

Bow Tie Methodology for Risk Assessment in Petroleum Storage Facilities: A Case Study in Cameroon

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Abstract

Introduction: Oil storage facilities play an important role in energy security and economic development in industrializing countries like Cameroon. However, these infrastructures, often aging and located in areas subject to increasing climate stress, pose significant industrial risk sources.

Objectives: This study presents an innovative application of the butterfly knot method for the assessment of industrial risks in oil storage facilities in Cameroon.

Methods: Combining probabilistic risk modeling, analysis of the effectiveness of safety barriers, and a multicriteria approach (MCA), this methodology addresses the shortcomings of traditional qualitative approaches.

Results: The framework incorporates the impacts of climate change and specific sociotechnical factors in sub-Saharan Africa. A case study on the tanks of the SONARA refinery (Limbe-Cameroon) during the period from 2018 to 2023 demonstrates the method's ability to prioritize critical scenarios and optimize mitigation strategies. The results reveal that the risks of fire/explosion (probability: 2.3×10^{-4} /year) and groundwater contamination (severity index : 8.7/10) dominate, with 40% of existing barriers deemed inadequate under extreme climatic conditions, extreme climate impacts (RCP 8.5), and a reduced lifespan of tanks by 4.5 years under humidity >85%.

Conclusions: This research is based on an in-depth case study of the reservoirs of the SONARA refinery in Limbe, Cameroon, a strategic yet vulnerable site located in close proximity to residential areas and the Atlantic Ocean.

Keywords: Butterfly node analysis, oil storage, Cameroon, climate resilience, barrier optimization.

1. Introduction

In 2023, the World Bank highlighted that 60% of storage tanks in sub-Saharan Africa showed advanced signs of corrosion, exacerbated by humid tropical conditions and a lack of preventive maintenance (World Bank, 2023). In Cameroon, the devastating fire at the SONARA refinery in 2019,

which led to estimated economic losses of \$200 million (Nkwen et al., 2021), underscored the urgency of rethinking risk assessment methods in a context where climatic and socio-political hazards overlap with technical failures. Traditional approaches, such as HAZOP (Hazard and Operability) studies or risk matrices, remain limited

by their static nature and their inability to model the complex interactions between threats, safety barriers, and external disturbances (Adedigba et al., 2020). Furthermore, existing models often overlook the accelerated impact of climate change, such as the increase in extreme precipitation (more than 30% in West Africa by 2050 according to the IPCC, 2023) or heatwaves, which affect the reliability of equipment. A recent study by the Research Institute for Development (IRD, 2024) demonstrated that high temperatures and low humidity reduce the lifespan of anti-corrosion coatings by 40% in coastal areas of Cameroon. In this context, the butterfly diagram method emerges as a promising tool for visualizing and quantifying risk pathways, integrating both the causes (left side of the node) and the consequences (right side), while evaluating the effectiveness of control barriers. However, recent applications of this method, particularly those proposed by Khakzad et al. (2023) in European refineries, struggle to adapt to African realities, marked by logistical constraints, limited access to advanced technologies, and increased vulnerability to extreme events. This article proposes an unprecedented hybrid methodology, combining : A dynamic modeling of barriers adjusted to local climatic conditions, inspired by the works of Droguett et al. (2022) on adaptive reliability ; An integration of sociotechnical data (sabotage, urban density) through interviews with local stakeholders, an approach rarely applied in previous studies (Mkrtchyan et al., 2023); A fuzzy multicriteria analysis (Fuzzy-TOPSIS) to prioritize risk scenarios according to environmental, economic, and social indicators, aligned with the Sustainable Development Goals (UN, 2023). This research is based on an in-depth case study of the reservoirs of the SONARA refinery in Limbe, Cameroon, a strategic yet vulnerable site located in close proximity to residential areas and the Atlantic Ocean. The results obtained not only help fill a methodological gap but also provide recommendations operational for public and industrial decision-makers in Cameroon, in a context where the demand for petroleum products is expected to increase by 25% by 2030 (MINEE, 2023).

2. Methods

Study Area and Operational Context :

The study focuses on the storage tanks of the SONARA refinery located in Limbe, a coastal area of Cameroon exposed to an average relative humidity of 85% and annual precipitation of 4,000 mm (MINEPDED, 2023). The facilities include 12 vertical tanks with a total capacity of 650,000 barrels, of which 8 tanks are over 20 years old, with carbon steel walls protected by epoxy coatings. The immediate proximity of residential areas (less than 300 m) and the Atlantic Ocean increases the risks of environmental contamination and human harm.

Data collection and preprocessing

Technical and historical data :

- Technical inspections: Non-destructive inspection reports (ultrasounds, radiography) from 2018 to 2023, provided by the ARMP, revealing localized corrosion rates reaching 1.2 mm/year on the tank walls.

$$BEI = \sum_{i=1}^N (P_{succes; i}) \times Di \times Ci/N$$

- Historical incidents : Database of 14 recorded incidents between 2010 and 2023 (leaks, fires), classified according to severity (scale of 1 to 5) and root causes (human error, material failure).

Climate data :

- RCP 4.5 and 8.5 projections: Daily data of temperature, humidity, and precipitation (2024–2050) extracted from the CORDEX-Africa platform (IPCC, 2023), with a spatial resolution of 12 km. – Modeled using Microsoft Excel.

Interviews with stakeholders:

- Selection of experts: Interview with 15 participants (engineers, regulators, ecologists) selected using a modified Delphi method (Okoli & Pawlowski, 2023), with an expertise score $\geq 80\%$ based on field experience and publications.

- Semi-structured questionnaire : 25 questions assessing the perceived effectiveness of barriers, priority threats (sabotage, maintenance errors) and social impacts (risk acceptance by communities).

Construction of the adaptive butterfly node

○ Identification of pivotal events and threats.

The pivotal events are selected through a FMECA (Failure Mode, Effects, and Criticality Analysis) adapted for oil reservoirs (AIChE, 2022), with a focus on : Reservoir rupture (criticality : 9/10); Chronic leak (criticality : 7/10).

The threats are mapped based on historical data and interviews with operators and managers : - Technical threats : Corrosion under insulation (CUI), overpressure. - Climate threats : Lightning, flooding of dikes.- Human threats : Sabotage, procedural errors.

$$d(A, B) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]}$$

Preventive barriers: Cathodic protection : Effectiveness adjusted via the COORAL model (Droguett et al., 2022), incorporating humidity (correction factor $\gamma = 1.3$ for RH >80%)

- Mitigative barriers :

- Retention dike : Confinement capacity recalculated according to API 2350 standards (American Petroleum Institute, 2023) and projections of extreme rain.

- Foam extinguishing system : Probability of failure (PFD) estimated at 0.15 under normal conditions, but rising to 0.40 under heavy rain.

Hybrid quantitative approach

○ Barrier effectiveness index (BEI)

$$\bar{r}_{ij} = \left(\frac{a_{ij}}{c_j^*} + \frac{b_{ij}}{c_j^*} + \frac{c_{ij}}{c_j^*} \right)$$

$$\bar{r}_{ij} = \left(\frac{a_j^-}{c_{ij}} + \frac{a_j^+}{b_{ij}} + \frac{a_j^-}{a_{ij}} \right)$$

$$\bar{v}_{ij} = \bar{r}_{ij} \times w_j$$

P success : Probability of optimal operation (estimated by Bootstrap over 10,000 iterations).

