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Application of Game Theory to Identifying Firefighting Strategies in Process Plants

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In the event of major fires in process plants, effective emergency response becomes highly challenging for firefighters. Ideally, the burning tanks should be suppressed, and the exposed tanks should be cooled to prevent fires from escalating and the onset of domino effects. When available resources are limited, prioritization becomes essential for firefighters as the domino effect can increase the number of threatened units beyond the operational capacity of firefighters. To address this scenario, the present study introduces a decision-making method based on Bayesian network and game theory to capture complexities and uncertainties arising from the sequential nature of firefighting actions and the dynamics of the domino effect. To do so, the interactions between firefighters and fire have been modeled via an extensive game, while Bayesian network has been used to model domino effects and calculate the payoffs needed in the game modeling. This approach is demonstrated to provide a more realistic representation of how priorities should be established during major fires in process plants and how firefighters should react to changing fire scenarios.

1. Introduction

Emergency response becomes crucial in process plants, including petrochemical facilities, tank terminals, and chemical manufacturing units, where there are large inventories of flammable, toxic, and pressurized substances. Fires in these environments can escalate rapidly, threaten human life, and damage not only the critical infrastructure but also the surrounding community. The analysis of the previous accidents has shown that insufficient or delayed firefighting responses are a major contributor to severe industrial accidents, particularly when initial events spread through physical or functional interactions among process units. Consequently, effective firefighting is not merely a reactive measure but a fundamental component of process safety management and emergency preparedness (Khakzad, 2021a).Firefighting at process plants becomes even more challenging when fire scenarios are followed up by domino effects, in which an initial fire or explosion causes secondary fires or explosions at nearby equipment. Previous research has demonstrated that domino effects are among the primary drivers of large-scale losses in process plants, particularly in densely packed installations (Cozzani et al., 2006; Khakzad et al., 2013). Previous studies also emphasize that escalation is not a single-step event, but a dynamic, multi-stage process that is influenced by spatial layout, equipment vulnerability, and environmental conditions such as wind direction and speed (Khakzad et al., 2024).
To explain further, when scenarios that involve the domino effect happen, firefighters have to act spontaneously and implement a plan that could lead to the proper choice, which would mean effectively minimizing the risk of fire spread. Several methods have been developed in previous studies to identify firefighting strategies aimed at interrupting fire escalation pathways under different conditions (Khakzad et al., 2021a). Previous studies have shown that emergency response measures can significantly reduce escalation probabilities when applied on time and with a prioritized manner, especially during the early stages of fire development. By integrating firefighting actions into probabilistic domino effect models, these studies moved beyond purely consequence-based assessments and highlighted the importance of response effectiveness in shaping accident outcomes (Khakzad et al., 2024).

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In many existing approaches, firefighting effectiveness is represented in a simplified or static manner, which limits the ability to capture adaptive decision-making during evolving domino-effect scenarios (Guo et al., 2023). Furthermore, resource limitation is one of the main issues that firefighters may need to deal with when approaching major fires in process plants: In other words, firefighting resources may not be sufficient to suppress all the burning units and cool all the surrounding units, which means there is still a chance for fire to spread due to the domino effect (Khakzad et al., 2024). Even in advanced probabilistic frameworks, the distribution and sequencing of firefighting resources are rarely optimized. Ignoring uncertainties in emergency response performance can lead to unrealistic estimates for risk reduction measures and may mask critical vulnerabilities in emergency preparedness (Khakzad et al., 2024).

The present study builds on recent advances in domino effect analysis by combining Bayesian Networks (BNs) with an extensive-form game framework to support firefighting decision-making in domino effect scenarios, while addressing limitations of previous studies. BNs are used to model fire escalation and associated uncertainties, while the extensive-form game captures both the main emergency scenario and possible subsequent scenarios (subgames) within a single, unified structure.

This enables adaptive decision-making without requiring structural modifications to the model as the fire propagates, in contrast to other decision support techniques such as influencing diagrams that require additional decision nodes and updated probability tables as fire spreads from one unit to another (Khakzad, 2021a). Firefighting actions are assessed using a risk-based utility function that accounts for escalation likelihood, the potential consequences if the fire spreads, and the effectiveness of the response.

