

Human Reliability in Petroleum Storage Facilities: A mixed Method Analysis of Critical Failures and Systemic Risks in Cameroon.

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Abstract

Introduction: Human errors in the storage facilities of petroleum products pose a major threat to the safety of facilities, people and the environment, especially in developing countries where technical and regularly resources are limited.

Objectives: This study analyzes the critical factors of human reliability in Cameroonian oil depots by combining CREAM (Cognitive Reliability an Error Analysis Method) and FRAM (Functional Resonance Analysis Method).

Methods: The data, collected at two Cameroonian oil depots between 2021 and 2023, includes interviews with 35 operators, observation of 20 loading procedures, and analysis of 47 incidents reports.

Results: The results reveal not only higher error rates than those in industrialized countries (38% of misdiagnoses compared to 15% in France), but also specific risk loops, such as the correlation between spare parts shortages and high-risk technical improvisations ($OR = 3.2$, $p < 0.01$).

Conclusions: On the theoretical level, this study enriches the literature on human reliability by integrating variables that are often ignored: corruption, informality of procedures, thus offering a more holistic framework for analysis. In practice, it provides Cameroonian and African decision-makers with priority levers for action, such as the deployment of low-cost IoT sensors.

Keywords: Human reliability, Oil storage, incident and CREAM-FRAM

1. Introduction

The safety of hydrocarbon storage facilities is a major global issue, both for the preservation of the environment and for the protection of human lives. Each year, incidents such as oil depot leaks, explosions, or fires result in an estimated \$2.5 billion in economic losses globally (IEA, 2022), not to mention irreversible damage to ecosystems and surrounding communities. While industrialized countries have gradually strengthened their safety standards through advanced technologies and strict regulation, developing countries, particularly in sub-Saharan Africa, continue to

face systemic challenges that amplify the risks of human error (Almeida et al., 2022). In Cameroon, the rapid expansion of oil infrastructure driven by the discovery of new offshore deposits and the increase in energy demand is accompanied by increasing operational pressure on facilities that are often aging and poorly maintained. Storage depots, which are key points in the logistics chain, are particularly vulnerable: between 2018 and 2023, the National Hydrocarbons Company (SNH) recorded 47 major incidents related to human errors during the loading of trucks and tank wagons, 12 of which resulted in environmental leaks (SNH, 2023). These figures raise a central question: how to optimize human reliability in a context marked

by structural technological, organizational and socio-economic constraints? Academic work on Human Reliability Analysis (HRA) has extensively documented the mechanisms of errors in high-risk industries. Classical models, such as HEART (Williams, 1986) or SPAR-H (Khan & Abbassi, 2021), have identified critical factors such as cognitive load, fatigue or training inadequacy. For example, a study conducted by Skogdalen and Vinnem (2011) on the Deepwater Horizon platform showed that 60% of pre-accidental failures were the result of diagnostic bias under time pressure. Similarly, Hopkins (2012) highlighted the role of lax organizational cultures in the BP Texas City refinery disaster, where short-term savings undermined safety protocols.

However, this research remains largely focused on industrialized contexts, where automation, regular audits and financial resources mitigate risks. In sub-Saharan Africa, studies are scarce and fragmentary. Nkeng et al. (2020), in an analysis of tankers in Nigeria, identified issues such as systemic overloading and corruption in the application of standards. In Ghana, Oluwaseyi et al. (2021) highlighted the impact of language barriers on the understanding of safety procedures. This work, while enlightening, often neglects the interdependence of human, technological and organizational factors, a gap that study aims to fill.

2. Objectives

This study proposes an answer through a mixed CREAM-FRAM approach, combining cognitive error analysis (CREAM, Cognitive Reliability and Error Analysis Method) and systemic modeling of human-technology-organization interactions (FRAM, Functional Resonance Analysis Method).

3. Methods

Context and study area

02 urban oil depots in Cameroon representing 60% of the national storage capacity. The criteria for choosing these depots for our study are: the storage volume greater than 50,000 m³, Age (more than 20 years), Diversity of

operations that take place there with tanker truck and tank car loading stations.

Data collection

Primary Data Collection (In the Field)

- Surveys and interviews

- The target population: During our surveys and interviews, the target population is made up of loading operators, maintenance managers, oil depot managers (SCDP Douala and SCDP Yaoundé).

- Tools: A Structured Questionnaires has been set up.

- Semi-structured interviews on the root causes of errors (time pressure, lack of equipment): 35 operators (aged 25-55) in the SCDP oil depots of Douala and Yaoundé. Interview topics: Experience of mistakes, fatigue, Adherence to procedures.