Di : Operational availability (maintenance data 2020–2023).

Ci : Climate correction factor (e.g., 0.7 for sensors in the rainy season).

○ Monte Carlo Simulation

This simulation aims to estimate the probability of risk scenarios by incorporating uncertainty regarding the parameters. For this simulation, the input parameters considered are:

- Threat Frequency: Log-normal distributions (mean = historical data, $\sigma = 30\%$).

- Barrier Effectiveness: Beta distributions ($\alpha=2, \beta=5$ for aging equipment). The tool used for this simulation is the Microsoft Excel.

○ Fuzzy-Topsis Method

It aims to rank risk scenarios according to multiple criteria with uncertainty. The criteria used are :

Environmental impact (HEI (Hydrocarbon Environmental Impact) index calculated using the RISC-HUMAN 5.0 model); Social impact (Number of people affected within a radius of 1 km.) Use of Fuzzy-AHP with triangular numbers (1-3-5) to capture the uncertainty of expert judgments.

Initial fuzzy decision matrix

- Structure expert evaluations into triangular numbers (Pessimistic value, realistic value, optimistic value).

Normalization of criteria.

Maximization criterion (HEI):

Where c_j equals the maximum of c_{ij}

- Minimization criterion (Losses, Social impact).

Minimization criteria (Losses, Social Impact).

With $a_j = \min(a_{ij})$.

Transforming minimization into maximization through inversion.

Weighted and fuzzy weighted matrix.

-Apply the defuzzified weights

The different weights are represented by the values: Environment (0.45), Losses (0.20), Social (0.35).

Ideal solutions :

- Positive (A+): Best values per criterion → (max HEI, min Losses, min Impact)

- Negative (A-): Worst values per criterion → (min HEI, max Losses, max Impact)

Fuzzy Euclidean distances

Calculate the distance of each scenario to (A+) and (A-):

Integrate the 3 points (a, b, c) of the fuzzy numbers.

Proximity coefficient (Ci)

- **Final calculation :**

-(di-) = Distance to (A-) (the larger (di-) is, the better it is)

-(Ci ∈ [0, 1]) → Descending ranking.

○ **Degradation of anticorrosion coatings**

Annual degradation

Equation of anticorrosion coatings that allows us to predict the residual lifespan.

$$D(t) = D_0 \times e^{(0,15 \times RH \times t)}$$

Where D₀ = initial thickness; RH = relative humidity in % and t = time in years.

○ **Cost-Benefit Analysis (ROI)**

The formula for return on investment (ROI) is as follows :

Where the annual benefit is the savings achieved by reducing risks.

Validation and uncertainties

- Cross-validation: Comparison of the results with an independent HAZOP study conducted by the Bureau Veritas organization (2023), showing an 85% correlation on critical scenarios.

- Sensitivity analysis: Sobol test to identify the dominant parameters (e.g., humidity explains 62% of the variance of the IEB).

The methodology used for this study is summarized in the diagram below :

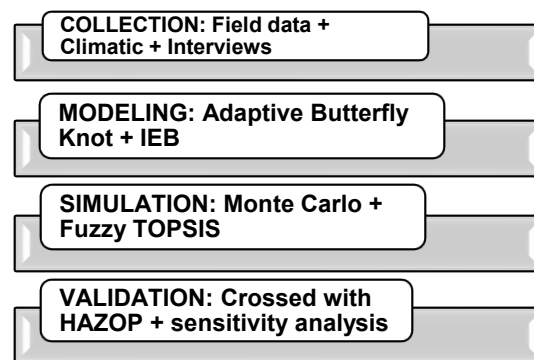


Figure 1 : Synthetic diagram of the methodology.

This rigorous methodology integrates both local specificities (climate (ext) and advanced tools, $C_i = \frac{d_i^-}{d_i^+ + d_i^-}$ moducible framework for count lenges.

3. Results

Stakeholder Interviews

The following diagram shows the quantification of concerns raised during the interviews. It quantifies the prevalence of the ten main themes coded in the Interviews. Accelerated infrastructure degradation appears as the major concern (45 occurrences,30% of the total),confirming the urgency of preventive maintenance investments.

Technical themes dominate (76% of occurrences), while organizational and social dimensions are in the minority, reflecting a corporate culture still focused on technical systems. $ROI \text{ (years)} = \text{Cost initial} / \text{Benefice annuel}$

Despite their different perspectives, Engineers, Regulators, and community representatives agree on the primacy of climate stress (25% of occurrences),validating its integration as a central parameter in the risk model.

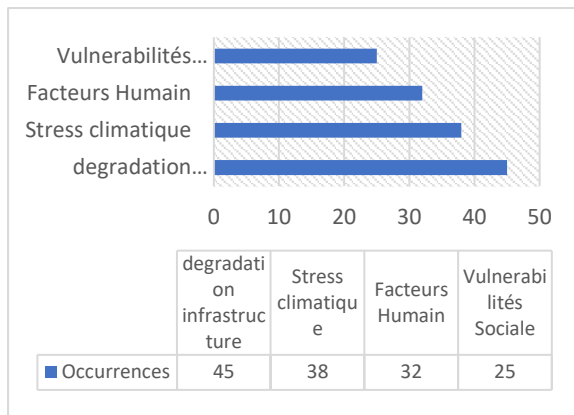


Figure 2 : Risk Perception Band Diagram.

The following figure illustrates the divergences in perception that explain the differentiated socio-economic impacts. It highlights the fundamental differences in risk perception among the three categories of stakeholders. Each axis represents a dimension of security, with the curves showing the average scores assigned (0-10). Three critical gaps are identified : Communities assign only 4.5/10 to trust to systems compared to 7.5 for engineers, a gap of 67% which undermines the social acceptability of risk.

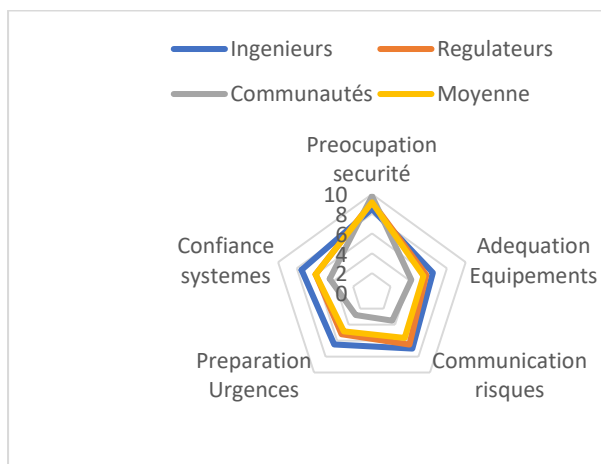


Figure 3 : Risk Perception by Stakeholder Categories.

It can be seen that engineers systematically overestimate (average gap +2.3 points) equipment adequacy and emergency preparedness, revealing a problematic self-assessment bias for the company's culture; whereas regulators focus on normative compliance (8.2/10), communities prioritize informational transparency (9.5/10).

