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Multi-Objective Optimization of Firefighting Strategies in Process Plants

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Ideal firefighting strategies at process plants would include 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 escalation into secondary fires via domino effect can be prevented until the fires are fully extinguished. However, when the number of burning units to suppress and exposed units to cool exceeds the firefighting capacity of a process plant, it is not feasible to conduct an ideal firefighting. Consequently, the plant owners need to conduct an optimal firefighting to address the following question: When all the burning and exposed units cannot be considered in firefighting, which ones should be prioritized and included in firefighting so that the risk of fire propagation in the plant can be minimized? For process plants that are close to other land-use developments (residential communities, infrastructures, etc.), conducting an optimal firefighting can become more challenging as it should minimize not only the risk of domino effect within the plant (onsite risk) but also risks posed to the nearby land-use developments (offsite risks). In the present study, considering onsite and offsite risks that may arise from domino effects in process plants, a methodology is developed based on goal programming – a multi-objective optimization technique – for identifying optimal firefighting strategies. Given limited firefighting resources, the developed methodology helps determine which units to suppress and which ones to cool in order to minimize as many risks as possible.

1. Introduction

Firefighting at tank terminals is usually considered as the last resort when it comes to fire prevention and protection. An ideal firefighting strategy should confine the fire and prevent its propagation to adjacent vessels until burning vessels are fully extinguished. However, when the number of vessels to protect – weather burning or exposed – exceeds the available resources, conducting an ideal firefighting is not feasible particularly if fire propagates from an originally burning vessel to adjacent vessels, creating a domino effect.

In the event of domino effects, the number of units in need of cooling grows exponentially with the number of burning vessels (Khakzad, 2021), quickly making the initially limited resources even less sufficient to conduct an ideal firefighting. In such cases, an effective firefighting strategy would be needed for optimal allocation of the available firefighting resources so as to limit or slow the domino effect until more resources become available. Such strategies should help the firefighters prioritize the burning and exposed vessels and decide which ones to include in firefighting.

For process plants that are near or within communities, an effective firefighting strategy should not only limit or control potential domino effects but also prevent from fire propagation toward the plant's boundary where there may be risk of damage to people and properties offsite or to adjacent plants via external domino effects. To achieve these multiple objectives via a single firefighting strategy, methodologies are required that combine domino effect models with optimization techniques while considering the resources, constraints, and objectives.

Despite many studies for modeling and assessing risk of fire-induced domino effects in process plants (Landucci et al., 2009, 2015; Khakzad et al., 2013; Janssens et al., 2015), work devoted to firefighting and its role in preventing and reducing risk of domino effects has been very few (Zhou et al., 2020; Khakzad, 2018, 2021). In these studies, the optimal strategies were identified considering merely one objective: Minimizing internal risk

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of domino effects. However, as previously discussed, an effective firefighting strategy should achieve several onsite and offsite risk objectives.
The present study is thus aimed at developing a methodology based on the goal programming for identification of optimal firefighting strategies in process plants with the aim of minimizing both internal and external risks of domino effect. In Section 2, fundamentals of firefighting, land use planning, and goal programming are briefly reviewed. Section 3 presents the methodology and discusses the results. Section 4 summarizes the main outcomes of the study.

2. Methods and Materials

2.1 Firefighting in process plants

When suppressing a tank fire, the emitting heat gradually decreases until the fire is completely extinguished. The average mitigated heat flux (q_m) is considered to be a fraction of the original heat flux q_o (unmitigated heat flux) as $q_m = \alpha\ q_o$, where α (0.0 < α < 1.0) is the suppression efficiency. Likewise, when cooling an exposed tank, the amount of mitigated heat flux received by the tank (q_c) is considered to be a fraction of the original heat flux q_r it would have received had it not been cooled, that is, $q_c = \beta\ q_r$, where β (0.0 < β < 1.0) is the cooling efficiency (Landucci et al., 2015). As a result, when a tank fire is suppressed, and an exposed tank in its vicinity is being cooled at the same time, the heat flux the cooled tank would receive from the suppressed tank fire would be $q_{mc} = \alpha\ \beta\ q_r$.
Since the probability of fire spread from a burning tank Ti to an exposed tank Tj is dependent on the heat flux Tj receives from Ti, the effect of firefighting – whether Ti should be suppressed, or Tj should be cooled, or both – on this probability can directly be taken into account by modifying the heat flux as:

