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وزارة التعليـــم العالـــي والبحث العلمـــي

Ministère de l'Enseignement Supérieur et de la Recherche Scientifique

المدرسة الوطنية المتعددة التقنيات

École Nationale Polytechnique

Département

Maîtrise Des Risques Industriels et Environnementaux

(MRIE)

End-of-study project dissertation for obtaining the State Engineer's degree in Quality, Health, Safety, Environnement and industrial risk management (QHSE-GRI)

Vulnerability Assessment for Disaster Risks of the LPG Storage at the Central Processing Facility (CPF)

Presented By :

Yasser Abderrahmane DENNI

Amine ZOUAGUI

Under the direction of:

Mr. Aboubakr KERTOUS	Assistant Professor A	-ENP
Mrs. Marya FODIL	Assistant Professor A	-ENP

Presented and defended publicly on July 07, 2025

Composition of the jury:

President	Pr. Hamid YOUSFI	Professor	-ENP
examinator	Dr. Souad BENTAALLA	Associate Professor B	-ENP
examinator	Dr. Malik SENOUCI-BEREKSI	Associate Professor B	-ENP

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Mémoire de projet de fin d'études pour l'obtention du diplôme d'ingénieur d'État en Qualité, Hygiène, Sécurité, Environnement et Gestion des risques industriels.

(QHSE-GRI)

Evaluation de la vulnérabilité aux risques de catastrophes du stockage de GPL au niveau de l'Installation centrale de traitement (CPF)

Présenté par :

Yasser Abderrahmane DENNI

Amine ZOUAGUI

Sous la direction de:

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الملخص

تفرض التشريعات الجزائرية تقييمات الهشاشة للصناعات عالية الخطورة، لكن توجد فجوات تنفيذية بسبب غياب منهجية معيارية. تطور هذه الرسالة إطار عمل هجين يجمع بين تقييم الهشاشة المنظم وأداة برمجية لتحليل شجرة الأخطاء. تم توثيق الإطار من خلال دراسة حالة لنظام تخزين الغاز البترولي المسال، حيث تم تحديد سيناريوهين حرجين وتحقيق انخفاض ملحوظ في درجات الهشاشة إلى مستويات مقبولة.

الكلمات المفتاحية: تقييم الهشاشة، تحليل شجرة الأخطاء، السلامة الصناعية، تخزين الغاز البترولي المسال، بقدر ما هو معقول عملياً.

Résumé

La législation algérienne impose des évaluations de vulnérabilité pour les industries à haut risque, mais des lacunes d'implémentation persistent faute de méthodologie normalisée. Ce projet de fin d'étude développe un cadre hybride combinant évaluation structurée de vulnérabilité et logiciel automatisé d'analyse de l'arbre des défaillances. Le cadre a été validé par une étude de cas sur stockage GPL, identifiant deux scénarios critiques et atteignant une réduction significative de vulnérabilité à des niveaux acceptables.

Mots-clés: Évaluation de la vulnérabilité, Analyse de l'arbre des défaillances, Sécurité industrielle, Stockage de GPL, ALARP.

Abstract

Algerian legislation mandates vulnerability assessments for high-risk industries, yet implementation gaps exist due to absent standardized methodology. This thesis develops a hybrid framework combining structured vulnerability assessment with automated Fault Tree Analysis software. The framework was validated through an LPG storage system case study, identifying two critical scenarios and achieving significant vulnerability reduction to acceptable levels.

Keywords: Vulnerability Assessment, Fault Tree Analysis, Industrial Safety, LPG Storage, ALARP

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Special recognition goes to the faculty and staff in the Industrial and Environmental Risks Control Department that provided the academic environment necessary for conducting this research.

Finally, we extend our appreciation to the broader academic community whose published works and research have informed and enriched this thesis.

Dedications

***To my Family**,*

Who stood by me through every challenge and triumph, providing unwavering support and encouragement when I needed it most. Your belief in me made this journey possible.

Abderrahmane

***To my family**,*

Your unwavering belief in me has been my greatest strength.

To my father, thank you for your constant encouragement.

To my sister, thank you for your pride in me and your unshakable faith in your big brother.

And above all, to my mother—thank you for raising me, loving me, supporting me, and believing in my dreams even when I didn't.

Without your support, I would not have come this far.

Thank you.

Amine

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Abbreviations list

ALARP – As Low As Reasonably Practicable

BLEVE – Boiling Liquid Expanding Vapor Explosion

CAFC – Central Area Field Complex

CPF – Central Processing Facility

EDD – Safety Case

EPC – Engineering, Procurement, and Construction

ETA – Event Tree Analysis

FCP – First Calgary Petroleums

FTA – Fault Tree Analysis

GSE – Sonatrach-ENI Group (*Groupement Sonatrach-ENI*)

HSE – Health, Safety, and Environment

ISDR – International Strategy for Disaster Reduction

LOC – Loss of Containment

LPG – Liquefied Petroleum Gas

MLE – Menzel Ledjmet East (*or* Menzel Ledjmet Est – Central Processing Facility)

NGO – Non-Governmental Organization

P&ID – Piping and Instrumentation Diagram

PII – Internal Emergency Plan

PPE – Personal Protective Equipment

PPI – Specific Emergency Response Plan

PSV – Pressure Safety Valve

RRF – Risk Reduction Factor

UNDRR – United Nations Office for Disaster Risk Reduction

UVCE – Unconfined Vapor Cloud Explosion

General Introduction

The growing complexity of industrial systems has brought with it an increased exposure to both natural and technological hazards. In such high-risk environments, even a single failure whether technical, human, or external, can lead to significant consequences for people, assets, and the environment. Managing these risks requires more than identifying potential hazards; it demands a deeper understanding of the systems at risk and how they respond to specific, credible accident scenarios. Two essential and often underestimated components of this process are the assessment of vulnerability and the construction of representative scenarios.

The scale of recent global disasters demonstrates why these challenges demand serious attention. Between 2000 and 2019, more than 7,348 major disaster events were recorded worldwide, leading to 1.23 million deaths and affecting over 4.2 billion people, according to the United Nations Office for Disaster Risk Reduction (UNDRR) [1]. Compared to the previous two decades, the number of disasters has more than doubled. While hazards may be unavoidable, such devastating outcomes are often the result of unaddressed vulnerabilities and a failure to anticipate how risks could unfold under real-world conditions.

Recognizing this, the Sendai Framework for Disaster Risk Reduction 2015–2030 for disaster risk reduction that was adopted by the United Nations Office for Disaster Risk Reduction (UNDRR) urges a shift from reactive disaster management to proactive risk reduction [2]. At the heart of this shift lies the need to understand who or what is vulnerable, to what, and under which conditions. Effective vulnerability assessment must therefore be tied directly to well-constructed, realistic scenarios that reflect the actual threats an industrial site may face.

Algeria has taken a significant step forward with the adoption of Law No. 24-04 on disaster risk prevention, response, and reduction within the framework of sustainable development [3]. This law repeals Law No. 04-20 on the prevention of major risks and the management of disasters [4]. One of its key advancements is the introduction of a legal obligation for high-risk activities to conduct vulnerability assessments. Under this framework, industrial operators are required to systematically evaluate how their installations, personnel, and surrounding environment may be affected by specific hazardous scenarios and to implement appropriate preventive measures. However, despite this regulatory progress, practical tools and methodologies remain limited, particularly those that integrate scenario-building with vulnerability analysis in a structured and reproducible way.

This thesis problem addresses that gap by proposing a scenario-based methodology for vulnerability assessment in high-risk industrial settings. The objective is to support both regulatory compliance and operational safety by offering a framework that links realistic scenarios to the evaluation of system weaknesses and exposure.

In chapter one, the national context is introduced by outlining Algeria's evolving disaster risk governance, and presents the background and motivations of the study. It also defines the research problem and sets out the objectives.

Chapter two explores the theoretical foundations of both vulnerability and scenario analysis. It defines essential concepts, examines relevant academic and institutional frameworks, and identifies key methodological challenges, with a particular focus on applications in industrial environments.

Chapter three details the development of the proposed assessment methodology. It presents the analytical framework, outlines the scenario-based structure, and explains the selection and interpretation of indicators used to evaluate vulnerability.

In chapter four, details on the software that was developed as part of a graduation project to address one of the key obstacles found in the problem statement.

In chapter five, the methodology is applied in a real-world context, demonstrating its operational value through scenario development, scoring, and analysis.

Finally, the conclusion summarizes the key findings of the research, reflects on the practical implications of the proposed model, and outlines recommendations for future studies and implementation pathways.

Through these five chapters, this thesis aims to contribute to the effective implementation of Algeria's disaster risk reduction strategy by offering a practical and replicable approach to vulnerability assessment, anchored in realistic scenarios and committed to fostering safety, resilience, and compliance.

Chapter 1

Context of the study and problem statement

Chapter 1. Context of the study and problem statement

This chapter sets the foundation for the work presented in this study. It outlines the broader context in which the research was conducted and identifies the key problem it aims to address. By establishing the institutional, regulatory, and practical background, it provides the necessary framework for understanding the objectives and direction of the project.

1. 1. Menzel Ledjmet East Project overview (MLE)

The Menzel Ledjmet East (MLE) project is a large-scale oil and gas development located in Block 405b of the Berkine Basin, southeastern Algeria. The project's core function is the extraction, processing, and export of dry gas, liquefied petroleum gas (LPG), condensates, and crude oil, all sourced from the MLE and CAFC fields [5].

The project is operated by Groupement Sonatrach-ENI (GSE), a joint venture between Sonatrach, Algeria's national oil and gas company, and ENI Algeria Production B.V.**,** a subsidiary of the Italian energy firm ENI. GSE was initially established in 2001 as a partnership between Sonatrach and First Calgary Petroleums (FCP) under a Production Sharing Contract. Following ENI's acquisition of FCP in 2008, the joint venture expanded its scope, particularly with the development of the Central Area Field Complex (CAFC) [6]**.**

On November 1, 2021, GSE became the sole operator of Block 405b, following the termination of the original SH-FCP Operating Agreement and the enactment of Presidential Decree No. 21-415, which ratified Amendment No. 5 to the hydrocarbons contract [7].

Block 405b initially covered 1,108 km², but exploration and delineation activities reduced its area to 466 km², focused around the MLE field. After successful technical and economic evaluations, production licenses were granted for 25 years (oil) and 30 years (gas), confirming the long-term viability of the project [6].

The Central Processing Facility (CPF), which serves as the operational hub of the project, is located in the Wilaya of Illizi, within the commune of Debdeb, about 220 kilometers southeast of Hassi Messaoud. The site lies entirely within Illizi Province, where more than 80% of drilled wells are situated. Administrative and logistics operations are managed from the GSE base in Hassi Messaoud [8]**.**

The CPF is positioned near the Algerian–Libyan border, roughly 1,000 km from Algiers, and is geographically bounded by:

- Menzel Ledjmet Nord to the south
- El Merk Field, developed by Anadarko, to the west
- Groupement Berkine (Hassi Berkine)
- Groupement Ourhoud

The following figure (fig 1) illustrates the localization of (bloc 405b) across the Wilayas of Ouargla and Illizi.

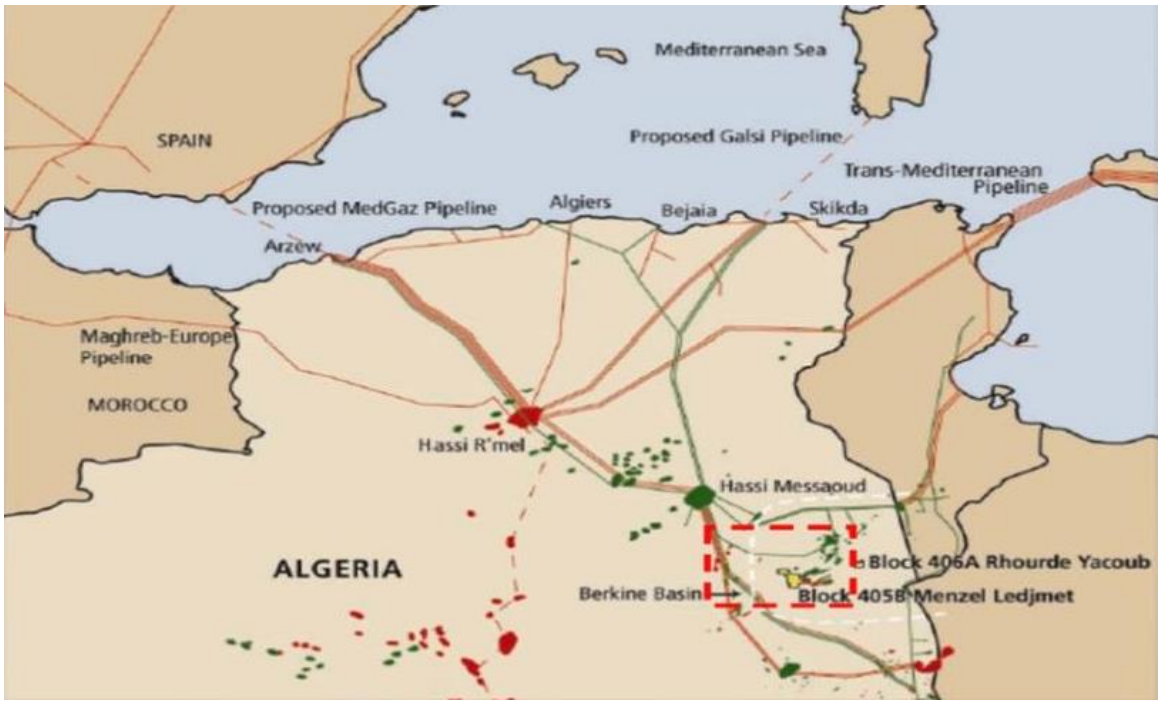

Figure 1: Location of the field area (bloc 405b)

1. 2. Problem statement

In 2024, Algeria enacted Law No. 24-04 of February 26, 2024, establishing a modern legal framework for disaster risk prevention, intervention, and reduction within the scope of sustainable development [3]. It repeals Law No. 04-20 on the prevention of major risks and disaster management, and aligns with the principles of the Sendai Framework for Disaster Risk Reduction, adopted at the Third United Nations World Conference in Sendai, Japan, on March 18, 2015 [2]. These regulations require vulnerability studies for all classified industrial installations, particularly in high-risk sectors such as oil and gas. Both frameworks define disaster risk as the result of the interaction between hazards and vulnerabilities within complex systems emphasizing the need for proactive and structured assessment methods.

However, while the law mandates the vulnerability study, it does not provide any clear methodology or standardized procedure for conducting it. There are no defined models, indicators, or technical steps to follow. This lack of guidance creates a major implementation gap: practitioners are expected to comply with the regulation, but have no official framework to apply in practice. As a result, assessments are inconsistent, difficult to compare, and limited in their ability to support informed decision-making.

The "Assessment of human, material, and environmental vulnerability to major industrial accidents or disasters" research has proposed a practical methodology, however when attempting to apply this methodology, the implementation fail at the critical question: How do we generate all possible scenarios

Traditional risk and vulnerability assessment approaches require extensive expert knowledge (expensive and limited), massive datasets (often unavailable), subjective expert judgment (inconsistent across practitioners), and manual scenario generation (prone to missing critical failure paths). In high-risk oil and gas operations, missing even one critical failure scenario could result in catastrophic consequences. This is especially problematic given the inherent uncertainty of risk defined not only by what is known, but also by what is not yet anticipated [9]. Risk is fundamentally linked to uncertainty, especially in complex systems where multiple interactions can produce unpredictable outcomes [10]. Without structured methods that account for uncertainty, current manual processes cannot ensure comprehensive coverage or robust decision-making.

The core issue is the lack of a reliable and scalable method to generate complete failure scenarios without depending on scarce expertise or unavailable data, which prevents full compliance with legal requirements and reduces the quality of safety assessments in industrial sites [10].

This challenge became the main focus of our work. We aimed to create an automated, standardized, and easy-to-use method for generating failure scenarios and carrying out vulnerability assessments. By filling this gap, our solution can help meet Algeria's new regulatory requirements and also support industries and students dealing with the same problem in other places.

1. 3. Research objectives

To address the challenges inherent in manual safety assessments and to guide the development of our automation tool, we established the following essential objectives:

- **Minimize the Expertise Bottleneck:** Reduce reliance on expensive and limited expert knowledge, which often leads to missed critical scenarios. The goal is to "democratize" this expertise and make it more accessible.
- **Standardize Safety Analysis:** Ensure consistent results regardless of who performs the assessment, improving reliability and minimizing human bias and errors.
- **Enable Rapid Iteration:** Allow quick evaluation of multiple risk-reduction measures in order to identify the most effective safety strategies.
- **Improve Detection:** Identify potential failure scenarios that might be overlooked in traditional manual analysis.

1. 4. Literature Review

This section reviews key academic contributions that were used to support the development of our approach to both risk and vulnerability assessment. These works provide foundational insights into how risk is conceptualized as the interaction between hazards, exposure, and vulnerability, and how vulnerability itself is understood as a dynamic, context-dependent, and scenario-specific attribute. The reviewed literature helps frame our understanding of how these concepts can be operationalized in practice, especially within industrial and environmental contexts where formal assessments are increasingly required.

1. 4. 1. Assessment of Human, Material, and Environmental Vulnerability to Major Industrial Risks

Hassani's doctoral research responds to the lack of practical methodologies for conducting vulnerability assessments in the context of Algeria's oil and gas industry, especially following the adoption of regulatory frameworks such as Law No. 24-04. The thesis proposes a semi-quantitative assessment method based on a matrix of intensity and sensitivity; each decomposed into sub-indicators. The originality of the work lies in its simplicity and accessibility: it uses easily available data and follows a logical sequence of steps, including validation loops, to produce results that are understandable and actionable by non-expert decision-makers. A case study involving an LPG storage sphere explosion scenario

demonstrates how the method can be applied in practice. The results showed that modifying the sphere's fill level significantly reduced vulnerability, illustrating how targeted mitigation can directly influence risk outcomes. This work directly informs our study by providing a structured and replicable model for industrial risk analysis [11].

1. 4. 2. Assessing Vulnerabilities to the Effects of Global Change: An Eight-Step Approach

Developed in response to the need for greater methodological coherence in global change research, this article proposes an eight-step framework for assessing vulnerability to environmental stressors. The authors argue that vulnerability is not a fixed trait but rather a relational function of exposure, sensitivity, and adaptive capacity. Central to their approach is the question "Who is vulnerable to what?", which encourages clarity and specificity in scoping vulnerability assessments. Their framework is designed to be interdisciplinary and adaptable, integrating both qualitative and quantitative methods. This structure supports assessments that are grounded in real-world contexts and relevant to policy and planning. The article's emphasis on scenario specificity and system complexity is directly relevant to our work, particularly in aligning risk analysis with clearly defined industrial hazards [12].