Further, subgame analyses are developed to identify optimal follow-up actions if an initial response fails. Together, these features allow for realistic and flexible optimization of firefighting strategies in process plants in the event of domino effects.

2. Game theory

Game theory examines situations in which multiple decision-makers (players) interact, and where the outcome for each player depends not only on their own decisions but also on the decisions made by others. As a result, Game theory has widely been used to provide a mathematical framework for analyzing decision-making processes that involve sequential actions, uncertainty, and strategic interactions. Game theory provides a structured way to compare alternative actions, anticipate possible future developments, and identify strategies that perform well under uncertainty rather than relying solely on static or heuristic decision rules (Bonanno, 2024).

Among different types of game theories, extensive-form game theory is well-suited for modeling dynamic and sequential decision problems. Extensive-form games represent games as a tree structure, where each node represents a decision point or an event, and each branch shows a possible action or event that can take place. This structure naturally draws on the evolution of scenarios over time, and how there is a possibility of multiple stages, conditional decisions, and alternative futures (Bonanno, 2024). This makes an extensive game approach a viable technique for the analysis of subgames and identification of optimal strategies.

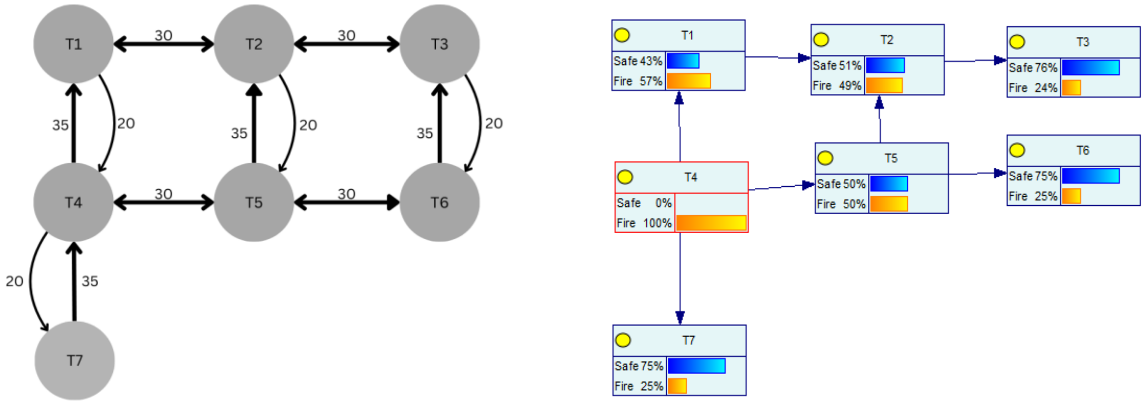
During an emergency response, such as a major fire in process plants, most of the time, there is sequential and time-dependent decision making, where the outcome of an action directly influences the upcoming options. Therefore, decisions must adapt as the situation unfolds and new information becomes available. Extensive-form game theory offers a strong framework for representing such dynamic and interdependent decision environments, in which strategies must account for uncertainty, evolving conditions, and the potential consequences of both current and future actions.

3. Method development and application

3.1 Case study

Consider an illustrative tank terminal in Figure 1a, consisting of seven storage tanks T1-T7. In case of individual tank fires, the heat flux values between the adjacent tanks have been presented beside the arrows connecting the tanks. For fire to propagate between the adjacent tanks, a minimum heat flux of 15 kW/m^2 for fire propagation is considered (Cozzani et al., 2006). Two fire scenarios are considered: (i) T4 catches on fire, and (ii) fire propagates from T4 to T5.

Also, assume that during each fire scenario, firefighters can only choose 3 tanks to act upon: suppress the burning tank(s) and/or cool the neighboring tank(s). This approach reflects the reality that firefighting resources are limited and highlights the need to identify the most effective sequence of actions under such constraints. It is worth mentioning that the case study and the assumptions regarding heat flux values and firefighting resources are for illustrative purposes.