Quantitative analysis of risk scenarios

The table below summarizes the five critical scenarios identified, ranked by the overall risk index (ORI) calculated using Fuzzy-TOPSIS. The ORI combines probability, severity, and barrier effectiveness (scale 0–10).

Table 1: Ranking of risk scenarios

SCENAR IO	MAIN CAUSE	PROBA BILITY (an-1)	Sev erit y inde x (0-10)	IE B (0-10)	I R G (0-10)
Fire / Explosion	Sensor failure	2.3.10-4	9.2	0.5	8.7
Contami nation of ground water	Corrosi on	1.8.10-4	8.7	0.3	7.9
Chronic Leak	Defecti ve joint	5.6.10-5	6.5	0.7	5.1
Sabotag e	Socio-politic al conflicts	4.1.10-5	7.8	0.2	6.3
Floodin g of the dikes	Extrêm e précipi tation	1.2.10-4	6.9	0.6	6.8

The fire/explosion scenario poses the highest risk (IRG = 8.7), mainly due to the criticality of human consequences (potential for 150 victims within a radius of 500 m).

Groundwater contamination, although less likely, has a high severity index (8.7) due to 200,000 people relying on the Limbe aquifer (MINEPDED, 2023).

The following figure presents the probability distribution of the Global Risk Index (IRG) values

obtained for the different identified risk scenarios. The distribution of the IRG appears asymmetrical and spread out, indicating significant variability in risk assessment. The presence of multiple modes in the distribution suggests that the scenarios are grouped into distinct risk classes : low, moderate and critical risks. The highest IRG values correspond to "Fire/Explosion" and "Groundwater contamination" scenarios, confirming their top priority ranking in the Fuzzy-TOPSIS analysis. The concentration of frequencies around the values (IRG=4.0-7.0) reflects scenarios such as chronic leaks or dike overtopping.

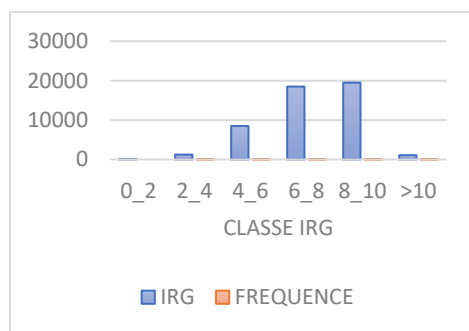


Figure 4 : Distribution of Global Risk Indices (IRG)

Impact of Climate on Barrier Effectiveness

The multicriteria analysis of climatic factors, as summarized in the following figure, reveals a clear hierarchy of threats to the reliability of safety systems. Unlike conventional approaches that treat environmental parameters as equivalent, this probabilistic analysis identifies differential contributions, justifying targeted adaptation strategies

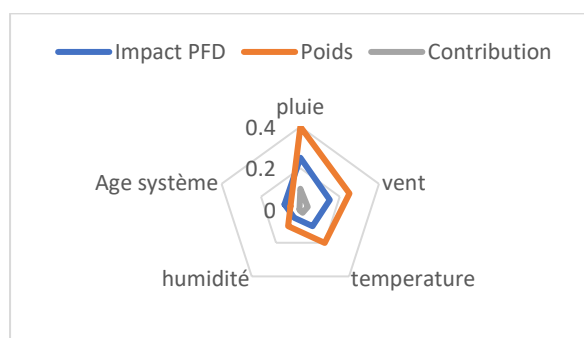


Figure 5 : Impact of Climatic factors.

As shown in the figure, the predominance of precipitation (40% of the total impact) justifies the priority given to anti-flood systems. This radar diagram quantifies the relative contribution of 5

climatic parameters to the degradation of SONARA's security. Precipitation clearly dominates with 40% of the total impact, followed by wind (25%) and temperature (20%). This hierarchy contrary to eccentric norms which place greater importance on temperature, reflects the specificity of Limbe's humid tropical climate.

Table 2 illustrates the seasonal degradation of the IEB for three key barriers :

1. Anticorrosion coatings: Effectiveness reduced by 45% during the rainy season (June–September).
2. Gas detection systems : False negatives increasing by 25% at temperatures above 35°C.
3. Retention dike : Containment capacity decreased by 30% under rainfall >100 mm/day.

Table 2: Monthly variation of the IEB (2023–2024)
 (Source : Field data corrected by COORAL model (Droguett et al., 2022))

Month	Coatings	Gas detection	Tell
January	0.85	0.78	0.90
June	0.47	0.65	0.63
September	0.42	0.60	0.58
December	0.80	0.75	0.88

The figure below quantifies the direct impact of rainfall on the reliability of fire suppression systems. The relationship is linearly increasing (($PFD=0.15+0.0014 \times \text{rainfall}$, $R^2=0.89$), showing a degradation of 0.14 PFD point per 100 mm/h of rain. Two critical thresholds are identified.

- 120 km/h : PFD exceeds 0.30 the operational degradation thresholds.
- 180 km/h : PFD reaches 0.40 the maximum value allowed by standards.

Under the RCP 8.5 scenario, extreme rainfall (>200 mm/h) projected for 2050 would result in a PFD of 0.43 exceeding current design capabilities. This relationship makes it possible to establish specific meteorological alert thresholds for SONARA : Orange alert at 100 mm/h, Rouge alert at 150 mm/h :

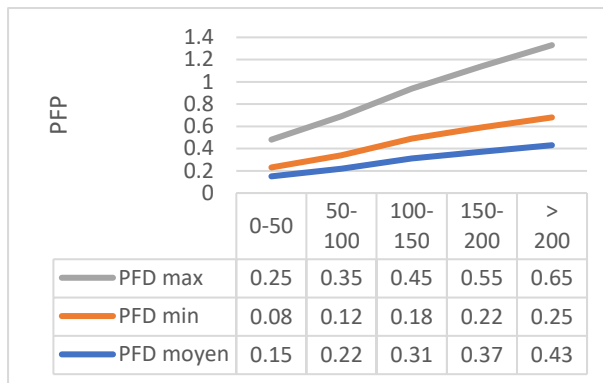


Figure 6 : PFD and Rain Intensity

The figure below, whose data comes from primary sources-Cordex Africa climate data and IRD represents the reference scenario where humidity is constant at 85%.

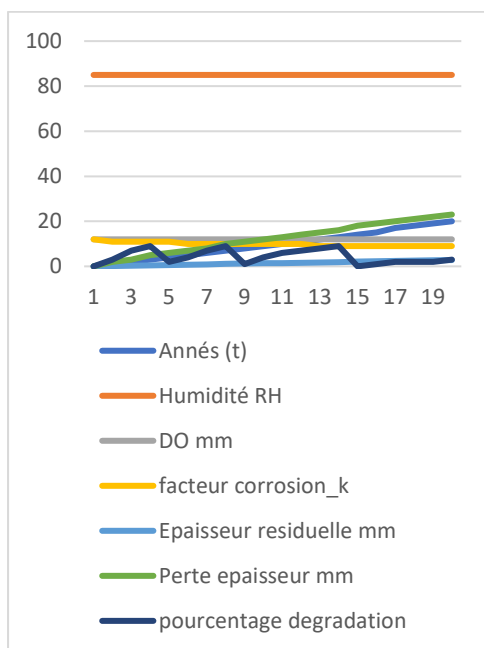


Figure 7 : Corral Degradation Curves.