1. 4. 3. The Risk Concept, Historical and Recent Development Trends

This article reviews the evolution of the risk concept, highlighting a shift from narrow probabilistic definitions toward broader understandings that emphasize events, consequences, and especially uncertainty. Aven categorizes risk definitions and evaluates their relevance to real-world decision-making. He shows that risk exists because the future is unknowable, and that uncertainty is not a secondary concern, but a core dimension of what risk represents. As such, systems are vulnerable not only to known hazards, but also to unidentified or emerging risks. This perspective reinforces the need for risk and vulnerability assessments to address the limits of knowledge, rather than rely solely on measurable probabilities [10].

1. 5. Vulnerability Study

In this section, we'll go over the conceptual foundations of the vulnerability study as applied in disaster risk assessment. We examine how vulnerability functions as a core element of risk and how it can be systematically evaluated in industrial contexts. The distinction

between vulnerability studies and hazard studies is clarified, highlighting the role of vulnerability in supporting prevention, preparedness, and emergency planning. We then discuss the limitations of traditional risk models and introduces more suitable frameworks for disaster scenarios, particularly those based on the interaction between hazard and vulnerability.

1. 5. 1. Definition of vulnerability

According to Article 2 of Law No. 24-04, vulnerability is defined as:

"the degree of exposure of people and property to risks, encompassing conditions related to physical, social, economic, or environmental factors or processes that weaken the resistance of these populations and their assets. [3]"

This definition presents vulnerability as a result of both exposure to hazards and the underlying conditions that reduce a system's or population's ability to resist harm. It highlights that structural, social, economic, and environmental factors all contribute to increasing the susceptibility of people and assets when faced with risk.

1. 5. 2. Definition of the Vulnerability Study

The vulnerability study is a structured assessment designed to identify, analyze, and evaluate the degree to which people, assets, or environments are susceptible to harm from disaster risk hazards whether industrial, technological, or natural in origin [11].

Mandated under Article 75 of Law No. 24-04, it is a legal requirement for all classified industrial installations prior to their establishment or operation. Unlike basic exposure assessments, the vulnerability study investigates the underlying factors that contribute to risk, including structural deficiencies in infrastructure or technical systems, organizational weaknesses such as gaps in safety procedures or management practices, and contextual elements related to site-specific conditions like terrain, proximity to hazards, or surrounding land use [3]

Within the framework of industrial risk management, the study supports targeted prevention by informing protective strategies and emergency planning. It serves as a decision-support tool for enhancing resilience, particularly in high-risk installations [13].

1. 5. 3. Purpose of the Vulnerability Study

The vulnerability study in disaster risk reduction aims to:

- Assess the installation's exposure to disaster risks, including natural hazards (e.g., floods, earthquakes), industrial accidents (e.g., explosions, toxic releases), cyber threats, and environmental degradation [3].
- Provide critical input for the development of Specific Intervention Plans (PPIs), as outlined in Article 10 of Decree No. 25-63 of January 28, 2025, which establishes the conditions and procedures for the formulation, implementation, and management of intervention plans for disaster risks. These plans aim to [13]:
    - Define preventive and response measures,
    - Strengthen organizational preparedness,
    - Coordinate actions to reduce the impact of potential disasters.

The vulnerability study is thus a key tool in Algeria's national disaster risk management and emergency planning framework.

1. 5. 4. The difference between Vulnerability study and safety case

While both the safety case and the vulnerability study are central components of Algeria's industrial safety framework, they differ significantly in scope, methodology, and purpose.

The safety case is primarily concerned with identifying the direct and indirect risks that an industrial activity may pose to people, property, and the environment. As stated in Article 55 of Executive Decree No. 21-319 of August 14, 2021, on the specific operating authorization regime for hydrocarbon installations and structures, and the procedures for approving risk studies related to exploration activities, its purpose is to define the technical and organizational measures necessary to reduce the likelihood and consequences of accidents [14]. It focuses on credible internal scenarios such as equipment failure, leaks, or fires and aims to implement safeguards that prevent or manage these events within the installation's boundaries [14].

In contrast, the vulnerability study evaluates how susceptible a site and its surrounding environment are to disaster risks resulting from internal malfunctions or external events [13].

It addresses low-probability, high-consequence scenarios such as earthquakes, floods, or cascading industrial failures, and emphasizes the exposure, sensitivity, and resilience of people, infrastructure, and critical systems [3]. Rather than focusing solely on accident causality, it asks: what would happen if protections failed, or if hazards exceeded expected conditions? This

broader and systemic perspective aligns with the precautionary principles of the Sendai Framework and supports proactive disaster risk governance.

The following table summarizes the key differences between both studies:

Table 1: difference between Vulnerability study and safety case

	Safety case	**Vulnerability Study**
Addressed risk type	Internal: leaks, overpressure, ignition, system failure	External: earthquake, flood, cyberattack; also internal hazard escalation
Risk reduction measures	Technical safeguards Organizational measures Internal Intervention Plans (PII)	Intensity reduction measures Risk adaptive measures Specific Intervention Plans (PPI)
Risk Assessment Perspective	Focuses on identifying and managing internal hazards and accident causality	Focuses on the system's susceptibility and the broader impact of extreme scenarios
Underlying Philosophy	Control what can realistically go wrong	Anticipate what can catastrophically go wrong

1. 6. Legal scope

This section outlines the legal and institutional foundations that define the scope, purpose, and implementation standards of vulnerability studies in high-risk industrial contexts, beginning with international conventions and followed by national legislation and regulatory provisions.

1. 6. 1. Sendai Framework for Disaster Risk Reduction

The international foundation for modern disaster risk governance is established by the Sendai Framework for Disaster Risk Reduction (2015–2030), adopted at the Third United Nations World Conference in Sendai, Japan, on March 18, 2015. As a member of the United Nations, Algeria is committed to implementing this framework and aligning its national legislation with its core principles [2].

The Sendai Framework defines disaster risk as:

“The potential loss of life, injury, or destroyed or damaged assets which could occur to a system, society or a community in a specific period of time due to natural or human-induced hazards, including technological, environmental, and biological risks. [2]”

It also emphasizes that disaster risk includes:

"Small-scale and large-scale, frequent and infrequent, sudden and slow-onset disasters caused by natural or man-made hazards, as well as related environmental, technological and biological hazards and risks. [2]"

This modern and systemic perspective stresses the importance of identifying all potential risks, regardless of their likelihood, frequency, or scale. It prioritizes not only the recognition of hazards but also the assessment of underlying vulnerabilities and the interconnected nature of systems. It further promotes key principles such as the precautionary approach, early warning, and prevention at the source.

1. 6. 2. Law No. 24-04: Algeria’s disaster risk reduction framework

In alignment with these international commitments, Algeria enacted Law No. 24-04 of February 26, 2024**,** establishing the rules for disaster risk prevention, intervention, and reduction within the framework of sustainable development. This law repeals and replaces Law No. 04-20 on the prevention of major risks and the management of disasters [3].

Under Article 2, disaster risk is defined as any probable threat natural, technological, or linked to human activity that could seriously harm people, property, or the environment. Vulnerability is presented as the degree of exposure to these risks, shaped by physical, social, economic, and environmental conditions that reduce a system’s ability to withstand harm [3].

A key advancement introduced by this law is the mandatory vulnerability study for all high-risk industrial activities, reinforcing Algeria’s transition from reactive disaster management to proactive risk reduction [3].

1. 6. 3. Legal provisions for the Vulnerability Study

According to Article 3 of Decree No. 25-63, the vulnerability study must cover [13]:

- Internal risks from the installation itself;

- External risks that could affect the site and endanger people, property, or the environment.

Article 11 makes the industrial operator responsible for the study, which must be carried out by certified firms or accredited public bodies. Article 12 requires the use of scientifically validated methods and provides for a future standardized framework (canvas) for both the study and its related Specific Intervention Plan (PPI) [13].

The study is not optional; it directly supports emergency planning and the national objectives set out in Law No. 24-04, including reducing disaster impacts and improving early warning systems. Failure to comply can invalidate emergency plans and lead to legal penalties as outlined in Article 86 of the law [13].

1. 7. Risk assessment model

A risk model is intended to provide a structured framework for identifying and analyzing potential threats in order to support informed and effective decision-making. In the context of disaster risk management, however, traditional models often prove inadequate for capturing the complexity and unpredictability of real-world events.

This section examines the limitations of conventional approaches and introduces more advanced models that are better adapted to the specific challenges of disaster risk.

1. 7. 1. Limits of the Classical Risk Model

Traditionally, risk has been assessed across many technical disciplines using a simple model based on the product of probability and consequence [10]:

$$R = P \,.\, C$$

Where:

- ➔ R: Risk
- ➔ P: Probability of occurrence
- ➔ C: Severity of the consequences

This classical formulation has been widely applied in fields such as nuclear safety, chemical engineering, and transportation. It offers simplicity and allows for the quantitative comparison and prioritization of scenarios based on a single risk value [10].

However, its application in the context of disaster risk raises several issues. In particular, the model assumes that [10]:

- That probabilities can be reliably estimated from empirical data or validated predictive models;
- Those consequences can be accurately quantified and compared across diverse scenarios.

In the context of disasters such as industrial explosions, major floods, or technological failures, these assumptions are often invalid. High-impact scenarios may lack sufficient historical precedent, making probability estimates speculative at best. Similarly, consequences can be non-linear, systemic, and cross-sectoral, making them difficult to quantify or reduce to a single scalar value [10].

As a result, conventional risk assessments tend to underrepresented low-probability, high-consequence events, even though these events may have the most devastating outcomes.

1. 7. 2. Disaster Risk model

Disaster risk is widely understood as the result of the interaction between a hazardous event and the vulnerability of the systems or populations exposed to it:

$$R = \text{Hazard} \times \text{Vulnerability}$$

To address the shortcomings of classical risk models, Aven (2012) proposes a broader formulation of risk that explicitly incorporates uncertainty and the underlying knowledge base [10]:

$$\text{Risk} = (\text{Consequences, Probability, Knowledge Base})$$

This formulation, endorsed by the United Nations Office for Disaster Risk Reduction (UNDRR, 2016) [15], underpins most contemporary disaster risk models. It conveys that the occurrence of a hazard alone does not constitute a disaster, rather, it is the presence of vulnerable systems, whether social, technical, or environmental, that determines the scale of impact. In this view, disaster risk emerges when hazards affect systems that lack the capacity to absorb, resist, or recover from the resulting consequences.

This formulation highlights two essential components:

- **Hazard**: the potential occurrence of a harmful physical, technological, or human-induced event;
- **Vulnerability**: the susceptibility of people, assets, and systems to suffer harm as a result of their exposure and sensitivity.

To make this model more effective in real-world applications especially in cases involving limited data, emerging risks, or rare and infrequent events it is essential to incorporate a third dimension: the Knowledge Base. This refers to the scope, quality, and reliability of the information used in the assessment. Its inclusion reflects the epistemic perspective on risk proposed by Aven (2012), who emphasizes that uncertainty, particularly that which stems from incomplete or evolving knowledge, must be explicitly considered, as it directly influences how hazards and vulnerabilities are identified, interpreted, and managed.

In this view, risk is not only a function of what might happen and to whom, but also of how confident we are in the information used to support those judgments. Acknowledging this uncertainty improves transparency and supports more resilient and adaptive decision-making, especially in high-risk industrial contexts.

This integrated perspective aligns with the Sendai Framework for Disaster Risk Reduction and Algeria's Law No. 24-04, both of which emphasize systemic, precautionary, and evidence-based approaches to disaster risk governance.

This chapter explored the central role of vulnerability in disaster risk assessment, distinguishing it from traditional hazard-based approaches and demonstrating its legal and methodological foundations in both international and Algerian frameworks. By reviewing how vulnerability can be systematically evaluated in industrial settings and how it fits into broader risk models, the chapter provides the conceptual base for developing operational assessment tools. The next chapter builds upon this foundation by presenting the structured methodology used in this study to evaluate disaster risk in practice, including scenario-building, hazard quantification, and vulnerability scoring

Chapter 2
Disaster Risk Assessment

Chapter 2. Disaster risk assessment

This chapter outlines the methodology adopted to assess disaster risk in industrial settings through a structured, scenario-based approach. It presents the logical framework and sequential steps necessary for identifying hazardous events, analyzing their causes and consequences, estimating their effects, and evaluating the vulnerability of exposed targets. The methodology integrates both hazard and vulnerability components and provides the tools needed to support risk-informed decision-making. It also introduces techniques for reducing vulnerability and highlights key considerations for re-assessment to ensure continuous improvement in safety performance.

2. 1. Proposed Model for the Evaluation of Disaster Risk

Building on the disaster risk formulation presented earlier (Risk = Hazard × Vulnerability) this sub chapter outlines a structured and operational approach for evaluating disaster risk in industrial contexts. The proposed model consists of two core components:

- **Hazard Assessment:** based on scenario-building and probability assessment;
- **Vulnerability Assessment:** based on intensity-impact pairing and target sensitivity.

2. 1. 1. Hazard Assessment Approach

As the first step of the proposed methodology, hazard assessment focuses on identifying credible hazardous scenarios and characterizing their key parameters. The results of this step guide the selection of relevant scenarios for vulnerability analysis and risk evaluation.

2. 1. 1. 1. Scenario-Based Characterization

Hazards are represented through clearly defined scenarios. Each scenario describes a specific threat and is characterized by the following parameters:

- **Hazard Type**: Nature of the threat (e.g., flammable, toxic, explosive, flood, or system failure);
- **Fault Trees**: Logical diagrams used to identify combinations of failures or triggering events that can lead to the release of a hazard. All plausible causal paths must be identified to avoid overlooking unidentified but credible risks, especially in complex or high-risk systems;

- **Event Trees**: Diagrams used to represent the possible progression of events once a hazard has been released, including branching paths of escalation or containment;
- **Spatial Extent**: The geographical reach of the hazard's impact;
- **Intensity**: Quantitative measures of the hazard's physical force (e.g., overpressure, heat flux, toxic concentration);
- **Consequences**: The expected effects on people, infrastructure, the environment, and operations derived from event tree outcomes.

This structure supports the identification of both well-known and emerging risks, including cascading or multi-hazard scenarios. It enables a comprehensive and logic-based approach to scenario construction for use in disaster risk modeling.

2. 1. 1. 2. Probability Estimation

- Each scenario is assigned a probability of occurrence based on:
- Historical event data (when reliable);
- Predictive modeling and simulation results;
- Expert judgment, particularly in data-scarce environments.

This step supports the prioritization of scenarios and helps characterize uncertainty in the absence of complete information.

2. 2. Vulnerability Assessment Approach

Vulnerability is treated as a hazard-specific and relational concept, following the perspective developed by Schröter, Polsky, and Patt (2005)**,** which frames vulnerability as a function of exposure, sensitivity, and adaptive capacity [12]. Their approach emphasizes clarity and contextual relevance in assessment by centering on the guiding question: *"Who is vulnerable to what?"* This aligns with Algeria's legal framework, which defines vulnerability as the degree of exposure to risk shaped by physical, social, economic, and environmental factors that reduce resistance.

In this study, vulnerability is evaluated using the methodological model proposed in the vulnerability assessment to industrial risk paper [11]. It is structured around two interdependent components:

- **Hazard Intensity**: the magnitude of the hazard at the point of impact, expressed through physical indicators such as thermal flux, overpressure, toxic concentration, or seismic acceleration;
- **Sensitivity of Exposed Targets**: the likelihood that people, infrastructure, or environmental assets will suffer damage, based on their structural robustness, protection measures, preparedness, and condition.

This formulation enables vulnerability to be assessed across sectors and regions, while also implicitly reflecting coping and adaptive capacities. Systems that are well protected or resilient are considered less sensitive and thus less vulnerable.

The vulnerability assessment relies on a data-based matrix that combines intensity and sensitivity indicators. This allows for:

- Cross-sectoral comparison of vulnerability levels;
- Integration of environmental and social dimensions;
- Identification of high-risk targets requiring specific mitigation efforts.

This structured and accessible framework supports practical decision-making in high-risk industrial contexts and provides a consistent foundation for disaster risk evaluation and prevention planning.

2. 3. Methodology steps

Building upon the conceptual framework for vulnerability assessment, this section lays out the practical methodology for its application. The following steps break down the evaluation process into a series of interlinked actions [11]. This structured approach ensures that the core principles of hazard in tensity and target sensitivity are applied consistently, providing a clear and repeatable workflow for practitioners in high-risk industries like oil and gas.

The methodology for this research involves the following steps:

2. 3. 1. Define Study Field

The initial step is to establish the scope of the assessment by defining the installation's operational context. This involves gathering all necessary background information and data about the facility and its environment.

I. **Historical Background**: Region’s geography/development

II. **Environment Data**:

- **A. Natural**; like earthquake activity. Meteorological data like wind, rain, Ground roughness, Cloud cover, Air temperature, Stability class, Inversion height, Relative humidity
- **B. Population**:
  1. **Inhabitant Counts**: Population density by city/zone nearby or within the vicinity
  2. **Vulnerable Groups**: Schools, hospitals, elderly care facilities, and residential areas
- **C. Other Facilities**:
  1. **Other Facilities**: Industrial installations, storage facilities, and processing plants near vicinity
  2. **Infrastructure Networks**: Transportation corridors, utilities, and communication systems

After establishing the external context, the focus narrows to the facility itself. A meticulous inventory of all process and storage equipment is necessary to understand the internal risks. This involves documenting technical specifications for all components, their configurations, and their containment systems, drawing from key engineering schematics.

III. **Facility Details:**

- **A. Storage Units**: Spheres/tanks - identify their capacity, volume, pressure, temperature and other relevant data
  1. **Tank Configuration**: Spherical vessels, cylindrical tanks, and specialized storage units
  2. **Containment Systems**: Secondary barriers and leak detection systems (i.e.: retention tanks)

B. Process Equipment

1. **Pipelines, Pumps**: Flow rate, pressure specifications and operational data
2. **Turbochargers**: Performance specifications and operational parameters
3. **PSV Valves**: Pressure safety valve settings and configurations
4. **Schematics**: Piping and instrumentation diagrams (P&IDs) and process flow diagrams

This comprehensive data collection provides the foundation for the next step of the assessment which is identifying potential hazards, detailed in the following section.

2. 3. 2. Identify Hazardous Scenarios

With the necessary data gathered, the next step is to identify all major hazard scenarios within the installation. This process focuses on, but is not limited to, the following potential events [16]:

❖ **Explosion Scenarios**

This category covers events characterized by a rapid, high-energy release, resulting in a destructive overpressure wave.

➢ **BLEVE (Boiling Liquid Expanding Vapor Explosion)**: Catastrophic tank failure with fireball formation

➢ **UVCE (Unconfined Vapor Cloud Explosion)**: Delayed ignition of dispersed flammable vapors

❖ **Fire Scenarios**

This category includes events where flammable materials combust, primarily producing intense thermal radiation.