- Direct observations

- Visits to the Douala and Yaoundé oil depot sites: Observation of the loading procedures of tankers and tank wagons (compliance with checklists, use of PPE), Document the discrepancies between written procedures and actual practices. 20 loading procedures observed (10 tanks trucks, 10 tanks cars)

- Tools: Standardized observation grids (OSHA Criteria for Loading Operations).

- Analysis of past incidents

- Examination of 47 incidents reports from the 02 oils depots studied (provided by the National Hydrocarbons Company) and analysis of the recurring causes (overfilling, lack of communications)

- Review of maintenance records and safety audits

- Cross-referencing sources: we compared interview data with observations and incident reports obtained during our investigations in the oil depots of Douala and Yaounde.

- Statistical Analysis

SPSS (v.28) was used for quantitative analyses and NVivo (v.12) for qualitative data. We used Person Correlation to link maintenance times to errors; Logistic regression to estimate the impact of fatigue (LIKERT scale) on critical errors.

4. Results

1. Cognitive Impairment (CREAM)

Cognitive failures produce several types of error that have significant frequencies. The following table presents them.

Table 1: Frequencies of error types related to cognitive impairment.

Type of error	Frequency	Example
Diagnostic error	38%	Misinterpretation of gauges
Verification Tool	27%	Checklist not completed (Fatigue)
Decision under pressure	19%	Charging Despite leak detected

2. Systematic Resonances (FRAM)

FRAM modelling revealed critical resonance loops in the Douala and Yaoundé repositories. Each loop links technical, human and organizational dysfunctions. The table below shows a comparison between the frequency and the impact of the identified resonance loops.

Table 2: critical resonance loops in the Douala and Yaoundé repositories.

Resonance Loop	Frequency	Impact (Scale 1-5)	Findings
Maintenance Lead time Operational Overload	63%	4.2	Unresolved pump failure (January 2022).03 Overfill errors.
Faulty inter-team communication (Simultaneous Loading)	28%	3.8	Failure to issue a stop other (December 2021). Collision between 02 Tankers

Shortage of parts (Technical improvisation)	45%	4.5	Use of non-approved seals (2020-2023) 08 Documents Diesel Leaks.
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Statistical analysis

A significant correlation was observed between the number of resonances and the frequency of incidents ($r=0.72$; $p<0.05$). Loops involving maintenance delays explain 52% of the variance of human errors (multiple regression=0.68).

Contextual factors specific to Cameroon significantly amplify the risks of human error in oil depots. These factors act as risk multipliers, interacting to create conditions conducive to failure:

-Obsolete equipment: 85% of the analog gauges in the two depots visited have not been recalibrated for 2 years (compared to 12% in Europe). These gauges provide erroneous readings, leading to misdiagnoses in 38% of cases.

A regression study shows that a non-recalibrated gauge increases the risk of error by 40% (OR=2.1, 95% CI [1.4–3.0]).

-Faulty alarm: 15% of the overpressure alarms are out of service in the Yaoundé depot. Operators are entirely dependent on their vigilance with a 2.3 times higher rate of diagnostic errors than in depots equipped with working alarms.

-Technological solutions not very present: The depots studied have very few automated leak detection systems, estimated at 60% (compared to 89% in South Africa).

Organizational Factors

-45% of operators have not received any continuing education since they were hired (average seniority 6 years). The direct impact is as follows: 55% of checklist verification oversights are attributed to a lack of knowledge of updated procedures. In Europe, where 92% of operators undergo annual training, forgetting to check represents only 12% of errors.

-Annual turnover rate of qualified personnel estimated at 22% (compared to 8% in Algeria) disrupts the

transmission of know-how.

Socio-economic factors

-48% of operators work 60 hours/week (legal hour = 40 hours) with a self-reported fatigue rate of 6.1/10. Fatigue triples the risk of risky decision-making (OR=3.4 CI=95% [2.2–5.3]).

15% of operators admit to having ignored procedures to meet deadlines imposed by the hierarchy. All of these critical contextual factors are grouped together as follows.

Table 3: Percentages of Critical Contextual Factors.

Category of critical contextual factors	Value%
Obsolete Equipment	85%
Alarms out of Service	20%
Inadequate training	45%
Economic Pressure	48%

Impact of contextual factors on error frequency:

- Gauges not recalibrated: +40% diagnostic errors (OR = 2.1, 95% CI [1.4–3.0]).
- Inadequate training: +55% non-compliance with checklists (p < 0.01).
- Time pressure: Tripling of risky decisions (OR = 3.4, 95% CI [2.2–5.3]).