$$q' = \beta^{X_j}.\alpha^{X_i}.q \tag{1}$$

where q is the heat flux Tj receives from Ti in the absence of any firefighting operations; q' is the mitigated heat flux due to firefighting (either extinguishing or cooling); and X_i and X_j are binary variables {0, 1} to determine which tanks should be included in the firefighting strategy: If Ti is burning, X_i = 1 denotes that Ti should be suppressed whereas X_i = 0 denotes that Ti should be left burning. Likewise, if Tj is exposed to heat, X_j = 1 denotes that Tj should be cooled whereas X_j = 0 denotes that Tj should not be cooled. In case Tj is exposed to two tank fires Ti and Tk, the received heat flux by Tj can be modified as:

$$q' = \beta^{X_j}(\alpha^{X_i}q_{ij} + \alpha^{X_k}q_{kj}) \tag{2}$$

where q_{ij} and q_{kj} are, respectively, the heat fluxes Tj receives from Ti and Tk in the absence of any firefighting operations.

2.2 Land use development regulations

Land use planning (LUP) is a non-structural safety measure to limit the impact of major industrial accidents on offsite assets (Cozzani et al., 2006). In case of new industrial plants, LUP is implemented via appropriate safety distances between plants and offsite assets. Existing plants that cannot afford such safety distances should consider LUP in their policies and procedures and, if necessary, take additional safety measures to ensure that offsite risks arising from their operation or from accidents at their facility are as low as reasonably practicable (Council Directive, 1996).
Among different methods developed for implementing LUP, risk-based methods have gained more popularity due to their consistency and applicability to a wider variety of hazardous industries and accidents (Khakzad and Reniers, 2017). In risk-based methods, based on iso-risk contours, the land around a major hazard installation (MHI) such as a process plant is divided into several zones, and based on the activities and vulnerability of land users, each zone is assigned to a specific activity or development.
For instance, in Canada, the land around a MHI is divided into 4 zones based on three iso-risk contours. Each contour represents a specific individual risk (IR) value: Zone 1 is identified with IR > 1.0E-4, in which no other land use is permitted; Zone 2 is identified with 1.0E-5 < IR < 1.0E-4, where only manufacturing and warehouses are allowed; Zone 3 is identified with 1.0E-6 < IR < 1.0E-5, where commercial activities, offices, and low-density residential houses are allowed; and Zone 4 is identified with IR < 1.0E-6, where all other land uses and activities such as institutions and high-density residential houses are allowed (Major Industrial Accidents Council of Canada, 1995).

2.3 Goal programming

Goal programming is a multi-objective decision making technique to find the best solution for an optimization problem by minimizing the (weighted) sum of deviations for all the objectives. In non-preemptive goal programming, all the objectives are considered to be of equal priority whereas in preemptive goal programming there is a hierarchy of priority levels for the objectives, and consequently the objectives of higher priority should be satisfied before the objectives of lower priority. As a result, in preemptive goal programming, the more important an objective the larger the penalty assigned to the deviations from that objective (Jeter, 2018). A typical goal programming problem with N variables and M objective functions (M goals) can be illustrated as:

$$Minimize\ \sum_{j=1}^{M} w_j.(d_j^+\ or\ d_j^-) \tag{3}$$
$$Subject\ to: (\sum_{i=1}^{N} a_{ij}.X_{ij} - (d_j^+ - d_j^-) = B_j)_{j=1}^{M} \tag{4}$$

where X_{ij} are the variables in the jth objective function; a_{ij} are the coefficients of the variables in the jth objective function; B_j is the goal in the jth objective function; w_j is the penalty for deviation from the jth goal; and d_j^+ and d_j^- are, respectively, the deviations above and below the jth goal.

