A Budget-Constrained Optimization Framework for Mitigating Domino Effects in Chemical Storage Facilities

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Priority Topic Area: **Process Safety and Learning Outcomes from Major Incidents**

1 – Aim/planned deliverables

Domino effects in chemical storage facilities can trigger catastrophic fires and explosions, as shown Figure 1-2.

Safety barriers (SBs) and emergency response (ER) are the primary means of stopping things from escalating, as shown in Figure 3.

This project develops budget-constrained co-optimization framework (SB+ER) that jointly allocates SBs and ER to minimize escalation risk. Key deliverables include

- **Constructing mixed-integer nonlinear models based on multiple scenarios;**
- **Investment guidelines for SB and ER;**
- **An open-source decision-support tool for safety planning in the chemical industry.**

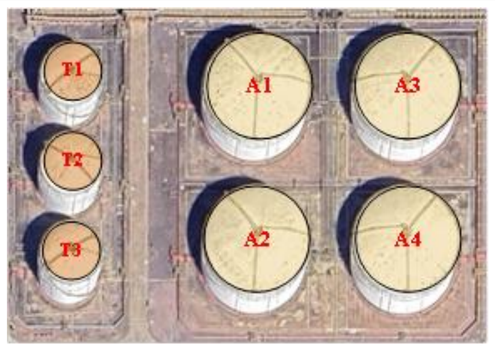

Figure 1. Layout of a chemical storage area

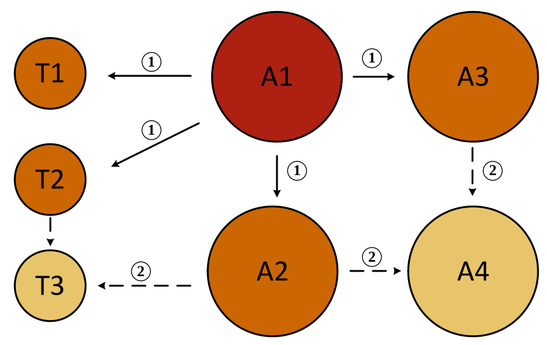

Figure 2. Accident propagation chain

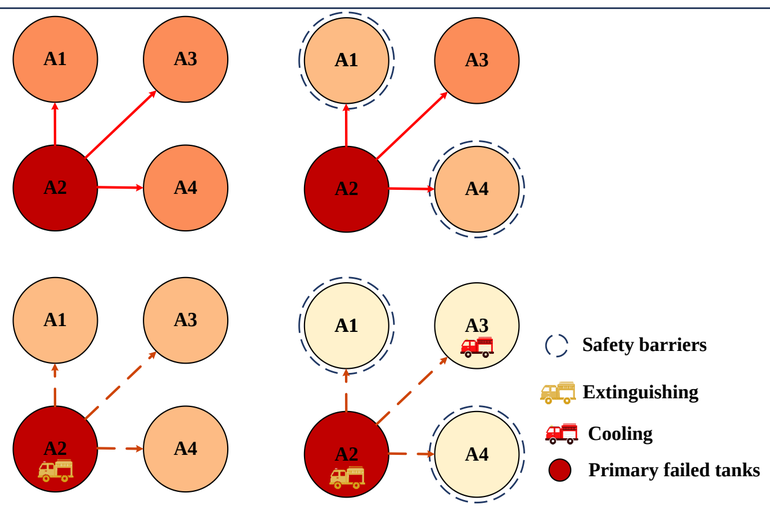

Figure 3. Role of SBs and ER resources (Note: Orange and yellow indicate tanks at high and low risk, respectively. SBs and ER are deployed to control escalation.)

2 – Methodology

We developed a scenario-based optimization model that jointly allocates safety barriers (SBs) and emergency response (ER) resources, as shown in Figure 4. It uses thermal radiation data and a probit function to estimate failure risk, balancing two objectives

An ε-constraint approach balances two objectives:

- **minimizing overall failure probabilities**
- **maximizing the minimum time to failure so tanks survive until firefighters arrive**

Three conditions were compared:

- **SB + ER** (One-step): Joint optimization of SBs and ER.
- **SB & ER** (Two-step): SBs optimized first, then ER resources added.
- **SB:** Optimization of safety barriers without ER consideration.

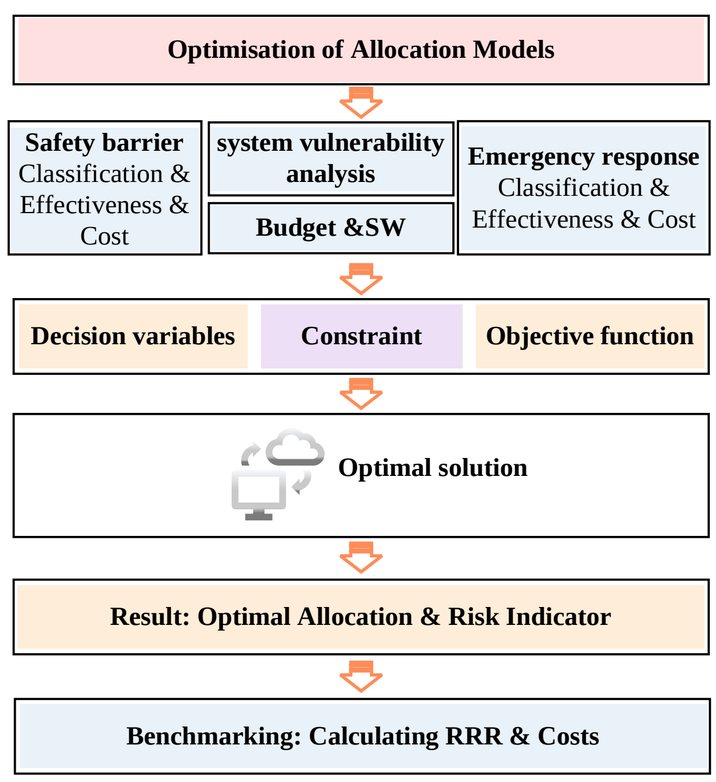

Figure 4. Framework for SB Optimization Considering ER Measures.