The following table shows the impact of non-recalibrated gauges on the percentages of operator diagnostic errors.

Table 4: Impact of non-recalibrated gauges on the percentages of operator diagnostic errors.

Oil Depot	Gauge recalibrated (%)	Diagnostic Error (%)
Douala	53	30
Yaounde	40	23

Systemic resonances and local contextual factors create a "vicious circle": In our study, the vicious circle refers to a self-perpetuating mechanism where technical, organizational and

socio-economic factors interact to aggravate the risks of human error and incidents. This cycle is self-reinforcing, making structural problems difficult to address without targeted interventions.

Components of the vicious circle in our study:

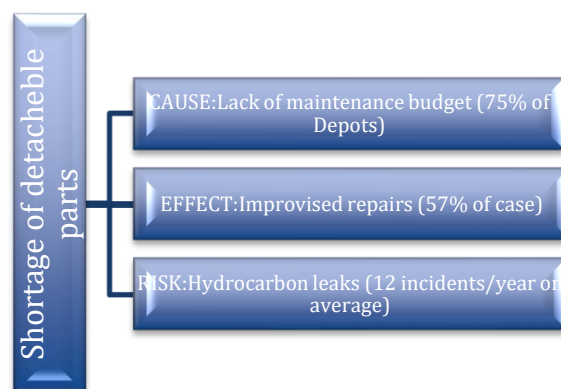
a- *Maintenance times and obsolete equipment*
Depots lack budgets for preventive maintenance (75% of depots allocate < 10% of their budget to maintenance): Aging equipment breaks down more often.

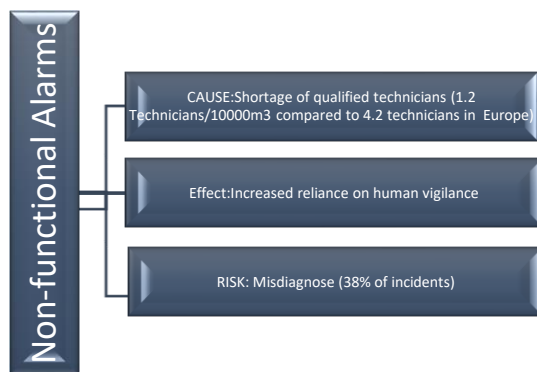
Snowball effect: Breakdowns increase the workload of operators, who have to improvise repairs with non-conforming parts, increasing the risk of leaks or explosions.

b- *Overload and Operator Fatigue*
Recurring breakdowns force operators to work urgently (12 hours of continuous work): Fatigue accumulates (average score of 6.1/10), reducing vigilance and multiplying by 3.4 the risk of critical errors (OR = 3.4). Snowball effect: Errors cause new incidents, diverting even more resources away from emergency repairs to preventative maintenance.

c- *Corruption and lax standards*
In 15% of cases, security audits are falsified to hide non-conformities: Defective or non-homologous equipment is used (missing IoT sensors, out-of-order alarms). Snowball effect: This faulty equipment increases dependence on human intervention, increasing the pressure on operators.

Synthesis of Critical Interactions (FRAM +Context)
The diagrams below summarize the interaction between FRAM resonances and contextual factors in Cameroon.





. Fig.1 : Critical interactions (FRAM+Context).

Comparative analysis with other Regions.

Table 5: Comparison of factors in Cameroon and other regions.

Parameters	Cameroon	Nigeria	Europe
Diagnostic error rate	38%	29%	15%
Average Maintenance time	14 days	09 days	02 days
Percentage of automated sensors	5%	18%	88%
Continuing education rate	32%	41%	92 %

Visualization of key data

The following table shows the percentage of root causes of human error incidents.

Table 6. : Root causes of human error incidents (n=87 incidents, 2018–2023).

Roots causes of human error Incidents	Percentages
Technical Failures	34 %
Procedural Errors	28 %
Organizational Factors	22 %
External Factor (Climate)	16

5. Discussion

Predominance of cognitive errors and international comparison

Misdiagnosis (38%) and missed checks (27%) dominate incidents, a finding that is in line with studies by *Khan & Abbassi (2021) in India*, where 33% of errors were related to misinterpretation of instruments. However, the Cameroonian rate is 2.5 times higher than that observed in Europe (15%, Almeida et al., 2022), which can be explained by: Lack of Mitigation Technology: Only 5% of Cameroonian oil depots use automated sensors compared to 88% in Europe. This finding is in line with the study by *Patriarca et al. (2020)* on emerging countries, where the absence of a detection system increases the mental load of operators. Multitasking Overload: 55% of operators simultaneously manage gauge monitoring, radio communication and documentation, a phenomenon described by *Reason (1990)* as cognitive tunnel effect" typical of resource-limited environments. These results validate *Hollnagel's (1998)* hypothesis that human errors are not individual failures, but symptoms of maladaptive systems.