3. Methodology

3.1 Case study

To demonstrate the application of 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 with diameter 30 m and volume 150,000 m^3. Considering the wind direction from south to north, the heat fluxes (exemplary numbers) received by exposed tanks and the houses in the event of tank fires are listed in Table 1.

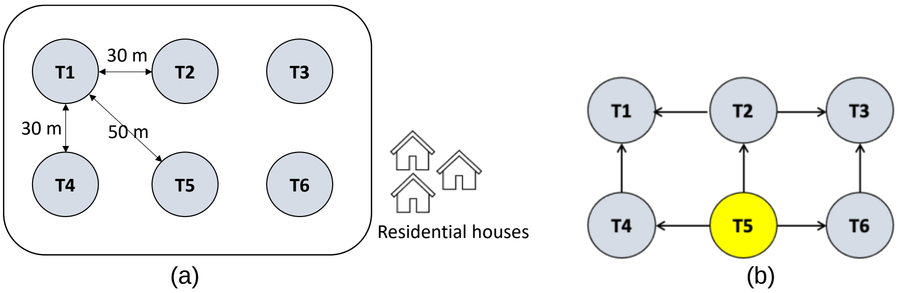


Figure 1. (a) An illustrative crude oil tank terminal near a residential community. (b) Potential domino effect given a tank fire at T5.

Table 1. Heat flux intensities (kW/m^2) received by exposed tanks (Tj) and houses in the event of tank fire at Ti.

Ti ↓	Tj →	T1	T2	T3	T4	T5	T6	Houses
T1		-	20	-	15	-	-	-
T2		20	-	20	-	15	-	-
T3		-	20	-	-	-	15	-
T4		25	-	-	-	20	-	-
T5		-	25	-	20	-	20	-
T6		-	-	25	-	20	-	5

Since all the tanks are atmospheric, a minimum heat flux of 15 kW/m^2 is considered as the threshold for damage and fire propagation to an exposed tank. Subsequently, the probability of fire propagation can be calculated using the probit function developed in Landucci et al. (2009):

$$Y = 9.25 - 1.85\ln(ttf) \tag{5}$$
$$ln(ttf) = -1.13\ln\left(\frac{q}{1000}\right) - 2.67 \times 10^{-5}\,V + 9.9 \tag{6}$$
$$p = \varphi(Y - 5) \tag{7}$$

where Y is the probit value, ttf (min) is the time-to-failure of the exposed tank; q (kW/m^2) is the received heat flux; V (m^3) is the volume of the exposed tank; $\varphi(.)$ is the cumulative density function of standard normal distribution, and p is the probability of fire propagation to the exposed tank. To facilitate the calculation of fire propagation probabilities, Khakzad (2021) proposed to use Eqs (5)-(7) to draw a p-q diagram and fit a curve to directly relate the fire propagation probability p to the amount of received heat flux q. Following their approach, the p-q diagram for the tanks of the tank terminal is drawn in Figure 2(a), and subsequently the approximate fire propagation probability $\hat{p}_f$ as a function of q can be calculated as:

$$\hat{p}_f = -0.0005\, q^2 + 0.051\, q - 0.4651 \quad (8)$$

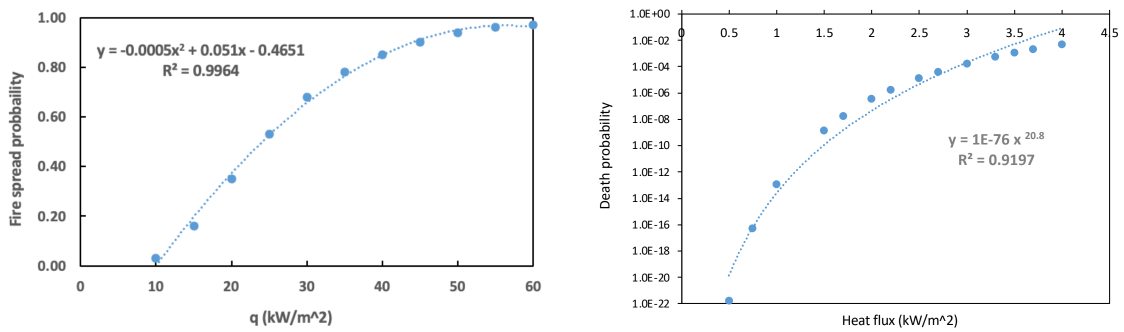
To calculate death probability for an individual exposed to heat flux, the equations presented in Eqs (9) and (10) can be used (Assael and Kakosimos, 2010):