➢ **Jet fire**: Turbulent diffusion flames from pipe or vessel failures

➢ **Pool fire**: Surface burning of spilled liquids in confined or unconfined areas

- ➢ **Flash fire**: Rapid combustion of vapor clouds without significant overpressure
- ➢ **Boilover**: Liquid fuel tank explosions with ejection of burning material

❖ **Loss of Containment (LOC)/Dispersion**

This category describes the initial breach of containment, which can lead to the formation of hazardous clouds or environmental damage, and may act as a precursor to fires or explosions.

- ➢ **Toxic Releases**: Airborne dispersion of hazardous chemicals
- ➢ **Flammable Vapor Formation**: Creation of explosive atmospheres

The primary method used for Scenario Identification is the BowTie methodology. This approach is favored for its ability to systematically and exhaustively link the causes of a critical event to its potential consequences. The methodology integrates two well-established techniques: Fault Tree Analysis (for causes) and Event Tree Analysis (for consequences), visually representing the flow from threat to outcome.

2. 3. 2. 1. BowTie Methodology

The construction of a BowTie diagram is a structured process centered around a "critical event." The analysis proceeds in three main stages [16]:

i. **Define the Critical Event**

The first step is to pinpoint the precise moment where control is lost over a hazard. This is the critical event (also known as the "top event" or "feared event"). It is not the cause of the incident, nor its consequence, but the event that separates the two. For example, in the context of a pressurized LPG storage sphere, the critical event is the Loss of Containment (LOC), the breach of the vessel itself.

ii. **Analyze Causes with Fault Tree Analysis (FTA)**

Once the critical event is defined, the left side of the BowTie diagram is developed using Fault Tree Analysis. This deductive approach identifies all credible threats (or causes) that could lead to the critical event. For an LOC scenario, threats could include overpressure, human error, external impact, corrosion, or mechanical failure. This analysis relies on historical data,

predictive models, and expert judgment to map the causal pathways. The result is a logical tree where lower-level failures combine to create the top event.

iii. Analyze Consequences with Event Tree Analysis (ETA)

With the causes established, the right side of the BowTie is constructed using Event Tree Analysis. This inductive approach explores the various potential outcomes that could follow the critical event. Each outcome path is determined by the success or failure of mitigating barriers (e.g., ignition sources being present, safety systems activating). For an LPG Loss of Containment, the consequences could range from the formation of a flammable vapor cloud to a BLEVE, a jet fire, or an unconfined vapor cloud explosion (UVCE), depending on the subsequent events.

iv. Construct Bowtie Diagram for LOC

Finally, the Fault Tree and Event Tree are combined to form the complete BowTie diagram. The critical event serves as the central knot, with the threats and causal pathways branching in from the left and the potential consequences branching out to the right. This integrated view provides a comprehensive, cause-and-effect map of the risk, visualizing how scenarios develop from initiation to final outcome.

2. 3. 3. Match to Propagated Effects:

From the consequences identified in the BowTie analysis, the next step is to determine the specific physical effects that will be generated. These effects are broadly categorized as:

- **Thermal Effects**, such as transient heat pulses or continuous thermal exposure.
- **Overpressure Effects**, resulting from explosion shockwaves.
- **Toxic Effects**, caused by the dispersion of hazardous substances.
- **Debris Effects**, involving the projection of fragments or structural components.

A single dangerous phenomenon can produce several of these effects simultaneously.
The table below illustrates the typical effects associated with each type of hazardous event, providing a clear map from phenomenon to potential impact.

Table 2: Consequences with associated physical effects [11]

Dangerous Phenomena	**Major Effects**			
	Thermal Effect	Overpressure Effect	Debris/Missile Effects	Toxic Effects
Pool Fire	X			X
Tank Fire	X			X
Torch Fire	X			
UVCE (Unconfined Vapor Cloud Explosion)	X	X	X	
jet Fire	X			
Flash Fire	X			
Toxic Cloud				X
Solid Fire	X			X
Missile Projection			X	
Overpressure Waves		X		
Fireball	X	X	X	
Environmental Pollution				X
Dust Explosion	X	X	X	
Boil-Over	X			

With the relationship between hazardous phenomena and their physical effects established, the methodology moves from qualitative identification to quantitative assessment. This crucial step involves defining specific intensity thresholds for each effect, which are necessary for defining threat zones.

2. 3. 4. Define Effect Thresholds and Threat Zones

After mapping the physical effects, the next step is to establish specific thresholds to quantify their potential impact. These thresholds define the boundaries of threat zones, geographical areas where harm to people or structures is expected. For this assessment, the limit values for thermal, overpressure, and toxic effects are adapted from the framework developed in "Assessment of Human, Material, and Environmental Vulnerability to Major Industrial Risks" [11]. The table below details these thresholds, categorizing them by their impact on both humans and structures.

Table 3: different effects thresholds (human vs structures) [11]

Thresholds of Effects on Humans

Type	Threshold	Effects / Zone
Overpressure	20 mbar	Irreversible effects (indirect effects zone via glass breakage)
	50 mbar	Irreversible effects (significant-hazard zone for human life)
	140 mbar	First lethal effects (serious-hazard zone for human life)
	200 mbar	Significant lethal effects (very-serious-hazard zone for human life)
Thermal	5 kW/m² (or 1000 [(kW/m²)^(4/3)·s])	Threshold of first lethal effects
	8 kW/m² (or 1800 [(kW/m²)^(4/3)·s])	Threshold of more severe (beyond initial lethality)
Toxic	SELS	Significant Lethal Effects Threshold
	SEL	Lethal Effects Threshold
	SEI	Irreversible Effects Threshold

Thresholds of Effects on Structures

Type	Threshold	Effects
Overpressure	20 mbar	Significant destruction of glazing
	50 mbar	Light damage to structural elements
	140 mbar	Severe damage to structural elements
	200 mbar	Domino effects
Thermal	5 kW/m²	Significant destruction of glazing
	8 kW/m²	Domino effects
	16 kW/m²	Prolonged exposure effects on non-concrete structures
	20 kW/m²	Concrete withstands exposure for several hours
	200 kW/m²	Concrete failure (collapse) within tens of minutes

These thresholds are the basis for mapping the geographical extent of potential harm. By modeling the propagation of each physical effect from its source, distinct threat zones can be delineated. Each zone corresponds to a specific threshold, representing an area within which a

certain level of damage or injury is probable. This visual representation is a critical tool for risk analysis, enabling practitioners to:

- **Visualize High-Risk Areas**: Immediately identify locations where people, infrastructure, or environmental assets are exposed to significant danger.
- **Inform Emergency Planning**: Determine appropriate evacuation distances, shelter locations, and emergency response strategies.
- **Guide Land-Use Planning**: Establish safe setback distances for critical infrastructure, assembly points, or future development.

The delineation of these zones is typically performed using specialized simulation software to ensure accuracy, as manual calculations can be complex and error-prone.

2. 3. 5. Identify Targets

Once the threat zones are mapped, the focus shifts to identifying all vulnerable targets located within their boundaries. This involves a systematic inventory of all assets that could be affected by the hazardous phenomena. The targets are categorized to ensure a comprehensive assessment:

- **Human Targets**: Including on-site workers and the surrounding population.
- **Infrastructural & Functional Targets**: Such as critical safety systems, transportation networks, and essential services like healthcare.
- **Environmental Targets**: Encompassing local fauna, flora, and the quality of air, water, and soil.
- **Socio-Economic & Cultural Targets**: Including sites of historical importance, national monuments, and key economic assets.

To ensure a thorough and consistent identification process, the following detailed checklist, is utilized:

Table 4: checklist for qualitative target identification [11]

No.	Target Type	Description / Examples	Check
Section I: Human Vulnerability			
1	Company workers		●
2	Workers of other nearby companies		●
3	General population		●
4	Sensitive population		●
Section II: Functional Vulnerability			
5	Health function	Hospitals, clinics or medical centers; mobile medical intervention systems (e.g., field hospitals); other…	●
6	Security function	Safety centers; police; gendarmerie; armed forces; …	●
7	Protection function	Firefighters; rapid-intervention teams; local crisis-management cells (information, communication, coordination, logistics…); …	●
8	Supply function	Water; energy; food; fuels; …	●
Section III: Environmental Vulnerability			
9	Wildlife	Animal reserves; parks (zoos); breeding centers; …	●
10	Flora	Nature reserves; parks; agricultural land; agricultural investment sites; …	●
11	Air	Atmosphere	●
12	Soil / Land	Groundwater; agricultural zones; geological structures and reserves; …	●
13	Aquatic systems	Seas; rivers; wadis; lakes; natural or artificial dams; …	●
Section IV: Monumental Vulnerability			
14	Historical monuments or cultural heritage	Any monument preserved by a public authority or NGO for its historical, cultural or heritage value	●
Section V: High-Level Socio-Economic Vulnerability (National or International)			
15	National or international economy		●
16	National or international security		●
17	National or international supply		●

The completion of this systematic checklist provides a comprehensive picture of all targets at risk. With both the hazard footprints and the exposed targets clearly defined, the methodology proceeds to its central and most critical step: evaluating the vulnerability of each target.

2. 3. 6. Vulnerability Assessment:

This assessment operationalizes the vulnerability framework by integrating hazard intensity (defined by the threat zones) with the sensitivity of the identified targets. The calculation of vulnerability is based on the following equation:

Vulnerability = Sensitivity × Intensity

In this formula, Sensitivity refers to the intrinsic characteristics of the exposed target (the "who"), while Intensity corresponds to the magnitude of the hazardous phenomenon at the target's location (the "what").

To ensure a systematic and repeatable assessment, both parameters are quantified using a standardized scoring system. The following table outlines the scale adopted for this analysis, providing clear definitions for the different levels of intensity and sensitivity.

Table 5: Vulnerability assessments matrix [11]

		Intensity							
		LI (1)	**MI (2)**	**SI (3)**	**HI (4)**		**Value Range**	**Code**	**Vulnerability Level**
Sensitivity	**LS (1)**	1	2	3	4		1–2	LV	Low Vulnerability
	MS (2)	2	4	6	8		3–4	MV	Medium Vulnerability
	SS (3)	3	6	9	12		6–8	SV	Significant Vulnerability
	HS (4)	4	8	12	16		9–16	HV	High Vulnerability

As the table illustrates, this framework employs a four-level scale for each of its core components:

- **Intensity (I)** is rated from Low (LI=1) to Medium (MI=2) to Significant (SI=3) to High (HI=4).

- **Sensitivity (S)** is rated from Low (LS=1) to Medium (MS=2) to Significant (SS=3) to High (HS=4).
- **Vulnerability (V)**, derived from the first two, is also rated from Low (LV=1) to Medium (MV=2) to Significant (SV=3) to High (HV=4).

To calculate a target's final vulnerability score, one must first independently evaluate the intensity of the hazard and the sensitivity of the target itself. The following sections provide the specific criteria for assigning these scores based on the type of physical effect and the nature of the exposed target.

2. 3. 6. 1. Evaluating Hazard Intensity

The intensity score is determined by matching the physical effect's magnitude within a threat zone to the criteria in the table below.

Table 6: Intensity Evaluation matrix [11]

Effects / Scale	**High (4)**	**Significant (3)**	**Medium (2)**	**Low (1)**
Effect on Humans				
Overpressure	> 200 mbar	140 – 200 mbar	50 – 140 mbar; 20 – 50 mbar (Indirect)	< 20 mbar
Transient Thermal	> 1 800 $[kW/m^2]^{4/3}\cdot s$	1 000 – 1 800 $[kW/m^2]^{4/3}\cdot s$	600 – 1 000 $[kW/m^2]^{4/3}\cdot s$	< 600 $[kW/m^2]^{4/3}\cdot s$
Continuous Thermal	> 8 kW/m^2	5 – 8 kW/m^2	3 – 5 kW/m^2	< 3 kW/m^2
Toxic	SELS	SEL	SEI	SER
Effect on Structures				
Overpressure	> 200 mbar	140 – 200 mbar	50 – 140 mbar	≤ 50 mbar
Transient Thermal	NA	NA	NA	NA
Continuous Thermal	> 200 kW/m^2	> 20 kW/m^2	8 – 20 kW/m^2	< 8 kW/m^2
Toxic	N/A	N/A	N/A	N/A

2. 3. 6. 2. Evaluating Target Sensitivity

The sensitivity score is assigned by evaluating the nature, function, and resilience of the human, structural, or environmental target against the criteria outlined in the table below.

Table 7: Sensitivity Evaluation matrix [11]

Sensitivity	Code	Description
Low	LS = 1	● Personnel trained and equipped to intervene in an emergency with protective gear against the phenomenon's effects
		● Buildings protected against potential effects (e.g. control rooms)
		● Presence of nearby shelters or refuge zones very close to human targets (especially for slowly evolving phenomena)
		● Underground installations in case of suppression or thermal effects
Medium	MS = 2	● Workers of the studied facility, with robustness based on job-specific knowledge
		● Workers of the studied facility, with robustness based on awareness of risks related to their activities
		● Workers of the studied facility, with robustness based on company-led risk-awareness campaigns
		● Workers of the studied facility, with robustness based on drills and simulation exercises
		● Workers of the studied facility, with robustness based on evacuation procedures tailored to likely risks
		● Workers of the studied facility, with robustness based on early detection and anticipation of the phenomenon
		● Equipment and installations specially designed to resist certain effects for a defined duration
		● Equipment and installations fitted with automatic protection systems (e.g. sprinkler or deluge systems)
Significant	SS = 3	● Local population and workers of neighboring businesses
		● Sites providing essential services (healthcare, safety, security, supply, transport, communications, etc.)
High	HS = 4	● Vulnerable populations (hospitalized patients, prisoners, schoolchildren, etc.)
		● Sensitive natural areas (seas, rivers, aquifers, zoos, etc.)
		● Cultural and historic monuments and sites

		● National economy and logistics infrastructure

Once both the Intensity (I) and Sensitivity (S) scores have been determined for each target under each scenario, the results are ready to be consolidated. This final step synthesizes the individual assessments into a comprehensive overview, allowing for clear documentation and the prioritization of risks.

2. 3. 7. The Vulnerability Canvas

To facilitate this process and provide a clear, non-technical summary of the findings, the following canvas is used. This template serves to document the complete assessment pathway for each identified scenario, from the initial threat to the final vulnerability score.

Table 8: Vulnerability Canvas (Non-technical summary template) [11]

Study area: **Company:** **Activity type:** **Installation studied:** **Date:**							
N°	**Scenario**	**Effect type**	**Effect zones**	**Targets affected**	**Sensitivity (S)**	**Intensity (I)**	**Vulnerability (V)**

With the canvas populated, each scenario's vulnerability score is evaluated against predefined acceptance criteria to determine the appropriate course of action:

- **Acceptable Scenarios:** If the vulnerability level is deemed acceptable (e.g., Low or Medium), the existing controls are considered sufficient and the scenario is documented as managed.
- **Unacceptable Scenarios:** If the vulnerability level is unacceptable (e.g., Significant or High), a dedicated action plan is required. This plan must outline feasible technical or organizational measures designed to reduce either the hazard intensity, the target sensitivity, or both.

The goal of any action plan is to reduce the risk to a level that is As Low As Reasonably Practicable (ALARP). The following section provides a detailed framework for developing these vulnerability reduction strategies.

2. 3. 8. Vulnerability reduction

When the vulnerability assessment identifies unacceptable scenarios, a structured action plan is required to reduce the risk to an acceptable level (ALARP). Effective vulnerability reduction targets the two constituent components of the vulnerability equation: Intensity and Sensitivity.

This is achieved through two distinct but complementary types of strategic measures:

- **Mitigation Measures** are proactive interventions designed to reduce the *Intensity* of the hazardous phenomena.
- **Adaptation Measures** are protective interventions designed to reduce the *Sensitivity* of the exposed targets.

The following sections detail the practical application of these strategies.

2. 3. 8. 1. Reducing Intensity (Mitigation)

Mitigation strategies focus on controlling the hazard at its source or along its propagation path, thereby shrinking the footprint of the threat zones. The primary goal is to lessen the physical impact of a potential event. Key approaches include:

- **Source Reduction:** Directly reducing the magnitude of the potential hazard, for instance, by lowering the inventory of hazardous substances stored on-site (e.g., reducing the volume of LPG in a sphere tank).
- **Separation and Siting:** Increasing the physical distance between a hazard source and vulnerable targets. This can involve relocating critical equipment or carefully siting new facilities away from populated areas or sensitive environments.

While mitigation is the first line of defense, it may not be possible to eliminate all risk. Therefore, these measures are typically complemented by adaptation strategies that address the residual risk.

2. 3. 8. 2. Reducing Sensitivity (Adaptation)

Adaptation strategies aim to enhance the resilience of the targets themselves, enabling them to better withstand the impact of a hazardous event should one occur. These measures are crucial

for protecting people, assets, and the environment within the identified threat zones. Key approaches include:

- **Structural Hardening & Barriers:** Reinforcing structures and installing physical barriers to resist impacts.
- **Emergency Preparedness & Response:** Establishing robust plans, protocols, and facilities for managing emergencies.
- **Strategic Land-Use Planning & Siting:** Using administrative controls and intelligent design to minimize exposure.
- **Personal Protective Equipment (PPE):** Providing individuals with direct protection against hazards.

The following sections provide a detailed examination of how these strategies are implemented.

Structural Hardening and Physical Barriers

A primary adaptation strategy involves physically hardening the facility to enhance its resilience. This is often achieved using passive barrier systems, which are generally more reliable than active systems (like water curtains) during an emergency.

- **Firewalls** are critical components, rated for their **Resistance (R)**, **Tightness (E)**, and **Insulation (I)**. An **REI 120** rating, for example, signifies that the barrier can maintain its structural integrity, prevent the passage of flames and hot gases, and limit heat transfer for 120 minutes.
- **Thermal Screens** are designed specifically to block heat radiation. While they may not offer the same level of insulation as a firewall, their focus on Resistance and Tightness provides crucial protection by reflecting the initial, intense thermal exposure from an event like a flash fire or fireball.

These barriers must be designed to withstand a specific thermal dose, with a typical target of keeping exposure below 600 $(kW/m^2)^{4/3}\cdot s$. For events of extended duration, however, physical barriers are not a complete solution, and evacuation must be prioritized.

Strategic Design and Siting of Refuge Areas

Beyond hardening the entire facility, the most critical adaptation for human safety is the provision of dedicated refuge areas. The effectiveness of these shelters hinges on their strategic placement and design.

The core principle is sitting refuge areas on the non-exposed faces of existing structures, using the building itself as a primary shield. This positioning must ensure that the shelter location remains within acceptable safety thresholds during an event, which are dependent on the possible threat zones.

Furthermore, refuge areas must be designed for both accessibility and operational function. This includes clear, universal signage distinct from fire alarms, supplemental communication systems (auditory and visual), and a minimum space of 1.5 m^2 per occupant. For larger facilities, multiple smaller shelters are often more effective than one large one for managing an evacuation.