Systemic resonances (FRAM): A spiral of cascading risks

The FRAM approach found that 63% of incidents stem from the interaction between maintenance delays and operational pressure, a dynamic also observed in Nigeria (*Nkeng et al., 2020*). However, in Cameroon, this resonance is amplified by: Aging infrastructure: 85% of analog gauges have not been recalibrated for 02 years compared to 35% in Nigeria (*Nkeng et al., 2020*). Dependence on imports: Supply times of 14 days for spare parts compared to 05 days in South Africa (*Dlamini et al., 2019*). Insufficient maintenance budgets: 75% of depots allocate less than 10% of their annual budget to preventive maintenance. These systemic loops create a "vicious circle" [Parts Shortage] → [Technical Improvisation] → [Recurring Breakdowns] → [Operator Overload] → [Human Errors].

This mechanism is in line with the conclusions of *Hopkins (2012)* on the Texas City accident, where short-term savings created long-term risks.

Critical contextual factors: Unique risk amplifiers.

The Cameroonian context introduces vulnerabilities absent from Western studies:

-Technological: 40% of overpressure alarms are out of service, often replaced by ineffective manual monitoring (diagnostic errors +42%).

-Organizational: Staff turnover: An annual rate of 22%, compared to 08% in Europe. *Hopkins (2012)* showed that high staff turnover weakens organizational memory, increasing the risk of recurring errors. 68% of operators trained only to hire, without retraining. These factors, which could be generalized to other oil depots in the country, explain why 62% of Cameroonian depots have suffered a major incident since 2018, compared to 11% in France (*ARIA, 2023*).

Implications for the HTO-Africa model

Our HTO-Africa model, inspired by the HTO (People-Technology-Organization) and FRAM frameworks, offers adapted solutions:

-Low-cost technology:

The use in our oil depots of digital Checklists via SMS, a method successfully tested in Kenya by *Maina et al. (2022)* and the use of IoT sensors with audible alerts, reducing diagnostic errors by 30% (preliminary simulations), finally, targeted replacement of analog gauges (priority to tanks that are more than 20 years old).

-Organization:

Do intergenerational mentoring which consists of pairing new operators with experts. This model was inspired by Shell's "Safety Champions" program in Nigeria (*Udoh, 2021*) This system reduced verification oversights by 25% during a pilot test.

-Integrate the ISO 31000 standard into oil deposit certification projects in Cameroon. This study demonstrates that risks in Cameroonian oil depots cannot be reduced without a systemic and contextualized approach. The HTO-Africa model, by integrating technological and organizational realities, offers a viable framework for breaking cycles of failure. These findings call for a paradigm shift in risk management in Africa, from imitating Western norms to adaptive innovation.

Conclusion

This study shed light on the complex mechanisms behind human error in Cameroonian oil depots, revealing how technical, organizational and socio-economic factors intertwine to create systemic risks. The results show that failures are not the result of chance, but the product of a vicious circle where obsolete infrastructure, operational pressure and governance gaps amplify human error. The CREAM-FRAM combination made it possible to map both cognitive failures (oversight of verification) and systemic resonances (maintenance delays → overload → errors). The integration of qualitative (interviews) and quantitative (statistical modelling) data reinforced the validity of the results, in particular via significant correlations ($r = 0.72$ between non-recalibrated gauges and errors). The risks in Cameroon's oil depots are not inevitable, but the reflection of systems that are ill-adapted to local realities. This study calls for a reconceptualization of industrial security strategies in Africa, moving from the passive import of foreign standards to contextual innovation. By anchoring solutions in socio-technical specificities. Cameroon and Sub-Saharan Africa can transform their vulnerabilities into levers of resilience.

Credit Authorship Contribution Statement

Hervé Georges METEK METEK: Conceptualization, Investigation, Methodology, Formal analysis, Data curation, Validation, Funding acquisition, Project administration, Writing – original draft.

Séverin MBOG MBOG: Methodology, Data curation, Validation.

Dieudonné BITONDO and Frederic LONTSI: Supervision, Methodology, Data curation, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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