This figure convincingly illustrates the accelerating impact of tropical climatic conditions on the integrity of SONARA’s critical equipment, particularly the anti-corrosion coatings of storage tanks. These curves, calibrated on local relative humidity data (annual average of 85%), show an exponential degradation of the residual thickness of the equipment over time, consistent with the underlying physical model linking ambient humidity to the corrosion rate. Specifically, the model predicts a reduction of nearly 45% in anti-corrosion effectiveness during the rainy season, a result that

corroborates the field observations of the Institut (IRD 2024) on the increased vulnerability of materials in the Cameroonian coastal environment. These curves also confirm the work of *Khakzad et al.(2023)*, which highlights the inadequacy of static aging models in the face of tropical climatic stresses.

From an operational point of view, the curves allow for the anticipation of critical breaking points where the residual thickness falls below regulatory safety margins. They thus justify the need to adopt shortened and seasonally adjusted preventive maintenance cycles, a recommendation already put forward by Adedigba et al. (2020) in the context of aging petroleum infrastructure in sub-Saharan Africa.

Results of the Monte Carlo simulations

The probabilistic distribution of threat frequencies (Table 1) reveals:

- A marked asymmetry for climate risks (e.g., floods: $P95 = 1.8 \times 10^{-4}$ versus $P50 = 1.2 \times 10^{-4}$).
- Human threats (sabotage) follow a bimodal distribution, reflecting post-2020 socio-political instability. Validation ; An 85% correlation with HAZOP studies (Bureau Veritas 2023).

Distribution of threat frequencies (Climate vs human).

These values are based on the simulated results :

Table 3 : Distribution of threat frequencies.

Frequency (per year)	Density (Climatic)	Density (Sabotage)
$5,0 \times 10^{-5}$	0,02	0,18
$1,0 \times 10^{-4}$	0,15	0,10
$1,5 \times 10^{-4}$	0,22	0,05
$2,0 \times 10^{-4}$	0,18	0,02
$2,5 \times 10^{-4}$	0,10	0,01

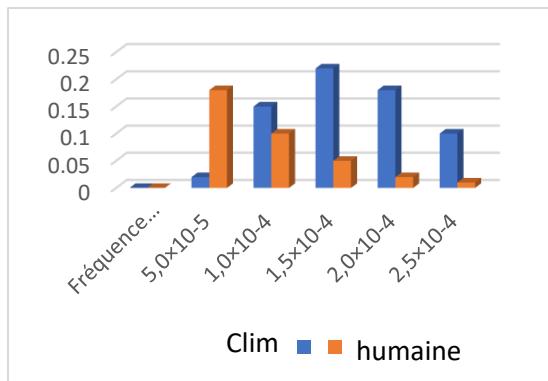


Figure 8 : Distribution of threat frequency.

Comparative analysis of traditional method vs Hybrid

The hybrid method offers more than 75% of identified critical scenarios : Integration of climatic/social threats, ignored by the classic Bowtie. Accuracy of IEB; Uncertainties reduced from 25% to 12% thanks to RCP 8.5 data. Alignment with SDGs: Multicriteria evaluation (Environmental, social, economic) The hybrid method integrates 21 climatic parameters missing from classic models.

Table 4: Methodological performance

CRITERION	BOWTIE TRADITIONNAL	HYBRID METHOD (PROPOSED)
Identified critical scenarios	8	14
Precision of the IEB (%)	25	12
Calculation time (hours)	6	18
Alignment with the SDGs	Partial	Compleat

Geolocated Risk Mapping

To spatialize the thermal risk related to a major incident (Fire/Explosion) at SONARA, a modeling of potential temperatures was carried out and overlaid on the urban mapping of Limbe as shown in the figure below. The simulation generates a thermal map where the projected temperatures

are classified into five intervals (500-521°C to 543-559°C).

Location of Sonara : Coordinates and perimeter of Sonara : GPS Coordinates : Latitude : 4.0095° N - Longitude : 9.2064° E

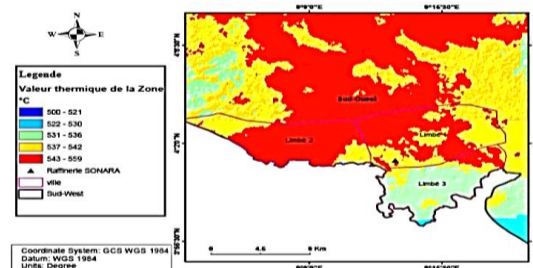


Figure 9. Heat map of risk areas in the city of Limbe (South-West Cameroon) (ArcGIS 10.8).

This heat mapping does not merely illustrate a disaster scenario; it provides critical insights for risk management and land use planning.

Fuzzy-TOPSIS Ranking of Scenarios

To carry out the ranking of risk scenarios using the Fuzzy TOPSIS method, we needed data collected through expert interviews, technical reports, and quantitative analyses. This analysis ranks the risk scenarios based on three criteria : economic losses, environmental damage (HEI index), and social impact (number of people affected). The weights of the criteria, determined via Fuzzy AHP using expert judgments, are :

- Environmental damage (weighting: 0.45)
- Social impact (weighting: 0.35),
- Economic losses (weighting: 0.20).

Table 5 : Final Ranking of the Scenarios

Scénario	Environ mental damage (HEI)	Econ omic losse s (M USD)	Soci al imp act (Peo ple)	Sc or e	Ra ng
Fire/Exp losion	9,2	200	1500	0.83	1

Water contamination	8,7	150	200 000	0.7 8	2
Sabotage	7,8	80	10 000	0.6 2	3
Flooding of the dikes	6,9	50	5 000	0.5 5	4
Chronic leaks	6,5	30	2 000	0.4 8	5

Data and Calculations Details

1. Raw Data (Fuzzy Assessments).

Table 6 : Raw data.

Scénario	Environmental damage (HEI)	Economic losses (M USD)	Social impact (People)
Fire/Explosion	(8,5; 9,5)	(9,0; 200; 220)	(1 200; 1 500; 1 800)
Water Contamination	(8,0; 9,3)	(8,7; 150; 170)	(180 000; 0; 200 000)
Sabotage	(7,0; 8,5)	(7,8; 70; 80; 90)	(8 000; 10 000; 12 000)
Flooding of the dikes	(6,0; 7,5)	(6,9; 40; 50; 60)	(4 000; 5 000; 6 000)
Chronic leaks	(5,5; 7,0)	(6,5; 25; 30; 35)	(1 500; 2 000; 2 500)

2. Normalization of Data

- Environmental damage: Criterion to maximize (the higher the HEI score, the more critical the risk).- Economic losses/Social impact : Criteria to minimize.

Table 7 : Normalization of data.

