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Advanced fuzzy quantitative risk assessment through the integration of computational fluid dynamics, individual and societal risks

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Dedication

***I** dedicate this work, the result of years of effort, patience, and perseverance, to:*

My beloved parents,

No words can fully express my deepest gratitude for your unconditional love, unwavering support, and the sacrifices you have made for my education and success. You are my greatest pride and my source of inspiration.

My family,

For their presence, encouragement, and constant support during the most challenging times.

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﴿ وَقُل رَّبِّ زِدْنِي عِلْمًا ﴾

(Surah Ta-Ha, Verse 114)

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Table of Content

List of Figures

List of Tables

List of Abbreviations

Abréviation	Signification
AIChE	American Institute of Chemical Engineers
ALARP	As Low As Reasonably Practicable
AMDEA	Activated Methyl Diethanolamine
AND	Logical AND Gate in FTA
APCI	Air Products and Chemicals Inc.
BLEVE	Boiling Liquid Expanding Vapor Explosion
BORA	Barrier and Operational Risk Analysis
CCPS	Center for Chemical Process Safety
CFD	Computational Fluid Dynamics
CMR	Propane Precooled Mixed Refrigerant
CO_2	Carbon Dioxide
DCS	Distributed Control System
DOI	Digital Object Identifier
EPC	Engineering, Procurement, and Construction
ETA	Event Tree Analysis
FIS	Fuzzy Inference System
FIR	Field Instrumentation Room
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
F-T	Fischer-Tropsch
GRIFF	Gas Release and Ignition Frequency Finder
GK1/GK2/GK3	Gas Pipelines Skikda supply lines
GL1K	Gazoduc Liquefaction 1 K Skikda complex code
H_2S	Hydrogen Sulfide
HAZOP	Hazard and Operability Study
HSE	Health and Safety Executive
IE	Initiating Event
IPL	Independent Protection Layer
IR	Individual Risk
ISO	International Organization for Standardization

KBR	Kellogg Brown & Root
LNG	Liquefied Natural Gas
LOPA	Layer of Protection Analysis
LP	Linear Programming
LPG	Liquefied Petroleum Gas
LSIR	Location-Specific Individual Risk
MCHE	Main Cryogenic Heat Exchanger
MDPI	Multidisciplinary Digital Publishing Institute
MOM	Mean of Maxima
MR	Mixed Refrigerant
Nm^3	Normal Cubic Meters
NRC	Nuclear Regulatory Commission
OR	Logical OR Gate in FTA
PE	Pivotal Event
PHAST	Process Hazard Analysis Software Tool
PLL	Potential Loss of Life
ppmv	Parts Per Million by Volume
PRICO	Poly Refrigerated Integrated Cycle Operations
QRA	Quantitative Risk Assessment
RIF	Risk Influencing Factor
SAFETI	Software for Assessment of Flammable, Explosive, and Toxic Impact
SIS	Safety Instrumented System
SR	Societal Risk
T-S	Takagi-Sugeno
TNO	Netherlands Organisation for Applied Scientific Research
U10/U20/U30/U40	Unit/Train Numbers
UK	United Kingdom
US	United States
WASH-1400	Reactor Safety Study
°C	Degrees Celsius
μ	Membership Function
σ	Standard Deviation

الملخص

تتناول هذه المذكرة تطوير منهجية لتقدير المخاطر الكمية بالاعتماد على المنطق الضبابي، وذلك بتطبيقها على وحدة الديبروبانايزر في مركب GL1K للغاز الطبيعي المسال بسكيكدة. يجمع هذا العمل بين QRA و BORAوبرنامجي SAFETIو MATLAB بهدف تحسين تقدير تكرارات الأحداث الأولية، والتعامل مع عدم اليقين، وتقييم المخاطر الفردية والمجتمعية

الكلمات المفتاحية : تقدير المخاطر الكمية، المنطق الضبابي، MATLAB، Fuzzy Logic Toolbox، BORA، SAFETI، الديبروبانايزر، الغاز الطبيعي المسال، المخاطر الفردية، المخاطر المجتمعية.

Abstract

This thesis develops an advanced fuzzy Quantitative Risk Assessment (QRA) methodology applied to the depropanizer column (T-301) of the GL1K LNG complex in Skikda. Hazardous scenarios were identified via HAZOP and modeled through Fault Tree/Event Tree Analysis (GRIF), with basic event frequencies revised using a BORA-based Mamdani fuzzy inference system in MATLAB across five Risk Influencing Factors. Consequences (pool fire, flash fire, fireball/BLEVE, VCE) were simulated with PHAST, and individual and societal risks quantified with SAFETI. Results show the fireball/BLEVE dominates risk, with the site-wide individual risk contour and FN curve both exceeding acceptability thresholds, supporting targeted risk-reduction recommendations for GL1K

Keywords: Quantitative Risk Assessment, Fuzzy Logic, MATLAB, Fuzzy Logic Toolbox, BORA, SAFETI, Depropanizer, LNG, Individual Risk, Societal Risk.

Résumé

Ce mémoire développe une méthodologie avancée de quantification des risques (QRA) fondée sur la logique floue, appliquée à la colonne dépropaniseur du complexe GNL GL1K de Skikda. Les scénarios dangereux ont été identifiés par HAZOP et modélisés par arbres de défaillances/d'événements (GRIF), avec des fréquences révisées via un système d'inférence floue de type Mamdani (BORA) sous MATLAB, intégrant cinq facteurs influençant le risque. Les conséquences (feu de nappe, feu éclair, boule de feu/BLEVE, VCE) ont été simulées avec PHAST, et les risques individuel et sociétal quantifiés avec SAFETI. Les résultats montrent que la boule de feu/BLEVE domine le risque, avec un contour de risque individuel et une courbe FN dépassant les seuils d'acceptabilité, appuyant des recommandations ciblées pour GL1K.

Mots-clés : quantification du risque, logique floue, MATLAB, Fuzzy Logic Toolbox, BORA, SAFETI, dépropaniseur, gaz naturel liquéfié, risque individuel, risque sociétal.

GENERAL INTRODUCTION

General Introduction

The rapid growth of the oil and gas industry and the increasing complexity of industrial installations have significantly increased the potential for major technological accidents. Facilities involved in the production, storage, and processing of hydrocarbons handle large quantities of flammable and toxic substances that may lead to catastrophic events such as fires, explosions, and toxic releases. These accidents can cause severe human casualties, environmental damage, economic losses, and social consequences [1].

The history of the process industry has been marked by several major accidents, including the Flixborough explosion (1974), the Seveso toxic release (1976), the Bhopal disaster (1984), and the Piper Alpha explosion (1988). These events highlighted the necessity of developing systematic approaches for understanding and managing industrial risks [3]. Consequently, Quantitative Risk Assessment (QRA) emerged as one of the most important tools for supporting decision-making and improving process safety.

The foundations of modern risk analysis were established by Kaplan and Garrick (1981) [2], who defined risk through three fundamental questions: What can happen? How likely is it to happen? What are the consequences? Their work laid the theoretical basis for modern QRA methodologies.

During the following decades, several organizations contributed to the standardization of QRA practices. The Center for Chemical Process Safety (CCPS) [5] developed comprehensive guidelines for conducting risk assessments in the chemical process industries. Similarly, the Health and Safety Executive (HSE) [6,8] proposed risk acceptance criteria and introduced the ALARP principle as a framework for risk management decisions. The Dutch TNO Yellow Book and Purple Book became international references for consequence modeling and quantitative risk calculations.

The development of computer technology considerably enhanced the practical implementation of QRA. Software tools such as PHAST and SAFETI [12,13] enabled engineers to simulate accidental scenarios and calculate individual and societal risks with a high level of detail. More recently, Computational Fluid Dynamics (CFD) techniques have been increasingly applied to improve the prediction of gas dispersion, fire dynamics, and explosion effects in complex industrial environments [1].

Despite these significant advancements, several authors have emphasized the limitations of conventional QRA. Bedford and Cooke (2001) [5] demonstrated that classical probabilistic approaches often fail to adequately represent epistemic uncertainty arising from incomplete knowledge and insufficient data. Cox (2008) [11] also showed that conventional risk matrices may produce inconsistent rankings and misleading results due to their discrete structure.

To overcome these limitations, researchers have increasingly turned toward fuzzy logic theory. The concept of fuzzy sets was first introduced by Lotfi Zadeh (1965) ;who proposed representing uncertainty through degrees of membership rather than binary values. Later, Zadeh (1973) [23] introduced linguistic variables and fuzzy reasoning, providing a mathematical framework for dealing with imprecise information.

The practical implementation of fuzzy logic was pioneered by Mamdani and Assilian (1975) [27], who developed the first fuzzy inference system for controlling industrial processes. Their work demonstrated the ability of fuzzy systems to reproduce human reasoning and make decisions under uncertainty.

The application of fuzzy logic to risk assessment has attracted increasing attention over the last two decades. Markowski and Mannan (2008) [28] proposed a fuzzy risk matrix capable of eliminating several deficiencies of traditional risk matrices and providing a more realistic representation of uncertainty in frequency and consequence estimates. Patel and Shah (2019) [36] compared different defuzzification techniques and demonstrated their influence on the accuracy of fuzzy decision systems.

More recently, several studies have proposed fuzzy-based frameworks for industrial risk assessment. Research published by MDPI (2024) introduced a fuzzy risk assessment framework capable of handling vague expert judgments, while MDPI (2025) developed a fuzzy model for risk assessment in complex systems. Furthermore, recent studies have highlighted the benefits of combining fuzzy logic with artificial intelligence techniques to improve risk prediction and support decision-making in high-risk industries .

In parallel, the Barrier and Operational Risk Analysis (BORA) methodology developed by Seljelid (2007) [43] introduced an innovative approach that integrates human, organizational, technical, and operational factors into quantitative risk assessment. The methodology uses Risk Influencing Factors (RIFs) to adjust generic frequencies and probabilities according to the specific conditions of a facility.

Although previous studies have made significant contributions to risk assessment methodologies, several limitations still remain. Most studies either focus on fuzzy risk assessment without integrating advanced consequence modeling tools or apply consequence modeling without adequately addressing uncertainty in frequency estimation and barrier performance. Moreover, very few studies have proposed an integrated methodology combining:

- fuzzy logic,
- Risk Influencing Factors,
- Computational Fluid Dynamics,
- individual risk assessment,
- and societal risk assessment within a single framework.

This gap is particularly important for Liquefied Natural Gas (LNG) facilities, where accident scenarios involve highly complex physical phenomena and potentially catastrophic consequences.

Therefore, the objective of this research is to develop an Advanced Fuzzy Quantitative Risk Assessment methodology through the integration of Computational Fluid Dynamics, Individual and Societal Risks, applied to the New LNG Mega Train of the GL1K complex in Skikda, Algeria.

The originality of this work lies in:

- integrating fuzzy logic into the BORA methodology to address epistemic uncertainty;
- adjusting initiating event frequencies and barrier failure probabilities using Risk Influencing Factors;
- combining advanced consequence modeling techniques with conventional QRA tools;
- evaluating both individual and societal risks;
- proposing a comprehensive and realistic framework for decision-making and risk management in LNG facilities.

The present research therefore contributes to bridging the gap between classical quantitative risk assessment and uncertainty-based approaches by developing an integrated methodology capable of providing a more realistic representation of industrial risks in complex process installations.

CHAPTER I

Theoretical Foundations Of Quantitative Risk Assessment And Fuzzy Logic Integration

I.1 Introduction

Industrial facilities handling hazardous materials operate under constant threat of major accidents that can result in catastrophic consequences for workers, the public, and the environment [2]. The chemical process industries, including oil and gas and petrochemicals, manage substances that, if released accidentally, can cause fires, explosions, toxic releases, and environmental damage [1,16].

This chapter establishes the theoretical foundation necessary for developing an advanced fuzzy quantitative risk assessment methodology. It begins with fundamental definitions of key terms in risk analysis according to international standards and regulatory guidelines. The chapter then presents a comprehensive classification of risk analysis methods, distinguishing between qualitative, semi-quantitative, and quantitative approaches [4,7]. The core of this chapter is devoted to Quantitative Risk Assessment (QRA), providing a detailed examination of its historical development, fundamental principles, systematic methodology, risk metrics, and the ALARP principle [8,16]. Recognizing the limitations of classical QRA in handling uncertainty and expert knowledge, the chapter introduces fuzzy logic theory as a mathematical framework for addressing these gaps [8,30] . Finally, the chapter describes the software tools MATLAB, GRIFF, and PHAST/SAFETI that constitute the computational infrastructure for implementing the proposed methodology [42,11,9,10].

I.2 Fundamental Definitions in Risk Analysis

I.2.1 Safety

Safety is defined as the state of being protected from harm or other non-desirable outcomes [2]. According to ISO 45001:2018, safety is the freedom from unacceptable risk of harm [15]. The Health and Safety Executive (HSE) defines safety as the control of recognized hazards to achieve an acceptable level of risk [2]. In the process industries, safety encompasses both occupational safety (protection of workers) and process safety (prevention of major accidents involving hazardous materials) [1]. Process safety deals with the prevention and control of incidents that have the potential to release hazardous materials or energy, leading to major accidents [1].

I.2.2 Hazard

The Center for Chemical Process Safety (CCPS) defines a process hazard as an inherent chemical or physical characteristic that has the potential to cause harm to people, property, or the environment [1]. Hazards can be classified into several categories: physical hazards (e.g., noise, radiation, temperature extremes), chemical hazards (e.g., toxic, flammable, corrosive substances), biological hazards (e.g., bacteria, viruses), ergonomic hazards (e.g., repetitive motion, poor workstation design), and psychosocial hazards (e.g., stress, workplace violence) [2].

I.2.3 Accident, Incident and Undesired Event

An accident is defined as an unplanned event that results in injury, ill health, or damage to property, environment, or production [15]. The CCPS defines an incident as an unplanned event resulting from the presence of hazardous substances or conditions, with adverse consequences for people, property, or the environment [1]. An undesired event is an event that has the potential to cause harm or loss [17]. In risk analysis, undesired events are typically identified as top events in fault trees or initiating events in event trees [7]. These events represent deviations from normal operation that could lead to accidents if not properly controlled.

I.2.4 Probability and Severity

Probability is the likelihood of a specific event occurring within a specified time period [17]. In risk assessment, probability can be expressed as a frequency (e.g., events per year) or a probability (dimensionless, between 0 and 1) [7]. The estimation of probabilities for hazardous events is a critical component of quantitative risk analysis, often based on historical data, fault tree analysis, or expert judgment [7].

Severity refers to the magnitude of the consequences of an incident [17], which can be measured in terms of human impacts (fatalities, injuries), environmental damage, property damage, business interruption, or reputational impact [1]. Severity assessment should consider both immediate consequences and potential escalation scenarios [7].

I.2.5 Risk

Risk is defined as the combination of the probability of occurrence of an event and the magnitude of its consequences [17]. This definition is expressed through the fundamental risk

triplet: what can go wrong, how likely is it, and what are the consequences [17]. Mathematically, risk is often expressed as:

Risk = Probability × Severity

However, this simple multiplication is often inadequate for complex industrial risks, and more sophisticated approaches are required [5]. The HSE distinguishes between individual risk (risk to a specific person) and societal risk (risk to a group of people) [13].

I.2.6 Fatality

A fatality is a death resulting from an accident or incident [2]. In quantitative risk assessment, fatality is the most severe consequence category and is often used as the primary metric for risk tolerance criteria [7]. The probability of fatality is determined through vulnerability models that relate the physical effects of hazardous phenomena (thermal radiation, overpressure, toxic concentration) to the probability of death [20].

Fatality rates are typically expressed as the probability of death per year for individual risk, or as the expected number of fatalities per year for societal risk [20]. For example, the UK HSE uses a maximum tolerable individual risk of 10^{-3} per year for workers and 10^{-4} per year for the public [13].

I.3 Classification of Risk Analysis Methods

Risk analysis methods can be classified into three main categories: qualitative, semi-quantitative, and quantitative methods [18]. Each category has distinct characteristics, applications, and limitations.

I.3.1 Qualitative Risk Analysis Methods

Qualitative risk analysis methods rely on expert judgment to identify hazards and assess risks using descriptive scales [5]. These methods do not involve numerical estimation of probabilities or consequences but instead use categories such as "high," "medium," and "low" [5].

- **Common qualitative methods include:**

• **Hazard and Operability Study (HAZOP):** A systematic technique for identifying hazards and operability problems in process plants [4]. HAZOP uses guide words (e.g., "no," "more," "less," "as well as") to systematically examine process deviations from design intent

[4]. The method is typically conducted by a multidisciplinary team and is most effective during the design phase or major modifications [4].

- **Failure Mode and Effects Analysis (FMEA):** A bottom-up approach that identifies potential failure modes of equipment or systems and evaluates their effects on system performance [1]. FMEA assigns severity, occurrence, and detection ratings to each failure mode to prioritize risk reduction efforts [1].

- **What-If Analysis:** A creative brainstorming technique where team members ask "what-if" questions to identify potential hazards and evaluate existing safeguards [1].

- **Checklist Analysis:** The use of prepared lists of known hazards and failure modes to systematically identify risks in a facility [1].

Qualitative methods are advantageous for their simplicity, ease of use, and effectiveness in identifying hazards [5]. However, they are limited by their subjectivity, inability to compare risks quantitatively, and potential for inconsistent results between different analysts [5].

I.3.2 Semi-Quantitative Risk Analysis Methods

Semi-quantitative methods combine qualitative judgment with numerical scoring to prioritize risks [19]. These methods assign numerical values to qualitative categories to enable ranking and comparison of risks [19].

- **Risk Matrices:** The most common semi-quantitative tool, risk matrices plot probability against consequence to determine risk levels [19]. The matrix is divided into zones (typically colored green, yellow, orange, and red) representing different risk tolerability levels [19]. Risk matrices are widely used due to their simplicity and visual clarity, but they suffer from limitations including rank reversals and inconsistent categorization [6].

- **Layer of Protection Analysis (LOPA):** A simplified quantitative method that uses order-of-magnitude estimates of consequence severity and likelihood [1]. LOPA evaluates the effectiveness of independent protection layers (IPLs) in reducing risk to acceptable levels [1].

- **Risk Scoring Systems:** Methods that assign numerical scores to various risk factors and combine them through algorithms to produce overall risk ratings [19].

Semi-quantitative methods provide more discrimination than purely qualitative approaches while avoiding the data requirements of full quantitative analysis [19]. However, they can create a false sense of precision and may not adequately address uncertainty [6].

I.4 Quantitative Risk Assessment (QRA)

I.4.1 Definition and Objectives

Quantitative Risk Assessment (QRA) is a systematic methodology for estimating the magnitude of risks associated with hazardous activities or installations [7]. QRA is defined as the systematic development of numerical estimates of the expected frequency and consequence of potential accidents associated with a facility or operation [7].

The primary objectives of QRA are:

- To identify and evaluate the risks associated with hazardous activities
- To provide a rational basis for comparing risk reduction alternatives
- To demonstrate compliance with risk tolerance criteria
- To support decision-making for siting, design, and operation of facilities
- To prioritize risk reduction measures based on their effectiveness
- To communicate risks to stakeholders in a transparent manner [7]

QRA provides a comprehensive framework for evaluating acute hazards and alternative risk reduction strategies in the chemical process industries [7].

I.4.2 Historical Development of QRA

The origins of modern QRA can be traced to the aerospace and nuclear industries in the 1960s and 1970s [21]. The WASH-1400 Reactor Safety Study, published by the U.S. Nuclear Regulatory Commission in 1975, established the methodological foundations for probabilistic risk assessment [21]. This landmark study systematically analyzed accident sequences using event trees and fault trees, providing numerical estimates of radioactive release frequencies and consequences [21].

The adoption of QRA in the chemical process industries was catalyzed by major industrial accidents in the 1970s and 1980s. The Flixborough disaster in 1974 (28 fatalities) and the Seveso incident in 1976 (toxic dioxin release) demonstrated the need for systematic approaches to major hazard analysis [4]. The Canvey Report of 1978 represented one of the first major applications of QRA methodology to a chemical industrial complex [22].

In the Netherlands, TNO developed the "Yellow Book" in 1983, providing standardized methods for calculating physical effects of hazardous material releases [23]. This was followed

by the "Purple Book" in 1999, establishing comprehensive QRA guidelines [24.]. The CCPS/AIChE published their seminal guidelines in 1989 (updated 2000), which have become the international standard [7].

I.4.3 Steps in QRA Methodology

The QRA process consists of several systematic steps:

• **Step 1: Hazard Identification** Systematic identification of potential hazards and accident scenarios using techniques such as HAZOP, FMEA, and checklists [7]. This step establishes the inventory of potential accidents to be analyzed.