Emergency Preparedness and Shelter Operations

Once a refuge area is designed and sited, its operational readiness is paramount. This requires comprehensive emergency preparedness, covering supplies, protocols, and maintenance.

Essential supplies must be maintained within each shelter, including sealing materials for doors and vents, potable water, complete first aid kits, battery-operated communication devices, and detailed emergency instructions. Crucially, all combustion-based devices are strictly prohibited to prevent oxygen depletion.

Safety protocols and maintenance are non-negotiable. Annual training drills are required to ensure all personnel are familiar with procedures. A regular maintenance schedule must be implemented to inspect the shelter, clear any obstructions, and replace expired supplies, ensuring the facility is always in a state of readiness.

Supporting Operational Controls

Finally, certain operational systems can be considered part of an adaptation strategy because they support the effectiveness of the protective measures above. Bypass installation systems, for example, allow for the emergency redirection of hazardous products to secure locations. By operating manual or remote-controlled valves, personnel can prevent a scenario from escalating, thereby ensuring that the conditions within the designated refuge areas remain within their design safety limits.

By implementing a combination of these mitigation and adaptation strategies, the overall vulnerability of the facility can be systematically reduced. However, the process is not complete until the effectiveness of these measures is formally verified.

2. 3. 9. Vulnerability re-Assessment

After an action plan has been fully implemented, the vulnerability assessment must be performed again. This crucial re-assessment repeats the core steps of the methodology, using the modified parameters (e.g., new barriers, hardened structures) to calculate a revised vulnerability score.

The primary objective is to confirm that the implemented measures have successfully reduced the vulnerability level to an acceptable, ALARP state. If this criterion is met, the risk is considered formally controlled. This iterative loop of assessment, reduction, and re-assessment is fundamental to a robust and dynamic safety management system.

2. 3. 10. Vulnerability assessment flowchart

The comprehensive, multi-step process detailed in this chapter, from initial data gathering to final re-assessment, can be visualized as a single, integrated workflow. The flowchart below provides a high-level summary of this methodology, illustrating the logical sequence and interdependence of each stage.

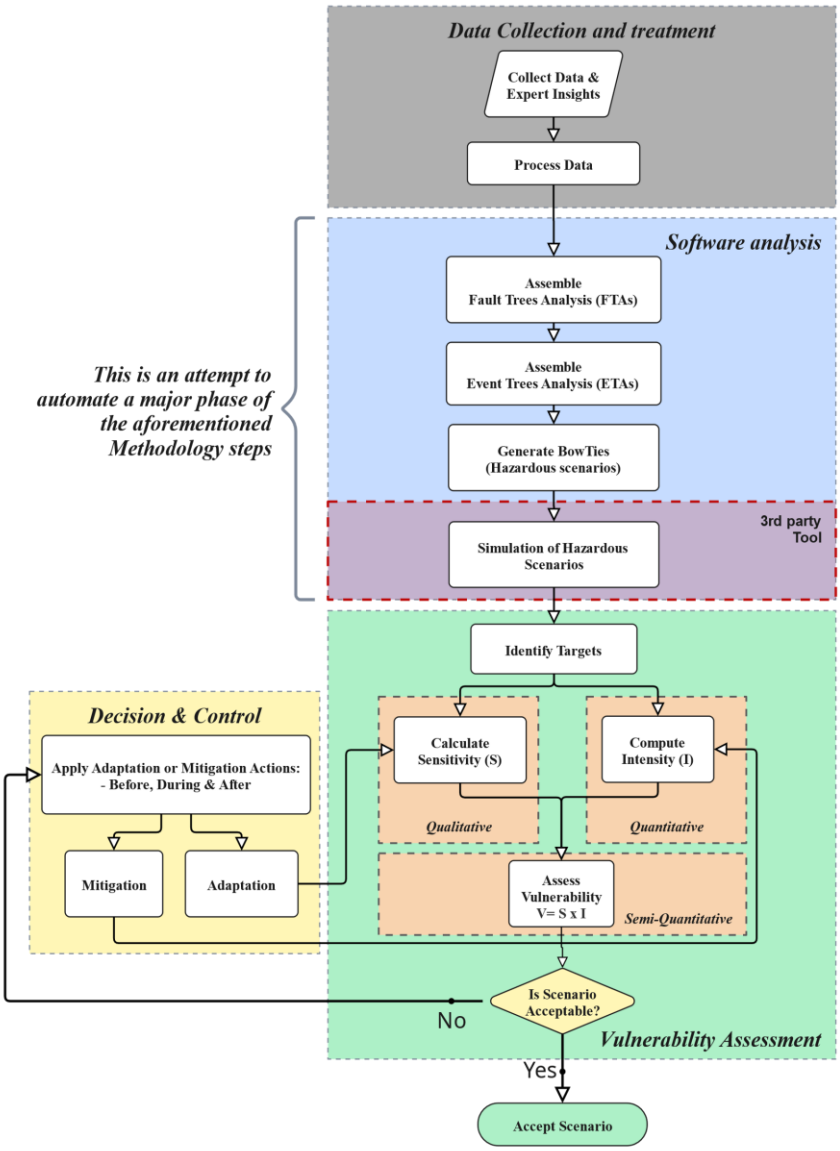

Figure 2: Vulnerability assessment flowchart

As the flowchart illustrates, the analysis phase of the methodology is particularly complex, traditionally requiring significant manual effort and specialized expertise. To address this bottleneck and enhance the framework's practical applicability, a dedicated software solution was developed as the core technical contribution of this thesis. Which will be presented in the next chapter.

Chapter 3
Software development

Chapter 3. Software Development

This chapter details the design and development of the software tool. The primary objective was to automate the most resource-intensive aspects of the vulnerability assessment, making the methodology more accessible to practitioners without requiring expensive commercial packages.

Due to the project's time constraints, the software's scope was strategically focused on automating Fault Tree Analysis (FTA). While this means the Event Tree Analysis (ETA) portion of a full BowTie must be handled separately, automating the complex "cause-side" analysis still represents a significant step forward.

To manage the "consequence-side" of the analysis, the software was designed to work in conjunction with PRISM, a third-party hazard simulation tool. This integrated approach creates an effective workflow: the developed software generates the fault tree, and PRISM is then used to model the consequences and delineate the corresponding threat zones.

The following sections will now explain the software's underlying system architecture and provide a detailed walkthrough of its operational workflow.

3. 1. 1. System Architecture and Operational Workflow

The software is designed as a standalone desktop application to provide a streamlined and user-friendly experience for conducting fault tree analysis. The entire process is structured around a clear operational workflow, guiding the user from initial setup to final analysis through the following key stages:

1) **Secure Login**
    a) Sign in with credentials.
2) **Build Fault Trees** *(in the "Build Fault Trees" tab)*
    a) **Define & Enrich Events:**
        i) **Event Types:**
            (1) **Basic Events (B#):** Causes without further breakdown (e.g., B1: Gas-detector failure)
            (2) **Underdeveloped Events (U#):** Causes not fully understood (e.g., U1: Human error)

(3) **Intermediate Events (E#):** Combinations of other events (e.g., E1: Gas release)

(4) **PhD Events (PhD#):** Complex, high-impact occurrences (e.g., PhD1: Jet fire)

ii) **Enrichment Options:**

(1) Add detailed descriptions & probability values (PoF)

(2) Tag each event (e.g., "electrical," "mechanical")

(3) Leverage semantic-similarity suggestions to prevent duplicates

b) **Construct Fault-Tree Logic:**

i) **Enter Description:** Type the name/description for your new Intermediate (E#) or PhD (PhD#) event.

ii) **Select Logical Gate:** Choose "AND" or "OR" to define how child events combine.

iii) **Attach Child Events:** link any mix of Basic (B#), Underdeveloped (U#), or existing Intermediate (E#) events, Use drag-and-drop or multi-select from the enriched event list.

Example: Define E2 "Valve Leak" by entering its description, choosing **OR**, then attaching B3 (Seal Failure), U2 (Maintenance Error), and E1 (High Pressure).

c) **Train Model:**

i) Click "Train Model" after creating or updating any event structure to capture those patterns for future fault-tree generation.

3) **Select Root Causes**

a) **Purpose:** Once event database is trained, choose which relevant Basic (B#) and Underdeveloped (U#) events for the study.

b) **How To:**

i) Browse or search the events list in "Select Root Causes" Tab.

ii) Select one or more B# or U# events.

iii) Click Generate Fault Trees

c) **Guiding Analytics:** to help with selection, you can leverage

i) **Apriori Mining:** Uncover frequent event patterns and association rules.

ii) **Suggested Links:** Reveal structural, statistical, and OR-coexistence insights to guide further refinement.

4) **Generate & Review Fault Trees**
    a) **Generation Modes:** Two Modes
        i) **Qualitative:** Structure only, In case PoF is missing in the event selection pool.
        ii) **Quantitative:** Includes probability values (PoF).
    b) **Results Inspection:**
        i) **Text View:** Hierarchical list showing each event's description, PoF, and any applied safety measures.
        ii) **Diagram View:** Visual Tree graph with color coding and PoF annotations.
5) **Apply & Analyze Safety Measures**
    a) **Measure Catalog:** Define and categorize safety measures; assign **Risk Reduction Factors (RRF)**.
    b) **Implementation:** Apply measures to specific event nodes and observe immediate probability reductions.
6) **Save & Export**
    a) **Auto-Save:** Triggers after each model training trigger.
    b) **Reporting:** Export text summaries and high-quality visual diagrams for presentations.

Data Quality Reminder: it should be noted that the accuracy of generated fault trees hinges on the richness and consistency of your event definitions.

3. 1. 2. Key Capabilities and Benefits

The software is designed to provide several key benefits that make the risk assessment process more effective and accessible:

- **Formalizes Hazard Definition:** Clearly defines potential failure scenarios by establishing a precise top event for the analysis.
- **Maps Causal Relationships:** Visually illustrates the logical connections between seemingly minor initiating events and a major system failure.
- **Offers Visual Clarity:** Represents complex failure logic in an intuitive, graphical tree format that is easy to interpret.

- **Facilitates Safety Planning:** Allows users to quantitatively assess the impact of safety measures by observing their effect on the top event probability.
- **Deepens System Knowledge:** Enhances the user's understanding of the system's design, interdependencies, and inherent vulnerabilities.

In essence, this software is engineered to make the complex task of fault tree analysis more manageable, insightful, and actionable, ultimately contributing to improved system safety and reliability.

Having established the software's purpose and benefits, the following sections will explore its technical implementation and the core functionalities that deliver these advantages.

3. 1. 3. Technical Implementation and Core Functionalities

The software's effectiveness is rooted in four core functionalities that work together to provide a comprehensive analysis: graphical representation, detailed textual output, a robust probabilistic calculation engine, and a system for implementing risk reduction factors. The following sections detail each of these components.

3. 1. 3. 1. Graphical Fault Tree Representation

A central feature of the application is its ability to generate an intuitive graphical representation of a fault tree. This visual output translates complex logical relationships between failure events into a clear and understandable diagram, making the analysis accessible to a wider range of stakeholders. The following image, generated by the tool, illustrates the causal pathway for a "Jet Fire" scenario, with application of safety measures (Combined RRF=0.06) on event B1 to reduce its PoF.

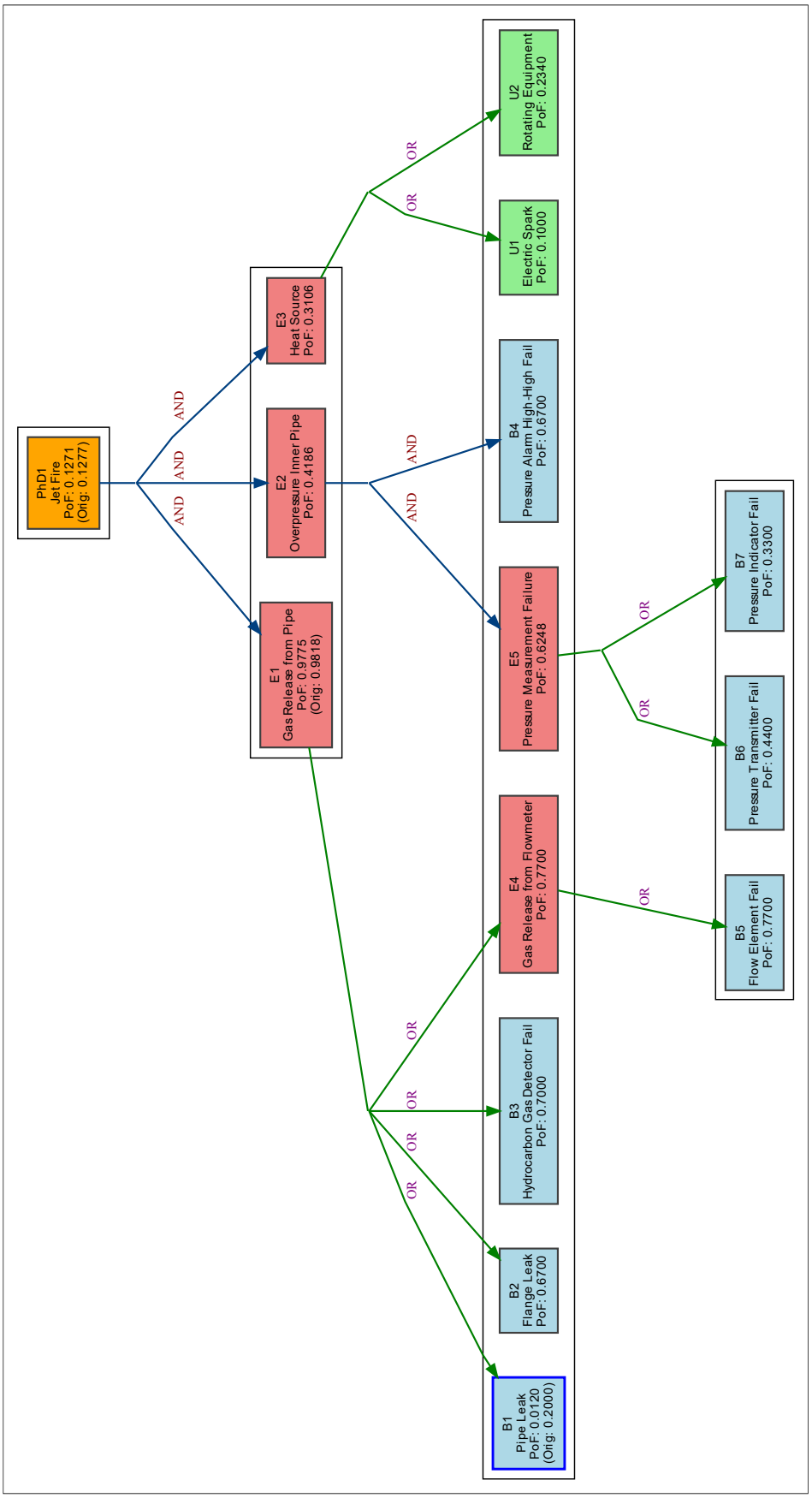

Figure 3: Jet fire fault tree diagram

While the graphical tree provides a high-level overview, a more detailed quantitative analysis is available through the software's textual output.

3. 1. 3. 2. Textual Output Format and Structure

For each analysis, the software generates a structured textual report that provides a complete quantitative breakdown of the fault tree. This output details the logical relationships between events and their calculated probabilities of failure (PoF).

Tree 1: PhD1 - Jet Fire (PoF: 0.1271, Original: 0.1277) (Components: 9)
PhD1 (PoF: 0.1271, Orig: 0.1277) = (E1 ∧ E2 ∧ E3)

Where:

E1 - Gas Release from Pipe (PoF: 0.9775, Orig: 0.9818) = (B1 ∨ B2 ∨ B3 ∨ E4)
E2 - Overpressure Inner Pipe (PoF = 0.4186) = (B4 ∧ E5)
E3 - Heat Source (PoF = 0.3106) = (U1 ∨ U2)
E4 - Gas Release from Flowmeter (PoF = 0.7700) = (B5)
E5 - Pressure Measurement Failure (PoF = 0.6248) = (B6 ∨ B7)

Basic Events:

*B1 - Pipe Leak (PoF: 0.0120, Orig: 0.2000)
B2 - Flange Leak (PoF = 0.6700)
B3 - Hydrocarbon Gas Detector Fail (PoF = 0.7000)
B4 - Pressure Alarm High-High Fail (PoF = 0.6700)
B5 - Flow Element Fail (PoF = 0.7700)
B6 - Pressure Transmitter Fail (PoF = 0.4400)
B7 - Pressure Indicator Fail (PoF = 0.3300)
U1 - Electric Spark (PoF = 0.1000)
U2 - Rotating Equipment (PoF = 0.2340)

Applied Safety Measures:

- *Pipe Integrity Monitoring (RRF: 0.20) applied to*:

- B1: Pipe Leak

- *Corrosion Inhibitor (RRF: 0.30) applied to*:

- B1: Pipe Leak

As shown in the report, the software lists each intermediate and basic event, its logical relationship to other events (using "∧" for AND, "∨" for OR), and its calculated PoF. It also

clearly indicates where safety measures have been applied by comparing the final PoF to the original probability ("Orig:"), providing a transparent view of the effectiveness of the implemented controls. This quantitative analysis is driven by the software's underlying calculation engine.

Having detailed the technical workings of the software, the following section will demonstrate its practical application in an industrial context.

3. 1. 4. Industrial Application

To validate its practical utility and guide its future development, the software was field-tested in an operational environment at a Central Processing Facility (CPF) in the oil and gas sector. This application served to assess its performance in a real-world context, identify its current strengths and limitations, and gather professional feedback.

3. 1. 4. 1. Performance Assessment and Future Roadmap

During its deployment, the tool successfully demonstrated its core capabilities, including the automated generation of fault trees from system data, the accurate calculation of top event probabilities, and the effective modeling of risk reduction measures.

The field test was also instrumental in identifying key areas for future enhancement. The primary limitations identified include the need for more sophisticated handling of complex Safety Instrumented Systems (e.g., voting logic), improved pattern recognition for advanced consequence modeling, and more robust analysis of inter-system dependencies. These findings have provided a clear and focused roadmap for the next phase of development.

3. 1. 4. 2. Conclusion of the Industrial Application

In summary, the industrial application was an invaluable step in the development lifecycle. Despite the prototype's limitations, the field test confirmed that its core concept is sound and has practical value in an industrial safety context. The experience of applying the tool to complex, real-world systems provided critical insights that have successfully bridged the gap between an academic proof-of-concept and a robust engineering tool with a clear path forward.

Chapter 4
Operational Implementation

Chapter 4. Operational implementation

This chapter presents a detailed case study applying the complete vulnerability assessment framework to System 33 at the Menzel Ledjmet Est (MLE) Central Processing Facility, operated by the Groupement Sonatrach-ENI (GSE). The objective is to demonstrate the practical application of the methodology, leveraging the software tool for fault tree analysis, to identify, evaluate, and characterize risks in a complex industrial system. This serves as a holistic validation of the study's primary objectives.

