

# Fuzzy Logic-Based Process Safety Management Framework for Risk Assessment in Liquefied Petroleum Gas Tanker Unloading

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Process Safety Management (PSM) has long been the cornerstone of hazard prevention in the oil and gas sector. However, conventional PSM tools—such as deterministic checklists, risk matrices, and semi-quantitative methods including Hazard and Operability Study (HAZOP) and Layer of Protection Analysis (LOPA)—are limited by subjectivity, rigid decision thresholds, and weak integration with dynamic operating conditions. This paper proposes a fuzzy logic-based risk assessment framework to complement PSM in the context of Liquefied Petroleum Gas (LPG) tanker unloading operations at filling plants. A Mamdani fuzzy inference system is developed using three critical operational drivers: pressure differential, storage-sphere fill level, and vapor temperature. These inputs are integrated to generate a continuous Risk Index (0–100) mapped onto four operational decision bands (green, yellow, orange, red). Simulation results indicate that high risk emerges when two drivers simultaneously reach elevated states, while severe risk may be triggered by a single very high temperature condition, highlighting the dominant role of thermal escalation. Compared to traditional risk matrices, the proposed approach provides a continuous and dynamic risk index, avoiding artificial discontinuities at decision thresholds while maintaining transparency and clear operational decision bands. The proposed framework enhances PSM robustness and supports proactive operational decision-making during LPG tanker unloading.

## 1. Introduction

Liquefied Petroleum Gas (LPG) storage and transfer operations are among the most hazardous activities in the oil and gas sector due to the potential for overpressure, overfill, and boiling liquid expanding vapor explosions (BLEVEs). Process Safety Management (PSM) frameworks, such as OSHA's regulation on highly hazardous chemicals (OSHA, 1992) and the CCPS Risk-Based Process Safety guidelines (CCPS, 2017), provide structured governance through hazard identification, barrier management, and training. Despite their maturity, conventional methods such as hazard and operability studies (HAZOP), risk matrices, and layer of protection analysis (LOPA) are constrained by subjectivity, rigid decision thresholds, and weak integration with dynamic operating conditions (ISO, 2018).

To overcome these limitations, several approaches have been proposed. Prescriptive codes such as the National Fire Protection Association (NFPA) Liquefied Petroleum Gas Code NFPA 58 (2020) set baseline compliance requirements but do not adapt to fluctuating risks. Research integrating HAZOP with fuzzy logic demonstrated that quantifying uncertainty improves the accuracy and usability of risk assessment in LPG filling operations (Oubellouch and Soulhi, 2024a). Comparative studies of artificial intelligence (AI) methods for risk assessment confirmed that fuzzy inference systems are more transparent and interpretable than black-box models, making them particularly appropriate for safety-critical decisions (Oubellouch and Soulhi, 2024b). On the theoretical side, fuzzy set theory (Zadeh, 1965) and its engineering applications (Ross, 2010) provide a robust basis for modelling vagueness and linguistic reasoning. Recent applications in chemical process safety further demonstrate (Mohamed, Hassan and Azzam, 2021) the ability of fuzzy systems to capture gradual risk escalation and support operational decision-making (Zhao, Li and Chen, 2022).

In LPG filling plants, road tanker unloading is widely recognized as one of the most critical operations due to its strong association with major accident scenarios. Analyses of LPG storage and transfer accidents indicate that unloading operations are frequently associated with initiating events such as overfilling, hose rupture, and vapor release, which can escalate into fires, explosions, or boiling liquid expanding vapor explosions (BLEVEs) (Palazzi et al., 2021). Thermal escalation has also been identified as a dominant aggravating factor in LPG accidents, where elevated temperatures alone may trigger severe consequences even under otherwise controlled operating conditions (Abbasi and Abbasi, 2007).

Compared to our previous studies addressing fuzzy-based risk assessment for LPG operations in a static or semi-quantitative manner, the present work introduces a continuous fuzzy-based risk index explicitly integrated within a Process Safety Management (PSM) framework. The proposed approach goes beyond risk ranking by directly linking fuzzy inference outputs to operational decision bands aligned with barrier verification and emergency response actions. This integration enables proactive and near real-time supervisory decision support during LPG tanker unloading operations, which was not addressed in our earlier publications.

