



Domino effect in industrial plants: A petri net based approach

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ABSTRACT

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In industrial settings, storing and managing hazardous materials carries a high risk of major accidents, especially from domino effects where one event sparks a chain of subsequent failures. These incidents can devastate human lives, ecosystems, and facilities. This paper presents a structured approach using Petri-net modeling to evaluate and forecast domino effects across industrial layouts. Unlike traditional risk assessments that struggle with the dynamic, time-varying, and probabilistic aspects of failure cascades, our framework supports real-time simulations of accident spread by modeling process units and safety conditions as "places" and failure occurrences as "transitions." We quantify risks through proven vulnerability models like probit functions for escalation pathways and event rates from historical records or fault tree analysis. This generates time-based failure patterns for at-risk equipment, delivering deeper insights into how risks develop. Beyond pinpointing key escalation routes, the method calculates time-specific escalation probabilities, equipping safety leaders with a powerful tool for preventing and controlling domino effects.

1. INTRODUCTION

Industrial plants often handle large volumes of flammable, toxic, and explosive materials, making them vulnerable to devastating accidents by nature. An initial trigger like a fire, blast, or chemical leak can spark a domino effect, where the primary event escalates dramatically through a series of follow-on incidents. Mastering the analysis and control of these cascades is essential to protect workers, ecosystems, and assets.

Although domino effects are well-documented in industrial safety research, their exact meaning in engineering contexts can be subtle. Here, we use the definition from Farid Kadri and Eric Chatelet [1]: "A domino accidental event is considered an accident in which a primary event propagates to nearby equipment, triggering one or more secondary events, resulting in overall consequences more severe than those of the primary event."

2. CHALLENGES IN DOMINO EFFECT PREDICTION

Current approaches to forecasting and controlling domino effects encounter key hurdles:

System Complexity: Today's industrial setups feature complex links between process units, utilities, and safety features, making it hard to model interactions and escalation routes.

Data Limitations: Reliable data on equipment specs, hazardous materials, and trigger events is frequently sparse or inaccurate, forcing assumptions that undermine risk analysis credibility.

Quantification Difficulties: Tools like MICADO [2] and DELVOSALLE [3] are mostly qualitative, falling short on the precise metrics needed for thorough risk evaluation.

Absence of a Unified Approach: No single, widely endorsed method fully tackles the evaluation and mitigation of domino risks across industrial environments.

Scenario Underrepresentation: Certain techniques emphasize isolated events at single units, missing potential overlapping or amplifying cascades from various origins. Fault tree methods have advanced this modeling as in [4], yet gaps persist.

Computational Demands: Sophisticated simulators, like fire dynamics software, demand heavy processing power, restricting their use in everyday risk checks.

3. ROPOSED METHODOLOGY: PETRI-NET MODELING FOR DOMINO EFFECT ANALYSIS

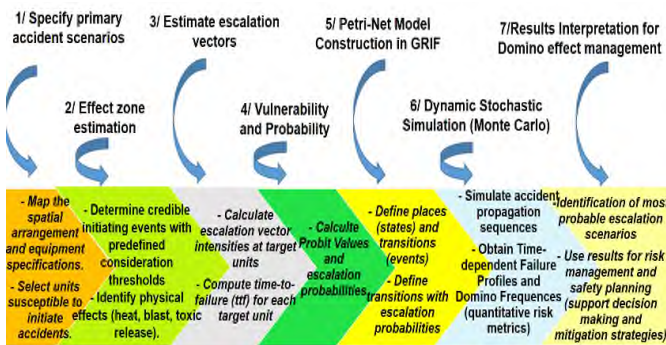


Figure 1. Steps of the Proposed Petri-Net Methodology for Domino Effect Assessment

Petri-net modeling emerges as a robust and versatile tool for addressing the above challenges in domino effect analysis. Its strengths include:

- **Visualization and Comprehension:** Petri-net models provide a clear graphical representation of the interdependencies and potential escalation pathways within an industrial facility, enhancing understanding and communication among stakeholders.
- **Dynamic Simulation and Analysis:** By simulating the propagation of accidents, Petri-nets enable the evaluation of various domino scenarios, supporting both qualitative insights and quantitative risk assessment.
- **Integration with Safety Systems:** Petri-nets can be seamlessly integrated with existing safety system designs, accounting for both system reliability and potential failure modes, thus offering a comprehensive framework for risk management.