• **Step 2: Frequency Estimation** of the likelihood of each identified scenario using historical data, fault tree analysis, event tree analysis, or expert judgment [7]. Frequencies are typically expressed as events per year.

• **Step 3: Consequence Analysis** Modeling of the physical effects of hazardous releases including dispersion of toxic or flammable materials, thermal radiation from fires, and overpressure from explosions [7]. This step determines the impact zones for each scenario.

• **Step 4: Vulnerability Assessment** Estimation of the probability of harm (fatality, injury, damage) to people, property, or the environment exposed to the hazardous effects [7]. Vulnerability is typically expressed as probit functions relating physical effects to probability of harm.

• **Step 5: Risk Calculation** Integration of frequency and consequence estimates to calculate risk metrics [7]. This includes calculation of individual risk (probability of fatality for a hypothetical person) and societal risk (probability of N or more fatalities).

• **Step 6: Risk Evaluation** Comparison of calculated risks against risk tolerance criteria to determine acceptability. The ALARP principle is applied to determine if further risk reduction is required [13].

• **Step 7: Risk Reduction and Management** Identification and implementation of measures to reduce risks to acceptable levels [7]. This may include inherent safety measures, engineering controls, administrative controls, and emergency response planning.

I.5 Fault Tree Analysis and Event Tree Analysis

I.5.1 Fault Tree Analysis (FTA)

Fault Tree Analysis (FTA) is a systematic, deductive method used to evaluate the causes of system failures and accidents [25]. Developed in the early 1960s by Bell Telephone Laboratories for the analysis of the Minuteman missile launch control system, FTA was later refined by Boeing and gained wide acceptance during the WASH-1400 Reactor Safety Study [45,38].

FTA is a top-down approach that focuses on identifying the root causes leading to a specific undesired event, known as the "top event" [25]. The analysis begins with the top event and breaks down the possible causes through a tree structure composed of logic gates (AND, OR, NOT) that connect basic events, intermediate events, and the top event [25].

Key components of FTA include:

- **Top Event:** The undesired system state or failure that needs to be analyzed
- **Basic Events:** Component failures or human errors that cannot be further decomposed
- **Intermediate Events:** Events that result from combinations of basic events
- **Logic Gates:** AND gates (all inputs must occur for the output to occur) and OR gates (any input can cause the output)
- **Minimal Cut Sets:** The smallest combinations of basic events that can cause the top event [25]

FTA is particularly useful because it allows for the identification of not just individual failures, but also combinations of failures that could occur in a system [25]. The technique provides both qualitative insights (identification of failure paths) and quantitative results (probability of the top event) [25].

Limitations of FTA include:

- Difficulty in modeling dynamic scenarios and time-dependent failures
- Binary nature (fail/success) that may not reflect gradual degradation
- Dependence on accurate data and thorough understanding of the system
- Potential for overlooking common cause failures if not explicitly modeled [25]

I.5.2 Event Tree Analysis (ETA)

Event Tree Analysis (ETA) is a complementary technique to FTA that defines the consequential events which flow from a primary initiating event [26.]. While FTA works deductively to identify root causes of an undesired event, ETA works inductively projecting how an initiating event can escalate into various outcomes [26,27].

ETA is a forward-looking approach that begins with a specific initiating event (such as a loss of containment, equipment malfunction, or human error) and maps out all possible subsequent events and outcomes [26]. Each branch in the event tree represents the success or failure of safety barriers such as alarms, interlocks, or operator actions [26].

Key concepts in ETA include:

- **Initiating Event (IE):** The first significant failure or disturbance that starts the accident sequence
- **Pivotal Events (PES):** Key points in the scenario where a safety function may succeed or fail
- **End States:** The possible outcomes ranging from safe shutdown to catastrophic loss [27]

The ETA methodology follows these steps:

1. Define the initiating event
2. List the pivotal events (safety barriers)
3. Map out each success/failure point
4. Create all paths to end states
5. Assign probabilities to each branch using historical data or expert judgment
6. Quantify end-states and analyze results [26]

Applications of ETA include:

- Design stage assessment of emergency shutdown systems
- Operation phase evaluation of failure responses
- Maintenance planning for high-criticality barriers
- Incident investigation and process safety barrier refinement [26]

When used together, FTA and ETA form a comprehensive "bow-tie" model: FTA identifies the causes of a hazardous event on the left side, while ETA analyzes the consequences and mitigation measures on the right side [28,27]. This integrated approach provides a complete picture of risk from causes to consequences.

I.6 Barrier and Operational Risk Analysis (BORA)

I.6.1 Main Elements in the Risk Model

The BORA handbook presents a novel risk model that aims to evaluate the risk factors associated with a specific platform in a comprehensive and customized manner [12]. Unlike traditional risk models that rely on industry-wide averages, this model considers the unique conditions and risk factors that are specific to each platform. By using risk influence diagrams, the model prioritizes and weighs each risk factor according to its relative importance. The model then adjusts the industry averages by platform-specific data to accurately reflect the probabilities of each risk factor occurring [12].

I.6.2 BORA Definition

The Barrier and Operational Risk Analysis (BORA) methodology is a comprehensive risk assessment tool designed to evaluate the safety and reliability of complex systems in various industries [42]. Developed by Norwegian experts in the field of risk and safety engineering, the BORA methodology has become a widely used technique for assessing the safety and risk of oil and gas facilities, process industries, and other high-risk systems [42].

The BORA methodology is based on a combination of quantitative and qualitative risk analysis techniques, including event tree analysis, fault tree analysis, and bow-tie analysis [42]. It emphasizes the importance of identifying and analyzing the barriers and safeguards that prevent or mitigate the consequences of hazardous events, as well as the importance of understanding the interrelationships between different parts of a complex system [42].

I.6.3 BORA Evolution Overview

BORA methodology has evolved over the years to become an important risk analysis tool in the oil and gas industry. The BORA methodology was first developed by the Norwegian oil and gas industry in the 1990s as a response to the Piper Alpha disaster, which highlighted the need for a more comprehensive risk assessment approach [42]. The methodology was designed to be flexible, transparent, and adaptable to different types of facilities and industries. The

development of BORA can be traced back to the early 1990s when Norwegian safety experts, led by Jan Erik Vinnem, initiated a research project aimed at developing a new and improved method for risk assessment [42].

I.7 The Main Steps of a BORA Analysis

I.7.1 System Identification

This is often done through task analysis. The purpose of task analysis is to highlight their interactions and describe the tasks to be performed to accomplish a mission.

A task analysis can also serve to predict or explain the performance of a human operator in a given environment. There are different means (methods, tools, etc.) to achieve this objective.

I.7.2 Identification of Initiating Events Related to These Tasks

These are failures or errors that can lead to an accident if they are not detected and corrected in time. These can be human errors, organizational/functional failures, or technical failures.

An example can be given by the replacement of a spare part during a maintenance operation, where this part is not correctly installed.

Similarly, the equipment itself may fail due to a technical failure, such as corrosion, fatigue, erosion, or other degradation mechanisms.

I.7.3 Assignment of Generic Frequencies for Each Initiating Event

The generic frequencies for each initiating event can be established from historical data on the undesirable consequence (Return of Experience) and statistical analysis based on the distributions of the frequency at which the initiating events have occurred. These frequencies are adjusted taking into account the RIF (Risk Influencing Factors) for a specific installation, that is, according to specific operating conditions.

Two methods are proposed to calculate the generic frequencies of initiating events:

• **Method A:** Using the Number of Equipment and the Distribution of Initiating Events the first solution uses frequencies established from generic data of undesirable consequences and the number of equipment combined with the probability distribution for the initiating events. This is probably the best approach when using the BORA methodology in an overall

QRA (Quantitative Risk Assessment). However, this will not give the frequency of the initiating event directly, but the frequency of consequences due to specific initiating events. However, this can also be used to take into account the effect of barriers for the specific installation.

This solution, based on an examination of all undesirable consequences, a distribution of these consequences has been applied. Expressed in terms of the probability that the cause of a consequence is a specific initiating event, given that a consequence has occurred. This shows, for example, that the initiating event (e.g., isolation) represents a total of 14% of all leaks or, in other words, that there is a probability of 0.14 that a leak is caused by this event.

From the number of equipment, the frequency of leaks caused by a certain initiating event can be found by multiplying the total leak frequency for a segment by the percentages of initiating events.

$$f_{GL,Eli} = f_{GL,Total} \cdot P_{Eli} \quad \text{(I.1)}$$

• **Method B:** Using Activity Data and Human Error Probabilities

The second solution uses the level of activity as a starting point (e.g., time to open equipment for maintenance/repair/inspection). This is combined with the human error probability to establish the frequencies of initiating events directly. This approach is likely to be better suited for studies of specific or limited problems that do not cover the entire installation.

Technical failures can be directly linked to the number of equipment, followed by adjustments based on RIF marking for the specific installation. For operational failures, the calculation can, in principle, be performed as follows:

$$f_{Ei} = NWO \cdot P_{(Ei/WO)} \quad \text{(I.2)}$$

Where:

- F_{EI} = Frequency of the initiating event
- **NWO =** Number of work operations/year
- $P_{(EI/WO)}$ **=** Conditional probability of the initiating event when WO is performed

I.7.4 Identification of Barriers and Development of the Barrier Block Diagram

This step consists of developing a basic risk model that covers a representative set of accident scenarios. The goal is to identify, illustrate, and describe the scenarios that could lead to the undesirable consequence on an installation.

The basic risk model forms the basis for the qualitative and quantitative analysis of risk and undesirable consequences and the safety barriers put in place to prevent these consequences. The basic risk model is illustrated by the Barrier Block Diagram (DBB). A barrier block diagram consists of an initiating event, arrows indicating the sequence of events, barrier functions, and possible outcomes. A horizontal arrow indicates that the barrier system fulfills its function, while the downward arrow indicates the failure of the barrier.

- A barrier block diagram corresponding to an event tree can be used as a basis for quantitative analysis.
- An initiating event for an accident scenario is the first significant deviation from a normal situation.
- A barrier function is defined as a function to prevent, control, or reduce accidents or undesirable events.
- A barrier system is a system that is designed and implemented to achieve one or more barrier functions.
- A barrier system can consist of different types of elements, for example, technical elements (hardware and software), operational activities performed by humans, or a combination of these. In some cases, there may be several barrier systems that address a barrier function.

I.7.5 Modeling of Safety Barrier Performance

The next step is to model the performance of the safety barriers. The purpose of this modeling is to analyze the specific performance of the installation's barriers and enable a specific analysis of the conditions of human, operational, organizational, and technical resources.

The safety barriers are described as separate "boxes" in the barrier block diagram. The following attributes regarding safety barrier performance should be allowed in the analysis:

a) The activating event or condition
b) Functionality or effectiveness
c) Response time

d) Reliability/availability
e) Robustness

In the BORA methodology, the performance of barrier systems is modeled by the Fault Tree.This top event must be the failure or degradation of the barrier system and must be adapted to each specific barrier in the different scenarios.

The results of the qualitative fault tree analysis are presented in the form of a list of basic events and an overview (minimal) of these basic events. The basic events are the "leaf" events of a fault tree (e.g., component failures and human errors), while a cut set defines a set of basic events whose simultaneous occurrence guarantees that the top event occurs. A cut set is said to be minimal if the set cannot be reduced without losing its status as a cut set.

I.7.6 Assignment of Generic Probabilities of Basic Events

In this step, the goal is to assign data on the basic events in the fault trees and perform a quantitative risk analysis using this data (quantitative analysis of fault trees and event trees).

In practice, extensive use of industry average data is necessary to perform the quantitative analysis. Several databases are available for presenting industry average data, such as OREDA for equipment reliability data, and THERP and COREDATA for human reliability data.

I.7.7 Calculation of the Undesirable Consequence Frequency Based on Basic Event Probabilities

The frequencies of the undesirable consequence following a specific loss of containment are based solely on generic input data and can now be calculated. This can be done in two different ways.

The first solution involves using Equation (II.1) which directly gives the frequencies of the consequence.

The second solution is to use the frequency of the initiating event calculated .

The leak frequency can then be calculated by taking into account the effect of the barriers, as illustrated in the barrier block diagram. The calculation is done according to the structure of the DBB.

The generic frequencies for consequences caused by the different initiating events can be calculated as follows (the equation will depend on the form of the DBB):

$$\mathbf{fG,EI = fEIi.Pf,SB1.Pf,SB2 \ldots\ldots\ldots\ldots\ldots\ldots Pf,SBi} \quad \textbf{(I.3)}$$

Where:

- $\mathbf{f_{G,EI}}$ = Generic frequency for consequence caused by initiating event i
- $\mathbf{f_{EIi}}$ = Frequency of initiating event i
- $\mathbf{P_f\ SB_i}$ = Probability of failure of barrier system i

These average values (basic event probabilities) are also corrected by RIFs. Specific plant data can be found, for example, from incident databases, log data, and maintenance databases.

I.7.8 Identification of RIF (Risk Influencing Factors)

The RIF can be identified by a risk influence diagram. The purpose of this diagram is to incorporate the effect of specific system conditions regarding human, operational, organizational, and technical RIFs on the probabilities of basic events, the frequencies of initiating events, and the performance of the barriers.

It is preferable to use both the bottom-up and top-down approaches to cover each case. Thus, each type of event can be considered in terms of complexity and variation. If possible, write a detailed taxonomy of RIFs based on factors and experience from the MTO (Man, Technology, Organization) case study.

If necessary, we must develop a risk influence diagram for each basic event. The number of RIFs that can influence each basic event is limited to six, in order to reduce the total number of RIFs in the analysis.

I.7.9 Assignment of RIF Weights and Scores

The RIFs are characterized by a "Weight" and a "Score". The weight tells us how much the RIF influences the probability (a high weight implies a strong influence; a low weight implies a low influence) and the score tells us the state of the RIF for the studied installation.

For example, the probability of making an error when replacing a flange gasket may depend on the mechanic's competence to do the job and the time pressure when the work is performed. If the competence is high, the probability will be low, while if the work situation is stressful, the probability may increase.

A five-point scale (from high importance to low importance) is applied. Quantitatively, the RIFs are given relative weights on the scale of 10-8-6-4-2. The weighting coefficients are normalized so that the sum of weights for the RIFs influencing a basic event must be equal to 1.

RIF scoring involves assigning a score to each RIF identified in the risk influence diagram.

Each RIF is assigned a score from A to F where score A corresponds to the best practice in the industry, score C corresponds to the industry average, and score F corresponds to the worst practice in the industry.

Table I.1: Generic scoring system for Risk Influencing Factors (RIF)

Score	Explanation
A	State corresponds to the best practice in the industry
B	State corresponds to a level above the industry average
C	State corresponds to the industry average
D	State corresponds to a level slightly below the industry average
E	State corresponds to a level significantly below the industry average
F	State corresponds to the worst practice in the industry

In BORA, a linear progression between A and F is assumed.

I.7.10 Adjustment (Correction) of Average Probabilities and Frequencies

In BORA, the average values of probabilities and frequencies are adjusted to take into account the specific conditions of the installations (thus reflecting the major interest of the BORA methodology).

$$\mathbf{Prev}(\mathbf{A}) = \mathbf{Pave}(\mathbf{A}).\sum_{t=1}^{n} \mathbf{Wi}.\boldsymbol{Qi} \quad \text{.....(I.4)}$$

Where:

- $\mathbf{P_{rev(A)}}$ = Adjusted (Revised) Probability
- $\mathbf{P_{ave(A)}}$ = Industry average probability (statistical) of occurrence of event A
- $\mathbf{W_i}$ = Weight of the RIF for event A
- $\mathbf{Q_i}$ = Measure of the RIF score, and n is the number of RIFs

$$\sum_{t=1}^{n} \mathbf{W}\boldsymbol{i} = \mathbf{1} \quad \text{.....(I.5)}$$

The challenge now is to determine the appropriate values for Qi and Wi.

To determine the Qi, we need to associate a number with each state score from A to F. The proposed method for determining Qi is:

1. Determine Plow(A) as the lower limit for Prev(A), given by expert judgment.
2. Determine Phigh(A) as the upper limit for Prev(A), given by expert judgment.
3. Then, for i = 1, 2, ... n:

$$\mathbf{Qi}(\boldsymbol{S}) = \begin{cases} Plow/\ Pave & \text{si } S = A \\ 1 & \text{si } S = C \\ Phigh\ /\ Pave & \text{si } S = A \end{cases} \quad \textbf{(I.6)}$$

Consequently, if the score is A, and Plow(A) is 10% of Pave(A), then Qi is equal to 0.1. If the score S is F, and Phigh(A) is ten times higher than Pave(A), then Qi is equal to 10. If the score S is C, then Qi is equal to 1.

Furthermore:

- If all RIFs have scores equal to C, then $P_{rev}(A) = P_{ave}(A)$
- If all RIFs have scores equal to A, then $P_{rev}(A) = P_{low}(A)$
- If all RIFs have scores equal to F, then $P_{rev}(A) = P_{high}(A)$

To determine the values of Qi for S = B, we assume a linear relationship between Qi(A) and Qi(C), and we use SA=1, SB=2, SC=3, SD=4, SE=5, and SF=6.

$$\mathbf{Qi}(\boldsymbol{B}) = \frac{\text{Plow}}{\text{Pave}} + \frac{(SB-SA)\cdot\left(\mathbf{1}-\frac{Plow}{Pave}\right)}{SC-SA} \quad \textbf{(I.7)}$$

To determine the values of Qi for S = D and E, we assume a linear relationship between Qi(C) and Qi(F).

$$\mathbf{Qi}(\boldsymbol{D}) = \mathbf{1} + \frac{(\boldsymbol{SD-SC})\cdot\left(\frac{\boldsymbol{Phigh}}{\boldsymbol{Pave}}-\mathbf{1}\right)}{\boldsymbol{SF-SC}} \quad \textbf{(I.8)}$$

Qi(E) is calculated as Qi(D) by using SE instead of SD in the formula.

- **Case 1:** $P_{low} = P_{ave}/10$,and $P_{high} = 10\times P_{ave}$
- **Case 2:** $P_{low} = P_{ave}/5$, and $P_{high} = 5\times P_{ave}$
- **Case 3:** $P_{low} = P_{ave}/3$, and $P_{high} = 3\times P_{ave}$
- **Case 4:** $P_{low} = P_{ave}/2$, and $P_{high} = 2\times P_{ave}$

I.7.11 Recalculation of Risk

The last step of the BORA methodology consists of determining the specific risk of the hydrocarbon production platform, by applying the platform's specific input data (Prev(A)) for all events in the risk model.

The use of these revised input data results in an updated risk picture including the analysis of the effect of the safety barrier performance introduced to prevent the undesirable consequence.

The revised risk picture takes into account the specific conditions of the platform, namely the technical, human, operational, and organizational conditions.

I.8 Individual Risk (IR) Metrics

Individual Risk (IR) represents the risk to a person at a specific location from a particular hazard, typically expressed as the annual probability of fatality [20]. Location-Specific Individual Risk (LSIR) contours provide graphical representations of equal risk levels across geographical areas [20].

Key IR metrics include:

- **Location-Specific Individual Risk (LSIR):**

The probability that an unprotected person permanently present at a specific location would die as a result of an accident at the hazardous installation [20]. LSIR is typically expressed in units of probability per year (e.g., 10^{-6}/year).

- **Average Individual Risk:** The average of the LSIR over a specific area or population group [20].
- **Maximum Individual Risk:** The highest LSIR value at any location [20].

The calculation of individual risk incorporates failure frequencies for each scenario, probabilities of exposure based on weather conditions, probabilities of effects including ignition probabilities, and vulnerability models relating physical effects to fatality probabilities [20].

I.9 Societal Risk (SR) Metrics

Societal Risk addresses the risk to groups of people and is typically expressed through fN curves showing the relationship between the cumulative frequency (f) of events causing N or more fatalities [20].

Key SR metrics include:

FN Curves: Log-log plots showing the cumulative frequency (f) of events causing N or more fatalities versus N [20]. The curve allows comparison with societal risk tolerance criteria.