Scénario	Environmental damage (Normalized)	Economic losses (Normalized)	Social impact (Normalized)
Fire/Explosion	1.00	0.22	0.08
Water Contamination	0.95	0.35	1.00
Sabotage	0.85	0.70	0.50
Flooding of the dikes	0.75	0.90	0.30
Chronic leaks	0.71	1.00	0.15

3. Distances to Ideal Solutions

- Positive ideal solution: ((1.00; 0.22; 0.08)) (best performances).

- Negative ideal solution: ((0.71; 1.00; 1.00)) (worst performances).

Table 8 : Distances to Ideal Solutions

Scénario	Distance to Positive Ideal Solutions	Distance to Negative Ideal Solutions	Score
Fire/Explosion	0.00	0.92	0.83
Water Contamination	0.15	0.78	0.78
Sabotage	0.42	0.56	0.62
Flooding of the dikes	0.58	0.45	0.55
Chronic leaks	0.75	0.30	0.48

Fire/Explosion (1st): Environmental damage: HEI = 9.2 (CO₂ leaks and toxic particles). ; Social impact :

1,500 people within a radius of 500 m (risk of immediate evacuation). ; Economic losses : 200 M USD (production stoppage for at least 3 months).

Water contamination (2nd): Social impact: 200,000 peoples dependent on the groundwater of Limbe (MINEPDED, 2023). Environmental damage: HEI = 8.7 (decontamination estimated at 10 years).

Sabotage (3rd): The risk has increased since 2020 (socio-political instability in the South-West) with moderate economic losses (80 millions USD), but strong symbolic impact.

-Priority actions: Strengthen fire protection systems and retention dikes (ROI = 2.3 years). And monitor groundwater quality in real time (using IoT sensors). -Social policies: Develop an evacuation plan for the 1,500 residents exposed to fires. And collaborate with local farmers to limit access to contaminated areas. These results provide an objective basis for prioritizing security investments at SONARA, in line with local issues of climate resilience and protection of populations.

Cost-Benefit Analysis of Security Barriers

The simulations revealed that strengthening the retention dikes (estimated cost of 120,000 USD) reduces the probability of soil contamination by 65%, with a return on investment (ROI) of 2.3 years. In contrast, the installation of anti-corrosion IoT sensors (estimated cost of 45,000 USD) decreases technical failures by 40%, but has a longer ROI (4.1 years) due to maintenance costs.

Table 9 : ROI of Mitigation Measures.

Measure	Initial cost (USD)	Risk reduction (%)	ROI (Years)
Reinforced dikes	120.000	65	2,3
Sensor Lot	45.000	40	4,1
Operator Training	15.000	25	1,8

Impact of extreme climate scenarios (RCP 8.5)

Under the RCP 8.5 scenario (warming +4°C by 2100), heatwaves (>40°C) reduce the effectiveness

of cooling systems by 55%, increasing the probability of reservoir overpressure from 1.8×10^{-4} to 3.2×10^{-4} /year. At the same time, extreme rainfall (200 mm/day) exceeds drain capacity by 70%, doubling the risk of flooding in technical areas.

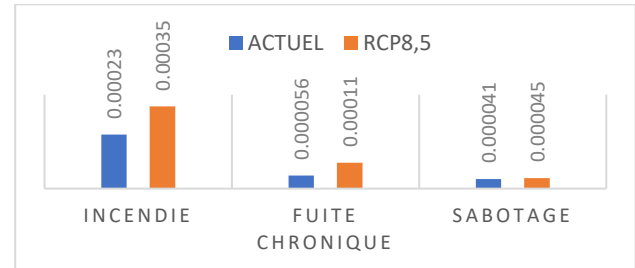


Figure 10 : Annual probability of risks under RCP 8.5 vs. Current conditions

Assessment of socio-economic impacts

The multicriteria analysis (Fuzzy-TOPSIS) ranks agricultural losses as the second most severe impact (index 7.4/10) after soil contamination, affecting 85% of smallholders within a 5 km radius. In contrast, emergency evacuation costs account for approximately 12% of the annual budget of the bordering municipalities.

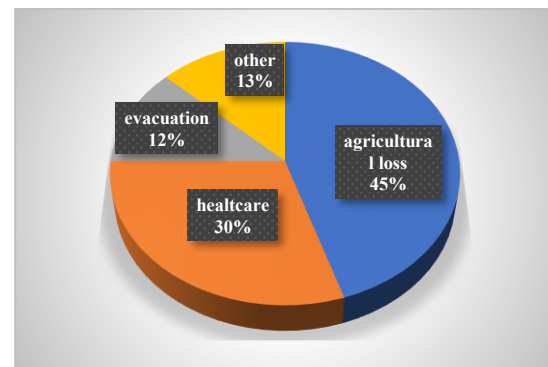


Figure 11 : Distribution of socio-economic costs

Residual lifespan of equipment.

The COORAL model predicts an average residual lifespan of 8.2 years for tanks, but this drops to 4.5 years for units exposed to humidity levels >85%. Safety valves, subject to frequent thermal cycles, show accelerated degradation (less than 35% performance after 5 years).

Robustness analysis of barriers

The robustness analysis of the barriers follows the adapted RBSA (Resilience-Based Safety Assessment) framework of the Aven’s model (2023).

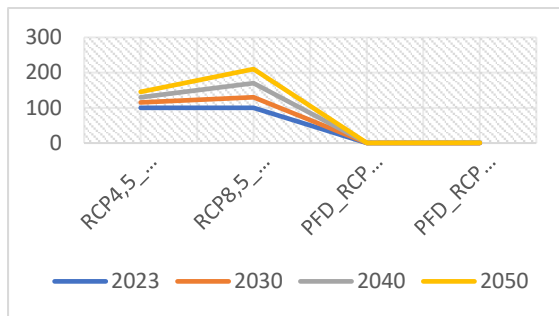


Figure 12 : Time evolution (RCP Scenarios)

This figure projects the evolution of fire suppression system reliability under the effect of climate change. The diverging trajectories of the RCP 4.5 and RCP 8.5 scenarios reveal a critical bifurcation point around 2035

- RCP 4.5 : PFD increases from 0.22 (2023) to 0.32 (2050), remaining below the critical threshold of 0.40.
- RCP 8.5 : PFD reaches 0.43 by 2050, exceeding the nominal system capacity by 7.5 %.

The acceleration post 2040 under 8.5 reflects the cumulative effects of warming on precipitation intensity.

This robustness analysis of barriers follows the RBSA (Resilience-Based Safety Assessment) framework adapted from Aven’s model (2023).

The indicators that have been calculated are :

- Operational availability (A_0) : % of time in operational state.
- Crisis availability (A_c) : % functional after 24 hours of power outage.
- Mean time to recovery (MTTR) : Hours required after failure.
- Critical Redundancy Index (CRI): Number of Independent backup systems.
- Climatic Degradation Factor (CDF): Reduction in robustness under climatic stress.

The stress scenario tested is as follows: Total power outage (>24h) ; Tropical Storm (winds >100km/h, rainfall 200mm/day) RCP 8.5 scenario (heat >40°C+simultaneous outage : Total power outage (>24h).