3 – Outputs/Results/findings

Different Allocation: The SB+ER approach results in a distinct optimal allocation compared to the sequential SB&ER method, as demonstrated in Figure 5.

Significant Reduction: Integrated optimization (SB+ER) dramatically cuts fire propagation probability—achieving over a 50% reduction versus SB&ER and SB alone, as shown in Figure 6.

Lowest Failure Risk: SB+ER consistently maintains the lowest overall failure risk, especially under limited budgets, enabling higher safety standards as shown in Figure 7.

Early Saturation: SB+ER reaches the diminishing returns point earlier, allowing facilities to achieve maximum risk reduction more quickly and avoid unnecessary spending.

Prioritized Allocation: The framework will be allocated preferentially to the storage tanks with the highest risk.

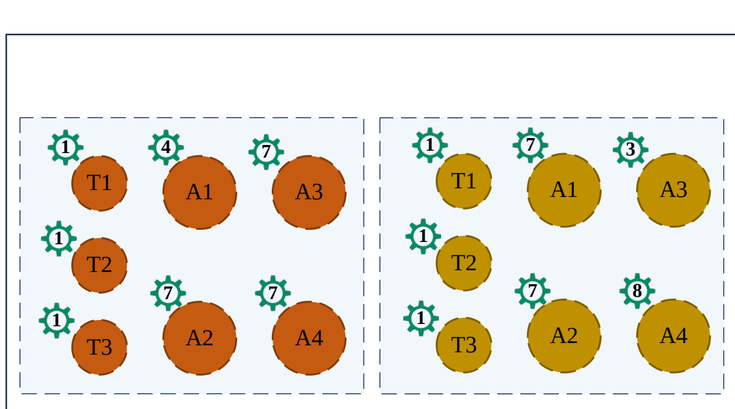

Figure 5. The optimal allocation of SBs is shown with and without ER resources

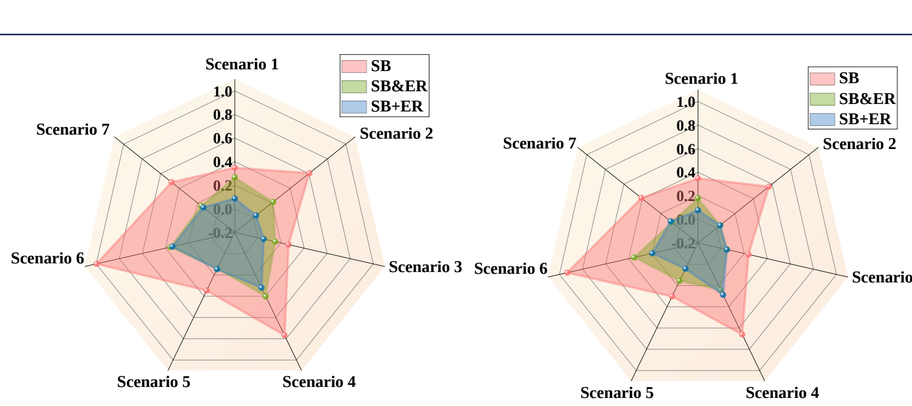

Figure 6. Propagation probability in different scenarios (Left. Budget = 1000 K€, Right. Budget = 1500 K€)

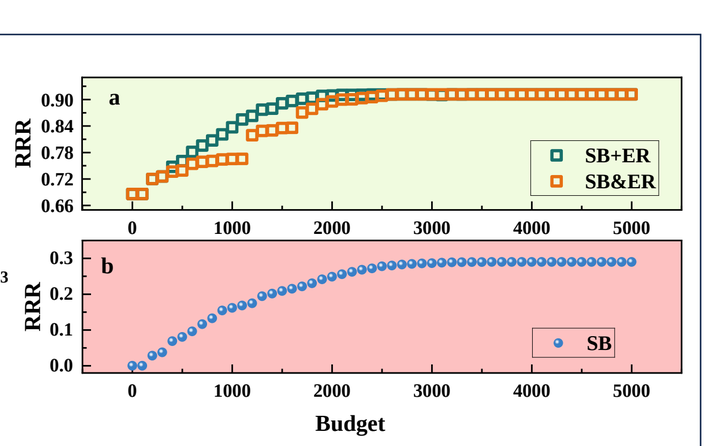

Figure 7. Comparison of RRR Under Different Budget

4 – Benefit to society (Add in your own most appropriate heading here)

This approach helps chemical industries prioritize safety investments under budget constraints, reducing the risk of domino accidents that threaten communities and the environment. By offering clear guidance on allocating barriers and emergency resources, the framework enables more effective and affordable safety planning. Its cost-effective strategy supports broader adoption, enhancing resilience, promoting sustainable industrial practices, and aligning with global goals for workplace safety and environmental protection.

5 – Next steps

Future work includes extending the model for multi-plant coordination, integrating uncertainties in meteorological conditions or barrier reliability, and refining real-time resource scheduling. Collaboration with industry partners will further validate its practicality and facilitate larger-scale implementation in diverse chemical parks.

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References/Acknowledgements

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Hou, Shuya, et al. "A quantitative risk assessment framework for domino accidents caused by double pool fires." Journal of Loss Prevention in the Process Industries 79 (2022): 104843.

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