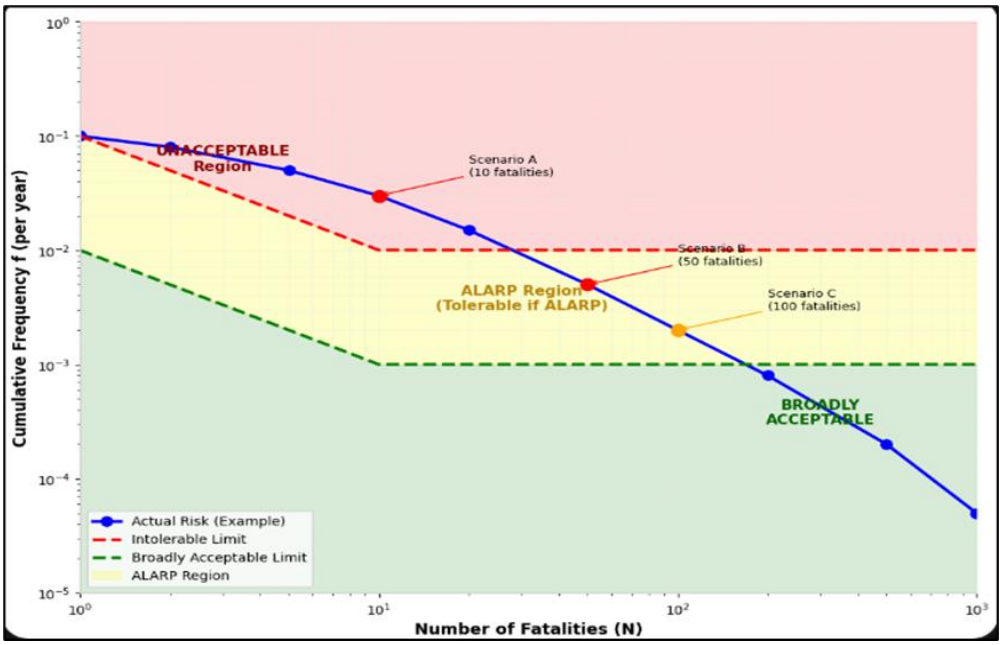

Figure I.1: FN curves and societal risk tolerance criteria

• **Potential Loss of Life (PLL):** The expected number of fatalities per year, calculated as the sum over all scenarios of (frequency × number of fatalities) [20].

• **Average Risk:** The PLL divided by the total population at risk [20].

Societal risk calculations require detailed population data within impact zones, accounting for varying occupancy patterns, sheltering effects, and evacuation capabilities [20].

I.10 The ALARP Principle

The ALARP (As Low As Reasonably Practicable) principle, defined by the UK HSE, provides the framework for risk tolerability decisions [13]. The principle requires that risks be reduced to a level where the cost of further reduction would be grossly disproportionate to the benefit gained [13].

ALARP defines three risk regions:

a) **Unacceptable Region:** Risks are intolerable except in extraordinary circumstances [13]
b) **ALARP Region:** Risks are tolerable only if properly assessed and reduced to ALARP levels [13]
c) **Broadly Acceptable Region:** Risks are negligible and no further reduction is required [13]

For individual risk, the UK HSE specifies:

- Workers: $>10^{-3}$/year unacceptable, 10^{-3} to 10^{-6}/year ALARP, $<10^{-6}$/year broadly acceptable [13]
- Public: $>10^{-4}$/year unacceptable, 10^{-4} to 10^{-6}/year ALARP, $<10^{-6}$/year broadly acceptable [13]

I.11 Advantages of QRA

- **Objectivity and Reproducibility:** QRA provides a systematic, documented approach that produces reproducible results [19]. The methodology is transparent and can be reviewed and verified by independent parties [19].
- **Comparison with Criteria:** QRA enables direct comparison of calculated risks against regulatory or corporate risk tolerance criteria [20]. This provides a rational basis for decision-making [7].
- **Cost-Benefit Analysis:** QRA supports evaluation of risk reduction measures by quantifying the risk reduction achieved relative to the cost of implementation [7].
- **Prioritization:** QRA results enable prioritization of risk reduction efforts based on quantitative measures of risk significance [19].
- **Communication:** QRA provides a common language for discussing risks with regulators, stakeholders, and the public [43].
- **Design Optimization:** QRA can be used during design to optimize facility layout, spacing, and safety system design [7].

I.12 Limitations of QRA

- **Data Requirements:** QRA requires extensive data on equipment failure rates, weather conditions, population distribution, and vulnerability. Such data may be unavailable or uncertain for new technologies or rare events [43].
- **Modeling Uncertainty:** The mathematical models used in QRA involve simplifications and assumptions that may not accurately represent complex physical phenomena [44].
- **Treatment of Uncertainty:** Traditional QRA often inadequately addresses epistemic uncertainty (lack of knowledge) as opposed to aleatory uncertainty (inherent randomness) [44].
- **Resource Intensity:** QRA is time-consuming and expensive, requiring specialized expertise and software [43].

- **Static Analysis:** QRA typically provides a snapshot of risk at a specific point in time and may not adequately capture dynamic changes in process conditions or operational practices [5].
- **Binary Logic:** Classical QRA relies on crisp boundaries and binary logic that may not reflect the gradual nature of many safety-critical phenomena [44].

I.13 Fuzzy Logic Theory and Integration in Risk Analysis

I.13.1 Foundations of Fuzzy Set Theory

Fuzzy logic theory was introduced by Lotfi A. Zadeh in 1965 through his seminal paper "Fuzzy Sets" published in Information and Control [8]. Zadeh proposed that the characteristic function of a set should not be restricted to binary values {0,1} but should be allowed to range continuously over the interval [0,1], representing degrees of membership [8].

Zadeh defined a fuzzy set A in a universe of discourse X through a membership function $\mu A(x)$ that assigns to each element $x \in X$ a grade of membership in the interval [0,1][8]. Formally, this is expressed as $\mu A: X \rightarrow [0,1]$, where $\mu A(x) = 1$ indicates full membership, $\mu A(x) = 0$ indicates non-membership, and intermediate values represent partial membership [8].

In 1973, Zadeh extended this foundation with his paper on the analysis of complex systems, introducing the concept of linguistic variables and fuzzy if-then rules [30]. A linguistic variable is a variable whose values are words or sentences in a natural or artificial language, rather than numerical values [30].

I.13.2 Membership Functions

The selection and definition of membership functions constitute a critical aspect of fuzzy system design [31]. Membership functions map input values to degrees of membership in fuzzy sets and can take various mathematical forms [31].

Common membership function types include:

- **Triangular:** Defined by three parameters (a, b, c) representing lower bound, peak, and upper bound [31]. The function increases linearly from a to b, then decreases linearly from b to c [31].
- **Trapezoidal:** Defined by four parameters (a, b, c, d) with a flat top between b and c, providing a range of full membership [31].

- **Gaussian:** Uses the exponential function $\mu(x) = \exp(-(x-c)^2/2\sigma^2)$, where c is the center and σ controls the width [31]. Gaussian functions provide smooth transitions and are continuously differentiable [31].
- **Generalized Bell:** Defined by $\mu(x) = 1/(1+|(x-c)/a|^{(2b)})$, where a controls width, b controls slope, and c is the center [31].

The choice of membership function shape significantly influences fuzzy system behavior and should be selected based on the specific requirements of the application [31].

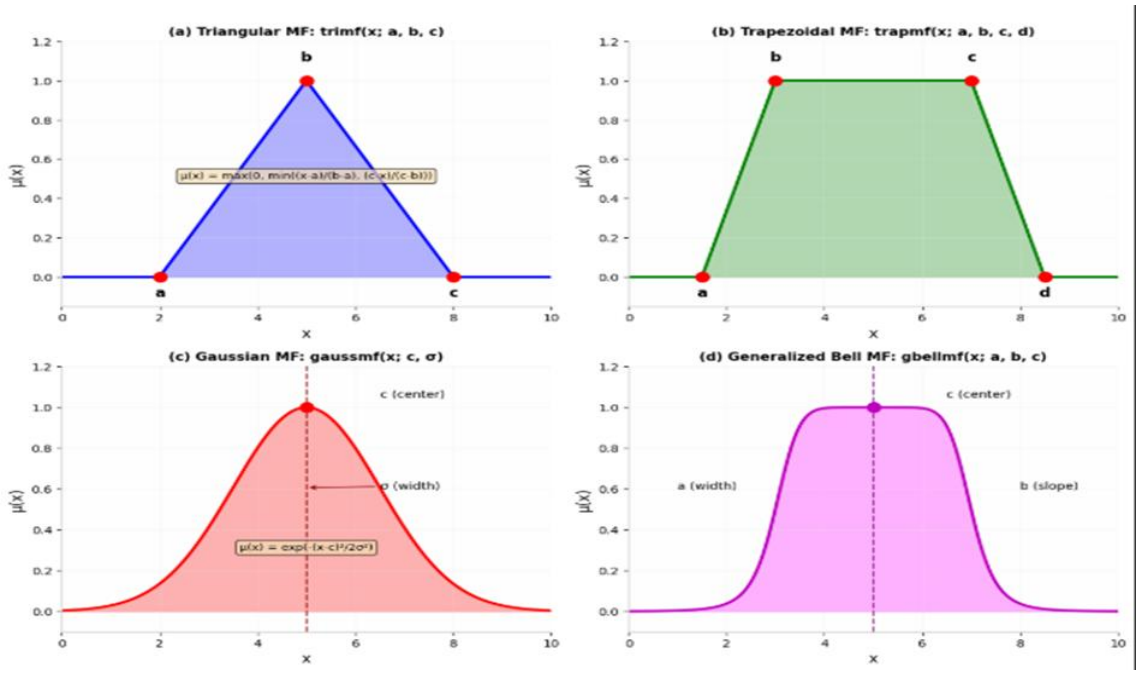

Figure I.2: Common types of membership functions

I.13.3 Fuzzy Set Operations

Fuzzy set theory extends classical set operations to handle partial membership [8.]. For fuzzy sets A and B with membership functions μA(x) and μB(x), the standard operations are defined as follows [8]:

- **Union:** $\mu\{A \cup B\}(x) = \max[\mu A(x), \mu B(x)]$
- **Intersection:** $\mu\{A \cap B\}(x) = \min[\mu A(x), \mu B(x)]$
- **Complement:** $\mu\{\bar{A}\}(x) = 1 - \mu A(x)$

These standard operators, known as Zadeh operators, represent only one family of possible fuzzy operators [32]. Alternative operators include algebraic product and probabilistic sum, as well as parameterized families such as Yager operators and Hamacher operators [32].

I.13.4 Fuzzy Inference Systems

The practical application of fuzzy logic requires inference mechanisms to process fuzzy rules [33]. Mamdani and Assilian developed the first fuzzy inference system in 1975 to control a steam engine and boiler pressure, synthesizing linguistic control rules obtained from experienced human operators [33].

The Mamdani FIS architecture consists of four stages:

1. **Fuzzification:** Conversion of crisp inputs into fuzzy sets using membership functions [33]
2. **Rule Evaluation:** Application of fuzzy operators to determine firing strength of each rule [33]
3. **Aggregation:** Combination of rule outputs into a single fuzzy set [33]
4. **Defuzzification:** Conversion of the aggregated fuzzy output into a crisp value [33]

In 1985, Takagi and Sugeno introduced an alternative approach that uses linear functions in the rule consequents rather than fuzzy sets [34]. The Takagi-Sugeno (T-S) model offers computational efficiency and facilitates stability analysis, making it suitable for complex system modeling [34].

I.13.5 Defuzzification Methods Defuzzification converts fuzzy output sets into crisp numerical values .

I.13.6 Common methods include :

Centroid (Center of Gravity): Calculates the geometric center of the aggregated membership function [31]. This is the most widely used method due to its intuitive appeal and continuity properties [35].

Weighted Average: Calculates the weighted sum of maximum membership values, suitable for symmetric output membership functions [35].

Mean of Maxima (MOM): Calculates the average of output values with maximum membership degree [35].

Bisector: Finds the vertical line that divides the area under the membership function into two equal parts [35].

The choice of defuzzification method can significantly affect the crisp output value and should be selected based on application requirements [35].

I.13.7 Advantages of Fuzzy Logic Integration in Risk Analysis

The integration of fuzzy logic with risk analysis addresses several fundamental limitations of traditional approaches :

1. Handling Linguistic Variables: Fuzzy logic enables direct use of linguistic terms (e.g., "high probability," "severe consequences") that experts naturally use to describe risks this eliminates the need for artificial translation of expert knowledge into precise numbers [37].

2. Representing Uncertainty: Fuzzy logic explicitly models epistemic uncertainty arising from incomplete knowledge, vague information, and subjective judgment. This is particularly valuable when historical data is scarce or unavailable [38].

3. Eliminating Rank Reversal: Fuzzy risk matrices avoid the rank reversal problems associated with traditional risk matrices, where small changes in input values can cause large changes in risk ranking due to discrete categorization [36].

4. Continuous Risk Gradation: Fuzzy logic provides continuous output scales rather than discrete categories, enabling more nuanced discrimination between risk levels [37].

5. Incorporating Expert Knowledge: Fuzzy systems can capture and formalize the tacit knowledge of experienced safety professionals through rule bases and membership functions [39].

6. Transparent Reasoning: The if-then rule structure of fuzzy systems makes the reasoning process transparent and explainable to stakeholders [40].

7. Flexibility: Fuzzy systems can be easily modified and tuned by adjusting membership functions and rules, allowing adaptation to specific applications [31].

Markowski and Mannan (2008) demonstrated that fuzzy risk matrices provide more realistic representation of uncertainty in frequency and consequence estimates compared to conventional crisp matrices [36]. Recent research has shown that hybrid frameworks integrating fuzzy logic with artificial intelligence techniques offer enhanced capabilities for risk prediction and decision support in complex industrial systems [40].

I.14 Software Tools for Advanced QRA

I.14.1 MATLAB and Fuzzy Logic Toolbox

- **History and Development**

MATLAB (Matrix Laboratory) was created in the late 1970s by Cleve Moler, then a professor of mathematics and computer science at the University of New Mexico [41]. Moler developed the first version of MATLAB in Fortran to provide his students with easy access to the LINPACK and EISPACK matrix software libraries [41]. The name MATLAB reflects its origins as an interactive matrix calculator [41].

In 1984, Cleve Moler, Jack Little, and Steve Bangert founded The MathWorks Inc. and commercialized MATLAB for the IBM PC [41]. The commercial version was rewritten in C and significantly enhanced with user-defined functions, toolboxes, and graphics capabilities The Fuzzy Logic Toolbox was introduced in the 1990s, providing comprehensive tools for creating and editing fuzzy inference systems [42].

- **Technical Capabilities**

MATLAB excels in performing complex numerical calculations with its array-based programming language users can easily manipulate matrices and perform operations including linear algebra, statistical analysis, Fourier transforms, differential equations, and optimization [11]. MATLAB provides a robust set of tools for data visualization, allowing users to create high-quality plots, graphs, and charts in both 2D and 3D formats [11].

Fuzzy Logic Toolbox Features The Fuzzy Logic Toolbox provides comprehensive capabilities for implementing fuzzy inference systems in risk assessment applications [42]:

- **Graphical User Interface:** The FIS Editor allows interactive creation and modification of fuzzy inference systems [42]
- **Membership Function Editor:** Enables definition and tuning of various membership function types [42]
- **Rule Editor:** Facilitates construction and editing of fuzzy if-then rules [42]
- **Rule Viewer:** Displays the inference diagram for active rules [42]
- **Surface Viewer:** Generates 3D plots showing output surfaces [42]

The toolbox supports both Mamdani and Sugeno-type fuzzy systems, enabling comparison of different inference approaches key capabilities include automated rule evaluation, defuzzification using multiple methods (centroid, bisector, MOM, SOM, LOM), and integration with MATLAB's broader computational and visualization capabilities [42].

I.14.2 GRIFF Software

- **Overview and Purpose**

GRIFF (Gas Release and Ignition Frequency Finder) is a specialized software tool developed for gas dispersion modeling and risk assessment in industrial facilities, particularly in the oil and gas sector [20]. The software was developed to address the need for accurate frequency assessment of gas releases and their potential ignition consequences in complex industrial environments.

- **Technical Capabilities**

GRIFF incorporates probabilistic models for release frequency estimation based on equipment type, operating conditions, and historical failure data the software handles multiple release scenarios including catastrophic ruptures, leaks of various sizes, continuous releases, and time-varying release rates [20].

- **Integration with Consequence Modeling**

GRIFF interfaces with consequence modeling tools to provide frequency data for QRA studies the software enables analysis of release scenarios, dispersion patterns, ignition probabilities, and explosion effects [20].

- **Application in QRA**

GRIFF outputs frequency data that can be directly imported into QRA software such as SAFETI for integrated risk calculations the software is particularly valuable for assessing risks from offshore and onshore oil and gas installations, petrochemical plants, LNG terminals, and hydrogen facilities [20].

I.14.3 Phast and SAFETI Software

- **History and Development**

Phast (Process Hazard Analysis Software Tool) and SAFETI (Software for Assessment of Flammable, Explosive, and Toxic Impact) developed by DNV represent the industry standard for quantitative risk analysis [10]. SAFETI was originally developed by Technica in 1982 as

one of the first integrated QRA software packages [45]. The software models both consequences and risks within a unified interface [10].

- **Phast Consequence Modeling**

Phast provides comprehensive consequence calculations enabling modeling of discharge, dispersion, fire, toxic, and explosion phenomena [9].The Phast consequence modeling methodology involves consecutive steps as described by Witlox [46]:

• **Step 1: Discharge Calculations** Discharge calculations are carried out to set release characteristics for the hazardous chemical, including depressurization to ambient conditions [46].

• **Step 2: Dispersion Calculations** Dispersion calculations determine the concentrations of the hazardous chemical when the cloud travels in the downwind direction [46].

• **Step 3: Effect Calculations** For flammables, ignition may lead to fireballs, jet fires, pool fires, or vapor cloud fires/explosions [46]. Radiation calculations are carried out for fires, while overpressure calculations are carried out for explosions [46].

- **SAFETI QRA Capabilities**

SAFETI calculates risk based on user-provided leak frequencies, ignition data, weather conditions, population distributions, and vulnerability data the software generates standard risk metrics including LSIR contours, FN curves, PLL, risk contours and transects, and societal risk maps [10].

- **Advanced Features**

Recent versions incorporate advanced capabilities including Phast CFD for detailed computational fluid dynamics modeling, SAFETI CFD integration, multi-component modeling, and advanced explosion modeling [13,1].

I.15 Conclusion

This chapter has established the comprehensive theoretical foundation necessary for developing an advanced fuzzy quantitative risk assessment methodology. Beginning with fundamental definitions of safety, hazard, risk, and related concepts according to HSE, ISO, and CCPS standards [2,15,1], the chapter ensured a common vocabulary aligned with international practice.

CHAPTER II

Industrial context and case study description

II.1 Introduction

This chapter provides a comprehensive description of the industrial context in which the advanced fuzzy quantitative risk assessment methodology will be applied. It begins with an overview of Sonatrach, the Algerian state-owned oil and gas company that operates the facilities under study [50]. It then describes the GL1K liquefaction complex located in Skikda, including its historical development, geographical location, and infrastructure [23]. The core of this chapter focuses on the new LNG Mega Train, which represents the most modern and significant production unit of the complex, detailing its process units, utility systems, and storage facilities [3].

II.2 Sonatrach: The Algerian National Oil and Gas Company

II.2.1 History and Establishment

Sonatrach (Société Nationale pour la Recherche, la Production, le Transport, la Transformation et la Commercialisation des Hydrocarbures) was founded on December 31, 1963, by decree 63-491 of the newly independent Algerian government [50]. The company was initially created to ensure responsibility for the transport and marketing of hydrocarbons [49]. The establishment of Sonatrach occurred shortly after Algeria gained political independence on July 5, 1962, following a bitter war of national liberation against French colonial rule [50].

In September 1966, the company's responsibilities were significantly expanded through decree No. 66-296, transforming Sonatrach into an integrated company covering research, production, transport, processing, and marketing of hydrocarbons [49]. This expansion reflected the Algerian government's vision of exploiting hydrocarbon resources to overcome the economic legacy of colonialism and establish the country as a major power in the southern Mediterranean region [50].

The 1970s marked a decade of consolidation for Sonatrach, with the company embarking on several joint ventures with foreign partners to increase exports of liquefied natural gas (LNG) [48]. The nationalization of hydrocarbons on February 24, 1971, represented a historic milestone, with Sonatrach assuming 100% responsibility for gas reserves and 77% participation in oil and condensate production [49].

The 1980s saw Sonatrach entering into full bloom, becoming one of the world's major suppliers of LNG [48]. In July 1981, the company adopted the name Entreprise Nationale

Sonatrach, coinciding with a restructuring that spun off certain operational areas to subsidiaries while retaining overall coordination [48].

II.2.2 Corporate Profile and Operations

Sonatrach is an integrated oil and gas company engaged in exploration, production, liquefaction, refining, marketing, and maritime transportation of hydrocarbons and petroleum products [47]. The company operates pipeline transport, storage, loading, and unloading infrastructure networks to transport crude oil, condensate, LPG, and natural gas [47].

As of recent data, Sonatrach produces approximately 90% of all Algerian export income and was the fourth largest exporter and producer of gas in the world in 2003 [48]. The company employs over 36,000 people and has guided Algeria toward its present status as the second largest global supplier of liquefied natural gas [15,34].