(a) (b)

Figure 1: a) Modelling fire propagation in a tank terminal as a directed graph. The arcs and numbers denote possible fire propagation paths and heat fluxes in kw/m^2. b) BN for modelling the domino effect triggered by a tank fire at T4 in the absence of firefighting actions.

3.2 Domino effect scenario modeling using BN

To describe each fire scenario mentioned in Section 3.1, BNs have been used to model these scenarios and possible domino effects in more depth (Khakzad et al., 2013). For example, in Figure 1b, the BN captures the probabilistic cause-effect relationships between adjacent tanks and how fire would propagate from T4 to the other tanks if no action is taken place. To calculate the probability of fire spread between the tanks, Eq(1) is employed, where Q_{ij} represents the radiative heat flux transferred from tank T_i to tank T_j. This equation is for illustrative purposes and has been adopted from Khakzad et al. (2021b). The value of 15 kW/m² corresponds to the critical heat flux threshold identified in Section 3.1, any heat flux below which makes the fire propagation to the adjacent tank very unlikely. This formula expresses the idea that the likelihood of fire spread increases as the received heat flux exceeds this threshold. For instance, since T1 receives 35 kW/m² of heat flux from a tank fire at T4 (see Figure 1a), the conditional probability of fire spread from T4 to T1, i.e., P_{41}, can be calculated using Eq(1) as: $P_{41} = 1 - \frac{15}{35} = 0.57$. Such probabilities are then used to populate the respective conditional probability tables in Figure 1b. Eq(2) defines the utility of each tank, denoted by $U(T_i)$. The term $10M represents the base value of a tank without considering additional factors that increase its importance and value, such as its ability to propagate fire to other tanks. This base value is then multiplied by the sum of the fire propagation probabilities, $\sum_{i=1}^{7} P_i$, which together represent the overall likelihood that a tank fire at T_i can spread throughout the tank terminal.
In Eq(2), $P(T_j|T_i)$ presents the probability of domino-effect-induced tank fire at tank T_j given an initial tank fire at tank T_i; these probabilities can be calculated using BNs similar to the one developed in Figure 1b. For instance, given a tank fire at T4 in Figure 1b, $\sum_{i=1}^{7} P(T_j|T_4) = 0.43 + 0.49 + 0.24 + 1.0 + 0.5 + 0.25 + 0.25 = 3.16$. By combining the economic value of a tank with its potential to trigger further fire escalations, Eq(2) provides a risk-based measure of tank criticality. This approach captures the true nature of domino effects and focuses on the tanks that exhibit a higher overall probability of spreading fire to their neighboring tanks and to the overall system. Consequently, the tanks with higher utility values can be identified as more critical and thus be given a higher priority for firefighting intervention and risk mitigation.

$$P_{ij} = 1 - \frac{15}{Q_{ij}} \tag{1}$$

$$U(T_i) = \$10\text{M} \times \sum_{j=1}^{7} P(T_j|T_i) \tag{2}$$

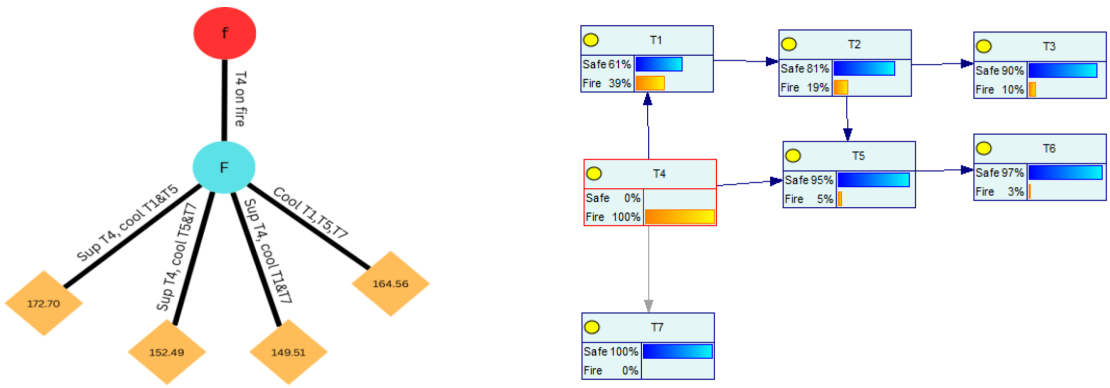
Table 1 lists the utility value of each tank. These utilities will be used in the next section to calculate the payoffs associated with the firefighting strategies. As shown in Table 1, T5 shows the highest utility value, which indicates that T5 has the greatest potential to trigger fire escalation and domino effect within the terminal, whereas T3 has the lowest utility. This result suggests that T5 should be considered the most critical tank in emergency response planning and prioritized in firefighting and cooling strategies. This modelling approach will also provide a structured way to evaluate how an initial fire can evolve into secondary events under different conditions.