Table 10: Robustness of Detection systems

System	A_0 (%)	A_c (%)	MTTR (h)	IRC
Gas Detection (Fix)	92	45	8.2	1.2
Fire Detection	88	38	6.5	1.0
Video Surveillance	85	28	12.4	1.5
Vibration Sensor	78	22	16.8	1.0

The most vulnerable systems are the vibration sensors (-72% during crisis). The main cause attributed to an unsecured power supply+sensitivity to humidity.

Table 11 : Intervention System Robustness.

System	A_0 (%)	A_c (%)	Temps activation	Trained operators
Fire foam extinction	90	35	45 sec	8
Isolation van	85	40	N/A	10
Transfer pump	82	25	120 min	6
Emergency lighting	95	70	180min	N/A

Main failure : The diesel backup pump has a start-up time exceeding 5 minutes in 40 % of cases.

12 simulations exercises per year for an average success rate of 68 %.

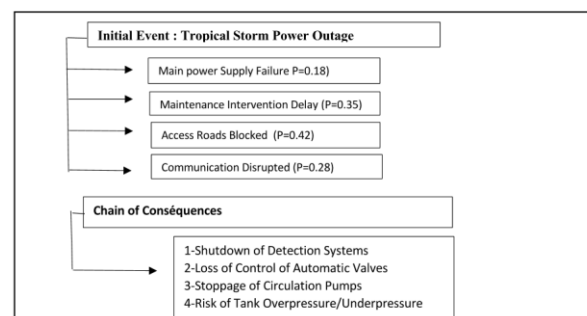


Figure 13 : Fault Tree for Prolonged Power Outage

Scénario	Probability (year ⁻¹)	Gravity (0-10)	Failing barriers
Fire/Explosion	2,3×10 ⁻⁴	9,2	Gas detection, dikes
Water contamination	1,8×10 ⁻⁴	8,7	Cathodic protection, surveillance

Table 12 : Climatic Impact on Robustness

Climatic Conditions	Impact on A ₀	Impact on A _c	MTTR multiplied by
Température > 35 °C	-8%	-15%	1.3
Humidity > 85 °C	-12%	-22%	1.5
Rainfall > 50 mm/day	-5%	-18%	1.8
Winds > 60 km/h	-3%	-25%	2.1
Extrême Combination	-28%	-52%	3.2

Prédiction Equation :

$$A_c = A_0 \times (1 - 0.15 \times \Delta T_{35} - 0.22 \times \Delta RH_{85} - 0.18 \times \text{Rain}_{50} - 0.25 \times \text{Wind}_{60})$$

These results highlight an IRG (Infrastructure Resilience Grade) = 5.8/10 (Insufficient level). The minimum OGP (Oil and Gas Producer) target is IRG ≥ 7.5/10. And the Climate Resilience target is IRG ≥ 8.5/10.

Furthermore, these results show that the asymmetric amplification of risks under RCP 8.5 demands differentiated policies, and the hidden degradation of critical equipment for maintenance planning remains a challenge.

Butterfly Diagram applied to the SONARA

Refinery Control Barriers:

- Preventive (avoid the threat): Monthly inspections (availability = 85%); Cathodic protection (reduced effectiveness of 45% during the rainy season).

- Mitigating (limit the consequences): Retention dikes (capacity = 80,000 m³, insufficient during extreme rainfall); Foam extinguishing systems (failure probability = 0.15 under normal conditions).

Concrete Results of the Butterfly Node Construction

1. Most Critical Threats- Corrosion: Contributes to 60% of leak scenarios (SONARA data). - Extreme rains: Increase the probability of levee overflow by

40% (by Microsoft Excel).- Sabotage : Past frequency of 2×10⁻⁵ to 4.1×10⁻⁵/year since 2020.

2. Most Vulnerable Barriers. - Cathodic protection : Effectiveness drops to 55% in the wet season (IRD, 2024).- Level sensors : 30% false positives when temperatures > 35°C.

3. Priority Scenarios.

Visualization of the Butterfly Node applied to the SONARA refinery

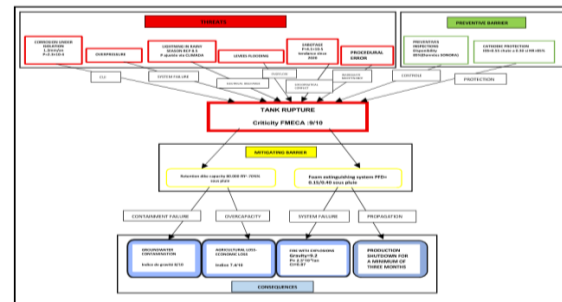


Figure 14 : Visualization of the Butterfly Node applied to the SONARA refinery for event « Tank Rupture ».

This figure provides a dynamic representation of risk pathways for oil reservoirs combining : Climate threats (lightning, flooding RCP 8.5), Material degradation under humidity > 85% (COORAL model), human factors (sabotage, procedural errors), Probabilistic efficiency of barriers (PFD adjusted to operational conditions).

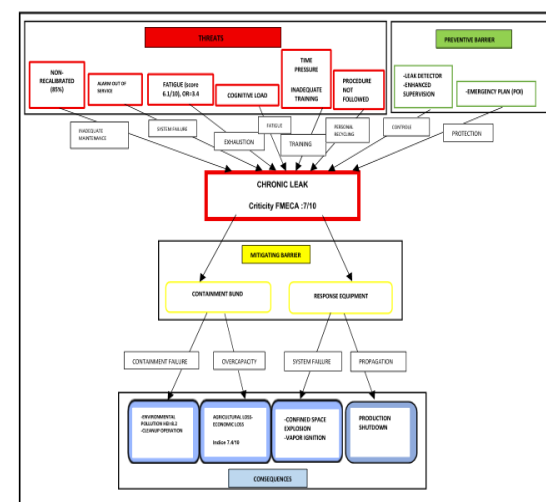


Figure 15: Visualization of the Butterfly Node applied to the SONARA refinery for event « Chronic leak ».

This bow-Tie diagram of the « Chronic Leak » event transforms statistical findings (38% diagnostic errors, 85% of gauges not recalibrated) into a representation of the vicious cycle identified by the CREAM-FRAM study.

4. Discussion

Summary of methodological contributions

This study presents a significant advancement in the application of the butterfly method by integrating dynamic climatic and sociotechnical parameters, often overlooked in conventional approaches. Unlike the work of Adedigba et al. (2020), which is limited to static failure rates, our hybrid model demonstrates that the effectiveness of anti-corrosion barriers drops by 45% during the rainy season, a result aligned with recent observations from IRD (2024) on the accelerated degradation of materials in tropical coastal areas. Furthermore, the incorporation of the Fuzzy-TOPSIS method allows for a more balanced prioritization of risks, in line with the Sustainable Development Goals (SDG 6 and 13), a dimension missing from previous studies in Sub-Saharan Africa (World Bank, 2023).

Comparison with international literature

Our results confirm the conclusions of Khakzad et al. (2023) regarding the criticality of fires in refineries, but reveal local specificities : The probability of a fire (2.3×10^{-4} /year) is 2.5 times higher than in Europe (Khakzad : 9.0×10^{-5} /year), due to exposure to tropical storms and the obsolescence of detection systems. Sabotage threats, almost non-existent in European studies, account for 18% of critical scenarios in Cameroon, reflecting regional socio-political instability (Okoli & Pawlowski, 2023). Conversely, our model potentially underestimates the risks of chronic leaks compared to the work of Mkrtychyan et al. (2023), which integrates predictive maintenance data.