Sonatrach operates major industrial complexes across Algeria, including liquefaction plants at Arzew and Skikda, refineries, and petrochemical facilities [49]. The company has also expanded internationally, forming joint ventures with major international energy companies [51].

II.2.3 Strategic Importance

Sonatrach holds a monopoly position in Algeria's hydrocarbon sector, controlling both direct and indirect aspects of the industry [48]. The company is the primary instrument through which the Algerian state exerts central control over hydrocarbon revenues, making it a crucial entity for the national economy [50].

The company's strategic objectives include maintaining and expanding LNG export capacity, developing new gas fields, and modernizing existing facilities to improve reliability and efficiency [51]. Recent investments include flare gas recovery projects, storage capacity expansion, and port infrastructure upgrades [51].

II.3 The GL1K Liquefaction Complex in Skikda

II.3.1 Location and General Overview

The GL1K natural gas liquefaction complex is located in Skikda, on the northeastern coast of Algeria, approximately 500 km east of Algiers [52]. The complex is situated between Oued Saf-Saf and the village of Larbi Ben M'Hidi, occupying a total area of 93 hectares [53].

Of this area, 55 hectares are occupied by the old units, while 38 hectares are dedicated to the new Mega Train [53].

The complex receives natural gas from the Hassi R'Mel gas fields via three major pipelines: GK1 (575 km, 40 inches diameter), GK2 (575 km, 42 inches diameter), and GK3 (786 km, 48 inches diameter) [53]. The strategic location on the Mediterranean coast enables efficient export of LNG to European, American, and Asian markets via LNG carriers [53].

II.3.2 Historical Development

The construction of the GL1K complex began in March 1969 as part of Algeria's strategic objective to enhance the valorization of natural gas resources, primarily from the Hassi R'Mel deposit [53]. The first LNG production took place in November 1972 through Unit 10 (U10), built by Technip [42,35].

The complex developed through three main phases:

• **First Phase (1971-1973):** Construction of trains 10, 20, and 30 by Technip of France, using the TEAL liquefaction process [52]. These units had a design capacity of approximately 1.1 billion cubic meters per year (0.85 million tonnes per year) each [52].

• **Second Phase (1981):** Commissioning of train 40, built by Prichard Rhodes using PRICO technology . Trains 5P and 6P, also built by Prichard Rhodes using PRICO technology, began operating in 1981 with a design capacity of 1.64 billion cubic meters per year (1.25 million tonnes per year) each [52].

• **Modernization (1990s):** All trains at Skikda were revamped as part of a modernization and revitalization program completed in the late 1990s [52].

By the 1990s, the complex had grown to six trains with a total capacity of approximately 7.68 million tonnes per year of LNG [52].

II.3.3 The 2004 Incident and Reconstruction

On January 19, 2004, a catastrophic explosion occurred at the GL1K complex during routine boiler maintenance operations on train 40 [54]. The incident, caused by insufficient purging of the boiler, destroyed three of the six trains (20, 30, and 40) and badly damaged another, killing 26 workers and injuring 74 . The explosion led to the immediate closure of the 335,000-bpd capacity refinery and LNG plant [54].

Following the incident, investigations were conducted and new plant designs eliminated the need for boilers, replacing them with more efficient gas-fueled turbines and compressors [54]. Trains 10, 5P, and 6P were brought back into production in November 2004, while the three destroyed trains were replaced by one larger, more efficient "Mega Train" [54].

In 2005, Sonatrach launched the reconstruction project to build a new single liquefaction train with 4.5 million tonnes per year capacity. KBR (Kellogg Brown & Root International) was awarded the engineering, procurement, and construction (EPC) contract in March 2007, with a contract value of approximately $2.8 billion [54]. The new train entered service in 2013 [54].

II.3.4 Current Status and Infrastructure

Currently, the GL1K complex consists of four natural gas liquefaction trains, though only one (the GL1K Rebuild/Mega Train) remains operational [42,17]. The original trains (5P and 6P) were placed under nitrogen storage in 2014, while train 10 was retired [42,17].

The complex includes:

- LNG storage and shipping facilities
- LPG unit (partially stopped, with storage, refrigeration, and loading sections operational)
- Utility systems (steam, water, air, nitrogen)
- Flare system
- Fire protection and detection systems
- Laboratory facilities
- Main control room and field instrumentation chambers

In March 2024, a new M3 jetty was commissioned at the Skikda terminal, capable of accommodating larger LNG carriers with capacity up to 220,000 cubic meters .A new LNG storage tank with 150,000 cubic meters capacity was also built [51]. The combined capacity of Algeria's Arzew and Skikda terminals is estimated at approximately 25.3 million tonnes per year [51].

Figure II.1: The GL1K SKIKDA natural gas liquefaction complex

II.4 The New LNG Mega Train

II.4.1 Overview and Process Technology

The new LNG Mega Train represents the most modern and technologically advanced production unit of the GL1K complex. Built by KBR and commissioned on March 27, 2013, the Mega Train uses the APCI (Air Products and Chemicals Incorporation) process for natural gas liquefaction [3]. The APCI C3MR (Propane Precooled Mixed Refrigerant) process is the most widely used LNG liquefaction technology globally, known for its energy efficiency and reliability [56]. The process employs propane to precool the gas before using a mixed refrigerant cycle, making it ideal for large-scale onshore plants [56]. The Mega Train has an installed production capacity of 4.5 million tonnes per year of LNG, equivalent to approximately 10 million cubic meters per year [3]. This single train replaces the three destroyed trains (20, 30, and 40) while offering significantly improved efficiency, safety, and environmental performance.

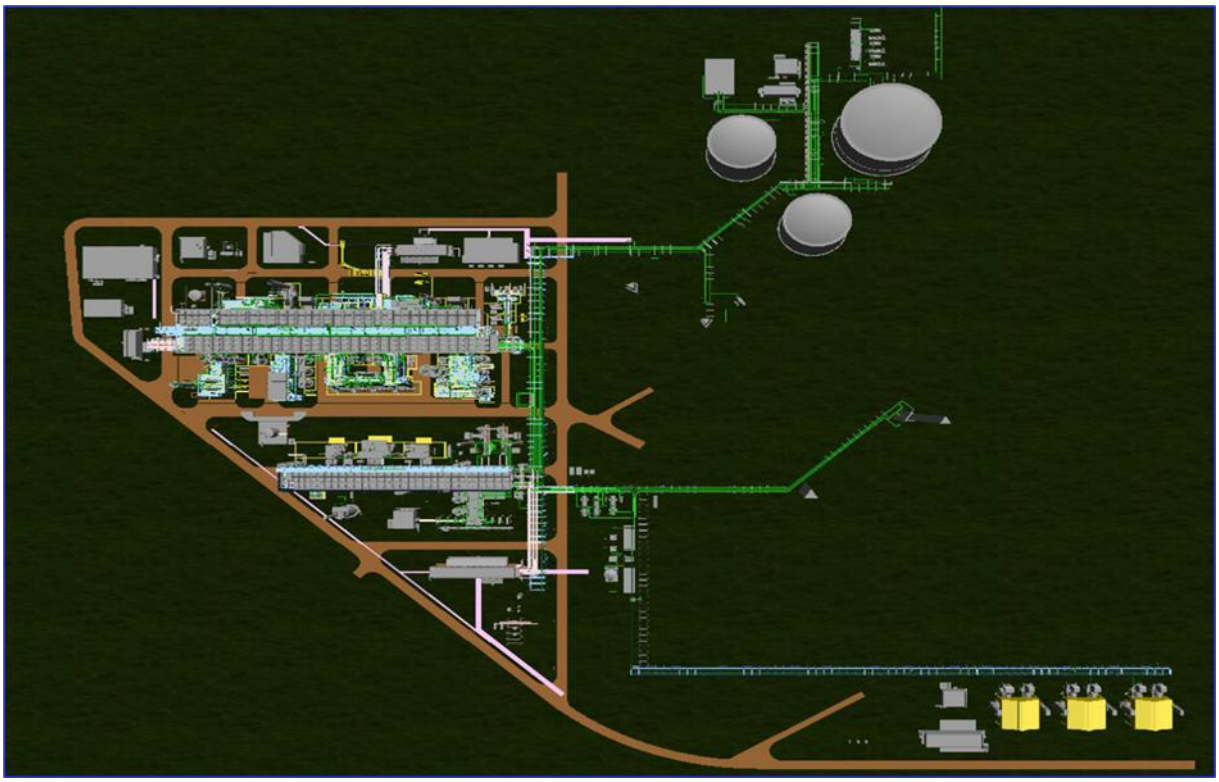

Figure II.2: Panoramic view of mega-train

II.4.2 Process Description and Main Sections

The LNG Mega Train consists of several integrated sections, each performing specific functions in the transformation of natural gas into LNG and by-products [3]:

- **Metering Section:** Measures the quantities of natural gas consumed, providing necessary elements for calculating plant balances.
- **Compression Section:** Compresses natural gas to 66 bars to facilitate liquefaction, reducing energy requirements and equipment size [3].
- **Acid Gas Removal Section (Decarbonatation):** Reduces CO_2 content from 0.21% in the feed gas to less than 50 ppmv using activated amine (aMDEA) at 40% concentration [3]. This prevents freezing and blockage in downstream cryogenic equipment.
- **Dehydration Section:** Dries the gas using three-bed molecular sieve configuration to reduce water content to less than 1 ppmv [48,47].
- **Mercury Removal Section (Demercurization):** Removes mercury using activated carbon bed impregnated with sulfur to reduce mercury content to less than 5 ng/Nm^3 [3].
- **Liquefaction Section:** The core process where treated natural gas is liquefied through pre-cooling with propane, washing in scrub column, and passage through Main Cryogenic Heat Exchanger (MCHE) [48,47].

- **Fractionation Section:** Separates heavy hydrocarbons from the scrub column into ethane, propane, butane, and gasoline (C5+) products [3].

II.4.3 Production Capacities and Products

The contractual production capacities of the new Mega Train are:

Table II.1: Production capacities

Product	**Annual Capacity**
LNG	4,500,000 tonnes/year
Ethane	164,700 tonnes/year
Propane	207,600 tonnes/year
Butane	171,400 tonnes/year
Naphtha (Gasoline)	108,700 tonnes/year
Helium-rich feed gas	163,100,000 Nm^3/year

The ethane is exported as vapor via pipeline to a local ethylene plant, while propane and butane are stored and loaded for export [55].

II.4.4 Utility Systems

The Mega Train includes comprehensive utility systems to support operations [3]:

Power Generation: Five gas turbine-driven generators (21.74 MW each) with five 1.7 MW diesel generators for backup, providing N+1 redundancy [3].

Air Production: Three compressors producing 3,300 Nm^3/h of service and instrument air [3].

Nitrogen System: Supplies inert gas for tank blanketing, equipment purging, and safe evacuation of hydrocarbon vapors for maintenance [3].

Hot Oil System: Provides heating duty for dehydration regeneration and other process heating requirements .

Fuel Gas System: Collects flash gas from liquefaction and boil-off gas from LNG tanks [3].

Fire Protection System: Includes fire water monitors, water spray systems, fire hydrants, CO_2 extinguishing systems, and portable/wheeled extinguishers [3].

Flare System: Provides safe disposal of hydrocarbon vapors and liquids from startups, shutdowns, upsets, emergencies, and routine operations [3].

II.4.5 Storage Facilities

The storage facilities for the Mega Train include [3]:

• **LNG Storage:** One full containment concrete tank with 150,000 cubic meters nominal capacity. Boil-off gas is recovered and routed to the fuel gas system [3].

• **LPG Storage:**

- One propane tank (66,000 m^3, full containment)
- One butane tank (66,000 m^3, full containment)
- Boil-off gas recovered and recondensed

• **Gasoline Storage:** One sphere with 3,000 cubic meters working capacity [3].

II.4.6 Control and Safety Systems

The Mega Train is equipped with advanced control and safety systems [3]:

- Main Control Room and Field Instrumentation Chambers (FIR)
- Distributed Control System (DCS) for process control
- Safety Instrumented System (SIS) for emergency shutdown
- Fire and Gas Detection System
- Laboratory for quality control

The control system ensures safe and efficient operation of the complex, with automatic protection against abnormal conditions [55].

II.5 Selected Units for Risk Assessment

For the purpose of this study, it was decided to limit the risk analysis to a single critical equipment in the fractionation train: **the depropanizer**. This simplification allows for an in-depth and detailed analysis while maintaining the representativeness of major hazards associated with pressurized distillation columns.

II.6 Conclusion

This chapter has provided the description of Sonatrach ,the GL1K liquefaction complex in Skikda and particularly the new LNG Mega Train establishes the physical and operational framework for the risk assessment study.

The next chapter will present the simulation results, demonstrating the practical application of the fuzzy QRA methodology to the depropanizer system, integrating computational fluid dynamics modeling with individual and societal risk calculations.

CHAPTER III

Quantitative risk assessment

III.1 Introduction

This chapter presents the quantitative risk assessment applied to the rupture of the depropanizer. The objective is to identify the accident sequences, revise their frequencies using fuzzy logic, model the consequences and evaluate the individual and societal risks using SAFETI.

The study follows the classical QRA workflow: hazard identification, scenario definition, frequency estimation, consequence modelling, and individual and societal risk calculation

III.2 Case study and problem definition

The depropanizer is a pressurized separation vessel used to separate light fractions from the process. In the event of rupture, it may release a large amount of flammable hydrocarbon, leading to atmospheric dispersion, rapid ignition, and thermal or overpressure effects on people and structures.

Figure III.1: depropanizer column

The selected scenario is the **rupture of the depropanizer**, treated as the initiating event. The analysis of this case makes it possible to assess the potential impact on the surrounding areas of the installation.

- **Problem statement**

This study aims to assess the risk level associated with the rupture of the depropanizer and to determine whether the existing safety barriers are sufficient to limit the consequences of

such an event. The main objective is to quantify the potential impact of this accident scenario on people, facilities, and the surrounding environment.

- **Study assumptions**

To perform the quantitative risk assessment, several assumptions were adopted. The rupture of the depropanizer is considered the main initiating event. The vessel contents are represented by the process fluid defined in the input data. Meteorological conditions are assumed to remain constant during each simulation, and receptors are considered fixed in space. The base frequencies are revised using a fuzzy approach that incorporates the selected influence factors. Finally, the safety barriers are assumed to operate or fail according to the logic of the fault trees and event trees.

III.3 Hazard identification

A Hazard and Operability (HAZOP) study was conducted on the depropanizer, focusing on deviations from normal operating parameters that could lead to loss of containment or escalation. The HAZOP was performed node by node, covering the feed section, column internals, overhead system, reboiler circuit, and relief/blowdown system

Table III.1: Hazard identification by HAZOP

Node	Parameter	Deviation	Cause	Consequence	Safeguard
Column overhead	Pressure	High	Condenser failure / blocked outlet	PRV activation, potential rupture if SRV fails	SRV, SIS high-pressure trip
Reboiler circuit	Temperature	High	Control valve failure open, steam supply excess	Overheating, pressure surge	Temperature controller, SIS trip
Column shell	Containment	Loss of	Corrosion, mechanical damage, overpressure	Catastrophic release of propane	Inspection program, SIS, SRV
Feed section	Flow	No flow / reverse	Pump failure, valve closure	Column flooding or drying	Flow alarm, operator response
Reflux system	Level	High	Reflux pump failure	Liquid carryover to overhead	Level alarm, SIS
Blowdown system	Pressure	Low	Inadvertent blowdown	Flash vaporization, cold shock	Blowdown valve interlock

➢ **Selected Hazardous Phenomena**

Based on the HAZOP analysis, the hazardous phenomenon selected for consequence modelling is:

- Catastrophic rupture of the depropanizer column (loss of containment of propane).

This scenario represents the worst credible case due to its potential to generate major thermal and overpressure effects and to threaten personnel, assets, and surrounding facilities.

III.4 Dysfunctional analysis

Dysfunctional analysis aims to identify the causes that may lead to the depropanizer rupture. It is represented by a fault tree linking the top event to the basic events.

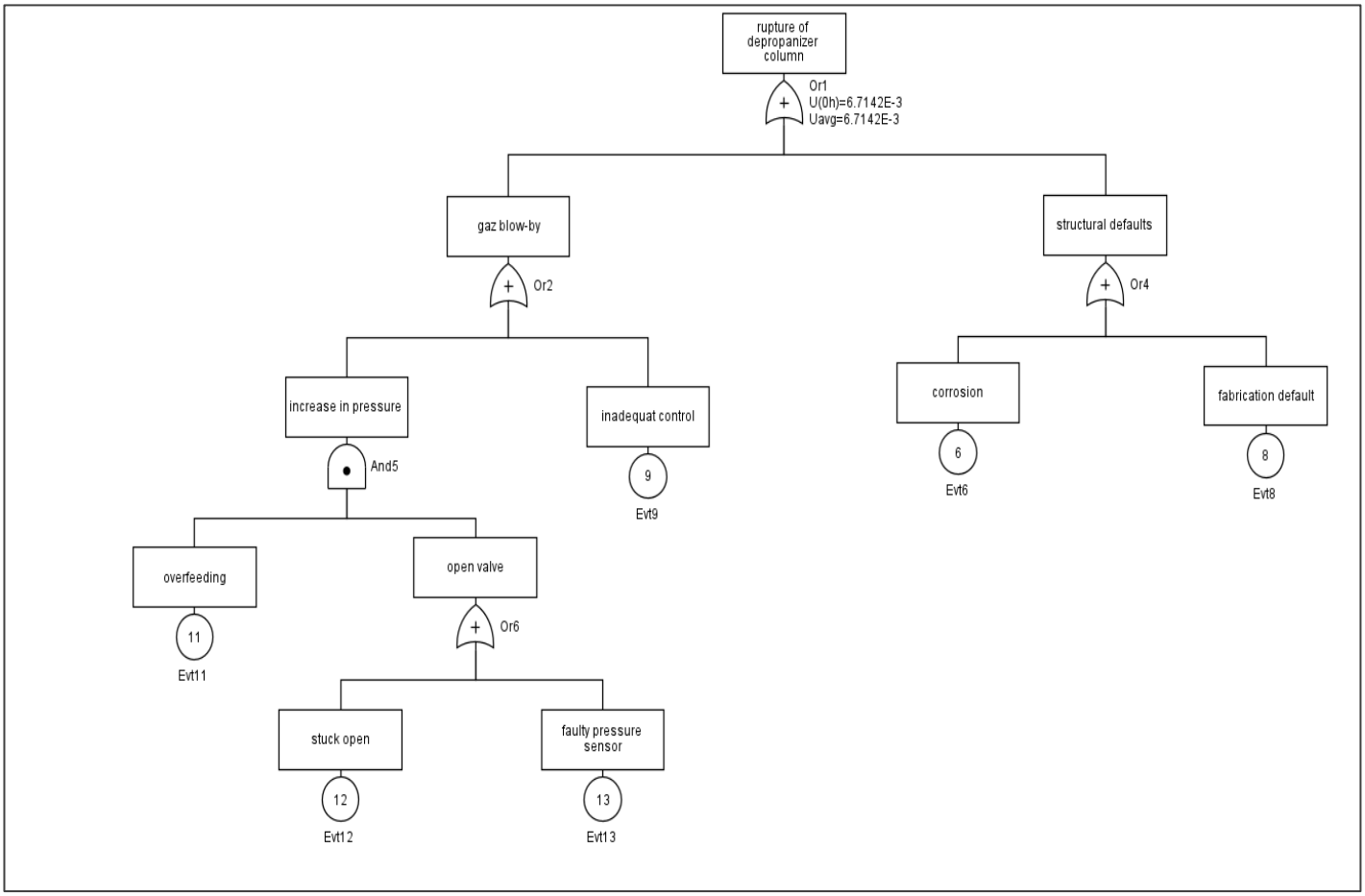

Figure III.2: fault tree of the top event rupture of the depropanizer column

III.5 Safety barriers

the main barriers are:

- the safety valve.

- the BPCS.
- the SIS.