Table 1: Risk-Based Utility Values of Storage Tanks Derived from Bayesian Network modelling

Tank	Risked-based Utility (million $)
T1	24.8
T2	27.9
T3	24.6
T4	33
T5	36.8
T6	31.1
T7	27.5
Total utility	205.7

3.3 Extensive game modeling

In Figure 2a, an extensive-form game is constructed to represent the sequential decision-making process which firefighters need to go through as they face possible fire escalation scenarios. Considering fire (f) and firefighters (F) as two players, firefighters' actions have been described and drawn by lines that connect to a possible payout/outcome.



(a) (b)

Figure 2: a) Extensive-form representation of firefighting decision-making given a tank fire at T4. The players, fire (f) and firefighters (F), are presented with circles. The branches present viable firefighting strategies (firefighters' move), and diamonds depict the respective payoffs. b) Modified BN given the firefighting strategy 'suppress T4, and cool T5 & T7.'

The outcomes of these actions – i.e., payoffs - are then evaluated using the risk-based utility function, developed in Eq(2), and the escalation probabilities under respective firefighting strategies. To account for suppression and cooling efficiencies, illustrative values are assigned: α = 0.7 for suppression and β = 0.5 for cooling (Khakzad, 2021a). Accordingly, in Eq(1),Q_{ij} will be multiplied by α and/or β based on what firefighting action has been taken. For example, consider $Q_{45} = 30\ kW/m^2$ in Figure 1a. if T4 is suppressed and T5 is cooled at the same time, then the mitigated heat flux that T5 would receive from T4 can be calculated as $Q_{45} = 30 \times 0.5\ \times\ 0.7 = 10.5\ kW/m^2$. The new heat flux then can be put into Eq(1) to evaluate the new probabilities of the fire propagation. Figure 2b illustrates the updated BN, where T4 is suppressed and T5 and T7 are cooled. To calculate the payoffs, Eq(3) can be used.

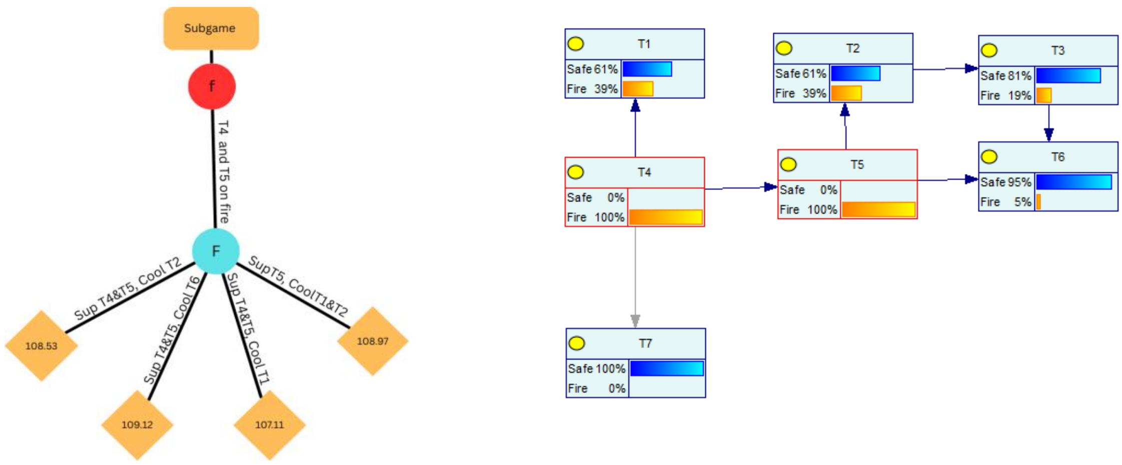
$$Payoff(f_i, F_j) = \$205.7M - \sum_{i=1}^{7} P(T_k | f_i, F_j).\, U(T_k) \quad (3)$$