In this study, we propose an advanced methodology based on the GRIF Petri-net modeling platform, building upon the dynamic risk assessment framework presented in [5]. Our approach also incorporates recent advances in the quantification of synergistic effects, as emphasized by the Fire Synergistic Effect Model (FSEM) [6], which highlights the importance of temporal escalation and cumulative impacts on equipment time-to-failure (TTF) and escalation probability.

3.1 Key Elements of the Methodology

Our methodology is structured around the following core components:

- **Scenario Definition :** Identification of potential domino scenarios based on the properties of stored hazardous materials, facility layout, and historical accident data.
- **Effect Zone Estimation :** Application of predefined physical thresholds to delineate the impact zones of

primary events and assess the likelihood of secondary event initiation.

- **Escalation Vector Analysis:** Integration of escalation vectors such as thermal radiation, blast overpressure, and toxic dispersion into the Petri-net framework to model their influence on accident propagation and consequence severity.

- **Probability Calculation:** Utilization of established vulnerability functions, including Probit models as outlined in the "Purple Book" [7], to quantify the probability of escalation for each scenario.

- **Domino Event Modeling:** Use of Petri-net elements to capture the dynamic propagation of events, enabling the simulation of complex, multi-stage domino sequences and the identification of critical escalation pathways.

4. GRIF-PETRI-NET METHODOLOGY FOR DOMINO EFFECT ASSESSMENT

Before applying the proposed methodology using GRIF-Petri-net on a case study we provide a brief and simple presentation of the steps to follow in figure 01.

4.1 Scenario Definition

The process begins by identifying all credible accident scenarios within the facility, considering the characteristics of stored hazardous substances, facility layout, and known accident scenarios following what was stated by (Kadri & Chatelet, 2013, p. 2) [1]

4.2 Effect Zone Estimation

For each primary event, the impact zone is estimated using predefined thresholds for escalation vectors such as described INERIS (2002, p. 7) [2]

4.3 Escalation Vector Analysis

The intensity of escalation vectors such as heat, blast, or toxic effects is then calculated. "The escalation vector is the physical effect (thermal radiation, overpressure, fragments) produced by the primary event, which may cause the escalation of the accident to nearby equipment" explain (Ding et al., 2019, p. 271) [6].

4.4 Effect Zone Estimation

To quantify the likelihood that an escalation vector will cause failure, probit models are used. The Purple Book (CPR 18E) provides the approach:

"The probability of escalation is calculated using probit functions, which relate the intensity and duration of the escalation vector to the probability of failure of the target" [7]

Kamil et al. (2019) further clarify: "The escalation probability is calculated using the probit model, which

links the heat radiation received by the equipment to the probability of failure" (Kamil et al., 2019, p. 311) [5].

4.5 Petri-Net Model Construction in GRIF

The GRIF Petri-net model is constructed by representing each process unit and its safety states as "places," and accident events (ignition, escalation, failure) as "transitions." Kamil et al. (2019) describe this step:

"The Petri-net model represents the system as a set of places (states of the equipment) and transitions (events such as ignition, escalation, and failure), with tokens used to indicate the current state" (Kamil et al., 2019, p. 309) [5].

4.6 Dynamic Simulation

The Petri-net simulation is run to dynamically observe how domino effects propagate over time. Kamil et al. (2019) note:

"The Petri-net model is simulated to capture the dynamic propagation of accidents and to calculate the frequency and probability of domino scenarios" (Kamil et al., 2019, p. 313) [5].

Ding et al. (2019) add: "The model allows for the quantification of synergistic effects and the time-dependent escalation probability" (Ding et al., 2019, p. 272) [6].