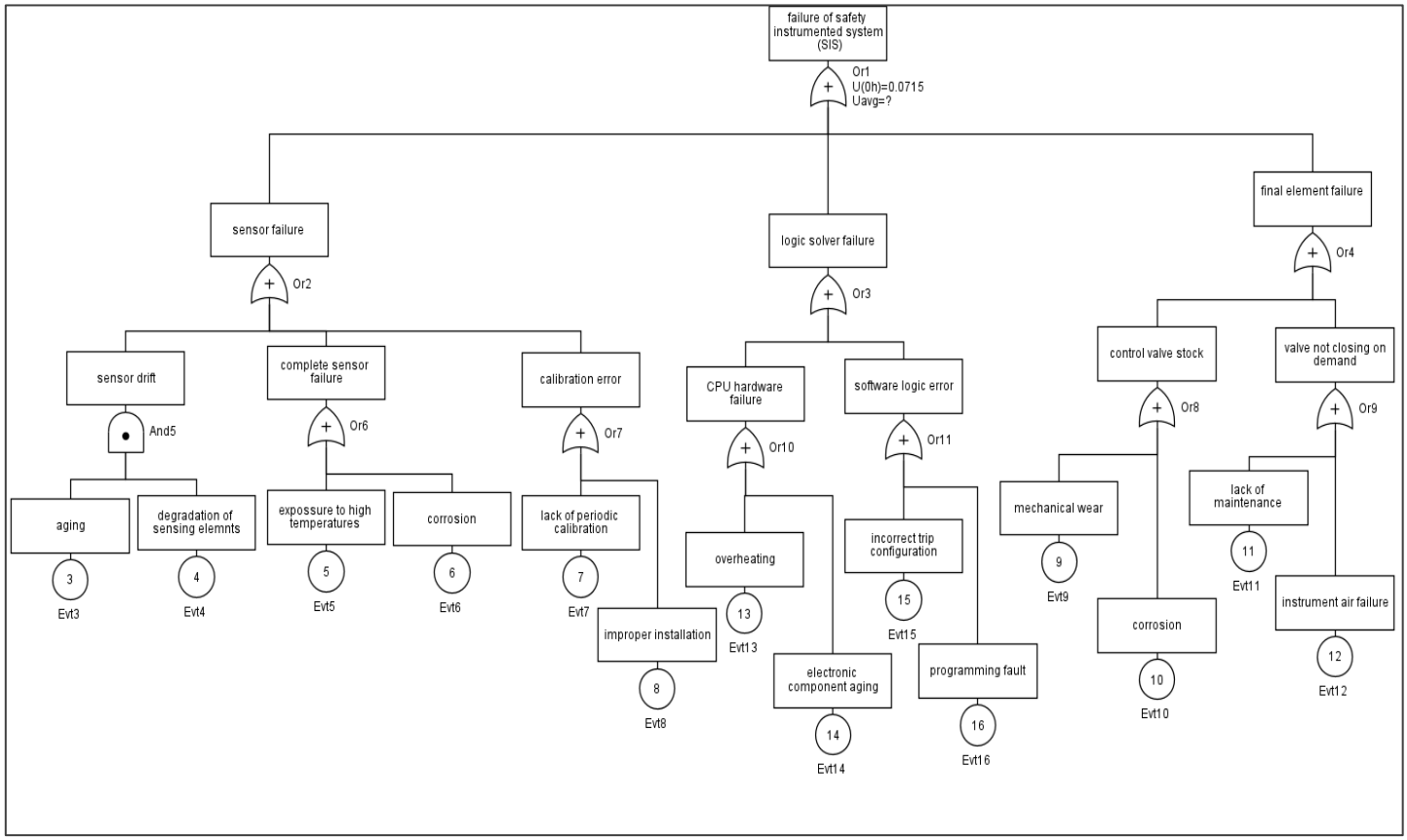

Figure III.3: fault tree of SIS failure

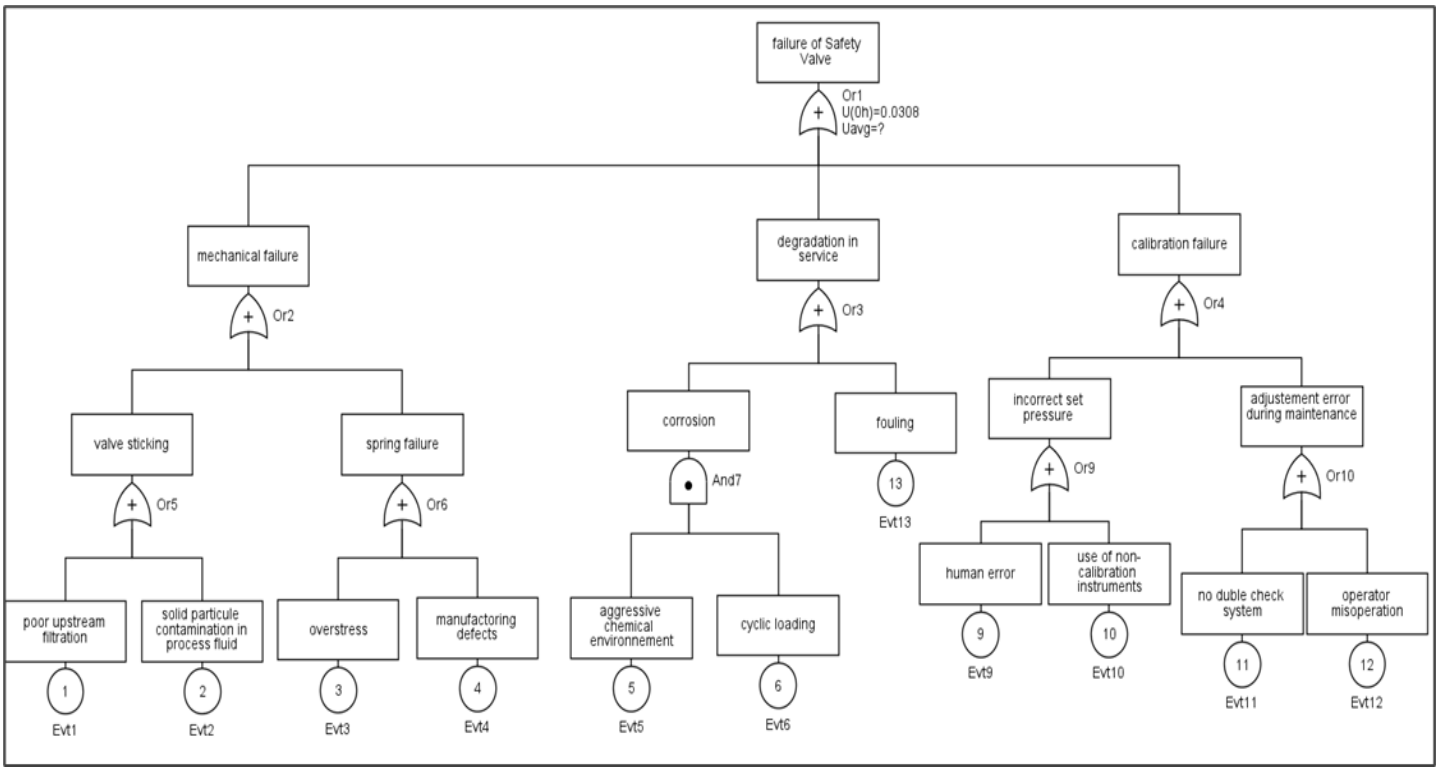

Figure III.4: fault tree of safety valve failure

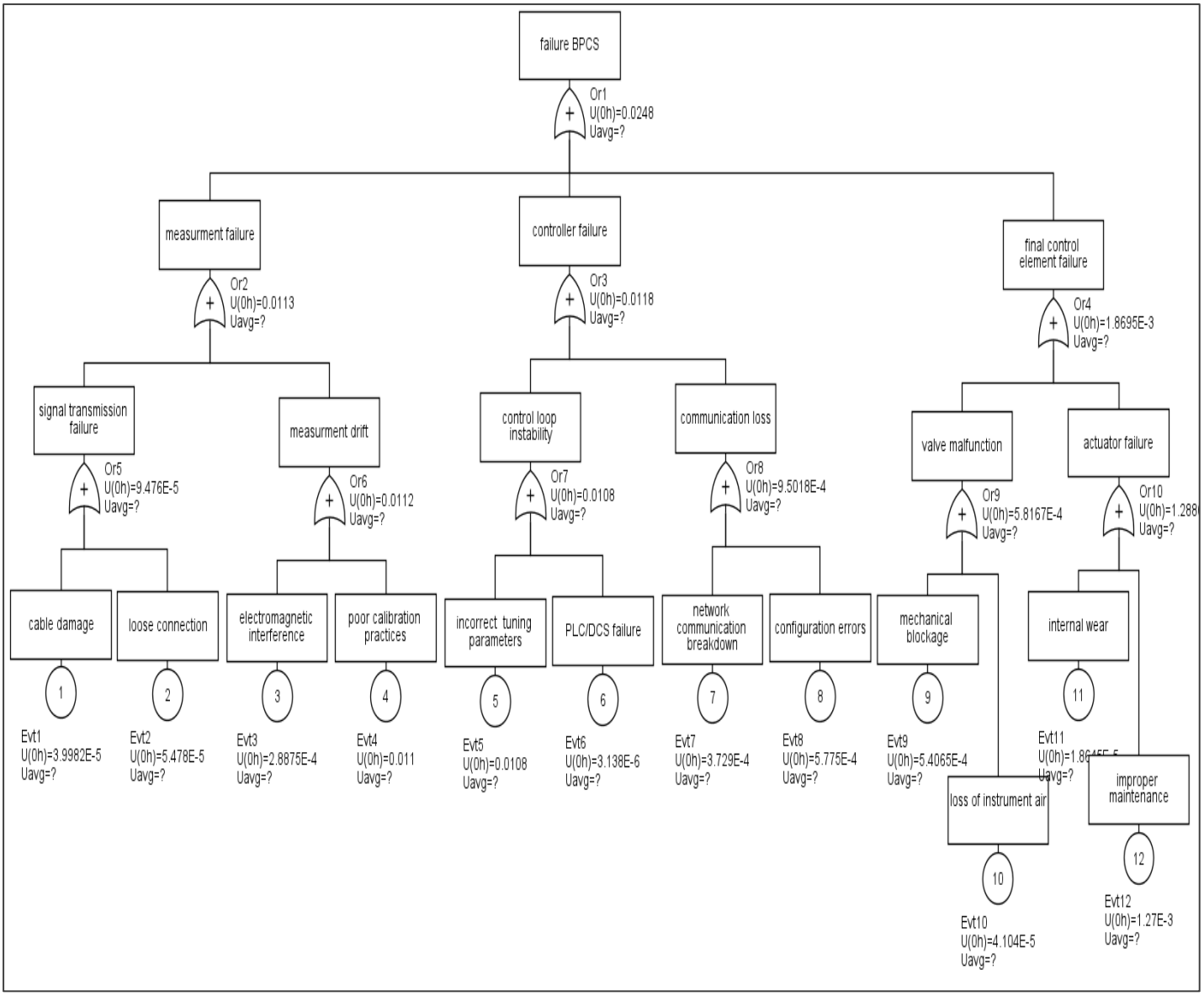

Figure III.5: fault tree of BPCS failure

frequency estimation

First, all basic event frequencies were collected from the available database. These frequencies provide the initial estimate of failures leading to the feared scenario. However, they do not fully reflect the uncertainty associated with real operating conditions.

To improve the estimate, influence factors were introduced:

- maintenance.
- power supply.
- design.
- operator.
- communication.

These factors were chosen because they directly affect system reliability, prevention quality, and the ability to respond to abnormal situations.

Table III.2: the influence factors table

Factor	**Code**	**Description**
Maintenance	F1	Quality and frequency of preventive and corrective maintenance activities on the column and its barriers
Power Supply	F2	Reliability and redundancy of electrical power supply to SIS and control systems
Design	F3	Adequacy of the original design (including safety margins, codes compliance, and layout)
Operator Performance	F4	Training level, experience, and human reliability of control room and field operators
Communication	F5	Effectiveness of communication between shifts, departments, and emergency response teams

- **Calculation of weights**

Weights were then assigned to each factor by expert judgement. This step translates the relative importance of each factor in the accident development process.

The experts ranked the factors according to impact level:

- highly influential factors receive high weights.
- moderately influential factors receive intermediate weights.
- weakly influential factors receive low weights.

Table III.3: example of normalized weight calculated from expert judgement of the basic event overfeeding

Overfeeding						
RIF	**Importance (weights)**					**Normalized weighting** $\frac{Wi}{TW}$
RIF	**High**				**Low**	
	(10)	**(8)**	**(6)**	**(4)**	**(2)**	
maintenance		x				0.57
design				x		0.29
power supply					x	0.14
Weight	0	8	0	4	2	1
Total weight	14					1

In this study, a fuzzy approach was adopted to revise the basic event frequencies. First, the initial frequencies were collected from the database. Then, several influence factors were introduced to account for uncertainty in operating conditions, namely maintenance, power supply, design, operator, and communication. A weight was assigned to each factor based on expert judgement. To represent uncertainty, each weight was converted into a fuzzy interval with a lower core equal to 20% below the central value and an upper core equal to 20% above it. A Mamdani-type fuzzy inference system was then developed in MATLAB using the Fuzzy Logic Designer. For each influence factor, three inputs were defined: lower core, core, and upper core, representing respectively the lower bound, the central value, and the upper bound of the expert estimate. The input and output ranges were set between 0 and 1, and the membership functions were defined as low, moderate, notable, significant, and high. The fuzzy rule base was filled manually to express the relationship between the input levels and the system output. The output of the fuzzy system is the fuzzy weight, which was then used to calculate the score and revise the frequency of each basic event.

Table III.4: the lower core / core / upper core table of the basic event overfeeding

RIF	**Lower core**	**Core**	**Upper core**
Maintenance	0.46	0.57	0.68
Design	0.23	0.29	0.35
Power supply	0.11	0.14	0.17

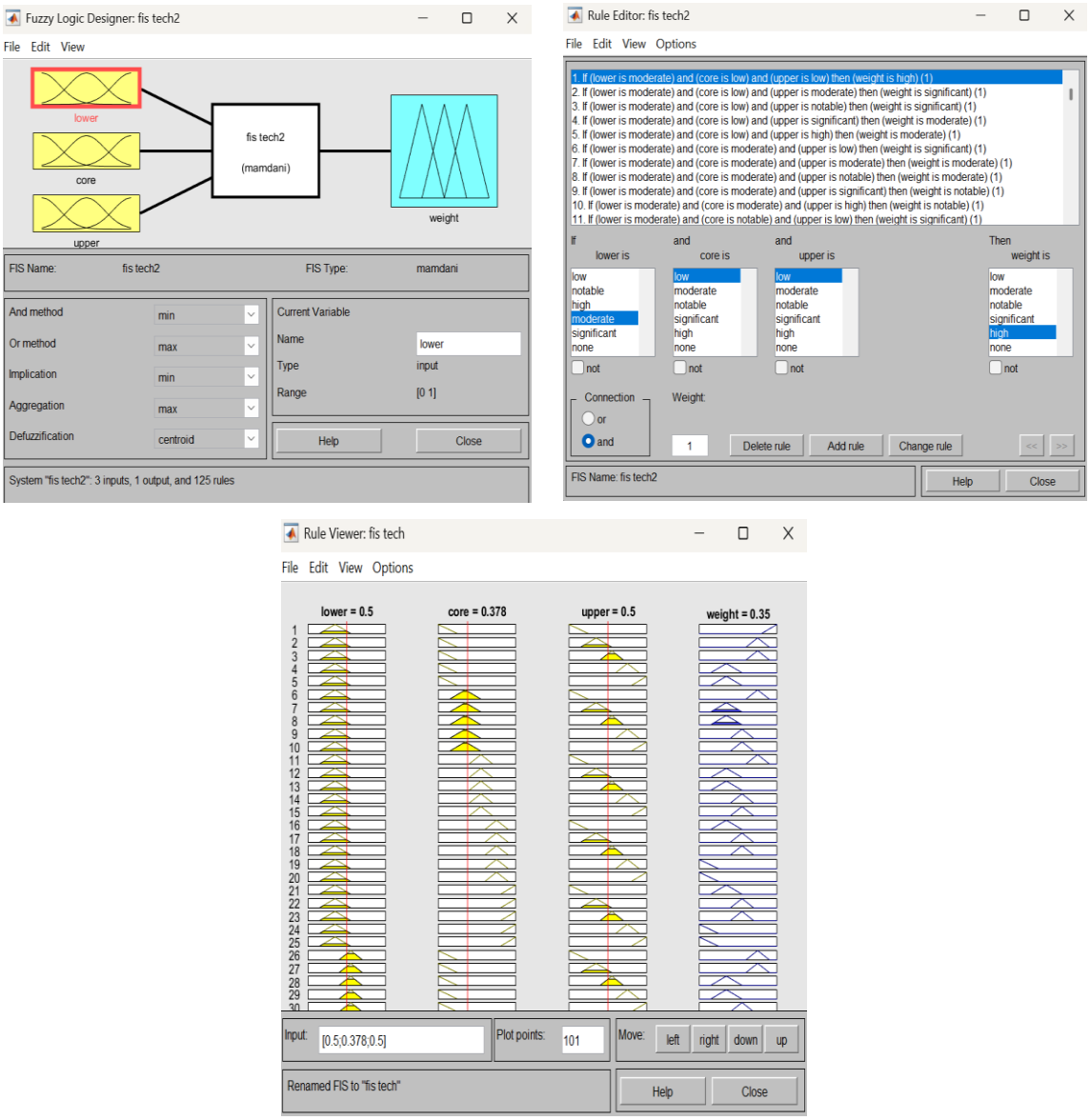

Figure III.6: workflow of the fuzzy logic system

Table III.5: example of calculated fuzzy weights of the basic event overfeeding

RIF	Lower core	Core	Upper core	Fuzzy weight
Maintenance	0.46	0.57	0.68	0.487
Design	0.23	0.29	0.35	0.411
Power supply	0.11	0.14	0.17	0.918

- **Calculation of scores**

After assigning a fuzzy weight to each influence factor, each RIF was scored from A to F according to its performance level. Score A indicated best industry practice, score C indicated

average industry practice, and score F indicated worst industry practice. This qualitative ranking was then used as an input for the score calculation and the revised frequency estimation.

Table III.6: RIFs scores

Factor	**Score**
Communication	B
Operator	A
Maintenance	B
Design	A
Power supply	C

Based on the equations introduced in Chapter 1, the score of each factor was determined for each basic event. The corresponding results are presented in the following table.