where $Payoff(f_i, F_j)$ is the payoff resulting from subsequent moves made by fire (f_i) and firefighters (F_j); $205.7M is the total utility, calculated in Table 1; $P(T_k | f_i, F_j)$ is the probability of fire at tank T_k given a specific fire scenario (f_i) and firefighting strategy (F_j), calculated using the BN (e.g., the BN in Figure 2b); and $U(T_k)$ is the utility of each tank, calculated using Eq(2) and listed in Table 1. For instance, given f = 'T4 on fire' and F =

'suppress T4 and cool T5 & T7' modelled using the BN in Figure 2b, the corresponding payoff can be calculated as:

Payoff = \$205.7M – (0.39 × \$24.8M + 0.19 × \$27.9M + 0.1 × \$24.6M + 1.0 × \$33M + 0.05 ×\$36.8M + 0.03 × \$31.1M + 0.0 × \$27.5M) = \$152.49M.

Given Eq(3), the payoffs for the feasible moves (firefighting strategies given a tank fire at T4) can be calculated, and the move with the maximum payoff (or, the minimum sum product of secondary fire probabilities and tank utilizes) can be identified as the best firefighting strategy, that is, F = 'suppress T4, and cool T1& T5', with a maximum payoff of \$172.70M. This extensive game then will continue into subgames which are used to identify optimal follow-up actions when an initial response does not succeed, enabling adaptive decision-making as the situation evolves. For instance, consider a case where the firefighting strategy adopted in the main game (Figure 2a) cannot fully contain the fire, and the fire thus spreads from T4 to T5, resulting in the subgame presented in Figure 3a.



(a) (b)

Figure 3: a) Extensive sub-game for the situation where fire spreads from T4 to T5. b) Modified BN given the firefighting strategy 'suppress T4 & T5, and cool T6.'

The same approach that was used in scenario (i) can be used to calculate the payoffs for feasible follow-up firefighting actions, as depicted in Figure 3, denoting F = 'suppress T4 & T5, and cool T6' as the best strategy which slightly outdoes the other strategies with a respective payoff of \$109.12M.

3.4 Comparison with previous studies

Considering the payoffs in Figure 2a, the leftmost action, i.e., suppressing T4 while cooling T1 and T5, represents the most effective firefighting strategy, as it can better confine the fire to T4 and prevent further escalation. This strategy results in an avoided loss of \$172.20M relative to the total utility value of \$205.7M reported in Table 1. Applying the same logic to the sub-game in Figure 3a, suppressing T4 and T5 while cooling T6 is identified as the optimal strategy when fire spreads from T4 to T5, yielding an avoided loss of \$109.12M. Although this action does not completely halt fire propagation, it slightly reduces the probability of escalation by lowering the effective heat flux between tanks compared to other strategies.