$$D = t_e . q^{4/3} \quad (9)$$

$$Y = -36.38 + 2.56 \ln (D) \quad (10)$$

where t_e (s) is the exposure time of the individual to heat flux; q (W/m^2) is the heat flux that the individual is exposed to, and D is the thermal dose. The probit value Y calculated using Eq (10) can then be converted into death probability via Eq (7). Similar to Figure 2(b), a p-q diagram can be drawn to develop a simple relationship between the death probability and the heat flux, considering t_e= 60 s. Subsequently, the approximate death probability $\hat{p}_d$ as a function of q can be identified as:

$$\hat{p}_d = 1\text{E} - 76 \times q^{20.8} \quad (11)$$



(a) (b)

Figure 2. (a) Probability of fire propagation to an atmospheric storage tank with diameter 30 m and volume 150,000 m^3 as a function of received heat flux. (b) Probability of death for an individual due to heat exposure for 60s.

3.2 Domino effect probabilities

To develop the fire propagation probabilities as a function of heat flux and firefighting strategy, the sequence of events during potential domino effects and their probabilities should be identified. Khakzad et al. (2013) employed Bayesian network (BN) for modelling and assessing the risk of domino effects in process plants. In their approach, considering the storage tanks as the nodes of the BN, arcs were drawn from tank Ti to tank Tj only if the heat flux the latter received from the former were equal or greater than a threshold value (e.g., 15 kW/m^2 for atmospheric tanks). The probit functions (Landucci et al., 2009) can then be employed to calculate the conditional probabilities P(Tj = fire |Ti = fire) needed to quantify the BN.

Considering the tank fire at T5 as an example, the potential domino effect in the tank terminal can be modelled as the BN in Figure 1(b) following the methodology developed in Khakzad et al. (2013). Given the BN, the probability of fire propagation to tank Ti, that is, P(Ti = fire) = P_i, can be calculated using the chain rule and the law of total probability as:

P_2 = P(T2 = fire | T5 = fire) (12)

P_4 = P(T4 = fire | T5 = fire) (13)

P_6 = P(T6 = fire | T5 = fire) (14)

P_1 = P_2.P_4.P(T1 = fire | T2 = fire, T4 = fire) + P_2.(1 – P_4).P(T1 = fire | T2 = fire, T4 = no fire) + (1 – P_2).P_4.P(T1 = fire | T2 = no fire, T4 = fire) (15)

P_3 = P_2.P_6.P(T1 = fire | T2 = fire, T6 = fire) + P_2.(1 – P_6).P(T1 = fire | T2 = fire, T6 = no fire) + (1 – P_2).P_6.P(T1 = fire | T2 = no fire, T6 = fire) (16)

The probabilities in Eqs (12)-(16) can be reformulated using Eq (1) and Eq (8) to account for the impact of possible firefighting strategies. For instance, Eq (5) can be formulated as:

P(T2 = fire | T5 = fire) = $-0.0005\ (\alpha^{X_5}.\beta^{X_2}.25)^2 + 0.051\ (\alpha^{X_5}.\beta^{X_2}.25) - 0.4651$.

Following the same approach, the individual risk at the houses (IR), if fire propagates to T6, can be calculated as:

$$\mathrm{IR} = \mathrm{P}_6.\,\mathrm{P(death|T6 = fire)} \tag{17}$$

where P_6 is calculated via Eq (13), and the conditional probability is calculated using Eq (11) as $\mathrm{P(death|T6 = fire)} = 10^{-76} \times (\alpha^{X_6}\ 4)^{\ 20.8}$.