Table III.7: Summary of RIF Factors, Fuzzy Weights and Qi for All Basic Events

Basic Event	**RIF Factor**	**Lower Core**	**Core**	**Upper Core**	**Fuzzy Weight**	**Qi**	**ΣQiWi**
Rupture of Depropanizer Basic Events							
Overfeeding	Maintenance	0.46	0.57	0.68	0.487	0.55	1.227
	Design	0.23	0.29	0.35	0.411	0.10	
	Power supply	0.11	0.14	0.17	0.918	1.00	
Vane stuck open	Maintenance	0.45	0.56	0.67	0.49	0.55	0.943
	Design	0.18	0.22	0.26	0.612	0.10	
	Power supply	0.18	0.22	0.26	0.612	1.00	
Faulty pressure sensor	Maintenance	0.54	0.67	0.80	0.264	0.55	1.081
	Design	0.14	0.17	0.20	0.851	0.10	
	Power supply	0.14	0.17	0.20	0.851	1.00	
Inadequate control	Maintenance	0.40	0.50	0.60	0.35	0.55	0.628
	Design	0.14	0.17	0.20	0.851	0.10	
	Power supply	0.26	0.33	0.40	0.35	1.00	
Corrosion	Maintenance	0.45	0.56	0.67	0.469	0.55	0.886
	Design	0.18	0.22	0.26	0.612	0.10	
	Power supply	0.18	0.22	0.26	0.612	1.00	

Fabrication default	Maintenance	0.34	0.43	0.52	0.35	0.55	
	Design	0.34	0.43	0.52	0.35	0.10	1.146
	Power supply	0.11	0.14	0.17	0.918	1.00	
Failure of SIS Basic Events							
Aging	Maintenance	0.40	0.50	0.60	0.35	0.55	
	Design	0.14	0.37	0.20	0.851	0.10	1.197
	Power supply	0.10	0.13	0.16	0.919	1.00	
Degradation of sensing elements	Maintenance	0.45	0.56	0.67	0.469	0.55	
	Design	0.18	0.22	0.26	0.612	0.10	0.931
	Power supply	0.18	0.22	0.26	0.612	1.00	
Exposure to high temperatures	Maintenance	0.34	0.43	0.52	0.35	0.55	
	Design	0.34	0.43	0.52	0.35	0.10	1.146
	Power supply	0.11	0.14	0.17	0.918	1.00	
Corrosion (SIS)	Maintenance	0.46	0.57	0.68	0.487	0.55	
	Design	0.22	0.28	0.34	0.44	0.10	1.395
	Power supply	0.11	0.14	0.17	0.918	1.00	
Lack of periodic calibration	Maintenance	0.48	0.60	0.72	0.55	0.55	
	Design	0.16	0.20	0.24	0.721	0.10	1.096
	Power supply	0.16	0.20	0.24	0.721	1.00	
Improper installation	Maintenance	0.18	0.22	0.26	0.612	0.55	
	Design	0.35	0.44	0.53	0.35	0.10	0.599
	Power supply	0.26	0.33	0.40	0.35	1.00	
Overheating	Maintenance	0.26	0.33	0.40	0.35	0.55	
	Design	0.26	0.33	0.40	0.35	0.10	0.578
	Power supply	0.26	0.33	0.40	0.35	1.00	
Electronic component aging	Maintenance	0.54	0.67	0.80	0.264	0.55	
	Design	0.14	0.17	0.20	0.851	0.10	1.081
	Power supply	0.14	0.17	0.20	0.851	1.00	
Incorrect trip configuration	Maintenance	0.34	0.43	0.52	0.35	0.55	
	Design	0.34	0.43	0.52	0.35	0.10	1.146
	Power supply	0.11	0.14	0.17	0.918	1.00	
Programming fault	Maintenance	0.48	0.60	0.72	0.55	0.55	
	Design	0.16	0.20	0.24	0.721	0.10	1.096
	Power supply	0.16	0.20	0.24	0.721	1.00	

Mechanical wear	Maintenance	0.54	0.67	0.80	0.264	0.55	
	Design	0.14	0.17	0.20	0.851	0.10	1.081
	Power supply	0.14	0.17	0.20	0.851	1.00	
Corrosion (final element)	Maintenance	0.54	0.67	0.80	0.264	0.55	
	Design	0.14	0.17	0.20	0.851	0.10	1.081
	Power supply	0.14	0.17	0.20	0.851	1.00	
Lack of maintenance	Maintenance	0.57	0.71	0.85	0.103	0.55	
	Design	0.11	0.14	0.17	0.918	0.10	1.066
	Power supply	0.11	0.14	0.17	0.918	1.00	
Instrument air failure	Maintenance	0.36	0.45	0.54	0.35	0.55	
	Design	0.07	0.09	0.11	0.927	0.10	0.640
	Power supply	0.36	0.45	0.54	0.35	1.00	
Failure of BPCS Basic Events							
Cable damage	Maintenance	0.46	0.57	0.68	0.487	0.55	
	Design	0.11	0.14	0.17	0.918	0.10	0.800
	Power supply	0.22	0.28	0.34	0.44	1.00	
Loose connection	Maintenance	0.48	0.60	0.72	0.55	0.55	
	Design	0.16	0.20	0.24	0.721	0.10	1.096
	Power supply	0.16	0.20	0.24	0.721	1.00	
Electromagnetic interference	Maintenance	0.26	0.33	0.40	0.35	0.55	
	Design	0.26	0.33	0.40	0.35	0.10	0.578
	Power supply	0.26	0.33	0.40	0.35	1.00	
Poor calibration practices	Maintenance	0.48	0.60	0.72	0.55	0.55	
	Design	0.16	0.20	0.24	0.721	0.10	1.096
	Power supply	0.16	0.20	0.24	0.721	1.00	
Incorrect tuning parameters	Maintenance	0.54	0.67	0.80	0.264	0.55	
	Design	0.14	0.17	0.20	0.851	0.10	1.081
	Power supply	0.14	0.17	0.20	0.851	1.00	
PLC/DCS failure	Maintenance	0.40	0.50	0.60	0.35	0.55	
	Design	0.14	0.17	0.20	0.851	0.10	0.628
	Power supply	0.26	0.33	0.40	0.35	1.00	
Network communication breakdown	Maintenance	0.40	0.50	0.60	0.35	0.55	
	Design	0.20	0.25	0.30	0.503	0.10	0.746
	Power supply	0.20	0.25	0.30	0.503	1.00	

Configuration errors	Maintenance	0.26	0.33	0.40	0.35	0.55	0.578
	Design	0.26	0.33	0.40	0.35	0.10	
	Power supply	0.26	0.33	0.40	0.35	1.00	
Mechanical blockage	Maintenance	0.54	0.67	0.80	0.264	0.55	1.081
	Design	0.14	0.17	0.20	0.851	0.10	
	Power supply	0.14	0.17	0.20	0.851	1.00	
Loss of instrument air	Maintenance	0.22	0.28	0.34	0.44	0.55	0.821
	Design	0.14	0.14	0.17	0.918	0.10	
	Power supply	0.46	0.57	0.68	0.487	1.00	
Internal wear	Maintenance	0.40	0.50	0.60	0.35	0.55	0.746
	Design	0.20	0.25	0.30	0.503	0.10	
	Power supply	0.20	0.25	0.30	0.503	1.00	
Improper maintenance	Communication	0.64	0.80	0.96	0.0995	0.55	0.127
	Operator	0.16	0.20	0.24	0.721	0.10	
Failure of Safety Valve Basic Events							
Poor upstream filtration	Maintenance	0.18	0.22	0.26	0.612	0.55	0.996
	Design	0.45	0.56	0.67	0.469	0.10	
	Power supply	0.18	0.22	0.26	0.612	1.00	
Solid particle contamination	Maintenance	0.10	0.13	0.16	0.919	0.55	1.050
	Design	0.50	0.63	0.76	0.418	0.10	
	Power supply	0.20	0.25	0.30	0.503	1.00	
Over stress	Maintenance	0.20	0.25	0.30	0.503	0.55	0.815
	Design	0.40	0.50	0.60	0.35	0.10	
	Power supply	0.20	0.25	0.30	0.503	1.00	
Manufacturing defects	Maintenance	0.20	0.25	0.30	0.503	0.55	1.237
	Design	0.50	0.63	0.76	0.418	0.10	
	Power supply	0.10	0.13	0.16	0.919	1.00	
Aggressive chemical environment	Maintenance	0.20	0.25	0.30	0.503	0.55	0.815
	Design	0.40	0.50	0.60	0.35	0.10	
	Power supply	0.20	0.25	0.30	0.503	1.00	
Cyclic loading	Maintenance	0.30	0.37	0.44	0.35	0.55	1.147
	Design	0.40	0.50	0.60	0.35	0.10	
	Power supply	0.10	0.13	0.16	0.919	1.00	
Fouling	Maintenance	0.11	0.14	0.17	0.916	0.55	1.432

	Design	0.57	0.71	0.87	0.102	0.10	
	Power supply	0.11	0.14	0.17	0.918	1.00	
Human errors	Maintenance	0.24	0.30	0.36	0.381	0.55	0.629
	Design	0.24	0.30	0.36	0.381	0.10	
	Power supply	0.24	0.30	0.36	0.381	1.00	
Use of non-calibrated instruments	Communication	0.34	0.43	0.52	0.35	0.55	0.241
	Operator	0.46	0.57	0.68	0.487	0.10	
No double check system	Communication	0.34	0.43	0.52	0.35	0.55	0.241
	Operator	0.46	0.57	0.68	0.487	0.10	
Operator misoperation	Communication	0.40	0.50	0.60	0.35	0.55	0.228
	Operator	0.40	0.50	0.60	0.35	0.10	

III.6 Revised frequency estimation

After calculating the scores assigned to each influence factor, the basic event frequencies were revised. This revision was performed by combining the initial event frequency, the fuzzy weight obtained from the Mamdani system, and the score calculated using the equations presented earlier. The resulting revised frequencies for each basic event are shown in the following table.

Table III.8: revised frequencies

Sub-system / Barrier	Basic Event	Average Frequency	Revised Frequency	Notes / Source
Rupture of Depropanizer	Overfeeding	1.0×10^{-1}	6.10×10^{-2}	BPCS loop failure frequency
	Valve stuck open	4.0×10^{-3}	3.77×10^{-3}	Control valve failure (TI=1 yr)
	Faulty pressure sensor	1.0×10^{-3}	1.08×10^{-3}	Sensor PFD (1oo1)
	Inadequate control	1.0×10^{-2}	6.28×10^{-3}	BPCS control loop PFD
	Corrosion	1.0×10^{-4}	3.08×10^{-5}	Pressure vessel degradation
	Fabrication default	1.0×10^{-4}	1.15×10^{-4}	Weld/defect probability
Failure of SIS	Aging	1.0×10^{-4}	5.98×10^{-5}	General equipment aging

	Degradation of sensing elements	5.0×10^{-5}	2.33×10^{-5}	Sensor drift/degradation
	Exposure to high temperatures	5.0×10^{-5}	2.86×10^{-5}	Environmental stress
	Corrosion	5.0×10^{-5}	1.395×10^{-2}	Enclosure/element corrosion
	Lack of periodic calibration	0.01	1.096×10^{-2}	Maintenance procedural gap
	Improper installation	1.0×10^{-3}	5.99×10^{-4}	Commissioning error
	Overheating	1.0×10^{-3}	2.89×10^{-4}	Cooling/enclosure failure
	Electronic component aging	1.0×10^{-4}	5.40×10^{-5}	Electronics wear-out
	Incorrect trip configuration	1.0×10^{-3}	1.15×10^{-3}	Programming/setup error
	Programming fault	1.0×10^{-4}	1.10×10^{-4}	Software defect
	Mechanical wear	5.0×10^{-5}	2.70×10^{-5}	Moving parts (solenoids, etc.)
	Corrosion (final element)	5.0×10^{-5}	2.70×10^{-5}	Final element corrosion
	Lack of maintenance	0.04	4.27×10^{-2}	Deferred maintenance
	Instrument air failure	1.0×10^{-2}	3.20×10^{-3}	Utility failure frequency
Failure of BPCS	Cable damage	1.0×10^{-4}	4.00×10^{-5}	Physical damage
	Loose connection	1.0×10^{-4}	5.48×10^{-5}	Intermittent failure
	Electromagnetic interference	1.0×10^{-3}	2.89×10^{-4}	EMI/RFI events
	Poor calibration practices	0.01	1.096×10^{-2}	Maintenance error
	Incorrect tuning parameters	0.01	1.081×10^{-2}	Commissioning error
	PLC/DCS failure	1.0×10^{-5}	3.14×10^{-6}	Controller hardware (MTBF ~100 yr)
	Network communication breakdown	1.0×10^{-3}	3.73×10^{-4}	Network fault
	Configuration errors	1.0×10^{-3}	5.78×10^{-4}	Software/config mistake
	Mechanical blockage	1.0×10^{-3}	5.41×10^{-4}	Instrument impulse line

	Loss of instrument air	1.0×10^{-2}	4.10×10^{-5}	Utility failure
	Internal wear	5.0×10^{-5}	1.86×10^{-5}	Mechanical components
	Improper maintenance	0.01	1.27×10^{-3}	Human error
Failure of Safety Valve	Poor upstream filtration	1.0×10^{-2}	4.98×10^{-3}	Process condition
	Solid particle contamination	1.0×10^{-2}	5.25×10^{-3}	Process fluid quality
	Over stress	1.0×10^{-3}	4.10×10^{-4}	Pressure cycling
	Manufacturing defects	1.0×10^{-5}	1.24×10^{-5}	QA defect probability
	Aggressive chemical environment	1.0×10^{-3}	4.10×10^{-4}	Material attack
	Cyclic loading	1.0×10^{-3}	5.70×10^{-4}	Fatigue
	Fouling	1.0×10^{-2}	7.16×10^{-3}	Build-up on seat/disk
	Human errors	1.0×10^{-2}	6.29×10^{-3}	Testing/maintenance error
	Use of non-calibration instruments	0.01	2.41×10^{-3}	Instrument error
	No double check system	0.1	2.41×10^{-3}	Administrative gap (high)
	Operator misoperation	1.0×10^{-2}	2.28×10^{-3}	Per demand

The revised basic event frequencies were introduced into GRIFF to calculate the top event frequencies. Using the fault tree logic, the software combines the basic events and provides the overall frequency of the feared event. These top event frequencies are then used in the consequence modelling stage.

The following table presents the calculated frequencies for the different top events considered in this study, namely depropanizer rupture, SIS failure, safety valve failure, and BPCS failure.

Table III.9: calculated frequencies for the different top events

Top event	Cause / barrier	Frequency	Comment
Depropanizer rupture	Loss of containment	0.0067	Main initiating event
SIS failure	Instrumented protection failure	0.0715	Safety barrier
Safety valve failure	Relief valve failure	0.0308	Safety barrier
BPCS failure	Control system failure	0.000039	Safety barrier

III.6.1 Event tree analysis

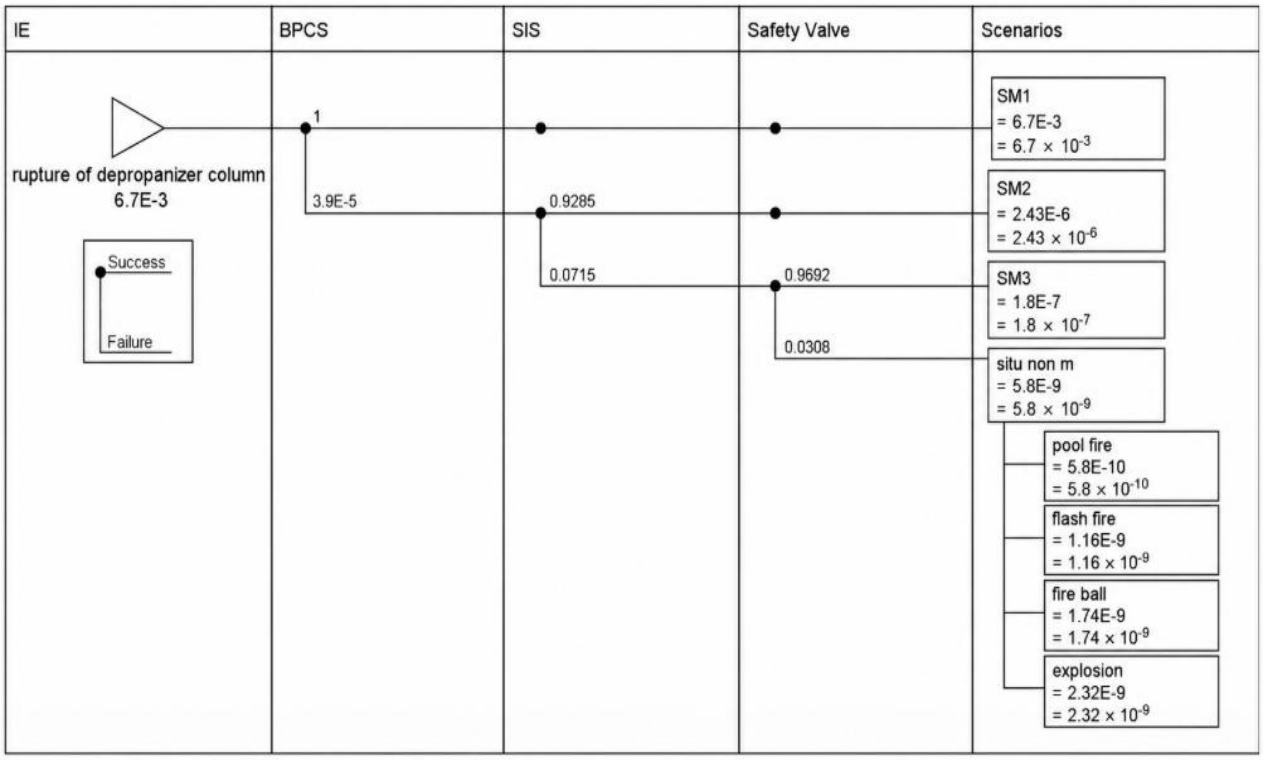

Figure III.7: Event Tree Analysis (ETA) for Depropanizer Column Rupture

Table III.10: frequencies of hazardous phenomenon

Scenario	Hazardous phenomenon	Reference	Frequency (year^{-1})
Catastrophic rupture	Immediate pool fire	1	**5.80×10^{-10}**
Catastrophic rupture	Flash fire	2	**1.16×10^{-9}**
Catastrophic rupture	Fireball / BLEVE	3	**1.74×10^{-9}**
Catastrophic rupture	VCE explosion	4	**2.32×10^{-9}**

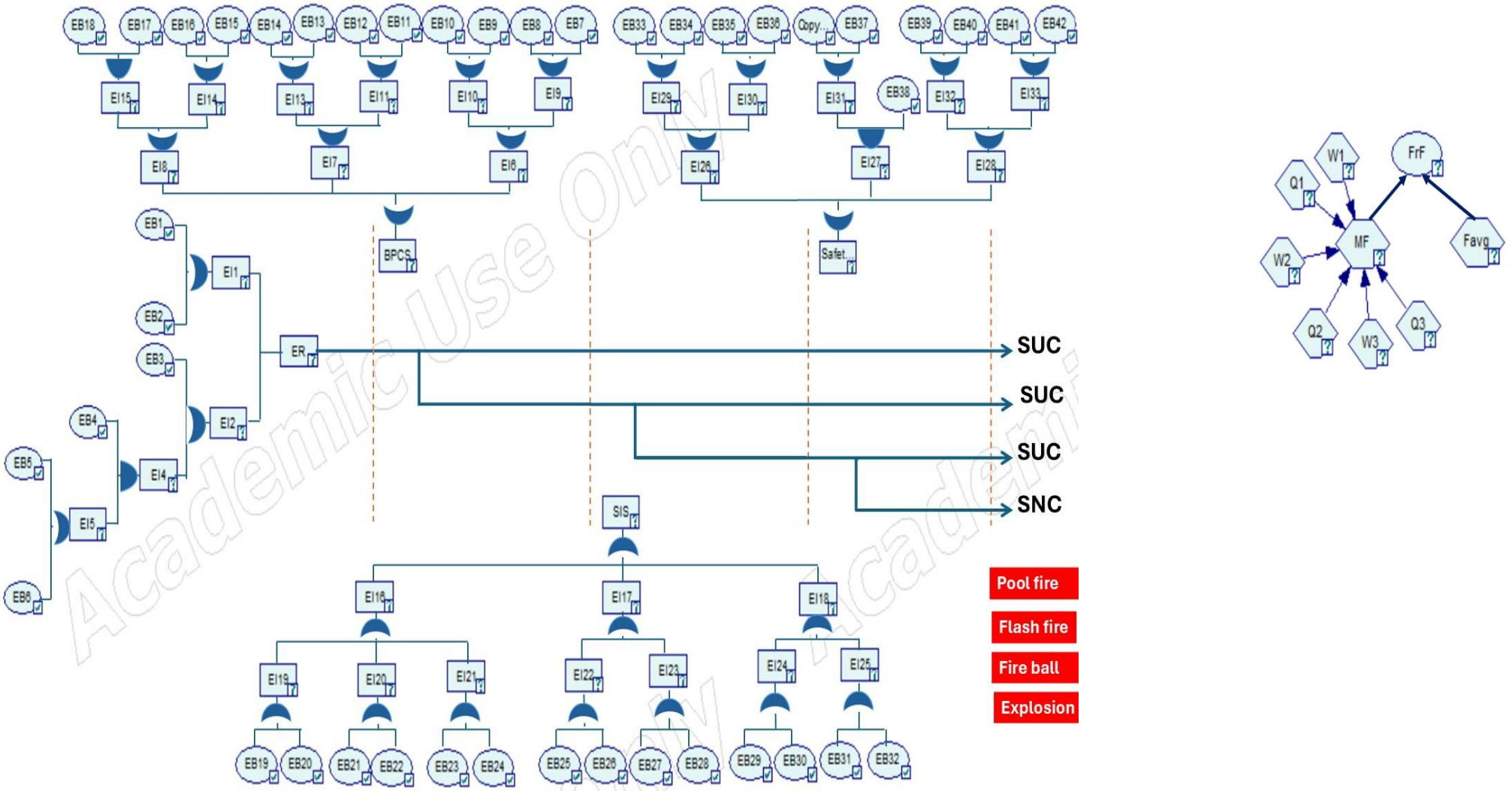

Figure III.8: Fuzzy Influence Diagram and bow-tie diagram analysis of the depropanizer column

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III.7 Consequence modelling and severity estimation

After calculating the top event frequencies in GRIFF, the next step is to estimate the severity of the scenarios using PHAST and SAFETI. The obtained frequencies are used as input data for consequence modelling. PHAST is used to simulate the accidental releases and the associated hazardous phenomena, including atmospheric dispersion, thermal effects, and overpressure effects. The resulting outputs are then imported into SAFETI to assess individual risk and societal risk.