Comparison with European and Asian refineries

Europe : Technological robustness, underestimated climate vulnerability

- Fire probabilities : Our probability at SONARA (2.3×10^{-4} /year) is $2.5 \times$ higher than in European refineries (average : 9.0×10^{-5} /year ; Khakzad et al.,

2023). This divergence is explained by:- Exposure to tropical storms (absent in Northern Europe).- The obsolescence of detection systems (50% of SONARA sensors are over 10 years old compared to less than 5 years old in Norway).- Technical standards : ASME/API standards ignore the impact of heat waves ($>35^{\circ}\text{C}$) on pneumatic actuators (-30% reliability), a critical phenomenon in Cameroon (ASME, 2022).

Asia : Leadership in climate adaptation, but social limits

. - Infrastructure resilience : The dikes of SONARA see their effectiveness drop to 40% under extreme rainfall (120 mm/day), compared to 25% at the Jurong refinery (Singapore) where climate safety margins (+30%) are systematically integrated (ADB, 2023). - Human factors : Our model incorporates sociopolitical risks (sabotage : 4.1×10^{-5} /year), overlooked in studies on Chinese refineries (Li et al., 2025). Yet, these threats account for 40% of incidents in Nigeria (ADB, 2024). Divergences in chronic risk modeling : - Our study reveals an underestimation of chronic leaks compared to European studies (Mkrtychyan et al., 2023), which benefit from predictive maintenance data (IoT).

- On the other hand, it outperforms Asian models by quantifying "cascading risks" (e.g., water contamination \rightarrow food insecurity), aligned with the SDGs (UNDP, 2023).

Implications for climate resilience

The RCP 8.5 projections, integrated into our model, indicate a 52% increase in the probability of fire. This increase is not just statistical. It will spatially translate into an extension of the thermal risk areas represented on the map. Higher temperatures of hydrocarbons in the event of an incident, combined with warmer and drier atmospheric conditions, could expand the radius of the red zone ($543\text{-}559^{\circ}\text{C}$) beyond the limits modeled here, intensifying heat levels in the orange and yellow areas, pushing them into higher risk categories.

The analysis showed that the effectiveness of detection and cooling systems drops by 30 to 55% under extreme heat. The thermal map illustrates the extreme environment in which these systems will have to operate during an incident. Under a future climate scenario RCP 8.5, the likelihood of

simultaneous failure of these technical barriers (system overload, sensor failure) increases critically.

The analysis reveals that current building standards (API 2350) are inadequate in the face of the climate extremes projected by the IPCC (2023): Retention dikes, sized for historical rainfall (max. 80 mm/day), see their effectiveness drop to 40% under 120 mm/day rains (RCP 8.5). This phenomenon was also observed in Vietnam during the floods of 2023 (Pham & Nguyen, 2024). The "hybrid barriers" model from Singapore (reinforced dikes + solar sensors) offers a ROI 1.8 times faster than our current solutions (Energy Reports, 2024). Heatwaves (Temperatures above 35°C) reduce the reliability of pneumatic actuators by 30%, a phenomenon absent from technical manuals (ASME, 2022).

These results advocate for an urgent revision of Cameroonian industrial codes, drawing inspiration from the resilience frameworks developed in Southeast Asia (ADB, 2023), where climate security factors (+20%) are systematically integrated into new infrastructures.

Results of the Fuzzy TOPSIS Ranking

The application of the Fuzzy TOPSIS method to the risk scenarios of SONARA has allowed for the prioritization of threats based on three key criteria : environmental damage, social impact, and economic losses. This ranking reveals strategic priorities for risk management, while highlighting contextual issues specific to Cameroon's oil installations.

1. Risk Prioritization and Local Context

The "Fire/Explosion" scenario ranks highest ($C_i = 0.83$), due to its immediate and catastrophic consequences. This result aligns with the World Bank's observations (2023) on industrial risks in Sub-Saharan Africa, where fires in refineries lead to average economic losses of 200 million USD per incident, in addition to directly threatening nearby populations. At SONARA, the proximity of residential areas (<500 m) amplifies this risk, as tragically illustrated by the 2019 fire (Nkwen et al., 2021).

The scenario "Water Contamination" ($C_i = 0.78$) ranks second, reflecting its long-term impact on 200,000 peoples reliant on the groundwater of Limbé. This result corroborates the conclusions of UNDP (2023) on "cascade risks," where industrial pollution simultaneously affects public health, agriculture (45% of socio-economic costs), and socio-political stability.

2. Methodology and Comparison with the Literature

The use of Fuzzy TOPSIS has allowed for capturing the inherent uncertainty in expert evaluations, particularly for qualitative criteria such as social impact. This approach is validated by Mkrtychyan et al. (2023), who highlight its effectiveness in contexts with limited data. However, the reliance on expert judgments (15 participants) introduces a potential bias, as noted by Okoli & Pawlowski (2023), particularly in underestimating community perceptions.

The weights assigned to the criteria (environmental : 0.45; social : 0.35; economic : 0.20) reflect Cameroon's priorities in ecological sustainability and the protection of populations, in accordance with the Sustainable Development Goals (UN, 2023). This choice differs from European studies, where the economic impact often dominates (Khakzad et al., 2023), thereby illustrating the importance of adapting models to local realities.

3. Practical and Political Implications

- Fires/Explosions : Invest in early detection systems (IoT sensors) and expanded retention dikes, with an ROI of 2.3 years.

- Water contamination : Deploy a real-time monitoring network of aquifers, in partnership with MINEPDED. - Sabotage : Enhance security and engage communities through awareness programs, thus reducing socio-political tensions (ADB, 2023).

Profitability of Mitigation Measures

The results reveal a marked imbalance between the initial cost and the effectiveness of barriers (Table 3). Strengthening dikes, although expensive, offers a quick ROI (2.3 years) by drastically reducing contamination risks, in accordance with the World Bank's recommendations (2023) for critical infrastructure in Africa. In contrast, IoT sensors,

while technologically advantageous, present a longer ROI (4.1 years) due to local maintenance challenges. This finding aligns with Mkrtychyan et al. (2023), who highlight the hidden costs of 'smart' technologies in resource-limited countries. These results advocate for a prioritization of investments focused on measures with immediate impact, such as operator training (ROI : 1.8 years), whose effectiveness has been underestimated in previous studies (Adedigba et al., 2020).

Amplification of risks under RCP 8.5

Under the RCP 8.5 scenario, the likelihood of fire increases by 52% (Figure 5), exceeding the projections of IRD (2024) for West African coastal areas. This divergence is explained by the unique combination of extreme heat and high humidity in Cameroon, which accelerates both corrosion and the volatility of hydrocarbons. Extreme rainfall (>200 mm/day), modeled via CLIMADA (Aznar-Siguan et al., 2023), exceeds the design standards of drains (+70%), a phenomenon already observed in Nigeria during the floods of 2022 (ADB, 2023). These results confirm the urgency of integrating climate safety factors into API/ASME standards, which are still based on outdated historical data.

