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Goal Programming Approach To Optimal Allocation Of Firefighting Resources During Domino Effects

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Ideal firefighting at industrial plants includes simultaneous suppressing and cooling of all the burning and exposed units, respectively, if firefighting resources are sufficient. As a result, the primary fires can be contained and their propagation into adjacent units via domino effect can be prevented. However, when the available firefighting resources are insufficient to handle all the burning and exposed units, conducting an ideal firefighting is no longer an option. Consequently, the plant's fire brigade need determine which units are more critical and should be suppressed or cooled so that the risk of fire propagation both inside and outside the plant could be minimized. With the majority of previous studies considering only the risk of fire inside the plant (Khakzad, 2018, 2021), the present study has developed a methodology based on goal programming for identifying optimal firefighting strategies considering both inside and outside risks.

When suppressing a burning unit, the emitting heat gradually decreases until the fire is completely extinguished. The average mitigated heat flux q' is considered to be a fraction of the original heat flux q (unmitigated heat flux) as $q' = \alpha\, q$, where α is the suppression inefficiency (i.e., the lower α, the higher the suppression efficiency). Likewise, when cooling an exposed unit, the amount of mitigated heat flux received by the unit (q') is considered to be a fraction of the original heat flux q it would have received had it not been cooled, that is, $q' = \beta\, q$, where β is the cooling inefficiency (i.e., the lower β, the higher the cooling efficiency) (Landucci et al., 2015; Khakzad et al., 2017). As a result, when a burning unit A is suppressed, and at the same time an exposed unit B in its vicinity of A is cooled, the heat flux B would receive from A would be:

$$q' = \alpha^{X_A} \cdot \beta^{X_B} \cdot q, \tag{1}$$

X_A and X_B are binary variables {0, 1} to determine whether a unit should be included in the firefighting (X = 1) or not (X = 0).

To demonstrate the methodology, consider a tank terminal near some low-density residential houses in Figure 1. The terminal comprises six identical storage tanks of crude oil. The fire propagation probabilities as a function of heat fluxes and firefighting strategies can be calculated using the methodology developed in Khakzad (2021). Considering a tank fire at $T5$ as an example, the probability of fire propagation to $T4$ can be modelled as $P_4 = P(T4 = \text{fire} \mid T5 = \text{fire})$. The probability of fire propagation to $T1$ can be modelled similarly using the chain rule and the law of total probability as $P_1 = P_2 \cdot P_4 \cdot P(T1 = \text{fire} \mid T2 = \text{fire}, T4 = \text{fire}) + P_2 \cdot (1 - P_4) \cdot P(T1 = \text{fire} \mid T2 = \text{fire}, T4 = \text{no fire}) + (1 - P_2) \cdot P_4 \cdot P(T1 = \text{fire} \mid T2 = \text{no fire}, T4 = \text{fire})$. Following the same approach, the individual risk at the houses (IR), if fire propagates to $T6$, can be calculated as:

$$IR = P_6 \cdot P(\text{death} \mid T6 = \text{fire}) \tag{2}$$

Land use planning guidelines can be used to determine the upper limit of offsite risks arising from major accidents at industrial plants. In Canada, for instance, the land around a process plant is divided into zones based on iso-risk contours, and then based on the activities and vulnerability of the users, each zone is assigned to a specific activity or development. Considering low-density residential houses, 1.0E-6 would be the upper limit for *IR* (Major Industrial Accidents Council of Canada, 1995).

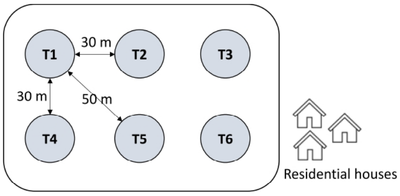

Fig. 1. An illustrative crude oil tank terminal near a residential community.

Having the domino effect probabilities and offsite risk at the houses (*IR*), the objectives of the firefighting can now be set out. Since the upper limit of individual risk at the houses is known via the land-use development regulations, one more assumption needs to be made regarding the allowable maximum internal risk (risk of damage to the tank terminal). For this purpose, assume that each tank costs \$1M (C_i = \$1M, for i = 1,2,…, 6), and the total available budget for repair and replacement of damaged tanks is \$2M. Considering this latter assumption, the risk of damage to the storage tanks can be defined as $R_T = \sum_{i=1}^{6} P_i . C_i$. Subsequently, the firefighting objectives, in a descending order of priority, can be specified as:

$$IR_H \leq 10^{-6} \qquad (3)$$

$$R_T = \sum_{i=1}^{6} P_i \leq 2 \qquad (4)$$

In addition to the foregoing objectives, constraints of the model need to be identified to complete the goal programming. For illustrative purposes, assume that the firefighting resources for the tank terminal are sufficient to include only two tanks in the firefighting strategy. This constrain can mathematically be expressed as:

$$\sum_{i=1}^{6} X_i = 2 \qquad (5)$$

Solving the above set of equations, the optimal values of X_i for different values of α and β can be calculated. For α = 0.4, β = 0.7 (namely, Case 1), the following optimal values can be obtained: $X_1 = X_2 = X_3 = X_4 = 0$ and $X_5 = X_6 = 1$, while for α = 0.7, β = 0.4 (namely, Case 2), $X_1 = X_3 = X_4 = X_5 = 0$ and $X_2 = X_6 = 1$.

As can be seen from the results, in both cases, T6 should be cooled ($X_6 = 1$) to decrease the probability of fire spread from *T*5 to *T*6. It is because *T*6 is the only tank that, if catches fire, can endanger the safety of people at the houses and is thus the most critical tank from an *IR* perspective. In Case 1, the suppression efficiency is higher than the cooling efficiency (lower α and β mean higher suppression and colling efficiencies, respectively), and thus it is better to suppress *T*5 ($X_5 = 1$) to reduce the probability of fire spread to the other tanks. However, in Case 2, the cooling efficiency is higher, and thus cooling *T*2 instead of suppressing *T*5 ($X_2 = 1$, $X_5 = 0$) seems to be more effective in reducing the likelihood of fire spread.

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