III.7.1 Design and Operating Parameters of depropanizer column

Table III.11: operating parameters of the depropanizer

Parameter	Value
Designation	Depropanizer column
Unit / Section	Fractionation unit
Contained substance	Propane (C_3H_8)
Operating pressure	12.9 bar
Operating temperature (bottom)	98 °C
Total propane inventory	10tonnes
Column height	25.7m
Diameter	1.2m
Material	Carbon steel

Table III.12: Propriétés physico-chimiques du propane

Acentric factor	0.152291	
Aerosol class number	8	
Critical pressure	42.48	bar
Critical temperature	96.68	degC
Flammable/Toxic flag	Flammable	
Melting point	-187.68	degC
Molecular weight	44.0965	
Normal boiling point	-42.04	degC

Reactivity with atmosphere	Not Strongly Reactive	
SRK alpha calculation flag	Soave	
Triple point pressure	1.685E-09	bar
Triple point temperature	-187.68	degC

Table III.13: Flammable Constants

Combustion at	0.96124	
Combustion ct	0.0403226	
Emissive power length scale	2.75	m
Heat of combustion	2.04311E+06	kJ/kmol
Immediate ignition category	Average	
Laminar burning velocity	0.464	m/s
Lower flammability limit	20000	ppm
Luminous/Smoky flame flag	Luminous	
Maximum burn rate	0.12	kg/m2.s
Maximum surface emissive power	160	kW/m2
Pool fire burn rate length	2	m
TNT explosion efficiency	0	%
Upper flammability limit	95000	ppm

Table III.14: Atmospheric conditions

Category	Parameter	Value	Units
Weather conditions	Wind speed	4.16667	m/s
Atmospheric stability	Pasquill class D	Neutral; little sun and high wind, or overcast/windy night	
General atmospheric parameters	Atmospheric temperature	30	°C

General atmospheric parameters	Relative humidity	70	%
General atmospheric parameters	Solar radiation flux	0.7	kW/m²
Mixing layer height	Stability A	1300	m
Mixing layer height	Stability A/B	1080	m
Mixing layer height	Stability B	920	m
Mixing layer height	Stability B/C	880	m
Mixing layer height	Stability C	840	m
Mixing layer height	Stability C/D	820	m
Mixing layer height	Stability D	800	m
Mixing layer height	Stability E	400	m
Mixing layer height	Stability F	100	m
Mixing layer height	Stability G	100	m
Building data	Building exchange rate	4	/h
Building data	Tail time	1800	s
Substrate data	Surface temperature for dispersion calculations	30	°C
Substrate data	Surface temperature for pool calculations	30	°C

- **Consequence modelling**

  - **Dispersion Analysis**

The dispersion analysis was performed to evaluate the propagation of the flammable vapor cloud following the catastrophic rupture of the depropanizer column.

Table III.15: Flammable cloud distances

Equipment	Scenario	Downwind distance to LFL (m)	Cloud area LFL (m2)	Ignition window (s)
Depropanizer column	Catastrophic rupture	550	187,338	220

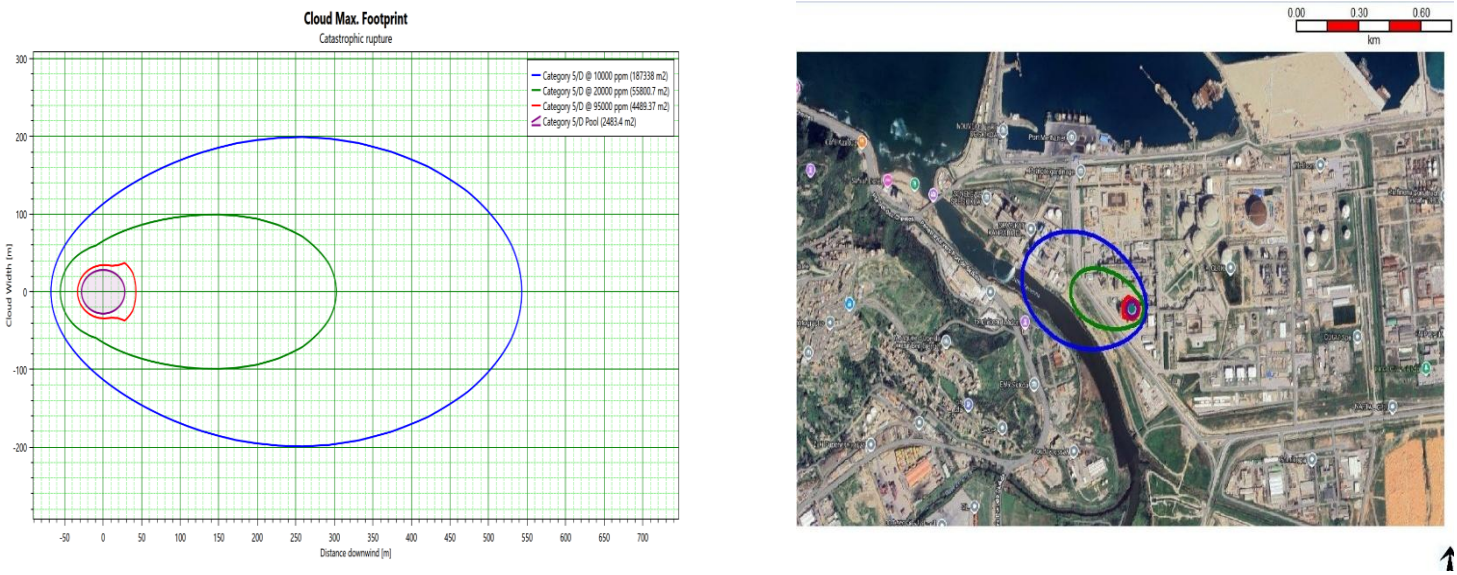

Figure III.9: dispersion max footprint

The simulation results indicate that the released propane cloud disperses under the influence of meteorological conditions, including wind velocity and atmospheric stability. The maximum dispersion distance reached 550 m, covering a significant area around the installation.

The flammable cloud footprint highlights the zones where gas concentration remains between the lower and upper flammability limits, representing potential ignition regions.

This dispersion phase constitutes the initial stage of accident escalation and may lead to secondary hazardous phenomena such as flash fire, fireball, or vapor cloud explosion if an ignition source is present.

- **Pool Fire Analysis**

Pool fire results from the ignition of the liquid propane pool formed on the ground following the accidental release. Two cases were modelled: the immediate pool fire (ignition at the moment of pool formation during catastrophic rupture) and the delayed pool fire (ignition

after a delay allowing the pool to reach its maximum extent during a leak scenario). The delayed case is generally the more penalising in terms of thermal effect distances.

According to the Pool Radius vs Time graph (category 5/D catastrophic rupture), the maximum pool radius reaches 28 m (Actual pool radius) at t 60 s. After this peak, the effective radius decreases progressively to 1.5 m at t = 1,300 s due to complete vaporisation of the liquid propane. The maximum pool area is 2,483 m2. The Radiation vs Distance for Immediate Pool Fire graph shows that the thermal flux reaches its maximum of 160 kW/m2 at the pool edge (r = 28 m), decreasing to 50 kW/m2 at 60 m, 25 kW/m2 at 105 m and 5 kW/m2 at 190 m.

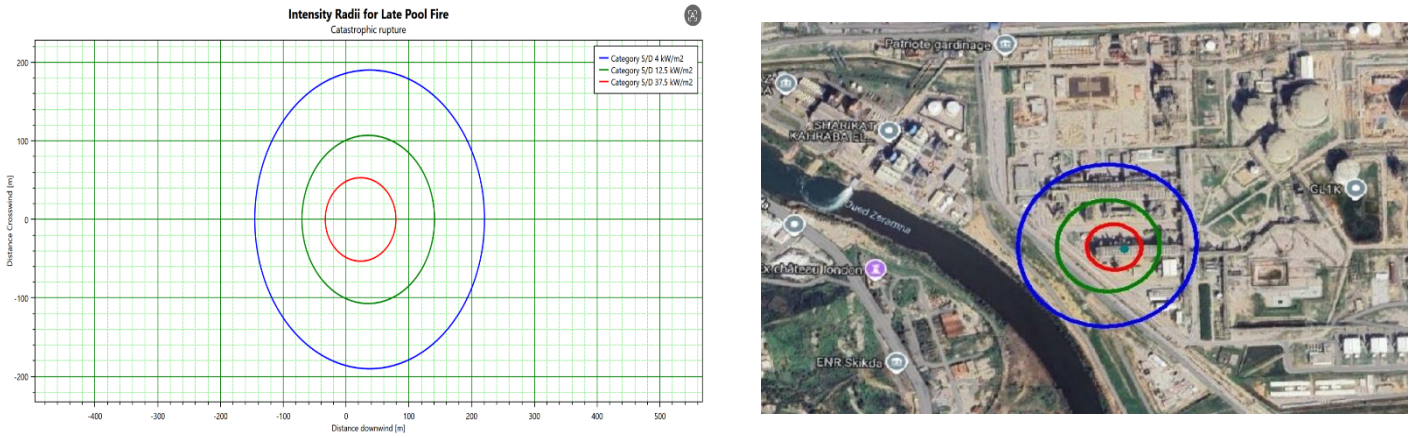

Figure III.10: Pool fire Thermal effect distances

Table III.16: Pool fire results Thermal effect distances

Equipment	Scenario	8 kW/m2 Lethal zone (m)	5 kW/m2 Irreversible zone (m)	3 kW/m2 Reversible zone (m)
Depropanizer column	Rupture Immediate	55	75	100

- **Flash Fire**

Flash fire corresponds to the ignition of a dispersed propane cloud in the absence of sufficient confinement to generate an explosion. Combustion propagates through the cloud between the LFL (2.1 vol.%) and the UFL (9.5 vol.%) without producing significant overpressure, but generates an intense and instantaneous thermal flux throughout the area occupied by the flammable cloud. Any person located within the flash fire envelope at the time of ignition is exposed to lethal effects.

The flash fire envelope is directly determined by the atmospheric dispersion results. As propane is a heavy gas (vapour density = 1.52), the cloud remains at ground level and dilutes slowly, increasing the surface area exposed to flash fire risk. The maximum downwind distance of the LFL envelope is approximately 550 m for the catastrophic rupture scenario, covering a total area of 187,338 m2.

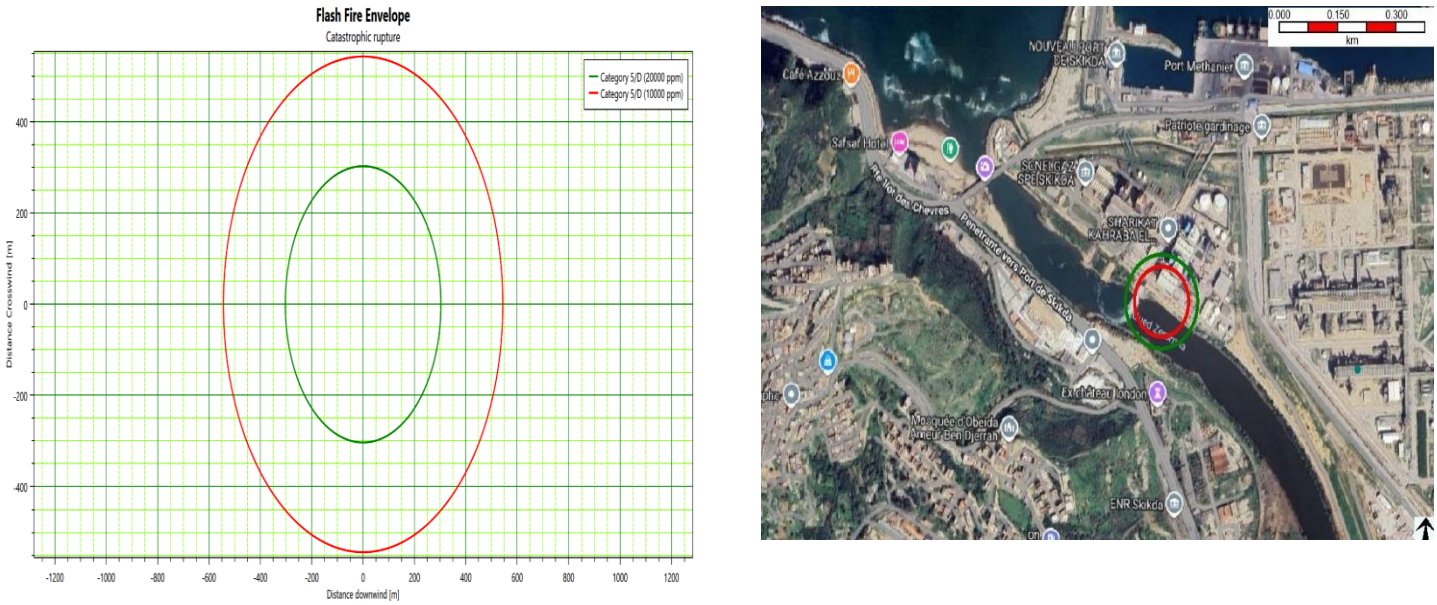

Figure III.11: Flash Fire Envelope Flammable cloud combustion zone

Table III.17: Flash fire results LFL effect distances

Equipment	Scenario	Downwind distance to LFL (m)	Cloud area LFL (m2)	Ignition window (s)
Depropanizer column	Catastrophic rupture	550	187,338	220

- **Fireball / BLEVE**

In the event of catastrophic rupture of the depropanizer column under the effect of an external fire (fire engulfment) or sudden mechanical failure, a BLEVE (Boiling Liquid Expanding Vapour Explosion) may occur accompanied by the formation of a fireball. This is an extremely short-duration phenomenon (a few seconds) but of very high thermal intensity. The Radiation vs Distance for Fireball graph shows a maximum thermal flux of 400 kW/m2 at the source, decreasing to ~100 kW/m2 at 150 m, ~30 kW/m2 at 350 m and ~12 kW/m2 at 600 m.

The Intensity Radii for Fireball graph presents the effect circles at three thermal intensity levels: the red circle (37.5 kW/m2) has a radius of approximately 200 m, the green circle (12.5 kW/m2) approximately 350 m, and the blue circle (4 kW/m2) approximately 750 m. The Lethality Ellipses graph shows that the fraction of lethality of 1 (100% mortality) corresponds to a radius of approximately 180 m around the source**.**

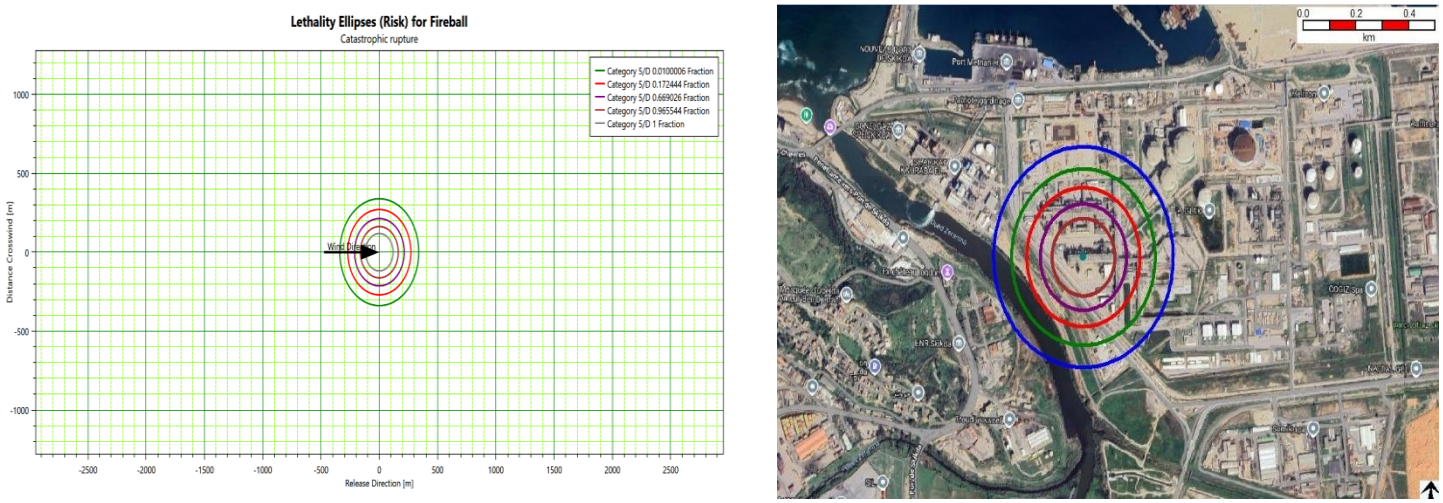

Figure III.12: Lethality Ellipses (Risk) for Fireball

Table III.18: Fireball / BLEVE results Thermal effect distances

Equipment	Scenario	Max flux (kW/m2)	37.5 kW/m2 Lethal zone (m)	12.5 kW/m2 Irreversible zone (m)	4 kW/m2 Reversible zone (m)
Depropanizer column	Catastrophic rupture	400	200	350	750

- **VCE Explosion (Vapour Cloud Explosion)**

In the event of delayed ignition of the propane cloud in the presence of confinement or obstacles, a VCE (Vapour Cloud Explosion) occurs. The Explosion Overpressure vs Distance graph reveals two distinct explosion sources (linked to two confined regions of the cloud), visible as two overpressure peaks on the curve. The first peak (blue curve 0.02068 bar) is located at x = 30-100 m with an overpressure of 3 to 20 bar, while the second peak (green and red curves 0.1379 and 0.2068 bar) is located at x ~ 500-540 m with a maximum overpressure of 19 bar. Beyond 600 m, overpressure falls below 0.02068 bar for all cases.

The Explosion at Distance graph (Explosions Radii at Distance) presents the effect zones from above. The blue ellipse (0.02068 bar reversible effects zone) extends to 1,200 m downwind and 1,100 m crosswind. The green (0.1379 bar) and red (0.2068 bar) ellipses are significantly smaller, with radii of approximately 200-250 m, concentrated around the main explosion source.

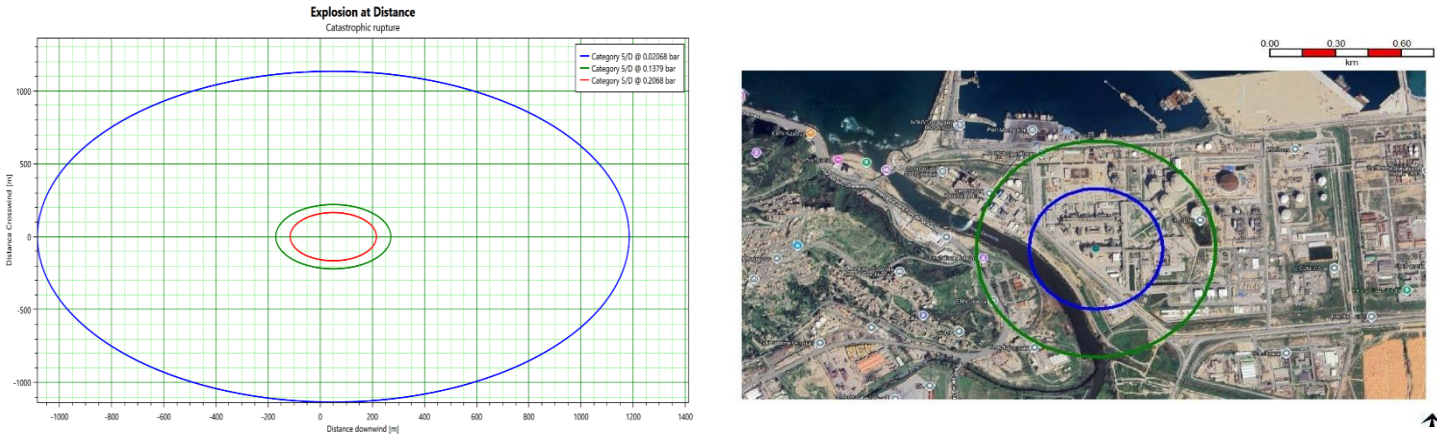

Figure III.13: Explosion at Distance Overpressure effect zones

Table III.19: VCE explosion results Overpressure effect distances

Equipment	Scenario	Overpressure (bar)	Max. downwind distance (m)	Effect zone description
Depropanizer column	Catastrophic rupture	0.02068	~1,200	Reversible zone window breakage
		0.1379	~250	Irreversible zone serious injury
		0.2068	~180	Lethal zone structural destruction

- **Summary of Effect Distances**

The following table summarises all effect distances calculated by PHAST for the five hazardous phenomena. These distances form the basis for the severity assessment and risk zone mapping around the depropanizer column**.**

Table III.20: Summary of effect distances all phenomena (PHAST)

Phenomenon	Scenario	Lethal zone	Irreversible zone	Reversible zone
Atmospheric dispersion	Rupture	LFL envelope ~550 m	LFL envelope ~550 m	LFL envelope ~550 m
Immediate pool fire	Rupture	55 m (8 kW/m2)	75 m (5 kW/m2)	100 m (3 kW/m2)
Flash fire	Rupture	LFL ~ 550 m	LFL ~ 550 m	LFL ~ 550 m
Fireball / BLEVE	Rupture	200 m (37.5 kW/m2)	350 m (12.5 kW/m2)	750 (4 kW/m2)
VCE Explosion	Rupture	~180 m (0.2068 bar)	~250 m (0.1379 bar)	~1,200m (0.02068 bar)

III.8 Risk Quantification (SAFETI)

SAFETI integrates the frequencies of hazardous phenomena calculated from the event trees, the population distribution across the site, and the dose–response functions to compute individual and societal risk indicators.