4. 1. Study Field

As per the established methodology, the first step is to define the study field. This involves a comprehensive characterization of the installation's operational context, including its environmental setting, surrounding activities, and specific facility details.

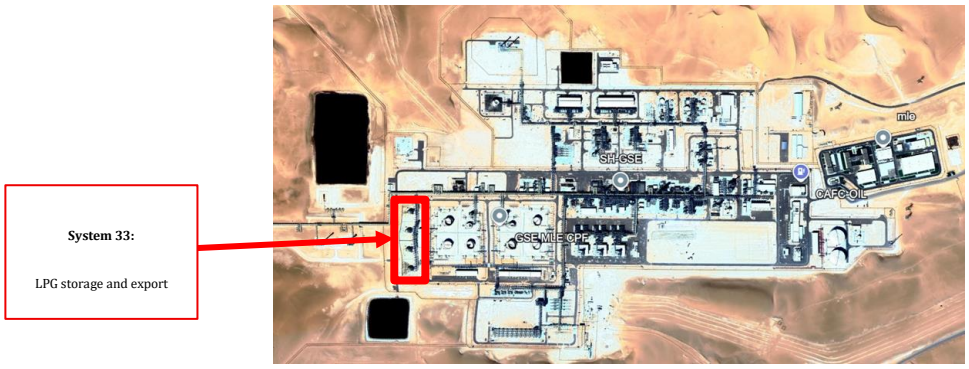

Figure 4: Satellite View and Geographical Location of the MLE CPF Site

4. 1. 1. Environmental and Climatic Context

A thorough understanding of the site's environmental characteristics is crucial for identifying potential natural hazards and their interactions with the facility. The data presented here is drawn from the approved safety case (EDD) for the MLE site.

- **Thermal Conditions:** The site experiences significant daily and seasonal temperature variations, with recorded highs of 45.8°C and lows of -1.2°C. These thermal amplitudes directly influence material selection and operational pressures.

- **Precipitation and Wind:** The region is arid, with negligible annual rainfall (15.7 mm in 2018). The wind regime is a key factor, with a dominant northeastern direction and gusts occasionally reaching 21.6 m/s, which can affect vapor cloud drift.
- **Seismicity:** According to Algeria's RPA 99 seismic regulations, the site is classified as Zone 0, indicating negligible seismic risk.
- **Natural Environment:** No sensitive ecosystems or protected natural areas have been identified in the immediate vicinity of the CPF.

4. 1. 2. Surrounding Activities and Infrastructure

The next component is to map the human and industrial landscape surrounding the CPF to evaluate external risks and potential exposures.

- **Neighboring Industrial Activity:** The MLE site is geographically isolated, with no major third-party industrial facilities nearby.
- **Transportation Networks:** The site is accessed via a dedicated service road and a local airstrip located **6 kilometers** south of the CPF. Strict traffic safety policies and prohibitions on overflights minimize transport risks.
- **Utility and Product Corridors:** An overhead high-voltage power line passes approximately **100 meters** from the CPF perimeter, representing a potential ignition source. A network of pipelines for crude oil, gas, and processed products connects the CPF to regional infrastructure, though all are under CPF operational control.
- **Residential and Populated Zones:** The facility is in a sparsely inhabited desert. The only significant populated areas are the operator's residential bases and a military camp, all situated more than 5 km away. Within a 3 km radius, the only facilities are a subcontractor base with approximately 20 people and a pipe yard with fewer than 10 staff.

4. 1. 3. Installation Description

With the external context established, the focus now shifts to the facility itself. The MLE Central Processing Facility (CPF) is a large, integrated complex responsible for the collection, processing, and export of hydrocarbons. This study focuses specifically on System 33, which is dedicated to the storage and export of liquefied petroleum gas (LPG).

4. 1. 3. 1. Off-Site Installations Supplying the CPF

The CPF is supported by a network of off-site installations that gather crude oil and natural gas from multiple production wells distributed across the MLE and CAFC fields. These installations consist of well pads, flowlines, manifolds, and trunk lines designed to route hydrocarbons efficiently to the CPF.

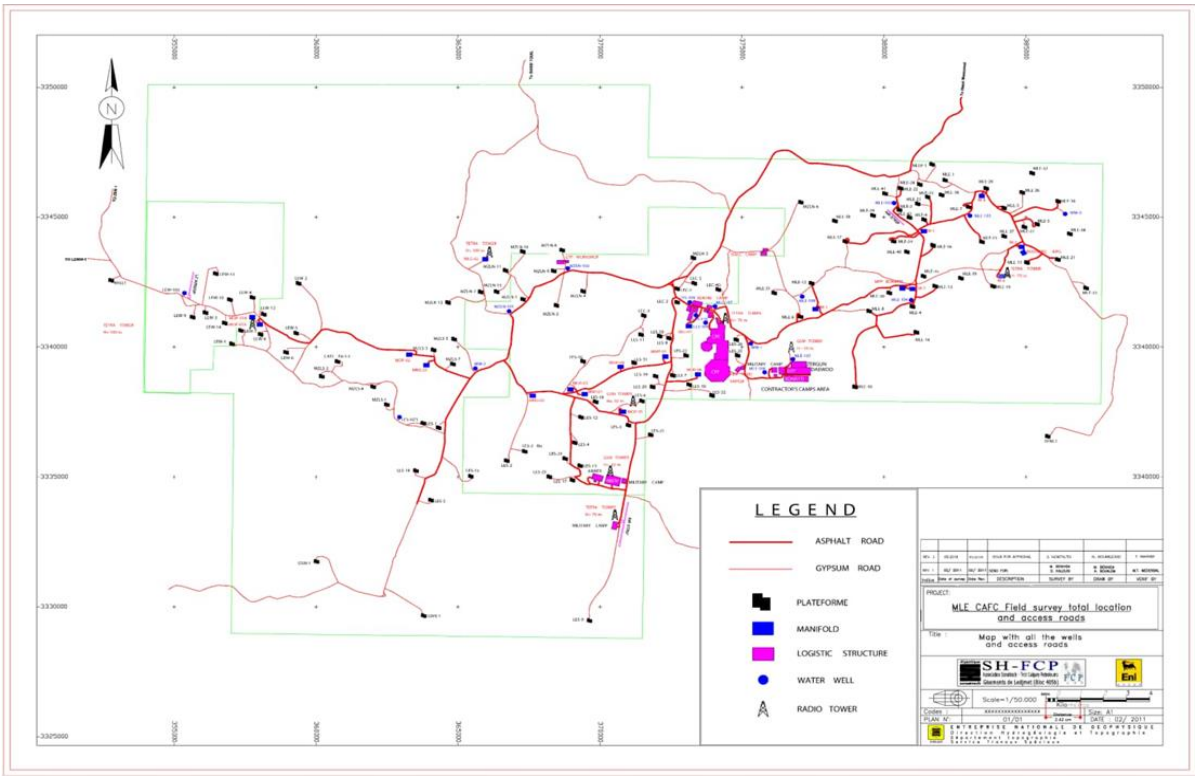

Figure 5: Schematic of Off-Site Installations Supplying the CPF

4. 1. 3. 2. CPF MLE - Process Overview

The Central Processing Facility (CPF) at MLE is the core installation designed to process multiphase production fluids and deliver four final products. To achieve this, the CPF integrates modular separation and treatment units, automated control systems, and robust safety infrastructure. The overall process is structured around two main treatment chains: one for gas, and the other for liquid hydrocarbons and LPG recovery.

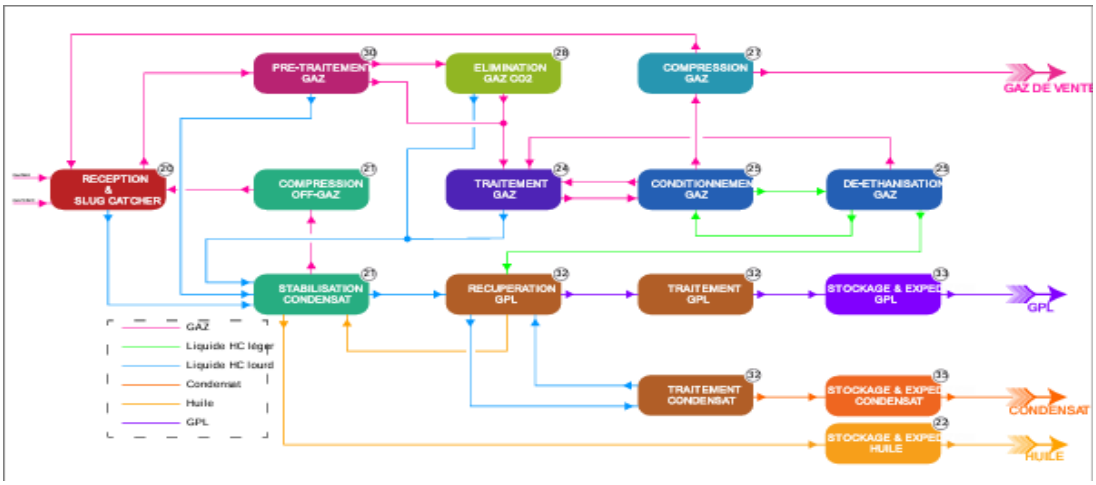

Figure 6: Simplified Process Flow Diagram of the MLE Central Processing Facility

The liquid phase, recovered from the slug catcher and upstream separators, passes through a series of processing units. Heavier C3+ components are further separated and transferred to the LPG fractionation column (CX-32-01), where propane and butane are separated and routed to System 33 for storage and export.

4. 1. 3. 3. LPG Storage and Export System

The system 33 serves as the final node in the LPG product stream. It receives liquefied products from the fractionation unit, stores them in either on-spec or off-spec spheres, and manages their final dispatch. As such, System 33 plays a central role in the stabilization, storage, and export of LPG from the CPF.

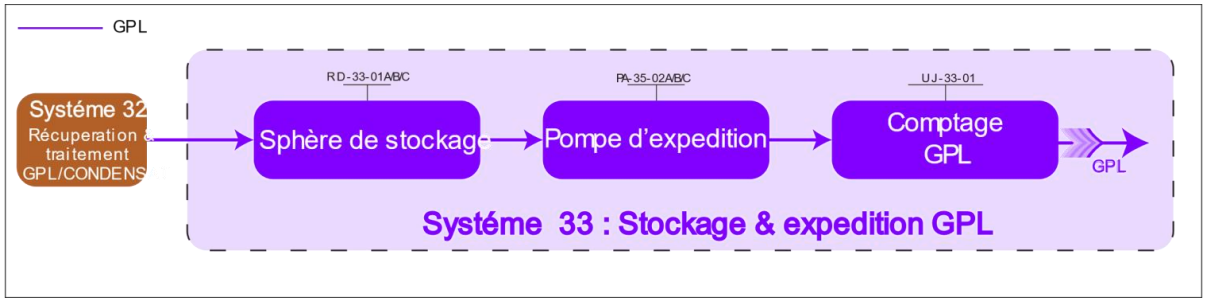

Figure 7: Simplified Process Flow Diagram of the system 33

4. 2. Identification of Hazardous Scenarios

With the study field defined, the methodology now proceeds to the identification of all major hazardous scenarios associated with System 33. This process begins by understanding the

inherent properties of the substance being handled and then applying the BowTie methodology to systematically analyze potential failure scenarios.

4. 2. 1. Inherent Hazards of LPG

The primary hazard in System 33 stems from the physicochemical properties of its contents, LPG, which is a mixture of approximately 67% propane and 31% butane. Key hazardous characteristics include:

- **High Volatility and Vapor Pressure:** With boiling points of -42°C (propane) and -1°C (butane), LPG rapidly evaporates upon release at ambient conditions, leading to large vapor clouds and a high risk of ignition.
- **High Flammability and Calorific Value:** LPG is highly flammable and has a high energy content, meaning it can sustain intense fires or powerful explosions.
- **Vapor Density:** Being heavier than air, LPG vapor tends to accumulate in low-lying areas, creating persistent, invisible ignition hazards.
- **High Thermal Expansion:** LPG expands significantly with temperature, which can lead to catastrophic over-pressurization and rupture of contained systems if not properly managed.
- **Other Hazards:** Potential for cold burns upon contact, and corrosivity if impurities like sulfur are present.

These inherent properties dictate the types of failures that must be analyzed.

4. 2. 2. Applying the BowTie Methodology

To systematically map the potential hazardous scenarios, the BowTie methodology is applied. This process is centered around identifying critical events and then analyzing their causes and consequences.

4. 2. 2. 1. The Critical Events

Based on the properties of LPG and the equipment in System 33, the following critical events (the "top events" for the BowTies) are identified [11]:

- **Leak from a storage sphere:** A partial loss of containment from a sphere, which could lead to a sustained release of flammable vapor.

- **Rupture of a storage sphere:** A catastrophic, instantaneous failure of a sphere, potentially leading to a BLEVE.
- **Leak from LPG export pump or piping:** A sustained release from the export system, typically due to seal or valve failure.
- **Rupture of LPG export pump or piping:** A high-energy mechanical failure of the export system, leading to a large, rapid release.

4. 2. 2. 2. Causes Analysis

For the critical event—Loss of Containment (LOC) of an LPG Sphere—the next step is to analyze all credible causes using Fault Tree Analysis (FTA). As detailed in Chapter 4, the custom-developed software tool is utilized to automate this process. This section provides a detailed, step-by-step account of how the software was used to build the knowledge base and generate the fault tree for this specific case study.

Step 1: Building the Fault Tree Knowledge Base

Before analyzing the specific case, the software's knowledge base was constructed using the authoritative industry reference, *Hazards, Threats and Consequences – Deep HAZID for Process Safety Management* by Robert Taylor [16]. This book provides detailed BowTie analyses for major industrial risks, including the specific causes and consequences related to LPG storage spheres. The following steps show how this knowledge was used to "train" the software.

A. Defining Basic Events

The process started by defining the fundamental failure modes, or Basic Events (B#). Each event was enriched with a description, a probability of failure (PoF), and descriptive tags. For example, the event "Operation outside design envelope" was created as a basic event.

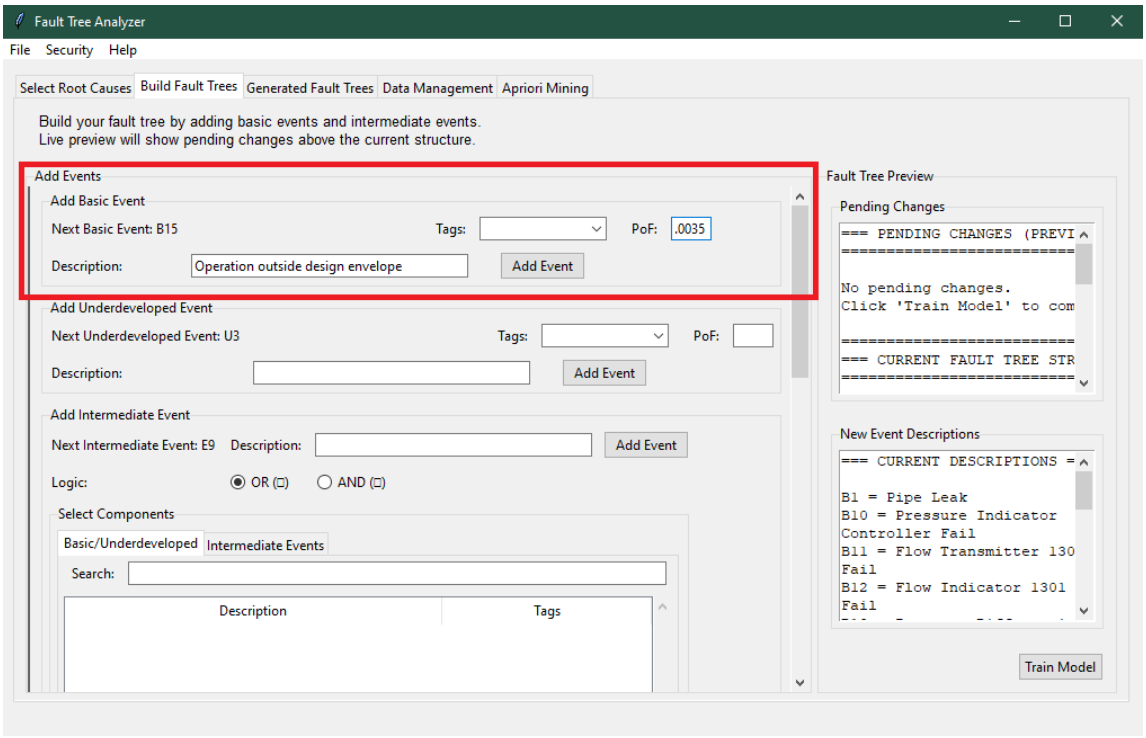

Figure 8: building FTA- defining Basic events like operation outside design envelope

B. Defining Intermediate Events

Next, Intermediate Events (E#) were constructed by logically combining basic events. For instance, the intermediate event "Internal corrosion" (E12) was defined by grouping all relevant basic corrosion events (e.g., *B44 - Corrosion under insulation*, *B40 - General corrosion*) under a single OR gate, as any one of these failures could lead to a loss of containment due to internal corrosion.

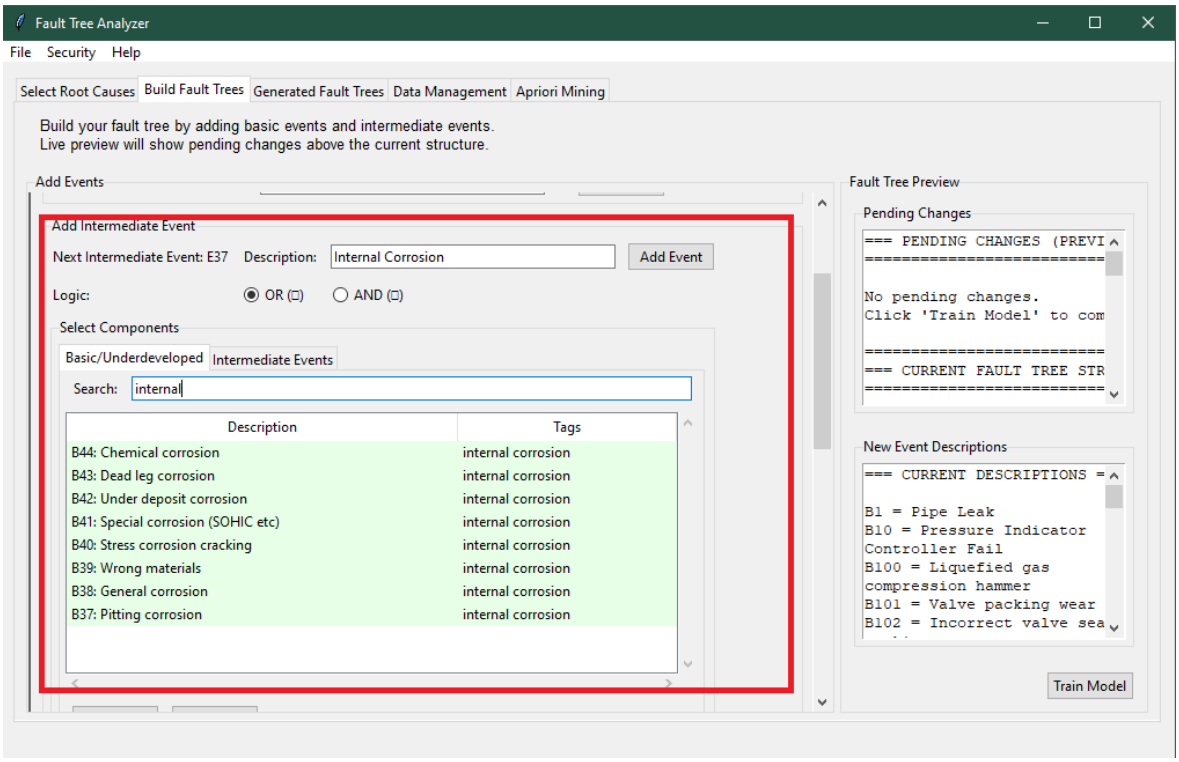

Figure 9: building FTA - defining intermediate events like Internal Corrosion

C. Defining the Top Event (PhD Event)

Finally, the Top Event (PhD#) for the analysis, "Rupture/Leak" (PhD2), was defined. This was achieved by combining all the previously defined intermediate events (E10 - Maintenance error, E11 - Welding defect, E12 - Internal corrosion, etc.) and any relevant basic events (like B22) under a single master OR gate. This represents the fact that a failure in any of these major categories could result in the top event.