## 2. Methodology

### 2.1 Case study: LPG tanker unloading operations

In the Moroccan downstream LPG sector, road tanker unloading is the dominant mode of supply for filling plants. Each tanker transports approximately 19–20 t of butane, which is discharged into pressurised storage spheres or horizontal cylindrical tanks. The operation is performed in more than 90 % of filling plants nationwide and has been consistently identified as the most hazardous step. Historical records confirm that unloading is disproportionately associated with hose ruptures, coupling leaks, overfill, and vapor releases, sometimes escalating into major incidents such as boiling liquid expanding vapor explosions (BLEVEs).

The unloading process requires operator intervention through a standardized sequence. The procedure begins with the completion of a dedicated unloading checklist to ensure equipment readiness and safety compliance. The operator then connects the two loading arms: one for the liquid phase and one for the gas phase. Once connections are verified, the compressor is started. It aspirates the vapor phase from the top of the storage sphere and discharges it into the tanker, thereby increasing tanker pressure. This pressure differential forces the liquid phase from the tanker through the second loading arm into the sphere until the target fill level is reached.

Figure 1 illustrates the main steps of the proposed fuzzy logic-based risk assessment framework, from hazard identification and selection of critical operational drivers to fuzzy inference and integration of the resulting Risk Index into Process Safety Management decision bands.

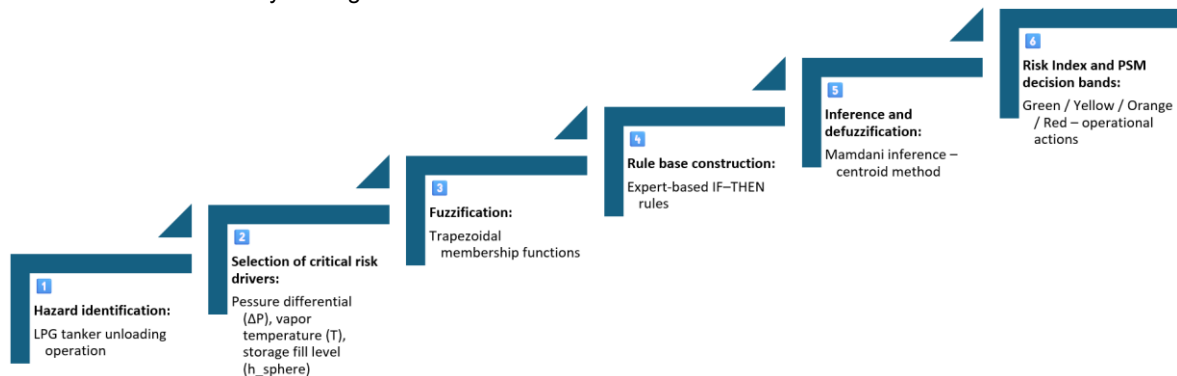


Figure 1: Methodological flowchart of the fuzzy logic-based Process Safety Management framework for LPG tanker unloading operations.

Throughout the operation, safety barriers are in place, including level gauges, pressure and temperature indicators, pressure relief valves (PRVs), and emergency shutdown valves (ESDs). Based on incident analyses, three operational drivers have been identified as critical for risk escalation: pressure differential ( $\Delta P$ ), vapor temperature (T), and storage sphere fill level ( $h_{\text{sphere}}$ ).

### 2.2 Fuzzy inference system design

Fuzzy set theory, introduced by Zadeh (1965) and applied to engineering systems by Ross (2010), provides an effective approach for managing uncertainty and linguistic reasoning. Unlike binary thresholds, fuzzy sets allow gradual transitions across states such as “low,” “medium,” or “very high.” This makes them particularly suited

for safety-critical processes where operational conditions fluctuate, and precise boundaries are difficult to establish.

A Mamdani fuzzy inference system (FIS) was designed to integrate  $\Delta P$ , T, and  $h_{\text{sphere}}$  into a single Risk Index. The model was constructed as follows:

Inputs:  $\Delta P$  (0–8 bar),  $h_{\text{sphere}}$  (0–100 %), and T (20–70 °C).

Output: Risk Index (0–100).

Membership functions: trapezoidal, with four linguistic sets {Low, Medium, High, Very High}.

Trapezoidal membership functions were selected due to their robustness, simplicity, and ease of interpretation, which are essential for safety-critical industrial applications. Compared to Gaussian or bell-shaped membership functions, trapezoidal functions reduce sensitivity to measurement noise and better reflect expert-defined operational envelopes commonly used in Process Safety Management practice. This choice enhances transparency, reproducibility, and practical usability of the fuzzy inference system for LPG tanker unloading operations.