"This Petri Net tool, the module Petri of the GRIF Software suite, is designed to model the behavior of complex dynamic systems using stochastic Petri nets with predicates and assertions. All the computations are performed by MOCA-RP (MOnte-CARlo - Petri Nets), TotalEnergies' high-speed calculation engine, which as its name suggests, is based on the Monte Carlo simulation, and is pushing the boundaries of modeling." [9]

4.7 Results Interpretation and Risk Quantification

Finally, the output is analyzed to identify critical domino paths and quantify risk. Kamil et al. (2019) summarize: "The results provide time-dependent failure profiles and frequencies for each domino scenario, supporting risk-informed decision making for safety management" (Kamil et al., 2019, p. 314). [5]

5. CASE STUDY: GASOLINE TANK FARM

5.1 System description and context

To demonstrate our proposed methodology, we apply it on a hypothetical case study of a gasoline tank farm. The studied scenario for sake of simplicity, is demonstrated in a facility containing three identical atmospheric storage tanks (Tank1, Tank2, Tank3). Each tank has a diameter of 40 meters and a height of 20 meters, enclosed within an 80 m × 80 m retention sump. The tanks are arranged with 40 meters spacing between Tank 1 and Tank 2, and between Tank 2 and Tank 3 (Figure 2). This configuration represents a common industrial layout where domino effects can propagate through heat radiation or blast impacts.

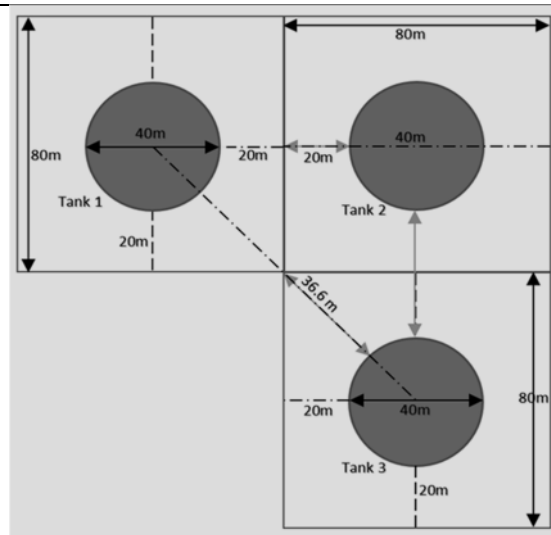


Figure 2. Plant of the gasoline tank farm

This simplified layout provides a controlled environment to test and validate the GRIF Petri-net methodology, allowing clear observation of domino effect pathways and escalation probabilities.

We assume that a loss of containment occurs in tank 1, with a frequency given in Table 01 with the necessary inputs, followed by ignition that sets tank 1 on fire. We will apply our proposed methodology to determine whether we can calculate the probability of fire spreading to the neighboring tanks (tanks 2 and 3) and to identify the possible escalation scenarios. We will also examine which scenario is most likely to occur. Additionally, we will assess whether a synergistic effect could arise, whether two tanks burning simultaneously could increase the impact on a third tank. We will calculate the time to failure (TTF) for each tank, taking into account the time evolution of the incident. Through this process, we aim also to test whether our approach can help us improve the safety system by enhancing our understanding and management of domino effect phenomena.

Table 1. key input parameters used in the Petri-net model and escalation calculations

Parameter	Symbol	Value	Unit	Description
Tank Diameter	D	40	M	Diameter of each tank
Tank Height	H	20	M	Height of each tank
Distance Tank1→Tank2	d12	40	M	Wall-to-wall spacing between Tank1 and Tank2
Distance Tank2→Tank3	d23	40	M	Wall-to-wall spacing between Tank2 and Tank3

Distance Tank1→Tank3	D13	36.6	M	Wall-to-wall spacing between Tank1 and Tank3
Heat Radiation at Tank2 from Tank1	HR_T1 →2	17.11	kW/ m ²	Calculated heat radiation
Time to Failure (Tank2)	ttf_T2	To calculat e	seconds	Time to failure under heat radiation
Ignition Probability	P_ignition	0.7	-	Probability that released fuel ignites
Loss of Containment Frequency	F_LOC	5×10 ⁻⁶	/year	Frequency of loss of containment

5.2 Estimation of Escalation Vectors

For each primary event, escalation vectors specifically heat radiation intensities are calculated at neighboring tanks. In order to minimize the complexity of calculations and to simplify the process as much as possible, especially since safety experts are not necessarily required to be specialists in mathematics or physics. We decided to use the Thomas model to calculate the heat flux received by adjacent tanks following the ignition of a burning tank. These calculations consider the distance between tanks and the physical properties of the fire, using validated engineering models embedded in the GRIF software. For example, heat radiation from Tank 1's fire affects Tank 2 and Tank 3 differently due to their relative positions and distances.