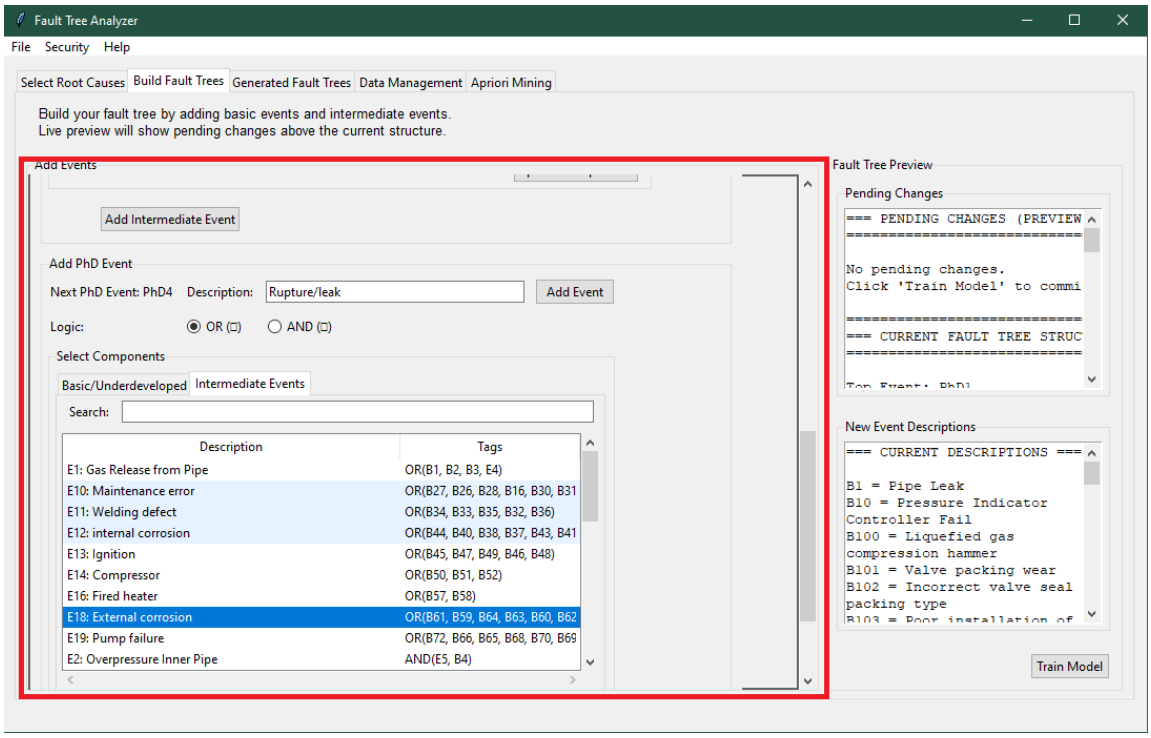

Figure 10: building FTA - Defining Complex events like Rupture/leak

D. Training the Model

With all the causal relationships from the reference book defined, the "Train Model" button was clicked. This action commits the entire logical structure—from basic events up to the top event—to the software's permanent knowledge base, making it available for future analysis.

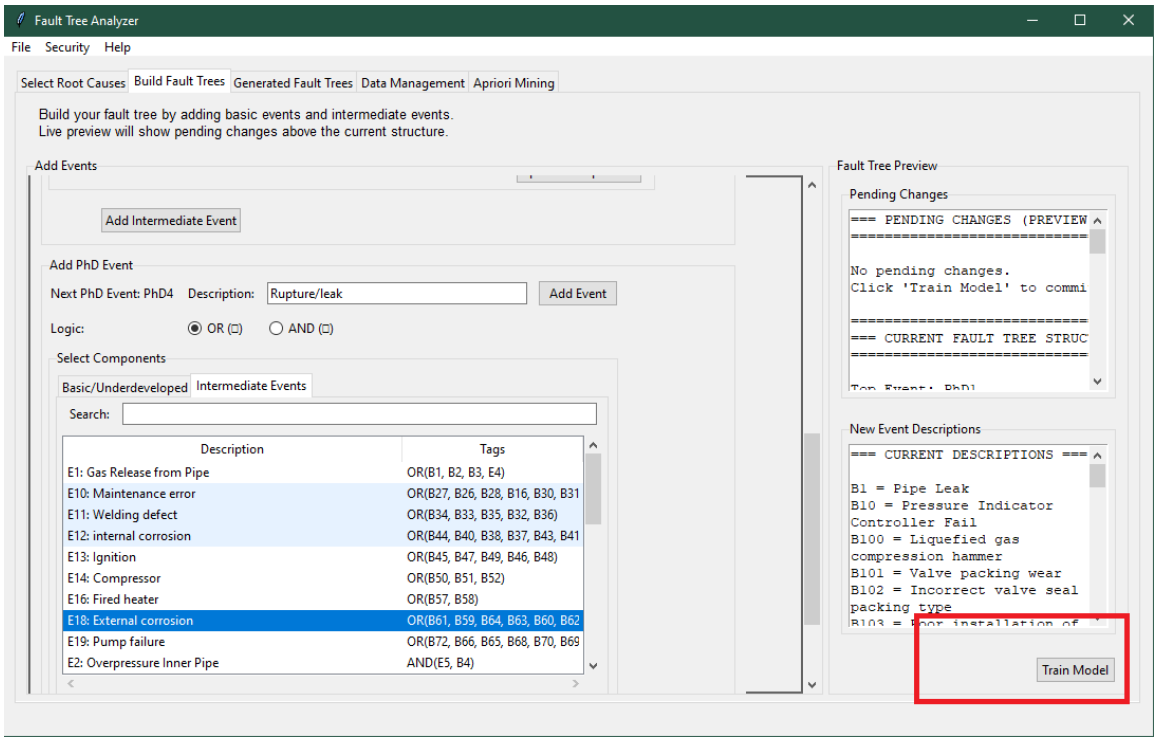

Figure 11: building FTA - Committing to changes by hitting "train model"

Step 2: Generating the Fault Tree for the Case Study

With the knowledge base trained, the analysis of the specific System 33 LPG sphere could begin.

A. Selecting Applicable Root Causes

In the "Select Root Causes" tab, the analyst reviewed the complete list of all basic events from the knowledge base and selected only those deemed credible for the specific context of the MLE CPF's System 33. This critical step applies expert judgment to tailor the generic model to the real-world asset.

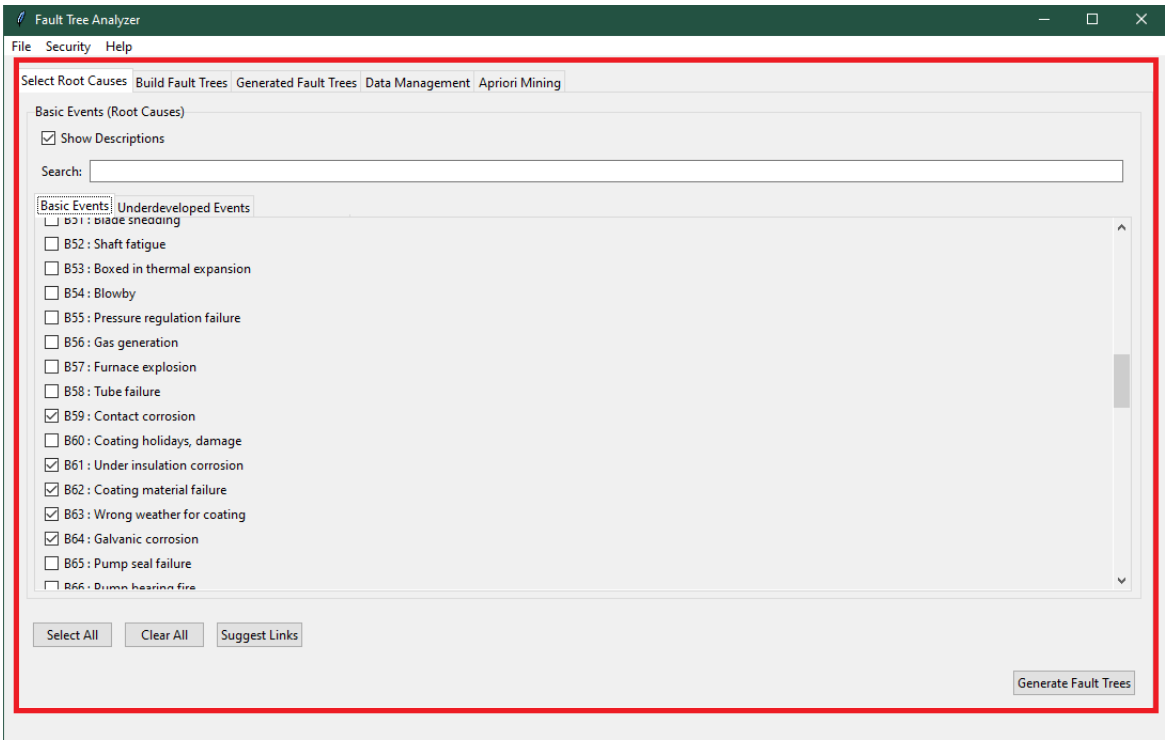

Figure 12: Selection of root causes for generation of FTA

B. Generating and Reviewing the Fault Tree

Once all applicable root causes were selected, the "Generate Fault Trees" function was executed. The software automatically processed the selections, constructed the full fault tree based on the trained logic, and calculated the final probability for the top event. The results were reviewed in the software's two main views.

Diagram View: This view provides an intuitive graphical representation of the entire fault tree, making the complex causal relationships easy to visualize. A high-level graphical representation of the fault tree for the LOC of the LPG sphere, as generated by the software, is shown below.

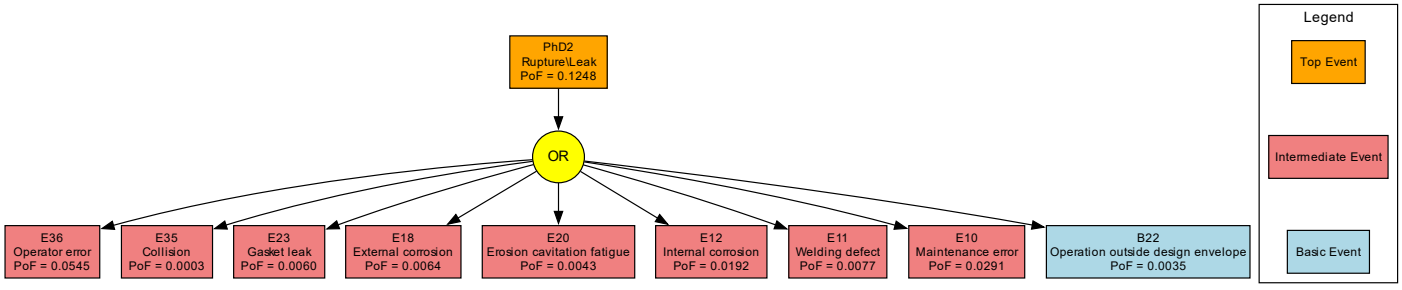

Figure 13: graphical representation of the fault tree for the LOC of the LPG sphere

Text View: This view provides a textual report. a high-level summary of the main contributors to the top event and their calculated probabilities of failure (PoF).

Tree 1: PhD2 - Rupture/Leak (Components: 48 - Nested within Intermediate events including the B22)

PhD2 (PoF = 0.1248) = (E36 ∨ E35 ∨ E23 ∨ E18 ∨ E20 ∨ E12 ∨ E11 ∨ B22 ∨ E10)

Where:

E10 - Maintenance error (PoF = 0.0291) = (B27 ∨ B26 ∨ B16 ∨ B30 ∨ B29)

E11 - Welding defect (PoF = 0.0077) = (B33 ∨ B35 ∨ B32 ∨ B36)

E12 - internal corrosion (PoF = 0.0192) = (B44 ∨ B40 ∨ B38 ∨ B37 ∨ B43 ∨ B41 ∨ B39 ∨ B42)

E18 - External corrosion (PoF = 0.0064) = (B61 ∨ B59 ∨ B64 ∨ B63 ∨ B60 ∨ B62)

E20 - Erosion cavitation fatigue (PoF = 0.0043) = (B74 ∨ B76 ∨ B75 ∨ B73)

E23 - Gasket leak (PoF = 0.0060) = (B89 ∨ B87 ∨ B90 ∨ B85 ∨ B88 ∨ B86 ∨ B92)

E35 - Collision (PoF = 0.0003) = (B132 ∨ B134 ∨ B133)

E36 - Operator error (PoF = 0.0545) = (B18 ∨ B17 ∨ B81 ∨ B20 ∨ B15 ∨ B19 ∨ B25 ∨ B24 ∨ B23 ∨ B21)

B22 - Operation outside design envelope (PoF = 0.0035)

This summary presents the primary intermediate events contributing to a potential Loss of Containment. For a complete and in-depth understanding of the causal pathways, the full fault tree diagrams showing the detailed breakdown of each intermediate event (e.g., E10, E11, E36) into their constituent basic events are provided in **Appendix [A]**. Note that B22 is a basic event and thus has no further decomposition.

With the causes analyzed, the methodology proceeds to the consequence analysis.

4. 2. 2. 3. Consequences Analysis

With the causes analyzed, the potential consequences of each critical event are mapped using Event Tree Analysis (ETA). This inductive approach explores the various outcomes that could follow a loss of containment, depending on factors like the presence of ignition sources and the effectiveness of immediate mitigation. The table below summarizes the plausible hazardous phenomena (consequences) identified for each critical event in System 33.

Table 9: Results of consequences analysis

Equipment	Critical event	Hazardous phenomena
Sphere storage tank	Leak	● Jet fire ● Flash fire ● UVCE
	Rupture	● BLEVE ● Fireball ● UVCE
Export pump	Leak	● Jet fire ● Flash fire ● UVCE
	Rupture	● UVCE

By combining the outputs of the Fault Tree and Event Tree analysis, a complete BowTie diagram is constructed for each hazardous scenario, providing a comprehensive cause-and-effect risk picture.

With the hazardous phenomena for all credible scenarios now identified, the methodology proceeds to the quantitative analysis of their physical effects.

4. 2. 3. Matching to Propagate Effects

To translate the identified hazardous phenomena (e.g., BLEVE, Jet Fire) into tangible threat zones, a quantitative consequence modeling analysis was performed. This was conducted using the PRISM simulation software, a specialized tool for modeling hazardous events.

The simulation requires two sets of primary inputs:

1. **Source Term Data**: Detailed parameters of the potential release, including equipment specifications (sphere volume, pump discharge rates), substance properties, and site-specific meteorological conditions. The complete input data sheet for this case study is provided in **Appendix [B**].

2. **Effect Thresholds:** The specific intensity thresholds for harm to humans and structures, as established in the methodology chapter (e.g., overpressure levels of 20, 50, 140, and 200 mbar; thermal radiation levels of 5, 8 and 16 kW/m²).

For each hazardous scenario, these inputs were entered into PRISM. The software then modeled the physical effects and generated a geographical map of the corresponding threat zones, displaying the contours for each intensity level overlaid on the CPF site plan. The table below summarizes the primary physical effects that were modeled for each phenomenon.

Table 10: Results of the matched effects to the scenarios found

Hazardous phenomena	Major effect
Jet fire	● Thermal effect
Flash fire	● Thermal effect
Fireball/BLEVE	● Thermal effect ● Overpressure effect ● High speed Debris

The direct output of this simulation process is a set of clearly defined threat zones for each scenario. This visual risk picture provides the foundation for the next crucial step in the vulnerability assessment.

4. 3. Target identification

With the threat zones for each hazardous scenario simulated by PRISM, the next step is to identify all vulnerable targets. The hazard analysis revealed that the catastrophic rupture of an LPG sphere gives rise to two distinct, equally critical worst-case scenarios:

1. **Unconfined Vapor Cloud Explosion (UVCE):** Characterized by a widespread overpressure wave, this scenario represents the greatest threat to structural integrity across the facility and to off-site infrastructure.

2. **Fireball (BLEVE):** Characterized by intense, localized thermal radiation, this scenario represents the most severe and immediate threat to human life and equipment at the source of the rupture.

While the physical effects and their reach differ, both scenarios originate from the same location. Consequently, the set of primary targets located within the combined hazard footprint is the same. The analysis therefore proceeds with a single, consolidated inventory of targets, presented in the table below. The specific vulnerability of each target to overpressure (from the UVCE) and to thermal effects (from the Fireball) will then be evaluated separately in the subsequent section.