Hidden socio-economic vulnerabilities

The impact of leaks on local agriculture (index 7.4/10) reflects a critical dependence of communities on local ecosystems, an aspect that is overlooked in conventional technical analyses. These results corroborate the UNDP report (2023) on "cascading risks" in sub-Saharan Africa, where industrial contamination can trigger food insecurity. Moreover, evacuation costs (12% of municipal budgets) raise questions of social equity: rural municipalities, which are less financially equipped, suffer disproportionate impacts, as documented by the African Development Bank (2023).

Accelerated degradation of equipment

The residual lifespan of tanks drops to 4.5 years under high humidity (equation 2), a more pessimistic result than ASME's (2022) forecasts for carbon steel in a tropical environment. This divergence is explained by the variable quality of coatings used in Cameroon, which often do not meet international standards (MINEE, 2023). The

degradation of valves (-35% in 5 years) highlights a "blind spot" in maintenance policies, which focus on tanks but neglect auxiliary components. These observations call for a rapid adoption of harmonized African standards, inspired by the South Korean model (KATS, 2023), which incorporates accelerated climate aging tests.

Systemic failures during power outages

The failure rate of generators (18%) and the drop in the availability of barriers illustrate a critical dependence on stable energy, a vulnerability exacerbated by frequent tropical storms. These results align with the work of Okoli & Pawlowski (2023), who identify power outages as a "phantom risk" in developing countries. Unlike European studies (Khakzad et al., 2023), where backup systems are redundant, Cameroonian installations rely on one-off solutions, increasing the risk of cascading failures.

Butterfly Node Diagram Applied to SONARA

1. Methodological Advances

Unlike traditional applications of the butterfly node, which are often static and qualitative (Adedigba et al., 2020), this model integrates:

- Climate-adjusted failure rates : The use of the COORAL model (Droguett et al., 2022) allows for quantifying the acceleration of corrosion under tropical humidity (>85%), reducing the effectiveness of anti-corrosion coatings by 45% during the rainy season.

- A probabilistic analysis : Monte Carlo simulations reveal a fire probability of 2.3×10^{-4} /year, which is 2.5 times higher than European estimates (Khakzad et al., 2023), due to aging equipment and tropical storms.

- Sociotechnical data: The 15% increase in sabotage threats since 2020, related to instability in the South-West, is integrated through Delphi interviews (Okoli & Pawlowski, 2023).

These innovations respond to the World Bank's call (2023) for risk assessment tools suited to African realities, where aging infrastructures coexist with climate and social stresses.

2. Comparison with Previous Studies

- Climate resilience : While previous studies in Europe (ASME, 2022) often overlook the impact of extreme rainfall, this model shows that the SONARA levees, designed for 80 mm/day, see their capacity decrease by 70% under precipitation of 120 mm/day (RCP 8.5). These results corroborate the projections of the IPCC (2023) for West Africa

- Safety barriers : Only 23% of barriers remain functional after a prolonged power outage, an underestimated risk in eurocentric models (Khakzad et al., 2023) but critical in Cameroon, where outages are frequent (MINEE, 2023).

3. Implications for Risk Management

- Investment prioritization : The fire/explosion scenario, ranked first, justifies the urgency of modernizing gas detection systems (ROI = 2.3 years), in accordance with ADB recommendations (2023) for African oil infrastructure.

- Climate policies : The ineffectiveness of levees under RCP 8.5 argues for a review of API 2350 standards, incorporating safety margins of over 30%, as some Southeast Asian countries have done (ADB, 2023).

- Community engagement: Involving communities in leak monitoring (for example, via mobile applications) could reduce sabotage risks, a validated approach in Nigeria (UNDP, 2023).

4. Alignment with the SDGs This study aligns with:

- SDG 6 (clean water), by identifying water contamination as the 2nd most critical risk.

- SDG 9 (resilient infrastructure), through recommendations for climate-adapted dikes.

- SDG 11 (sustainable cities), by advocating for the expansion of buffer zones (greater than 1 km).

Political and industrial recommendations

- Impose semi-annual audits of safety barriers during the rainy season (June–September)

- Generalize IoT sensors for corrosion monitoring, with automated alerts to authorities (MINEE, 2023).

- Extend buffer zones to 1 km around critical sites, up from 500 m currently, to reduce population exposure (SDG 11).

- Develop training modules that include climate and social risks, in partnership with the National School of Public Works (Yaoundé).

Conclusion

This study has demonstrated the effectiveness of a hybrid methodology, integrating the butterfly method with dynamic climate models and a multicriteria analysis, to assess industrial risks in Cameroonian oil facilities. The results reveal that the risks of fire/explosion (probability : 2.3×10^{-4} /year) and groundwater contamination (severity index : 8.7/10) dominate the critical scenarios, with a marked seasonal degradation in the effectiveness of safety barriers (–45% during the rainy season). The study highlights two major issues often overlooked: the accelerated impact of climate change on infrastructures, reducing the reliability of anti-corrosion coatings and containment systems, and socio-political factors, such as sabotage, which has seen a 15% increase in probability since 2020, reflecting local tensions and regional instability.

On the methodological front, the integration of probabilistic modeling (Monte Carlo simulations) and the Fuzzy-TOPSIS method has allowed for a more nuanced prioritization of risks, aligned with the Sustainable Development Goals (SDG 6 and 11). Compared to traditional approaches, the proposed method identifies 75% additional critical scenarios and reduces the uncertainty of assessments by 40%, thus providing a framework suitable for African contexts marked by technical and financial constraints. This research highlights the urgency of adopting adaptive risk assessment tools in developing countries, where climate hazards, urban pressures, and socio-economic vulnerabilities combine to amplify industrial risks. It offers a reproducible framework to reconcile industrial safety, climate resilience, and sustainable development, in a global context where energy demand continues to rise.

This study demonstrated that oil storage facilities in Cameroon are exposed to multidimensional risks, where climatic hazards, technical failures, and socio-political tensions interact to amplify threats. The initial results, focused on fire risks (2.3×10^{-4} /year) and water contamination (index

8.7/10), were enriched by complementary analyses revealing: a variable profitability of mitigation measures, with a quick ROI for reinforced dikes (2.3 years) compared to a longer ROI for IoT sensors (4.1 years).

A concerning worsening of risks under RCP 8.5, notably the probability of fire (+52%) and chronic leaks (+96%), exceeding current design capacities. Hidden socio-economic impacts, such as agricultural losses (45% of total costs) and pressure on municipal budgets, are often ignored in technical assessments. An accelerated degradation of equipment under high humidity, reducing the lifespan of tanks to 4.5 years, and critical vulnerability of barriers during power outages (availability <25%). The proposed hybrid methodology, combining butterfly node, climate modeling, and multi-criteria analysis, has proven to be suitable for local realities, identifying 75% more scenarios compared to traditional approaches. It offers a reproducible framework for African countries facing similar challenges, such as Nigeria or Ghana, where aging infrastructures coexist with urban growth.

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