Rule base: 27 IF–THEN rules derived from expert knowledge and operational envelopes.

Example rules include:

If  $\Delta P$  is Low AND T is Low AND  $h_{\text{sphere}}$  is Low, then Risk is Low

If  $\Delta P$  is High AND  $h_{\text{sphere}}$  is High, THEN Risk is Severe.

If T is Very High THEN Risk is Severe regardless of other inputs.

Inference engine: Mamdani min–max with centroid defuzzification.

Additional representative fuzzy rules were included to capture critical escalation scenarios frequently observed during LPG tanker unloading operations. For instance:

IF pressure differential is High AND vapor temperature is High, THEN Risk is Severe.

IF storage sphere fill level is Very High, THEN Risk is Severe, regardless of pressure differential.

IF vapor temperature is Very High, THEN Risk is Severe, even under moderate pressure conditions.

These rules reflect conservative safety reasoning and ensure that dominant hazards such as thermal escalation and overfilling are adequately represented within the fuzzy inference system.

### 2.3 Risk bands and integration with PSM

The defuzzified Risk Index was partitioned into four decision bands to align with operational practice in PSM. Table 1 summarizes the operational decision bands associated with the defuzzified Risk Index and their corresponding Process Safety Management actions.

Table 1: Risk bands for LPG unloading operations

Risk Index	Band	Operational guidance
< 30	Green	Monitor normal operations
30–60	Yellow	Anticipate; reduce $\Delta P$ or redistribute load
60–80	Orange	Prepare to stop; verify PRV and ESD readiness
$\geq 80$	Red	Immediate stop and controlled shutdown

This mapping bridges fuzzy outputs with barrier-based procedures, ensuring that operators receive clear and actionable guidance. It transforms continuous, uncertain conditions into operationally usable safety decisions, overcoming the rigidity of conventional risk matrices.

The fuzzy inference system and all simulation analyses were implemented using MATLAB® Fuzzy Logic Toolbox (MathWorks Inc.). This environment was selected due to its robustness, transparency, and widespread adoption in engineering applications involving fuzzy-based decision support systems.

## 3. Results and discussion

### 3.1 Risk surface: pressure differential vs. fill level

The first simulation explored the interaction between pressure differential ( $\Delta P$ ) and sphere fill level ( $h_{\text{sphere}}$ ) at a constant temperature of 40 °C. Risk remains Low for  $\Delta P \leq 2$  bar and  $h_{\text{sphere}} \leq 40$  %. As  $\Delta P$  rises to 3–5 bar and  $h_{\text{sphere}}$  approaches 60–70 %, the Risk Index gradually increases into the Medium and High regions. Two dominant discontinuities emerge:

- $\Delta P \geq 6$  bar shifts risk abruptly to High or Severe even at mid-levels.
- $h_{\text{sphere}} \geq 80$  % locks the system in High risk regardless of  $\Delta P$ .

Operational implication: limit  $\Delta P$  to <3 bar when  $h_{\text{sphere}} > 60$  % and avoid filling beyond 80 % by redistributing loads across storage spheres.

Figure 2 illustrates the variation of the Risk Index as a function of pressure differential and storage sphere fill level at a constant vapor temperature of 40 °C

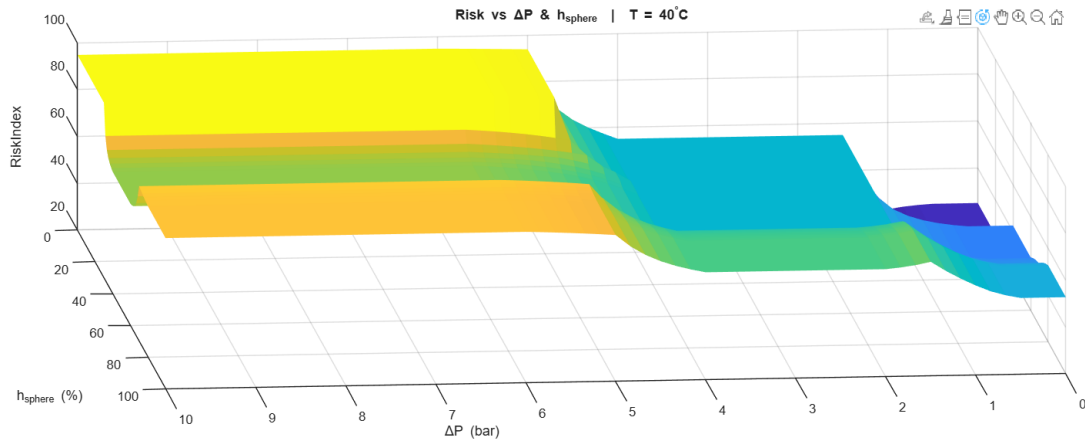


Figure 2: Risk vs  $\Delta P$  and storage-sphere fill level ( $h_{sphere}$ ) at  $T = 40\text{ }^{\circ}\text{C}$