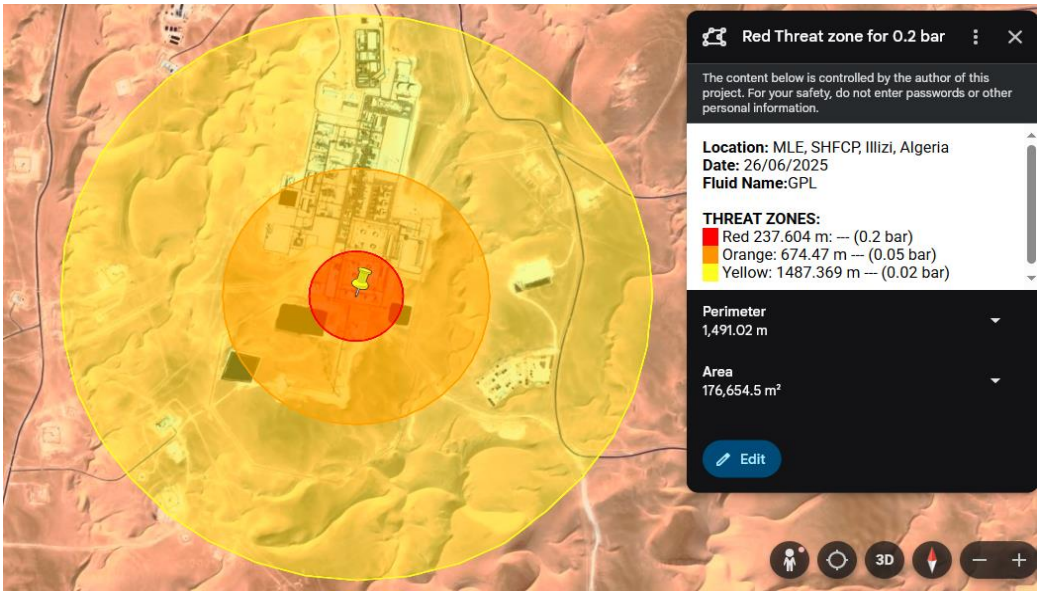

Figure 14: UVCE overpressure effect zones

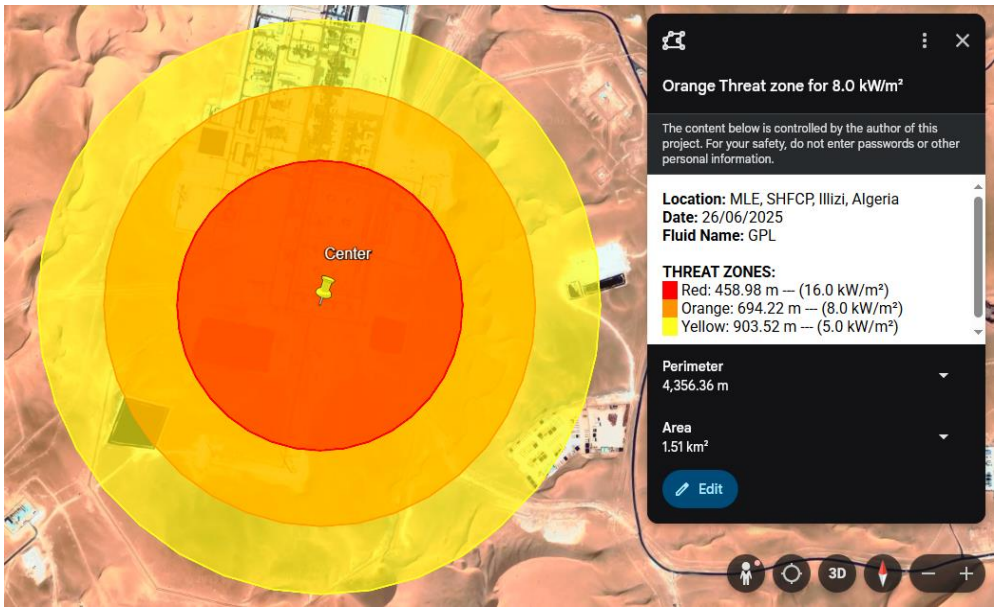

Figure 15: Fire ball thermal effect zones

By overlaying the worst-case threat zone maps on the CPF site plan, a detailed inventory of all exposed targets was compiled. The following table applies the systematic checklist developed in the methodology chapter to the specific context of System 33.

Table 11: Targets identification

No.	Target Type	Check	Observation for MLE System 33
T1	Company Workers (at source)	Yes	A maintenance crew of up to 8 people is conservatively assumed to be performing work directly at the hazard source (the LPG sphere).
T2	Protection Function (at source)	Yes	The on-site intervention team is assumed to be conducting activities near System 33 and could be among the first responders exposed to the initial effects.
T*	Infrastructural Domino Effect	Yes	The three other 500 m³ LPG spheres are in close proximity. A failure of one could trigger a cascading failure in the others, representing a critical functional vulnerability that could dramatically escalate the initial event.
T4/T5	Socio-Economic Impact	Yes	A prolonged shutdown would impact the National & International Economy and Supply. This is assessed as a single socio-economic consequence covering financial penalties, contract breaches, and disruption to energy exports.
T6	Main Workforce (Distant)	Yes	The main CPF workforce is located in the administrative area and living quarters (> 1 km away). They are considered a target for the far-reaching UVCE overpressure wave.
T7	Protection Function Assets (Distant)	Yes	The main fire station and its primary response equipment are located over 1 km from the hazard source. The building's structural integrity is a target for the widespread UVCE overpressure wave.

Note on Checklist Application:

- **Boundary:** For direct physical impacts, a study boundary of a 2 km radius is used. Targets beyond this (e.g., General Population, Health Function, Security Function) are marked as not applicable unless exposed to the UVCE overpressure wave.
- **Assumptions:** To ensure a conservative assessment, it is assumed a maintenance crew (T1) is at the hazard source and the response team (T2) is nearby.
- **Checklist Adaptation:** An "**Infrastructural Domino Effect**" target (marked **T*** as it's not in the original template) has been added under Functional Vulnerability. This is a critical adaptation for this specific case study, as the potential for cascading failures between closely-packed equipment like the LPG spheres is a major risk in process facilities that must be explicitly identified.

With the hazards, threat zones, and exposed targets now fully defined and cataloged according to the established checklist, the analysis proceeds to the final step: the vulnerability assessment.

The complete summary of simulated scenarios for all other identified hazardous scenarios is provided in **Appendix [B]** for reference.

4. 4. Vulnerability Assessment

With the exposed targets identified, the final step is to apply the quantitative framework to determine their vulnerability. A key finding of the hazard analysis is that the catastrophic rupture of an LPG sphere presents two distinct worst-case scenarios, each driven by a different physical phenomenon:

1. **Unconfined Vapor Cloud Explosion (UVCE):** This scenario is dominated by overpressure effects. While its thermal impact is secondary, the blast wave has a much wider geographical reach, making it the worst-case for assessing structural damage and widespread, lower-level impacts.

2. **Fireball (BLEVE):** This scenario is dominated by intense thermal radiation. Its effects are more localized than the UVCE blast wave, but it is far more lethal to any personnel in the immediate vicinity, making it the worst-case for assessing human survivability at the source.

To conduct a comprehensive assessment, the vulnerability of the identified targets must be evaluated against both scenarios. The following canvases present these parallel analyses.

4. 4. 1. Vulnerability Canvas 1: UVCE Scenario (Overpressure Effects)

This analysis focuses on the widespread structural and human impact from the blast wave. Targets are assessed against the overpressure thresholds from the methodology.

Table 12: Vulnerability Canvas 1: UVCE Scenario

Study area: Menzel Ledjmet Est (MLE) CPF
Company: Groupement Sonatrach-ENI
Activity type: Oil & Gas Processing
Installation studied: System 33: LPG Storage & Export
Scenario: Catastrophic Rupture of LPG Sphere with UVCE

N°	Effect type	Effect zones	Targets affected	Sensitivity (S)	Intensity (I)	Vulnerability (V = S × I)
T1	Overpressure	> 200 mbar (Lethal)	Maintenance crew at source	2 (Medium)	4 (High)	8 (Significant)
T2	Overpressure	> 200 mbar (Lethal)	Response team at source	1 (Low)	4 (High)	4 (Medium)
T*	Overpressure	> 200 mbar (Domino Effect)	Adjacent LPG Spheres	4 (High)	4 (High)	16 (High)
T4/T5	Overpressure	**Facility Destroyed/Damaged**	National supply & economy	4 (High)	4 (High)	16 (High)
T6	Overpressure	20 mbar (Indirect)	Main workforce in offices	2 (Medium)	1 (Low)	2 (Low)
T7	Overpressure	20 mbar (Glazing)	Fire station building	3 (Significant)	1 (Low)	3 (Medium)

The UVCE canvas highlights the widespread structural risks. To provide a complete picture, the analysis now shifts to the second worst-case scenario: the Fireball, which poses a more severe, localized threat to on-site personnel and equipment.

4. 4. 2. Vulnerability Canvas 2: Fireball Scenario (Thermal Effects)

This analysis focuses on the severe, localized human and equipment impact from intense thermal radiation.

Table 13: Vulnerability Canvas 2: Fireball Scenario

Study area: Menzel Ledjmet Est (MLE) CPF **Company: Groupement Sonatrach-ENI** **Activity type: Oil & Gas Processing** **Installation studied: System 33: LPG Storage & Export** **Scenario: Catastrophic Rupture of LPG Sphere with Fireball**						
N°	**Effect type**	**Effect zones**	**Targets affected**	**Sensitivity (S)**	**Intensity (I)**	**Vulnerability (V = S × I)**
T1	Thermal	> 8 kW/m² (Lethal)	Maintenance crew at source	2 (Medium)	4 (High)	8 (Significant)
T2	Thermal	> 8 kW/m² (Lethal)	Response team at source	1 (Low)	4 (High)	4 (Medium)
T*	Thermal	> 8 kW/m² (Domino Effect)	Adjacent LPG Spheres	4 (High)	4 (High)	16 (High)
T4/T5	Thermal	**Facility Destroyed /Damaged**	National supply & economy	4 (High)	4 (High)	16 (High)

The vulnerability scores in the canvases above are derived from the direct application of the methodology's scoring criteria. The following notes provide a detailed justification for the key Intensity (I) and Sensitivity (S) values assigned to each target.

Note on Vulnerability Scoring:

- **New Targets (UVCE):** The wider reach of the UVCE blast wave introduces new targets not affected by the Fireball's thermal radiation. **T6** represents the main workforce in offices located >1km away, and **T7** represents the fire station building itself, both within the 20 mbar zone.
- **Intensity (I):** For all targets at the source, the intensity is considered High (I=4) for both scenarios, as they are located within the most severe effect zones (lethal/domino). For distant targets (T6, T7), the intensity is Low (I=1), corresponding to the 20 mbar threshold.

- **Sensitivity (S):** The sensitivity scores are assigned based on the criteria established in the methodology, as follows:
    - **T2 (Response Team) is rated Low (S=1):** This aligns with the LS=1 criterion for "Personnel trained and equipped to intervene in an emergency."
    - **T1 (Maintenance Crew) and T6 (Main Workforce) are rated Medium (S=2):** This aligns with the MS=2 criterion for "Workers of the studied facility," who are assumed to have job-specific knowledge and risk awareness from company training and procedures.
    - **T7 (Fire Station) is rated Significant (S=3):** As the primary emergency response asset, it falls under the SS=3 criterion for "Sites providing essential services (safety, security, etc.)."
    - **T*** (Domino Effect) and **T4/T5** (Socio-Economic) are rated High (S=4):*The potential for cascading failures and the impact on "National economy and logistics infrastructure" place these targets in the highest sensitivity category, HS=4, due to their critical importance and the potential for severe, widespread consequences.

The analysis clearly shows that, regardless of the specific phenomenon, the vulnerability levels for the National Supply/Economy (T4/T5) and the potential for a *Domino Effect (T)** are High (HV). Furthermore, the UVCE scenario highlights a Medium (MV) vulnerability for critical off-site infrastructure. These findings confirm that the risk is unacceptable and that a robust action plan targeting both thermal and overpressure effects is required.

4. 5. Vulnerability Reduction

Based on the assessment's conclusions, the following targets are prioritized for intervention to reduce their vulnerability to an ALARP (As Low As Reasonably Practicable) level:

High Vulnerability (HV) Targets (V > 8):

- **T*: Adjacent Critical Infrastructure (Domino Effect)**
    - **UVCE Impact:** Highly vulnerable to catastrophic structural failure from overpressure effects (>200 mbar).
    - **Fireball Impact:** Highly vulnerable to containment failure from extreme thermal radiation (>8 kW/m²).

- **Priority:** This is the highest priority for on-site risk reduction, as a cascading failure would multiply the consequences of the initial event.

- **T4/T5: National Supply & Economy**
  - **Impact:** The vulnerability of this target is a direct consequence of the others. The destruction of the facility under either the UVCE or Fireball scenario leads to an inevitable and severe socio-economic impact.
  - **Priority:** Reducing this vulnerability depends entirely on preventing the catastrophic failure of the on-site infrastructure (**T***).

Significant Vulnerability (SV) Target (V = 8):

- **T1: On-site Maintenance Crew**
  - **UVCE Impact:** Exposed to lethal overpressure effects.
  - **Fireball Impact:** Exposed to lethal thermal radiation.
  - **Priority:** Protecting human life is paramount. Measures must be robust enough to address both rapid-onset scenarios.

To address these unacceptable vulnerabilities, the following sections outline a series of proposed mitigation and adaptation measures designed to reduce both hazard intensity and target sensitivity.

4. 5. 1. Mitigation measures

Mitigation strategies aim to reduce the *intensity* of the hazard at its source.

Measure M1: Reduce LPG Sphere Inventory by 20-30% (Addresses All Targets)

The justification is a highly effective *source reduction* strategy. By implementing a formal policy to operate the LPG spheres at a reduced maximum inventory, the total energy of a potential release is significantly decreased. This measure is expected to substantially shrink the hazard footprints for both the UVCE and Fireball scenarios. Critically, it is projected to narrow the 20 mbar overpressure zone so that it no longer reaches distant personnel locations (>1 km), effectively removing them from the physical hazard area.

4. 5. 2. Adaptation measures

Adaptation strategies aim to reduce the *sensitivity* of the targets by enhancing their ability to withstand the hazard's impact.

- **Measure A1: Install Inter-Sphere Blast & Fire Walls (Addresses T*)**
    - **Justification:** This is a *structural hardening* strategy designed to prevent a domino effect. The construction of reinforced concrete walls, engineered to an appropriate REI (Resistance, Integrity, Insulation) rating, between the adjacent LPG spheres would serve as physical barriers. These walls would absorb a significant portion of the overpressure wave from a UVCE and block the intense thermal radiation from a Fireball, thereby reducing the *sensitivity* of the adjacent spheres and breaking the chain of cascading failures.

- **Measure A2: Construct a Hardened Shelter (Addresses T1)**
    - **Justification:** This is an *emergency preparedness* strategy focused on life safety. To protect the on-site crew, a dedicated Shelter must be constructed within their immediate work area. In line with the methodology, this structure must be engineered to withstand the worst-case overpressure (>200 mbar) and thermal flux (>20 kW/m²). By providing a survivable space within a lethal zone, this measure drastically reduces the *sensitivity* of the human targets. The shelter must be equipped with independent communication, emergency supplies, and be integrated into regular evacuation drills.

- **Measure A3: Enhance Early Warning & Evacuation Protocols (Addresses T1)**
    - **Justification:** This is an *emergency preparedness* measure that complements Measure A2. The facility's process safety alarms (e.g., high pressure, gas detection) must be linked to an unmistakable, site-wide evacuation siren. The goal is to minimize the time between the detection of a critical failure and the moment personnel have successfully reached the safety of the Shelter. By improving the speed and reliability of the response, this adaptation reduces the crew's exposure time and thus their effective *sensitivity*.

- **Note on Target T4/T5:** The vulnerability of the National Supply and Economy is not addressed by a single, direct measure. Its sensitivity is absolute and its vulnerability score is a direct consequence of the physical destruction of the facility. Therefore, the successful implementation of the adaptation measures above (particularly A1) is the only effective strategy for reducing the vulnerability of T4/T5.

The next step is to re-assess the vulnerability post-measures to see their effectiveness, which will be presented in the following section

4. 6. Vulnerability reassessment

Following the proposal of the mitigation and adaptation measures, a reassessment is performed to quantify their impact on the overall vulnerability. This step assumes the successful implementation of all proposed measures. The revised vulnerability scores are presented in the updated canvases below.

4. 6. 1. Reassessment Canvas 1: UVCE Scenario (Overpressure Effects)

This first reassessment canvas focuses on the UVCE scenario. It evaluates how the implemented measures, such as inventory reduction and enhanced safety protocols, have lowered the vulnerability of each target to the blast's overpressure effects. The updated scores below reflect the anticipated risk reduction in this revised operational context

Table 14: Reassessment Canvas 1: UVCE Scenario

Study area: Menzel Ledjmet Est (MLE) CPF **Company: Groupement Sonatrach-ENI** **Activity type: Oil & Gas Processing** **Installation studied: System 33: LPG Storage & Export** **Scenario: Catastrophic Rupture of LPG Sphere with UVCE (Post-Measures)**						
N°	**Effect type**	**Effect zones**	**Targets affected**	**Sensitivity (S)**	**Intensity (I)**	**Vulnerability (V = S × I)**
T1	Overpressure	> 200 mbar (Lethal)	Maintenance crew at source	1 (Low)	3 (Significant)	3 (Medium)
T2	Overpressure	> 200 mbar (Lethal)	Response team at source	1 (Low)	3 (Significant)	3 (Medium)
T*	Overpressure	> 200 mbar (Domino Effect)	Adjacent LPG Spheres	2 (Medium)	3 (Significant)	6 (Significant)
T4/T5	Socio-Economic	Facility Destroyed	National supply & economy	4 (High)	3 (Significant)	12 (High)

4. 6. 2. Reassessment Canvas 2: Fireball Scenario (Thermal Effects)

This second canvas shifts the focus to the Fireball (BLEVE) scenario. It reassesses the vulnerability of the identified targets to intense thermal radiation, factoring in the risk mitigation from the reduced inventory and enhanced emergency response protocols. The resulting scores illustrate the comprehensive vulnerability reduction achieved across both major hazard scenarios

Table 15: Reassessment Canvas 2: Fireball Scenario

Study area: Menzel Ledjmet Est (MLE) CPF
Company: Groupement Sonatrach-ENI
Activity type: Oil & Gas Processing
Installation studied: System 33: LPG Storage & Export
Scenario: Catastrophic Rupture of LPG Sphere with Fireball (Post-Measures)

N°	Effect type	Effect zones	Targets affected	Sensitivity (S)	Intensity (I)	Vulnerability (V = S × I)
T1	Thermal	> 8 kW/m² (Lethal)	Maintenance crew at source	1 (Low)	3 (Significant)	3 (Medium)
T2	Thermal	> 8 kW/m² (Lethal)	Response team at source	1 (Low)	3 (Significant)	3 (Medium)
T*	Thermal	> 8 kW/m² (Domino Effect)	Adjacent LPG Spheres	2 (Medium)	3 (Significant)	6 (Significant)
T4/T5	Thermal	Facility Destroyed	National supply & economy	4 (High)	3 (Significant)	12 (High)

The updated vulnerability scores in the canvases above reflect the combined impact of the proposed mitigation and adaptation measures. The following notes provide a criterion-based justification for each change in the Intensity (I) and Sensitivity (S) scores.

