scenario (item 14) | 3 | 3 | (9) moderate | - Standardised sampling procedure.<br>- Operator training and awareness.<br>- Periodic inspection and maintenance. | **Recoverability**<br>- Standardized sampling procedure.<br>- Operator training and awareness. |

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