Lang et al. (2011) argue that given a tank fire, the exposed tanks in the vicinity of the burning tank should be cooled. Adopting their guideline in the present study would result in the second-best strategy identified in the current study, represented by Figure 2a, with a payoff of \$164.56M, compared to the best strategy with a payoff of \$172.20M. D'Amico (2015) assigns priority to each tank based on the magnitude of heat flux it is exposed to. This would lead to Tanks T1 and T5 as the highest-priority candidates for cooling, followed by Tank T7. This prioritization approach is more consistent with that proposed by the present study (i.e., suppress T4 and cool T1&T5). However, since D'Amico (2015) did not prioritize between suppressing and cooling, adopting their approach could leave the firefighters wondering between 'suppress T4 and cool T1&T5' and 'cool T1 & T5 & T7' as the best strategy. For the second fire scenario, which is represented in Figure 3, where both T4 and T5 are on fire, Lang et al. (2011) again approached the problem by cooling all exposed vessels surrounding the fire, that is, T1, T2, T6 and T7. However, this strategy is not feasible in the current study due to limited firefighting resources. D'Amico (2015) has a very similar approach as Lang et al. (2011) to this scenario, but it provides the firefighters with more information, which is to prioritize the cooling of T1 and T2 over T6 and T7 as they receive higher heat fluxes. The issue with this approach is that firefighters would still end up with two burning tanks to suppress (T4 and T5) and two exposed tanks to cool (T1 and T2) whereas their resources are only sufficient to handle three tanks.

4. Conclusions

This study combined BNs and extensive-form game theory to model domino effects and identify effective firefighting strategies under limited resources. A novel risk-based utility function has been introduced to calculate the payoffs in the game modeling. The results show that the proposed approach outperforms the guidelines given in the previous studies by effectively reducing fire escalation and associated damage. Nevertheless, the present study has limitations that should be addressed in future studies to verify its effectiveness and applicability. For one thing, the model should be modified to account for a broader range of random parameters and factors, including wind speed and direction, and existing fire protection systems, which may significantly influence fire behaviour and escalation pathways in real scenarios. Future work should focus on extending the scope of the study and considers a more realistic representation of real-life process plants as well as the possibility of fire escalation not only inside the process plant but also toward the offsite building and infrastructure. Particularly, the efficacy of the method should be examined for process plants of greater size and complexity and concurrent fire scenarios. Moreover, the application of dynamic Bayesian network (DBN) for domino effect modelling seems to capture more effectively the uncertainties and interdependencies arising from fire propagation and updated firefighting strategies.

References

Bonanno, G., 2024, Game Theory, <https://faculty.econ.ucdavis.edu/faculty/bonanno/PDF/GT_book.pdf> accessed 28.01.2026.

Cozzani, V., Gubinelli, G., & Salzano, E., 2006, Escalation thresholds in the assessment of domino accidental events, Journal of Hazardous Materials, 129(1–3), 1–21.

D'Amico, M., 2015, Risk-based fire protection strategy in crude oil storage facilities, International Fire Protection <https://ifpmag.com/risk-based-fire-protection-strategy-in-crude-oil-storage-facilities/> accessed 28.01.26.

Guo, L., Wang, Z., Zhao, D., Zhao, K., & Guo, P., 2023, Modeling the effect of emergency response on domino effects in the coal gasification process by fuzzy hierarchical analysis and Bayesian network, PLOS ONE, 18(2), e0279346.

Khakzad, N., Khan, F., Amyotte, P., & Cozzani, V., 2013, Domino effect analysis using Bayesian Networks, Risk Analysis, 33(2), 292-306.

Khakzad, N., 2021a, Optimal firefighting to prevent domino effects: Methodologies based on dynamic influence diagram and mathematical programming, Reliability Engineering & System Safety, 212, 107577.

Khakzad, N., 2021b, A tutorial on fire domino effect modeling using Bayesian networks Modelling, 2(2), 240–258.

Khakzad, N., Landucci, G., & Reniers, G., 2017, Application of dynamic Bayesian network to performance assessment of fire protection systems during domino effects, Reliability Engineering & System Safety, 167, 232–247.

Khakzad, N., Salzano, E., & Amyotte, P., 2024, A graph-based optimization methodology for identifying firefighting strategies aimed at domino effects, The Canadian Journal of Chemical Engineering, 102(8), 2714–2723.

Lang, X.Q., Liu, Q.Z., Gong, H., 2011, Study of fire fighting system to extinguish full surface fire of large-scale floating roof tanks, Procedia Eng.,11, 189–195.