The "Thomas model" in the context of heat flux calculations typically refers to the use of the Thomas algorithm, which is a specialized, efficient method for solving tridiagonal systems of linear equations that arise when discretizing the one-dimensional heat diffusion (conduction) equation using finite difference methods.

5.3 Time-to-Failure (ttf) Calculation

Using the heat radiation intensity, the time-to-failure for each exposed tank is calculated with the correlation:

$$\ln ttf_{Ta \rightarrow Tb} = -1.13 \cdot \ln(HR_{Ta \rightarrow Tb}) - 2.67 \cdot V / 100000 + 9.9$$

where HR is the heat radiation intensity (kW/m²) emitted from tank a to tank b, and V is the tank volume (m³). This formula captures the dynamic vulnerability of tanks exposed to thermal radiation, reflecting how longer exposure reduces structural integrity [07] .

5.4 Probit Model for Escalation Probability

The time-to-failure values feed into a probit function to estimate escalation probability (we considered only heat radiation as escalation vector) :

$$Y = 12.54 - 1.847 \times \ln(ttf_{Ta \rightarrow Tb}) \quad [7]$$

$$PES = 1.005 / (1.0 + \exp(-Y_{Ta \rightarrow Tb} / 0.6120 + 5.004 / 0.6120)) \quad [7]$$

This quantifies the likelihood that the heated tank will fail and propagate the accident, integrating both intensity and duration of exposure [5].

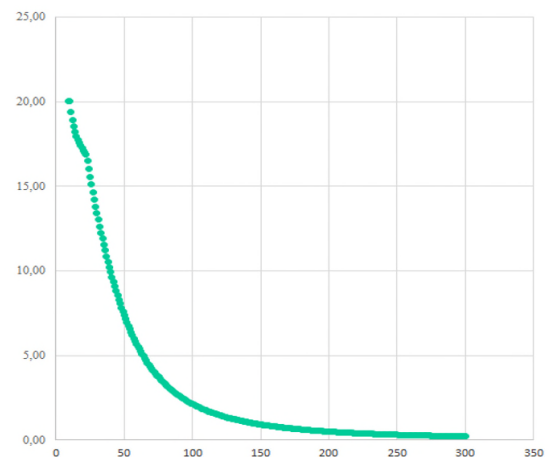


Figure 3. Received Heat Flux Versus Distance Between Tanks Predicted by the Thomas Model

5.5 Construction of the GRIF Petri-Net Model

Each tank's safety states (intact, exposed, failed) are modeled as places, while events such as ignition, escalation, and failure are transitions. Tokens represent the current state of each tank, moving through the Petri-net as events occur. [8]

The model incorporates the calculated escalation probabilities and ignition probabilities (e.g., Pignition=0.7) as transition weights, allowing stochastic simulation of accident propagation sequences.

Table 2 : Equations inserted to the GRIF-Petri-Net Model and inherent results

FLOAT	YT32	12.54-1.847*LN_ttfT32	2.861
FLOAT	YT23	12.54-1.847*LN_ttfT23	2.441
FLOAT	YT13	12.54-1.847*LN_ttfT13	0.467
FLOAT	YT12	12.54-1.847*LN_ttfT12	1.414
INT	V	2.5E4	2500
FLOAT	P ignition	0.7	0.7
FLOAT	PEST32	1.005/(1.0+exp(-YT32/0.6120+5.004/0.6120))	0.030
FLOAT	PEST23	1.005/(1.0+exp(-YT23/0.6120+5.004/0.6120))	0.015

FLOAT	PEST13	$1.005/(1.0+\exp(-YT13/0.6120+5.004/0.6120))$	6.062 E-4
FLOAT	PEST12	$1.005/(1.0+\exp(-YT12/0.6120+5.004/0.6120))$	2.842 E-3
FLOAT	LN_ttfT32	$-1.13*\ln(HR_T32)-2.67*V/100000+9.9$	5.240
FLOAT	LN_ttfT23	$-1.13*\ln(HR_T23)-2.67*V/100000+9.9$	5.468
FLOAT	LN_ttfT13	$-1.13*\ln(HR_T13)-2.67*V/100000+9.9$	6.536
FLOAT	LN_ttfT12	$-1.13*\ln(HR_T12)-2.67*V/100000+9.9$	6.023
FLOAT	HR_T32	$2*HR_T12$	34.22
FLOAT	HR_T23	HR_T12+HR_T13	27.98
FLOAT	HR_T13	10.87	10.87
FLOAT	HR_T12	17.11	17.11
FLOAT	F_LOC	5E-6	5E-6