Note on Reassessment Scoring:

- **Intensity Reduction (M1):** Reducing the LPG inventory lowers the event's source energy. This is logically projected to reduce the Intensity for all targets at the source (T1, T2, T*, T4/T5) from High (I=4) to Significant (I=3). For distant targets (T6, T7), this measure is projected to shrink the 20 mbar overpressure zone so that it no longer reaches their location. While their score remains Low (I=1), the underlying risk is effectively removed.
- **Sensitivity Reduction:**

- **T1 (Maintenance Crew):** The combination of a hardened Shelter (Measure A2) and enhanced protocols (A3) directly satisfies the methodology's criteria for Low Sensitivity (LS=1), specifically the "Presence of nearby shelters or refuge zones". This justifies a reduction from the initial Medium (S=2) to Low (S=1).
- **T* (Adjacent Spheres)**: Installing blast/fire walls (Measure A1) fulfills the criteria for "Equipment and installations specially designed to resist certain effects" under the Medium Sensitivity (MS=2) category. This justifies a significant reduction from the initial, unprotected state of High (S=4) to Medium (S=2).
- **T2 (Response Team):** This target's Sensitivity remains Low (S=1). As "personnel trained and equipped to intervene," they are already at the lowest sensitivity level, and the proposed measures do not change this.
- **T4/T5, T6, T7:** These targets' sensitivities remain unchanged at High (S=4), Medium (S=2), and Significant (S=3) respectively, as the proposed measures do not alter their inherent nature or function.

4. 7. Results Discussion

With the quantitative impact of each measure now justified, the analysis can shift from individual scores to a holistic evaluation of facility safety. The reassessment demonstrates the practical value of the vulnerability analysis framework as a tool for targeted risk reduction. By systematically applying mitigation and adaptation measures aligned with the methodology, significant improvements in safety were achieved:

- **Domino Effect Prevention:** The vulnerability of adjacent critical infrastructure (T*) was successfully reduced from High (V=16) to Significant (V=6). This is the most critical achievement, as it contains the accident and prevents a far more catastrophic cascading failure.
- **On-Site Life Safety:** The vulnerability of the on-site maintenance crew (T1) was reduced from Significant (V=8) to Medium (V=3). This represents a major enhancement in personnel protection, moving the risk from a level requiring immediate action to a more manageable state.

- **Off-Site Safety:** The mitigation measure of reducing inventory proved highly effective, shrinking the hazard footprint to a degree where distant assets like the main offices (T6) and fire station (T7) are no longer considered to be in a significant threat zone.
- **Residual Risk:** The vulnerability of the socio-economic targets (T4/T5) remains High (V=12). This is a realistic outcome, acknowledging that for critical national infrastructure, any major incident will have severe consequences. However, the risk of that incident occurring has been substantially lowered by protecting T*.

The successful application of this framework in the case study provides a strong foundation for the final conclusions of this thesis, which will now be present

General Conclusion

The effective management of major industrial risks hinges not only on identifying potential hazards, but on fundamentally understanding and reducing vulnerability. In high-stakes environments like the oil and gas sector, unaddressed vulnerabilities in people, processes, and infrastructure can transform a manageable incident into a catastrophic disaster. This thesis has centered on this critical concept, developing a comprehensive framework to move vulnerability assessment from a theoretical requirement to a practical, actionable, and repeatable engineering discipline.

This thesis began by identifying a significant challenge within Algeria's industrial safety landscape: while new laws require vulnerability assessments for high-risk facilities, there is no standard, practical guide on how to perform them. This leaves safety practitioners with inconsistent, subjective methods that may fail to identify all critical dangers.

To address this problem, this research developed a practical solution made of two parts: a clear, step-by-step methodology for assessing vulnerability, and a custom-built software tool to automate the most difficult part of the analysis—understanding the root causes of failure.

The value of this combined approach was demonstrated through a detailed case study of an LPG storage facility. The methodology proved effective in a real-world setting, successfully identifying the two most critical worst-case scenarios: an explosion (UVCE) threatening the facility's structure, and a fireball threatening the lives of on-site workers. The analysis pinpointed the highest risks—the potential for a domino effect and the danger to the on-site crew—and showed how well-chosen safety measures could significantly reduce these vulnerabilities to more manageable levels.

The process of applying the framework also revealed important opportunities for improvement, leading to the following recommendations for future work:

1. **Improve the Core Methodology:** The case study required a specific modification to properly account for the risk of a domino effect. This suggests that the base methodology itself could be strengthened by formally including domino analysis as a standard step for all process facilities.
2. **Make the Software Smarter:** The current software analyzes each piece of equipment by itself. A crucial next step is to teach it to understand the connections between

systems—for example, how a failure in a nearby export pump could directly cause a leak in a storage sphere. This would create a more complete and realistic analysis of causes.

3. **Complete the BowTie Automation:** To make the software a complete risk analysis tool, the next major development goal should be to add Event Tree Analysis (ETA). This would allow users to analyze both the causes and the potential consequences of an accident from start to finish within a single program.
4. **Enhance Consequence Simulation:** The simulations used in the case study did not fully model the impact of a domino effect. Future work should aim for better integration with simulation tools that can show how an initial failure cascading to other equipment would change the size and severity of the final hazard zones.

In closing, this thesis successfully delivered a validated framework and a functional software prototype that directly met the needs of Algeria's new safety regulations. By providing a more structured, repeatable, and accessible way to assess vulnerability, this work offers a tangible contribution to improving the safety and resilience of the nation's most critical industries.

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APPENDIX

Appendix A:

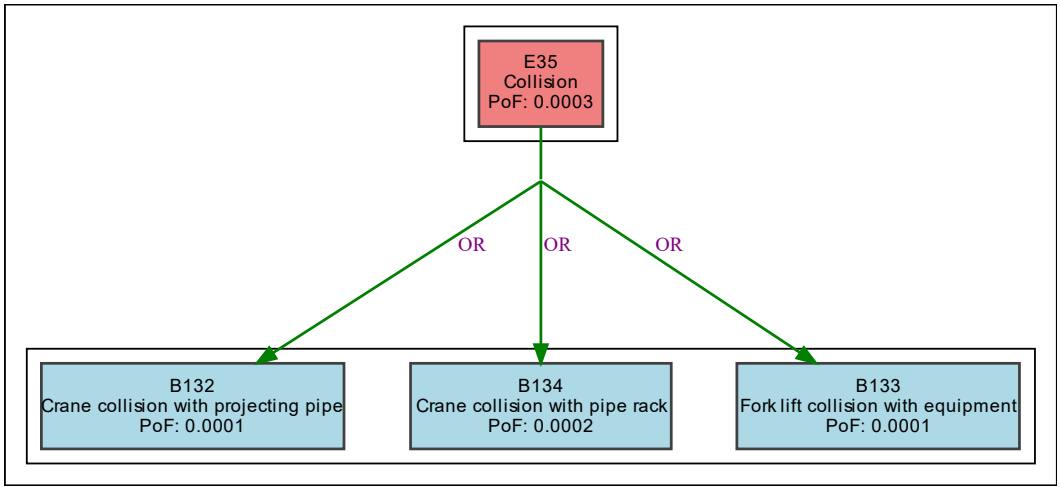

Figure A.1: Breakdown for the collision intermediate event

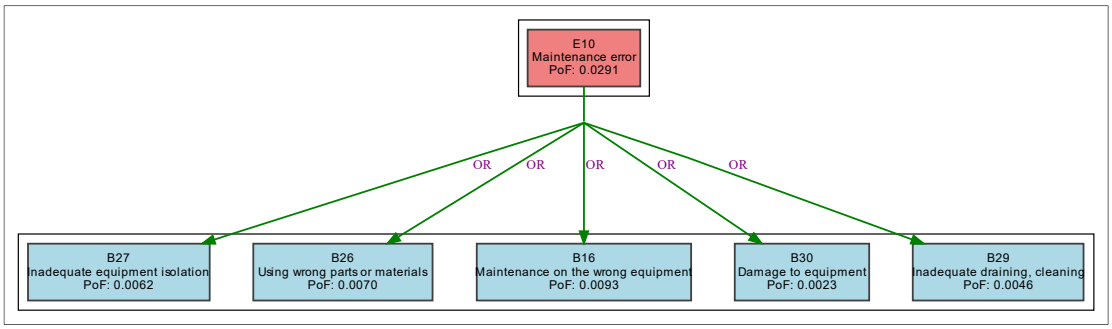

Figure A.2: Breakdown for the maintenance error intermediate event

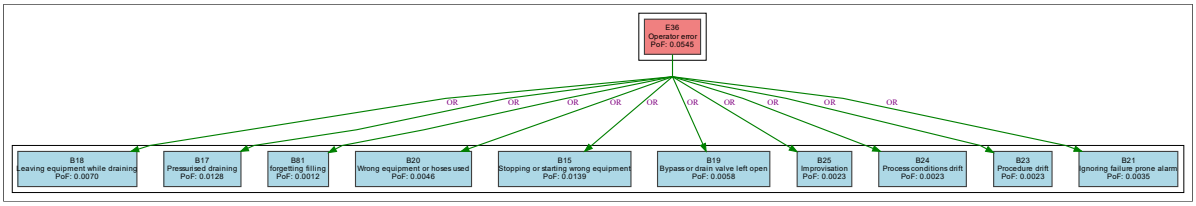

Figure A.3: Breakdown for the operator error intermediate event

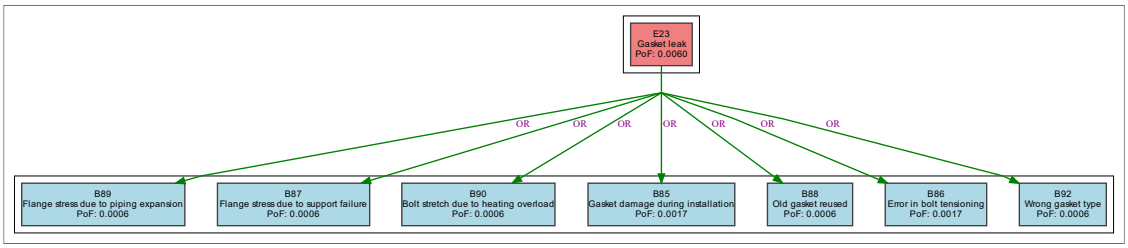

Figure A.4: Breakdown for the gastek leak intermediate event

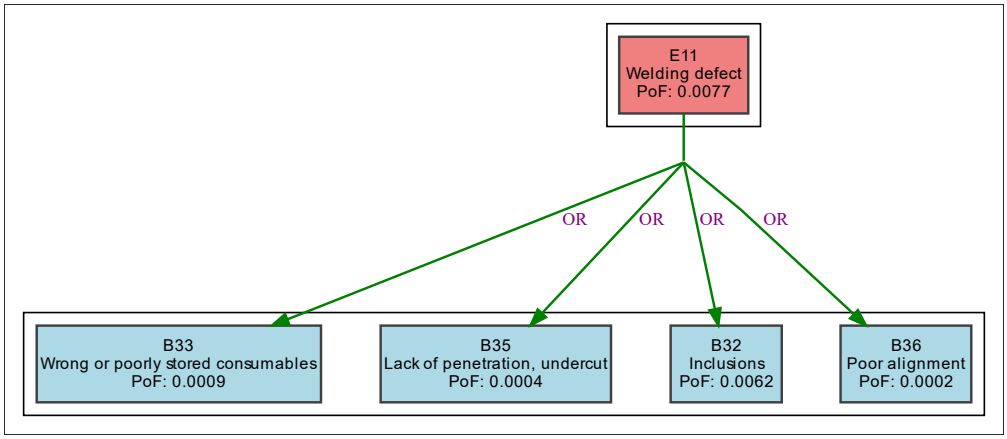

Figure A.5: Breakdown for the welding defect intermediate event

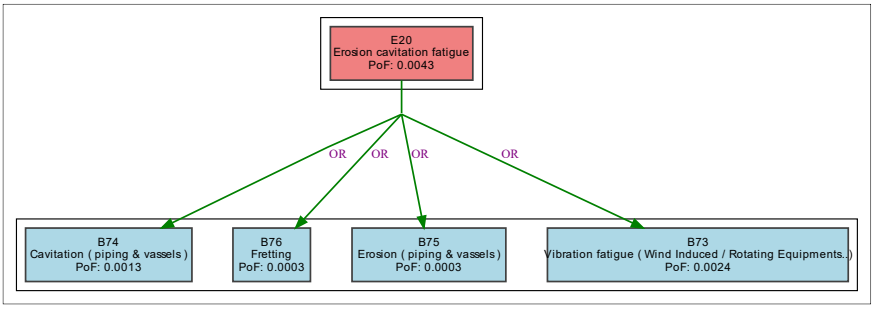

Figure A.6: Breakdown for the erosion cavitation fatigue intermediate event

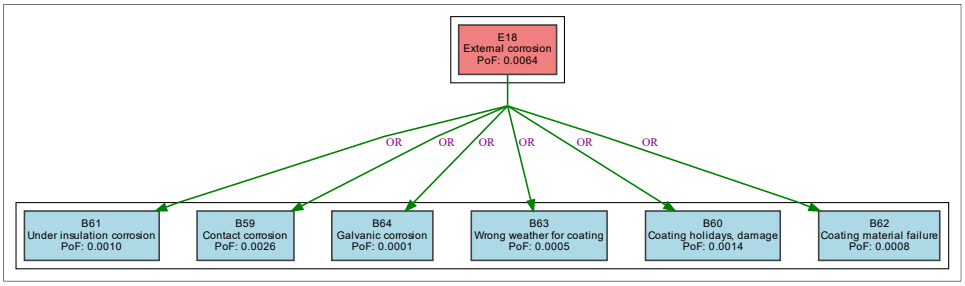

Figure A.7: Breakdown for the External corrosion intermediate event

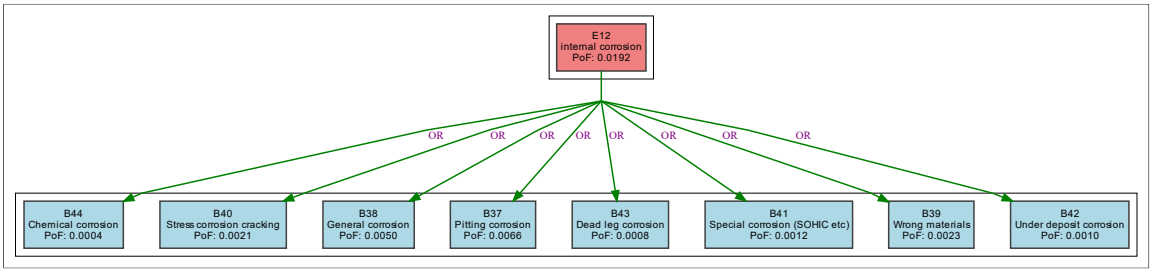

Figure A.8: Breakdown for the Internal corrosion intermediate event

Appendix B:

B.1 MODELING OF HAZARDOUS PHENOMENA: LPG SPHERE TANK

B.1.1 Study tab

Input	Value
Site Name	MLE, SHFCP, Illizi, Algeria
Fluid name	GPL
Study date	26/06/2025
Location coordinates	Latitude : 30.184302 Longitude : 7.691886

B.1.2 Material tab

Since propane is the majority component of the mixture, it will be considered the representative fluid for the analysis.

Input	Value
Phase	Biphasic
Material	Propane

B.1.3 Weather tab

Input	Value
Temperature	298.15 K (25°C)

Wind velocity	16 m/s
Relative humidity	35%
Air density	1,163542 kg/m3

B.1.4 Source term

Input	**Value**
Source configuration	Storage vessel
Vessel	Sphere
Diameter	9.85 m
Filling rate	40%
	60%
	80%
Breach position	1 m
Breach diameter	25 mm
	Rupture
Pressure	16.9 bar
Vessel temperature	332.15 K (59°C)
Initial vapor fraction	0.15

Output	Value		
Discharge rate	40%	25 mm	1.086 Kg/s
		Rupture	2802.04 Kg/s
	60%	25 mm	1.086 Kg/s
		Rupture	2802.04 Kg/s
	80%	25 mm	1.086 Kg/s
		Rupture	2802.04 Kg/s

B.1.5 Jet fire

B.1.5.1 Effects distances

Breach diameter 25 mm

Filling rate	5 KW/m2	8 KW/m2	16 KW/m2	20 KW/m2	200 KW/m2
40%	9.78 m	9.33 m	8.83 m	8.71 m	0.6 m
60%	9.78 m	9.33 m	8.83 m	8.71 m	0.6 m
80%	9.78 m	9.33 m	8.83 m	8.71	0.6 m

B.1.6 VCE

B.1.6.1 Effects distances

Breach diameter 25 mm

Filling rate	20 mbar	50 mbar	140 mbar	200 mbar
40%	223.733 m	101.455 m	45.668 m	35.741 m

60%	223.733 m	101.455 m	45.668 m	35.741 m
80%	223.733 m	101.455 m	45.668 m	35.741 m

Rupture

Filling rate	**20 mbar**	**50 mbar**	**140 mbar**	**200 mbar**
40%	1180.525 m	535.327 m	240.966 m	188.586 m
60%	1351.364 m	612.797 m	275.837 m	215.877 m
80%	1487.369 m	674.47 m	303.598 m	237.604

B.1.7 BLEVE: Fire ball

B.1.7.1 Effects distances

Filling rate	**5 KW/m2**	**8 KW/m2**	**16 KW/m2**	**20 KW/m2**	**200 KW/m2**
40%	728.199 m	559.857 m	370.703 m	321.815 m	NR
60%	826.1976 m	634.913 m	420.0837 m	364.5172 m	NR
80%	903.515 m	694.216 m	458.976 m	398.275 m	NR

B.2 MODELING OF HAZARDOUS PHENOMENA : LPG EXPORT PUMP

B.2.1 Study tab

Input	**Value**

Site Name	MLE, SHFCP, Illizi, Algeria
Fluid name	GPL
Study date	26/06/2025
Location coordinates	Latitude: 30.184579 Longitude: 7.692001

B.2.2 Material tab

Since propane is the majority component of the mixture, it will be considered the representative fluid for the analysis.

Input	**Value**
Phase	Biphasic
Material	Propane

B.2.3 Weather tab

Input	**Value**
Temperature	298.15 K (25°C)
Wind velocity	16 m/s
Relative humidity	35%
Air density	1,163542 kg/m3

B.2.4 Source term

Input	Value
Source configuration	Short pipe
Diameter	152.4 mm
Breach position	1 m
Breach diameter	0.9D = 137 mm
Pressure	76.6 bar
Pipe roughness	Commercial steel: 0.045

Output	Value
Discharge rate	114.9 Kg/s

B.2.5 Jet fire

B.2.5.1 Effects distances

	5 KW/m2	8 KW/m2	16 KW/m2	20 KW/m2	200 KW/m2
Distance (m)	110.13	96.22	79.87	75.33	18.7

B.2.6 VCE

B.2.6.1 Effects distances

	20 mbar	50 mbar	140 mbar	200 mbar
Distance (m)	1164.195	527.922	237.633	185.977