### 3.2 Risk surface: pressure differential vs. vapor temperature

At a fixed  $h_{sphere}$  of 50 %, the relationship between  $\Delta P$  and temperature ( $T$ ) was analysed. For  $T \leq 35\text{ }^{\circ}\text{C}$ , risk remains Low/Medium up to  $\Delta P \approx 4\text{--}5$  bar. As  $T$  increases to 40–55 °C, Medium/High risk regions appear, reducing the safety buffer to PRV activation. A critical threshold is observed at  $T \geq 55\text{ }^{\circ}\text{C}$ : Severe risk arises even at moderate  $\Delta P$  values. The combination of  $\Delta P \geq 5$  bar and  $T \geq 55\text{ }^{\circ}\text{C}$  produces a Severe plateau.

Operational implication: in hot conditions, operators should reduce compressor throughput by 1–2 bar. If  $T \geq 55\text{ }^{\circ}\text{C}$ , transfer should be slowed or suspended, with PRVs and ESDs verified before continuation.

Figure 3 shows the combined effect of pressure differential and vapor temperature on the Risk Index for a fixed storage fill level of 50 %

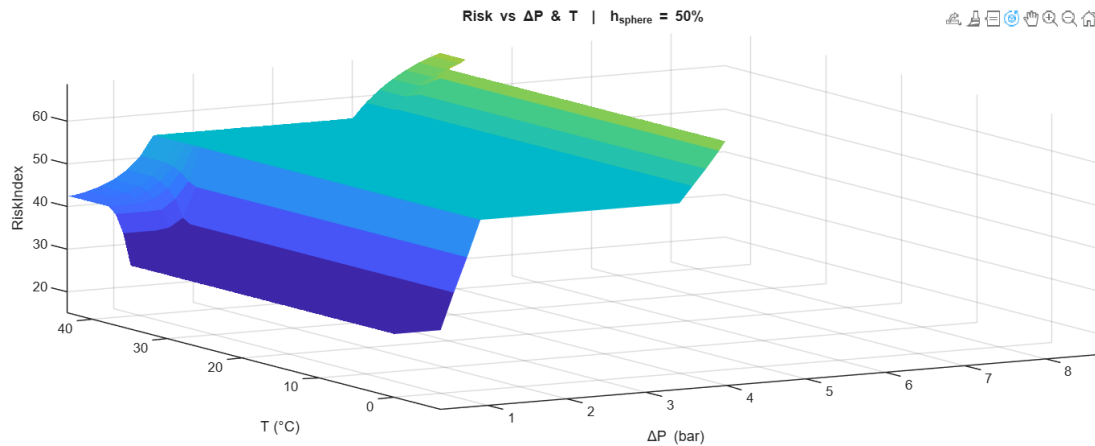


Figure 3: Risk vs  $\Delta P$  and vapor temperature ( $T$ ) at  $h_{sphere} = 50\text{ }%$

### 3.3 Risk surface: temperature vs. fill level

A third simulation assessed the combined effect of  $T$  and  $h_{sphere}$  at a fixed  $\Delta P$  of 3 bar. Results show Low risk for  $T \leq 35\text{ }^{\circ}\text{C}$  and  $h_{sphere} \leq 50\text{ }%$ . When  $h_{sphere}$  approaches 80–90 %, risk escalates to High regardless of temperature, highlighting overfill as a dominant hazard. Conversely, when  $T \geq 55\text{--}60\text{ }^{\circ}\text{C}$ , risk climbs to Medium/High even for mid fill levels (~50–60 %). At elevated  $T$  and high  $h_{sphere}$ , the system enters Severe risk, independent of  $\Delta P$  control.