5.6 Dynamic Simulation and Scenario Exploration

The GRIF software runs Monte Carlo simulations of the Petri-net, exploring all possible domino sequences, including simultaneous and synergistic events. For example, heat radiation from multiple tanks is summed to model synergistic effects on a target tank's failure probability [6].

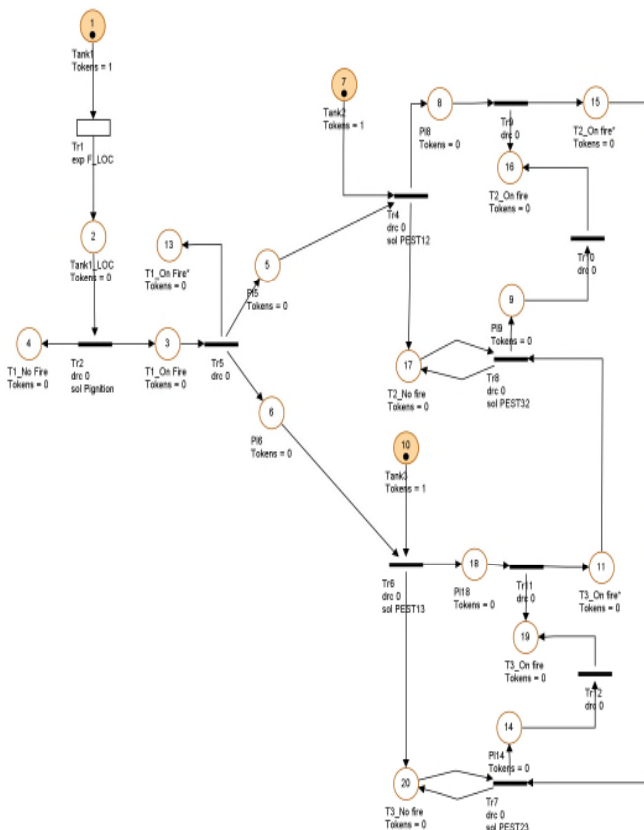


Figure 4. GRIF-Petri-net model [15]

Table 3 : Frequencies of each transition calculated by the GRIF-Petri-Net Model

Transitions	Frequencies *10E-2/year
Tr1 : 1	4.989E-4
Tr2 : 2	4.989E-4
Tr4 : 4	3.4916E-4
Tr5 : 5	3.492E-4
Tr6 : 6	3.492E-4
Tr7 : 7	1.020E-6
Tr8 : 8	2.700E-7
Tr9 : 9	1.020E-6
Tr10 : 10	0.0
Tr11 : 11	2.700E-7
Tr12 : 12	2.000E-8

The simulation outputs frequencies and probabilities for each domino scenario, enabling identification of the most critical escalation paths are grouped in table3.

Table 04 : Present simulation results highlighting the most critical domino sequences and their likelihood. [15]

Transition No.	Scenario Description	Frequency (per year)	Escalation Probability (P_ES)
Tr1	Tank1 LOC	4.989 × 10 ⁻⁶	-
Tr2	Tank2 LOC	4.989 × 10 ⁻⁶	-
Tr4	Tank1 → Tank2 Escalation	3.492 × 10 ⁻⁶	2.842 × 10 ⁻³
Tr5	Tank2 → Tank3 Escalation	3.492 × 10 ⁻⁶	1.5 × 10 ⁻²
Tr12	Tank1 → Tank2 → Tank3 Domino	2.0 × 10 ⁻¹⁰	Combined

The analysis of simulation results reveal that:

- The direct escalation from Tank 1 to Tank 3 is possible but has a very low probability ($PEST1 \rightarrow T3 = 6.062 \times 10^{-4}$), making it unlikely to cause a domino effect.
- The most probable domino sequence is Tank 1 → Tank 2 → Tank 3, with a frequency of 2×10^{-10} per year, corresponding to transition 12 in the Petri-net.
- Synergistic effects, such as combined heat radiation from Tank 1 and Tank 3 on Tank 2, significantly increase escalation probability, demonstrating the importance of considering multiple simultaneous sources.
- Time-dependent failure profiles provide insights into the temporal progression of accidents, allowing safety managers to prioritize interventions based on when secondary failures are most likely.