Only the catastrophic rupture scenario of the depropanizer column is considered in this analysis, giving rise to four hazardous phenomena: immediate pool fire flash fire , fireball/BLEVE , and VCE explosion .

III.8.1 Site Population Distribution

The population data integrated into SAFETI was established from a detailed survey of all facilities located within the study perimeter. A total of 1,128 persons are present on site, distributed across 19 categories of facilities ranging from process units and workshops to office buildings and support services. This population was geo-referenced in SAFETI to enable spatial computation of individual and societal risk

Table III.21: Site population distribution used in SAFETI

Location / Facility	Population (persons)
Mega Train and Fractionation Units	5
Control Room	10
Utilities and Storage Tanks	4
Power Generation Control Room	1

Old Unit 1	50
Old Unit 2	80
Old Unit 3	10
Old Unit 4	1
Laboratory	53
Mechanical Workshop	147
Office Buildings	523
Maintenance Personnel	73
Other Buildings	20
Emergency Response Unit	40
Helium Unit	50
Human Resources Department (HR)	25
Infirmary	6
Administration Building	15
Other Offices	15
TOTAL POPULATION	**1,128**

III.8.2 Individual Risk Assessment

Individual risk (IR) is defined as the probability of fatality per year for a hypothetical person located at a fixed point in space and present at that location at all times (24 hours a day, 365 days a year). SAFETI computes IR contours by integrating, over all weather conditions and ignition scenarios, the probability of death at each spatial location resulting from the combined effect of all hazardous phenomena.

- **Individual Risk Contour Map**

The Multi-Vulnerability IR contour map was generated by SAFETI 8.22 at a risk level of 1E-06 per average year (1 fatality per million years), accounting for both outdoor and indoor vulnerability of the site population. Three concentric risk zones are visible:

- Red contour: fireball radiation effect level highest thermal intensity zone, corresponding to the zone of near-certain fatality for the fireball/BLEVE scenario
- Yellow contour: fireball radiation effect level (1) intermediate thermal intensity zone
- Blue contour: fireball radiation effect level (2) outer thermal intensity zone

- Green contour: overall individual risk contour at 1E-06 per year the outermost boundary within which the annual individual risk exceeds one in a million

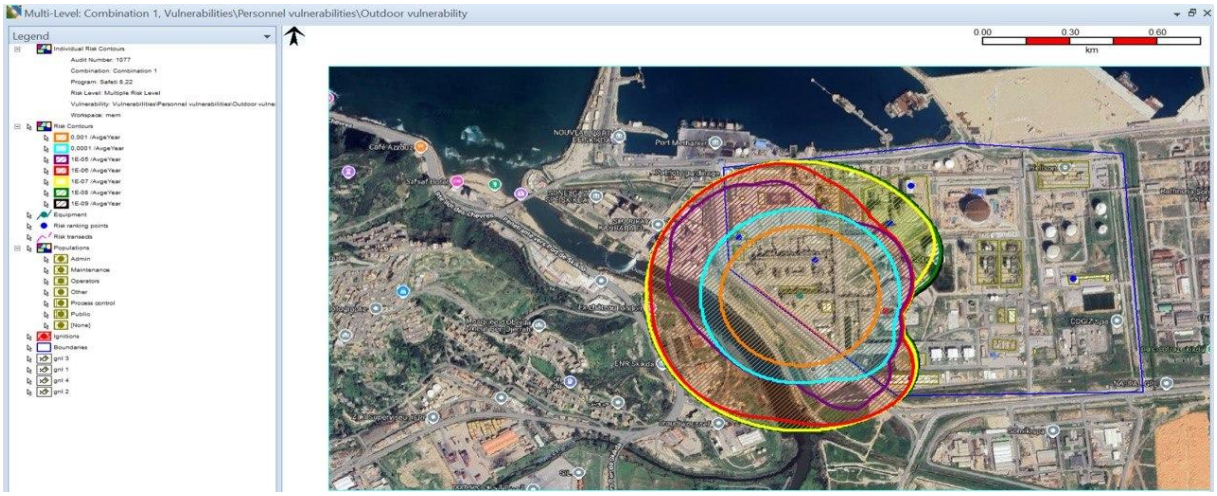

Figure III.14: Individual Risk contour map Multi-Vulnerability

- The IR contour map reveals that the 1×10^{-6}/year risk contour (green) encompasses the entire GL1K site, extending well beyond the immediate vicinity of the depropanizer column. This result is primarily driven by the fireball/BLEVE scenario (Ref. 3), whose thermal radiation effect zones dominate the spatial risk distribution across the site. The red innermost zone covers the core process area, including the fractionation units and adjacent facilities. The blue outer zone extends to cover a large portion of the site population, including office buildings and the mechanical workshop.
- The presence of all population groups administrative staff, maintenance personnel, operators, process control teams within the 1×10^{-6}/year contour indicates that all 1,128 on-site workers are exposed to an individual risk exceeding the broadly acceptable threshold of 1×10^{-6} per year, confirming the critical nature of the identified risk and the immediate need for risk reduction measures.
- **Thermal Radiation Exceedance Curve**

  The Thermal Radiation Exceedance Curve (Figure III.15) presents the cumulative annual frequency of exceeding a given thermal radiation level at the risk ranking point, for four computed curves: the individual run at the risk ranking point, the individual run for the fireball scenario only, the combined Combination 1 at the risk ranking point, and the combined Combination 1 for the fireball scenario.

All four exceedance curves are essentially flat (horizontal) across the entire thermal radiation range from 0.5 to 10 kW/m², stabilising at a cumulative frequency of approximately 4.7×10^{-8} per year for the Combination 1 and Fireball curves. This horizontal profile demonstrates that the thermal radiation exceedance frequency is controlled by a single dominant scenario: the fireball/BLEVE. Since the fireball is an all-or-nothing event at the distances considered, the frequency of exceeding any radiation level from the lowest (0.5 kW/m²) to the highest (10 kW/m²) is identical and equal to the fireball occurrence frequency itself. In other words, whenever the fireball occurs, it simultaneously generates radiation exceeding all thresholds shown on the curve.

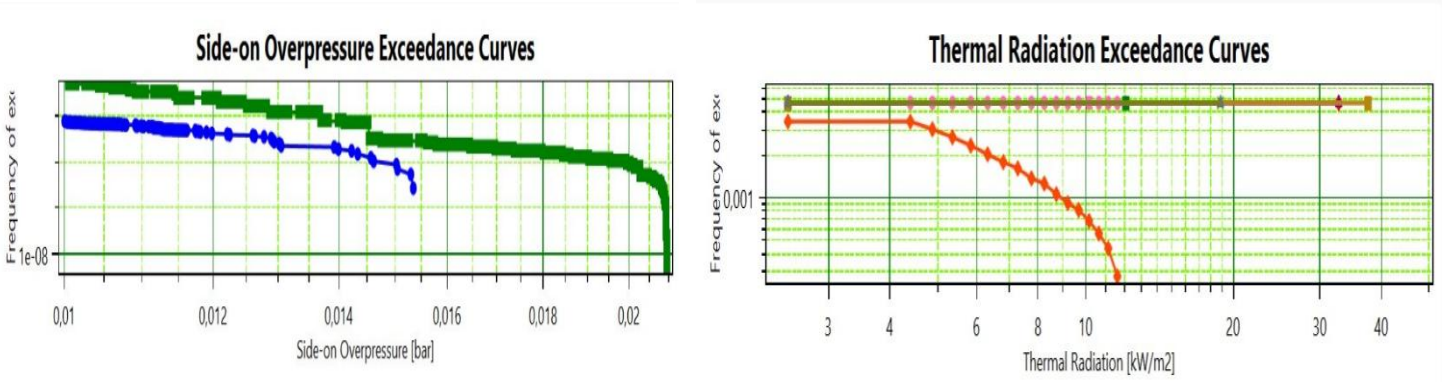

Figure III.15: Thermal Radiation / overpressure Exceedance Curves

III.8.3 Societal Risk Assessment FN Curve

Societal risk quantifies the risk to a group of people and is expressed as the relationship between the frequency of an accident and the number of fatalities it causes. It is represented by the FN curve (Frequency vs Number of fatalities), which plots the cumulative annual frequency F of accidents causing at least N fatalities against N on a log-log scale.

SAFETI 8.22 generates the Smoothed FN curve by integrating all hazardous phenomena, their frequencies, the population distribution, and the dose–response functions over all weather conditions. The acceptability of societal risk is assessed against two regulatory criterion lines:

- Maximum criterion line (red): upper limit above this lines the risk is unacceptable and immediate corrective action is mandatory
- Minimum criterion line (yellow): lower limit below this line the risk is broadly acceptable
- Between the two lines: ALARP region (As Low As Reasonably Practicable) risk must be reduced as far as reasonably practicable

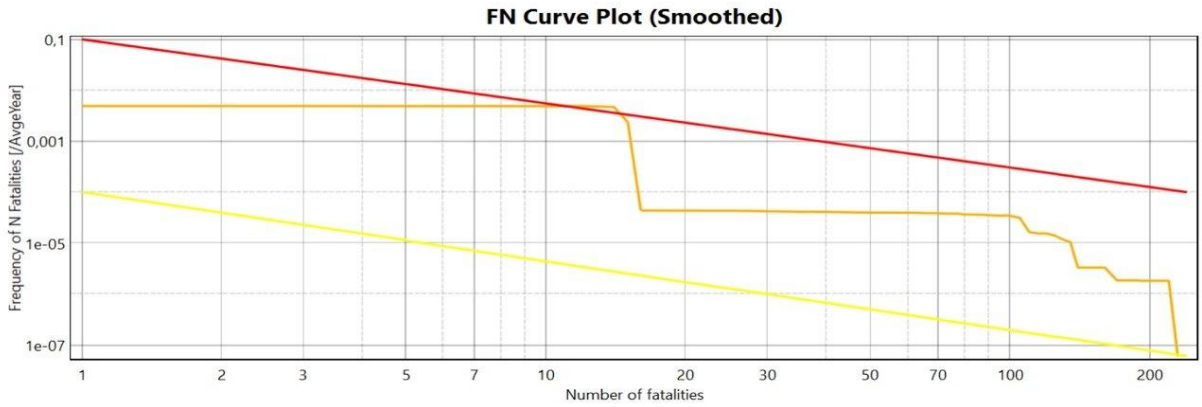

Figure III.16: FN Curve Plot Societal risk

- **reading and Interpretation of the FN Curve**

The smoothed FN curve exhibits the following key characteristics, read directly from the SAFETI output:

- **At N = 1 fatality**: the cumulative frequency F(N=1) ≈ 3×10^{-9} per year, representing the combined annual frequency of all scenarios causing at least one fatality
- **Step drop at N ≈ 20 fatalities**: the FN curve drops from approximately 2×10^{-9} to 9×10^{-10} per year. This transition corresponds to the boundary between the lower-severity scenario (immediate pool fire, ~5 persons in the lethal zone) and the higher-consequence scenarios (flash fire, fireball/BLEVE and VCE explosion), where the number of potential fatalities increases sharply
- **Curve extends to N ≈ 220 fatalities**: reflecting the worst-case scenario in which a large fraction of the 1,128-person site population is simultaneously affected by the combined thermal radiation of the fireball and the overpressure of the VCE explosion
- **The entire FN curve lies above the maximum criterion line (red)** for all values of N from 1 to ~220, confirming that the societal risk of the depropanizer catastrophic rupture scenario falls in the **unacceptable zone** across all fatality levels

III.9 Severity Assessment and Risk Classification

Risk classification combines the frequency of each hazardous phenomenon with the severity of its consequences on people and structures this combination is presented in criticality matrices that constitute the central decision-making tool for risk management prioritisation.

- **Frequency Scale**

Table III.22: Quantitative frequency scale

Class	Frequency (per year)	Denomination
5 (A)	$F \geq 10^{-2}$	Very likely
4 (B)	$10^{-3} \leq F < 10^{-2}$	Likely
3 (C)	$10^{-4} \leq F < 10^{-3}$	Unlikely
2 (D)	$10^{-5} \leq F < 10^{-4}$	Remote
1 (E)	$F < 10^{-5}$	Extremely remote

- **Severity Scale**

Table III.23: Severity scale for consequences

Level	Denomination	Lethal zone SELS (fatalities)	Irreversible zone SEL (serious injuries)	Reversible zone SEI(minor injuries)
5	Disastrous	> 100	> 1,000	> 10,000
4	Catastrophic	10 to 100	100 to 1,000	1,000 to 10,000
3	Major	1 to 10	10 to 100	100 to 1,000
2	Serious	≤ 1	≤ 10	10 to 100
1	Moderate	0	≤ 1	< 10

- **Exposed Population per Effect Zone**

The number of persons exposed in each effect zone was estimated by superimposing the PHAST effect distances onto the site population map . For each hazardous phenomenon and each effect level, the number of persons located within the corresponding distance from the depropanizer column was counted. These values are used to determine the severity level .

Table III.24: Estimated number of exposed persons per effect zone

Phenomenon	Lethal distance (m)	Persons exposed	Irrev. distance (m)	Persons exposed	Rev. distance (m)	Persons exposed
Immediate pool fire	55	~5	75	10	100	15
Flash fire	~550	~500	~550	~500	550	800
Fireball / BLEVE	200	~100	350	~400	750	900
VCE explosion	~180	~80	~250	~200	1,200	1,000

- **Reference Table for Severity Classification**

The following table presents the complete severity classification for each hazardous phenomenon. For each reference, the frequency class and the severity level are determined and assigned. The severity level is based on the number of persons in the lethal zone (SELS), which represents the worst-case consequence indicator retained for risk classification.

Table III.25: Reference table for severity and frequency classification

Ref.	Scenario	Phenomenon	Frequency (year^{-1})	Freq. Class	Persons in lethal zone	Severity Level
1	Catastrophic rupture	Immediate pool fire	5.80×10^{-10}	1 (E)	~5	2 Serious
2	Catastrophic rupture	Flash fire	1.16×10^{-9}	1 (E)	~500	5 Disastrous
3	Catastrophic rupture	Fireball / BLEVE	1.74×10^{-9}	1 (E)	~100	4 Catastrophic
4	Catastrophic rupture	VCE explosion	2.32×10^{-9}	1 (E)	~80	4 Catastrophic

Ref. 1 (pool fire) 5 persons in lethal zone → Severity level 2 (Serious, ≤1 fatality expected at mean).

Ref. 2 (flash fire) ~500 persons in lethal zone → Severity level 5 (Disastrous, >100 fatalities).
Ref. 3 (fireball) ~100 persons in lethal zone → Severity level 4 (Catastrophic, 10–100 fatalities).
Ref. 4 (VCE) ~80 persons in lethal zone → Severity level 4 (Catastrophic).

- **Criticality Matrix People**

The criticality matrixis constructed by crossing the severity level (rows) with the frequency class (columns) for each of the four hazardous phenomena. Each reference (1 to 4) is placed in the cell corresponding to its frequency class and severity level . Three risk zones are defined:

- Green zone: broadly acceptable risk no immediate action required beyond maintaining existing barriers
- Yellow zone (ALARP): risk must be reduced as far as reasonably practicable cost-benefit analysis required
- Red zone: unacceptable risk immediate and mandatory corrective action required regardless of cost

Table III.26: Criticality matrix Consequences on people

Severity \ Frequency	1 (E) Extremely remote	2 (D) Remote	3 (C) Unlikely	4 (B) Likely	5 (A) Very likely
5 Disastrous	Ref. 2				
4 Catastrophic	Ref. 3 / Ref. 4				
3 Major					
2 Serious	Ref. 1				
1 Moderate					

■ **Green =** Acceptable risk

■ **Yellow =** ALARP (reduce as far as reasonably practicable)

■ **Red =** Unacceptable risk (immediate action required)

Interpretation of Results

The criticality matrix reveals a clearly differentiated risk profile across the four phenomena:

Flash fire (Red zone, Severity 5 Disastrous): This is the most critical scenario. The LFL envelope extends to ~550 m, encompassing virtually the entire site population (~500 persons in the lethal zone). Despite its extremely low frequency (1.16×10^{-9}/yr, Class 1E), the catastrophic magnitude of potential consequences places it firmly in the unacceptable zone. It demands the highest priority for risk reduction.

Fireball/BLEVE and VCE explosion (Yellow zone, Severity 4 Catastrophic): Both phenomena fall in the ALARP zone with approximately 80–100 persons potentially in the lethal zone (fireball lethal radius 200 m; VCE lethal radius ~180 m). The fireball scenario is particularly significant as it drives the individual risk contour map and the thermal radiation exceedance curve. Risk reduction measures are required as far as reasonably practicable.

Immediate pool fire (Green zone, Severity 2 Serious): The pool fire has the lowest consequence level (~5 persons in the lethal zone, lethal radius 55 m) and the lowest frequency (5.80×10^{-10}/yr). It falls in the broadly acceptable zone. Existing safeguards (ESD, gas detection) are sufficient to manage this risk, subject to their continued maintenance.

- **Criticality Matrix Structures**

Table III.27: Criticality matrix Consequences on structures (catastrophic rupture)

Severity \ Frequency	1 (E)	2 (D)	3 (C)	4 (B)	5 (A)
5 Disastrous					
4 Catastrophic	Ref. 4				
3 Major	Ref. 3				
2 Serious	Ref. 1 / Ref. 2				
1 Moderate					

III.10 Conclusion

This chapter presented the application of the integrated fuzzy QRA-BORA methodology to the depropanizer column of the GL1K complex in Skikda. The main outcomes can be summarized as follows.

The PHAST consequence modeling identified four hazardous phenomena arising from catastrophic rupture: immediate pool fire, flash fire, fireball/BLEVE, and VCE explosion. The fireball/BLEVE proved the most penalizing, with a lethal zone of 200 m and an irreversible zone of 350 m, while the VCE explosion could affect distances up to 1,200 m for reversible effects.

The SAFETI risk quantification revealed that the 1×10^{-6}/year individual risk contour encompasses the entire site, exposing a significant portion of the 1,128 on-site personnel to above-tolerable risk levels. The fireball/BLEVE scenario was identified as the dominant contributor to both individual and societal risk.

The FN societal risk curve lies entirely above the maximum criterion line, placing the risk in the **unacceptable zone** for all fatality levels (N = 1 to ~220). This result demands immediate implementation of risk reduction measures.

The fuzzy logic integration successfully addressed uncertainty in frequency estimation by adjusting basic event frequencies through five RIFs (maintenance, power supply, design, operator performance, communication) using a Mamdani inference system in MATLAB. Revised frequencies showed significant deviations from generic industry data, reflecting the specific conditions of the GL1K installation.

The criticality matrix classified flash fire in the unacceptable red zone (~500 persons in lethal zone), fireball/BLEVE and VCE in the ALARP yellow zone (~80 –100 persons in lethal zone), and pool fire in the acceptable green zone (~5 persons in lethal zone).

Study limitations include the single-equipment focus, static population data, and inherent subjectivity in expert-based RIF scoring. Future work should extend the analysis to other critical Mega Train equipment, incorporate CFD modeling, develop dynamic risk models, and conduct cost-benefit analyses for barrier optimization.

In conclusion, the proposed fuzzy QRA approach proved effective for realistic risk quantification under uncertainty, providing actionable insights for industrial safety decision-making at the GL1K complex.

GENERAL CONCLUSION

General Conclusion

The hydrocarbon industry faces major risks from handling dangerous substances under pressure and high temperature. This study proposed and applied an advanced Quantitative Risk Assessment methodology integrating fuzzy logic and the BORA method to the depropanizer column of the GL1K liquefaction complex in Skikda.

All initial objectives were successfully met: hazardous scenarios were identified through HAZOP and fault tree analysis; frequencies were estimated from industrial databases and revised using RIF-based fuzzy inference in MATLAB; consequences were modeled with PHAST for pool fire, flash fire, fireball/BLEVE, and VCE explosion; and individual and societal risks were quantified with SAFETI, revealing exceedance of tolerance thresholds across the site.

The study demonstrates that coupling classical QRA with BORA and fuzzy logic offers three major advantages: better uncertainty management through formalized expert judgment, installation-specific risk model personalization beyond generic data, and transparent, traceable reasoning via fuzzy rule formalism.

Based on the criticality matrix and FN curve results, the following actions are recommended:

1. Immediate priority: Address the flash fire scenario (unacceptable zone) through enhanced early detection and automatic suppression systems.
2. ALARP compliance: Conduct cost-benefit analysis for fireball/BLEVE and VCE explosion scenarios to identify optimal risk reduction measures.
3. Continuous monitoring: Update revised frequencies regularly based on operational changes, incidents, and inspection results.
4. Methodology extension: Expand the analysis to all critical Mega Train equipment for a comprehensive site-wide risk map.

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