3.3 Application of goal programming

Having the domino effect probabilities and the arising risk at the houses, 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 (Section 2.2), 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 cost \$1M (C_i = \$1M, for i = 1, …, 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:

$$IR_H \leq 10^{-6} \tag{18}$$

$$R_T = \sum_{i=1}^{6} P_i \leq 2 \tag{19}$$

In addition to the foregoing objective functions, 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 only sufficient to include two tanks in the firefighting strategy. This constrain can mathematically be expressed as:

$$\sum_{i=1}^{6} X_i = 2 \tag{20}$$

To formulate the goal programming, the objective functions can further be extended as:

$$IR_H = 10^{-6} + y_1^+ - y_1^- \tag{21}$$

$$R_T = 2 + y_2^+ - y_2^- \tag{22}$$

Where y_i^+ and y_i^- are positive variables that denote, respectively, the upper and lower deviations from the respective goal. For instance, y_1^+ refers to the deviation of IR above 10^{-6}, which is unwanted and should be penalized, while y_1^- refers to the deviation of IR below 10^{-6}, which is desired. Subsequently, the single objective function and the constraints can be specified as:

$$\mathrm{Minimize}\ Z = M\ y_1^+ + y_2^+$$

$$Subject\ to\colon \begin{cases} IR - \ y_1^+ + y_1^- = 10^{-6} \\ R_T - y_2^+ + y_2^- = 2 \\ \sum_{i=1}^{6} X_i = 2 \\ X_i = \{0,1\} \quad \mathrm{for}\ \ i = 1,\dots,6. \\ y_i^+ \geq 0\ and\ y_i^- \geq 0\ \ \mathrm{for} \quad i = 1,2 \end{cases} \tag{23}$$

where M is a very large number to heavily penalize if IR > 10^{-6}. For illustrative purposes, one may set M = 1.0E12 to ensure the first goal is satisfied before an optimal solution is found for the second goal. Solving the above system of equations using the Microsoft Excel® Solver Toolpak for different values of firefighting efficiency parameters α and β, the optimal values of X_i are listed in Table 2.

Table 2. Optimal values of firefighting variables for different firefighting efficiencies given the tank fire at T5.

	X_1	X_2	X_3	X_4	X_5	X_6
Case 1: α = 0.4, β = 0.7	0	0	0	0	1	1
Case 2: α = 0.7, β = 0.4	0	1	0	0	0	1

According to the results in Tale 2, in both cases, T6 should be cooled (X_6 = 1) to decrease the probability of fire spread to T6 as it is the only tank that, if catches fire, can endanger the safety of people at the houses. When the suppression efficiency is higher than the cooling efficiency (Case 1), it is better to suppress T5 (X_5 = 1) to reduce the probability of fire propagation to the other tanks. However, when the cooling efficiency is higher, cooling T2 instead of suppressing T5 ($X_2 = 1$, $X_5 = 0$) seems to be more effective in reducing the likelihood of domino effect.

4. Conclusions

Optimal allocation of firefighting resources in process plants during major fires, particularly when the extent of fire – in terms of involved units and endangered assets – exceed the available resources, is very crucial for protecting the plant as well as offsite assets. While an ideal firefighting strategy aims to contain and fully suppress the fire before it spreads to other units, an optimal firefighting strategy aims to contain the fire, in the best-case scenario, or limit the extent or slow the pace of fire spread in the hope of buying more time for emergency measures (e.g., onsite and offsite evacuations) and arrival of support from nearby plants and/or communities.

In the present study, after modelling potential fire propagation scenarios (domino effects) in a tank terminal, a methodology was developed based on the goal programming for identifying optimal allocation of limited firefighting resources. Compared with the previous studies, the developed methodology can take into account a variety of on-site risks (e.g., risk of internal damage) and offsite risks (e.g., risk of damage to nearby communities and infrastructures) in identifying optimal firefighting strategies. The developed methodology is sufficiently flexible to accommodate a variety of goals and constraints depending on credible fire scenarios, potential domino effects, available firefighting resources, and risks.

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