6. DISCUSSION OF THE RESULTS

The application of the GRIF Petri-net methodology to the gasoline tank farm case study confirms several key advantages:

- **Dynamic and Comprehensive Modeling:** The GRIF Petri-net methodology enables dynamic simulation of domino effect propagation, capturing both sequential and simultaneous escalation events. In our case study, this allowed identification of the critical domino sequence Tank 1 → Tank 2 → Tank 3 and quantification of its frequency, reflecting realistic accident progression.

- **Integration of Physical and Probabilistic Models :** By combining physical escalation vector calculations (heat radiation intensities) with probabilistic vulnerability assessments (probit models), the methodology provides a quantitative basis for estimating escalation probabilities [07] and [06]. In current application, this integration yielded time-to-failure estimates and escalation probabilities that informed the Petri-net transitions, enhancing model accuracy.

- **Ability to Model Synergistic Effects :** the case study demonstrated this by calculating combined heat radiation on Tank 2 from Tanks 1 and 3, improving the realism of escalation probability estimates.

- **High Computational Efficiency :** The GRIF Petri module uses MOCA-RP, a Monte Carlo engine optimized for Petri-net simulations, enabling exhaustive and efficient analysis of complex systems [11] . This efficiency supports practical application to real-world industrial layouts.

Despite of the previous advantages, we can notice several limitations and gaps:

- **Parameter Uncertainty and Assumptions:** The accuracy of the model depends heavily on input parameters such as ignition probabilities and loss of containment frequencies and ignition probability = 0.7

- **Limited Scope of Escalation Vectors:** The current application focuses only on heat radiation as the escalation vector but to have comprehensive risk assessment we must consider all possible escalation vectors which may lead to have other domino scenarios and have numerous complicated results .

- **Model Complexity and Scalability:** While Petri nets are powerful, their state space can grow exponentially with system size and complexity, potentially leading to computational challenges for very large facilities [12] .

- **Visualization and Communication:** The Petri-net graphical representation can become complex and difficult to interpret for stakeholders unfamiliar with the methodology [13].

7. CONCLUSIONS

This research underscores the effectiveness of Petri-net modeling as a powerful tool for predicting and managing domino effects within industrial layouts. By providing a rigorous and dynamic framework, the methodology enhances our ability to analyze complex accident propagation scenarios, thereby contributing significantly to the development of safer and more resilient industrial environments. Incorporating this Petri-net based approach into safety management practices enables more accurate identification and quantification of escalation risks associated with hazardous substances. Consequently, it supports informed decision-making aimed at minimizing potential domino effect incidents, ultimately fostering greater protection for both communities and the environment. To further strengthen this methodology, several improvements are proposed:

Incorporate Uncertainty Quantification: Implement Monte Carlo-based uncertainty propagation to provide confidence intervals for escalation probabilities and frequencies, improving decision-making robustness [11] .

Multi-Vector Escalation Modeling: Integrate blast, fragments, and toxic release escalation vectors alongside heat radiation, using validated physical and probit models to capture full domino effect complexity [06] .

Hierarchical and Modular Petri Nets: Develop hierarchical Petri-net models that decompose large facilities into manageable modules, enabling scalability and easier maintenance [12] .

Enhanced Visualization and User Interface: Leverage modern graphical interfaces and dashboards to present simulation results intuitively, facilitating stakeholder engagement and training [13] .

Integration with Safety Barrier and Mitigation Modeling: Extend the methodology to model the effectiveness of safety barriers and emergency response actions dynamically, allowing evaluation of risk reduction strategies [14] .

By adopting these enhancements, the Petri-net methodology can evolve into an even more comprehensive and practical tool for industrial risk assessment, ultimately advancing our collective goal of achieving safer industrial operations and protecting public and environmental health. [15]

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