Operational implication: unloading should be rescheduled or redistributed when high ambient temperatures coincide with storage levels above 80 %. Early stop preparation is recommended whenever Very High

temperature or high fill levels are observed, even with moderate  $\Delta P$ . Figure 4 presents the risk surface associated with vapor temperature and storage sphere fill level at a constant pressure differential of 3 bar

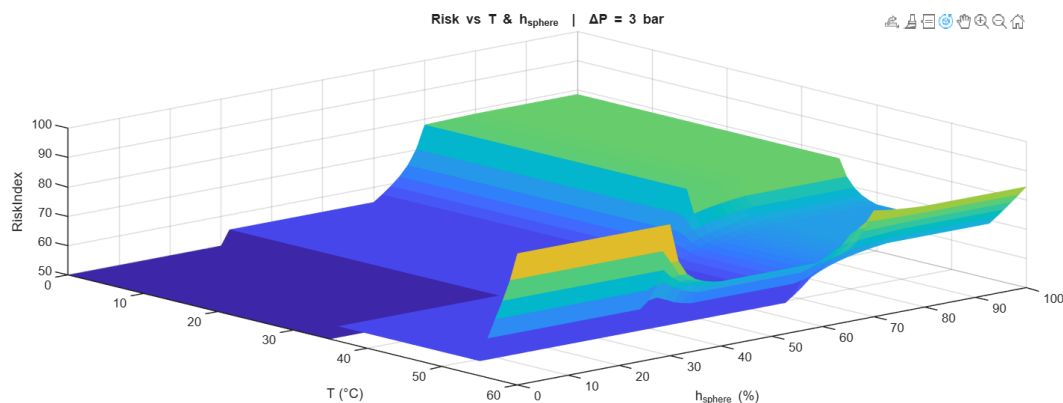


Figure 4: Risk surface for  $T$  and  $h_{sphere}$  at  $\Delta P = 3$  bar.

### 3.4 Comparative discussion

The fuzzy inference system demonstrates that risk escalation is continuous and interpretable, in contrast with conventional matrices where binary thresholds dominate. Results confirm that High risk emerges when two parameters simultaneously reach their “High” state, while Severe risk can be triggered by a single “Very High” temperature. These outcomes are consistent with industry observations where thermal escalation and overfill drive most LPG incidents.

By embedding results into PSM decision bands, the framework provides explicit operational guidance. Supervisors can anticipate unsafe conditions, validate safety barriers, and implement controlled shutdowns when necessary. Compared to traditional tools, the fuzzy model offers a transparent and operationally usable approach to managing uncertainty during LPG unloading.

From a validation perspective, the proposed fuzzy logic-based framework was assessed through consistency checks, expert judgment, and comparison with documented accident mechanisms reported in the literature. Although direct calibration against large-scale historical incident datasets was not performed, the dominant risk patterns identified by the model are fully consistent with established accident analyses related to LPG storage and transfer operations. In particular, the strong influence of overfilling and thermal escalation highlighted by the fuzzy risk surfaces aligns with accident scenario studies, where these initiating events are recognized as primary contributors to major LPG accidents. This qualitative validation confirms that the model behavior is physically meaningful and coherent with real-world process safety experience.

The integration of a continuous risk index into operational decision-making is consistent with previous contributions published in *Chemical Engineering Transactions*, which emphasize the importance of dynamic risk assessment and barrier-based decision support in process safety management (Paltrinieri et al., 2014; Cozzani et al., 2013).

## 4. Conclusions

This study proposed a fuzzy logic-based framework to enhance Process Safety Management during LPG tanker unloading operations by integrating key operational drivers into a continuous and interpretable Risk Index. Unlike conventional risk matrices, the proposed approach captures gradual risk escalation and directly links risk levels to operational decision bands aligned with barrier management and emergency response actions.

The results demonstrate that the framework is particularly effective in highlighting dominant accident drivers such as thermal escalation and overfilling, which are widely recognized as critical contributors to major LPG accidents. By embedding fuzzy inference outputs into practical PSM decision-making, the model supports proactive supervision and timely intervention during unloading operations.

Overall, the proposed framework provides a transparent and operationally usable tool that complements existing PSM practices in LPG filling plants. Future work will focus on integrating real-time operational data, human factors, and data-driven calibration techniques to further strengthen predictive capability and industrial applicability.

## Nomenclature

$\Delta P$  – Pressure differential between tanker and storage sphere, bar

T – Vapor temperature, °C

h\_sphere – Storage sphere fill level, %

PRV – Pressure relief valve

ESD – Emergency shutdown valve

PSM – Process Safety Management

FIS – Fuzzy inference system

P&ID- Piping and Instrumentation Diagram

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