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RESEARCH ARTICLE

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Optimization of firefighting strategies in process plants with emphasis on domino effects and safe evacuation

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Abstract

Effective firefighting and evacuation are integral parts of emergency response plans in process plants, which play a key role in protecting human lives and assets in the event of major fires. Given sufficient firefighting resources, firefighters would suppress all the burning vessels and cool off all the exposed vessels in order to contain the fire and prevent a fire-induced domino effect. However, when the number of critical units—whether on fire or exposed to fire—exceeds the firefighting resources, firefighters should decide how to optimally allocate the resources so as to best satisfy the safety goals. To facilitate such decisions, the present work aims to develop a methodology for effective firefighting under insufficient resources. The methodology seeks out two safety goals via optimal firefighting strategies: (1) providing for the safety of evacuees, and (2) reducing the risk of domino effects. Although both safety goals are attempted to be satisfied at the same time, a higher priority is assigned to the first goal as long as the evacuation is underway. When the evacuation is complete, all the resources are focused on the second goal. The study shows that a multi-objective optimization approach to identifying firefighting plans outdoes single-objective optimization approaches in that several safety goals could be met at once. Although only two safety goals are considered in the present study, the methodology is flexible enough to accommodate several goals such as safety of offsite people and assets.

KEYWORDS

domino effect; evacuation; firefighting; optimization, goal programming; thermal dose

1 | INTRODUCTION

In the context of fire safety in process plants, inherently safer design techniques,[1] such as Safety-by-Design,[2,3] aim to eliminate or reduce fire hazards at the design stage of vessels and processes, for instance, by reducing the inventory of flammable chemicals or by providing sufficiently long safety distances. However, when these measures fail to meet the safety requirements, additional operational and procedural measures should be taken to lower the risk of fire to a practicable level. Being very costly and resource demanding, firefighting is usually considered as the last resort when it comes to fire safety in process plants. Firefighting plans should thus be identified and optimized via risk-based decision-making techniques to ensure the safety goals are met to the best of available resources and constraints.[4]

An ideal firefighting strategy should confine the fire and prevent its spread to adjacent vessels until burning vessels are fully extinguished. However, when the number of vessels to protect—whether on fire or exposed to fire—exceeds the available resources, conducting ideal firefighting is not feasible, particularly if fire spreads from burning vessels to exposed vessels, creating a domino effect.

In the event of a domino effect, the number of units in need of protection grows exponentially with the number of burning vessels.[5] This quickly makes the initially limited resources even less sufficient for conducting ideal firefighting. In such cases, an effective firefighting strategy would be needed to prioritize the critical vessels and optimally allocate the available resources to which, so as to best satisfy the safety goals (e.g., reducing risk of domino effect, protecting onsite personnel and offsite assets). To achieve these safety goals, methodologies are required to combine domino effect models with optimization techniques while considering the available resources, constraints, and goals.

Considering domino effects as the most resource-demanding event caused by fire in process plants, many studies have been devoted to modelling and risk assessment of domino effects.[6–16] However, work conducted on optimal firefighting and its role in preventing and reducing the risk of domino effects has been limited.[5,17–21] Khakzad combined domino effect models with decision-making and optimization techniques such as dynamic influence diagram (an extension of dynamic Bayesian network [BN]),[5] mathematical programing,[5] and information theory,[20] to find optimal firefighting strategies. Considering onsite property losses of domino effects as the only risk, Cincotta et al.,[17] developed a resiliency metric and argued that optimal firefighting strategies are those that could maximize the resiliency of the plant. Aside from the foregoing studies, there have been relevant studies for identifying and optimizing firefighting schedules rather than firefighting strategies.[18,19] In the foregoing studies,[5,17–20] optimal firefighting strategies were identified considering only one objective: reducing the probability of potential domino effects, or in other words, reducing the internal risk of property loss due to domino effects. To address this drawback, Khakzad proposed employing multi-objective optimization to consider several safety goals in identifying optimal firefighting strategies.[21] In the present study, a methodology is developed based on goal programming—a multi-objective optimization technique—for identification of optimal firefighting strategies with the aim of minimizing the probability of domino effects and onsite risk of fatalities while evacuation of the personnel is underway. The main steps taken in developing the methodology are presented in Figure 1.

Considering heat flux as the main factor that endangers the safety of evacuees and causes domino effects, a process plant is first modelled as a heat graph for a given fire scenario and its potential domino effect. Goal programming is then employed to find the optimal firefighting strategy that can best provide for the safety of evacuees and reduce the probability of the domino effect. In Section 2, fundamentals of firefighting and goal programming are briefly reviewed. Section 3 presents the methodology via a case study. The results are presented and discussed in Section 4. The main outcomes of the study are summarized in Section 5.

2 | METHODS AND MATERIALS

2.1 | Thermal grid

Exposed to fire, the thermal dose ($W^{4/3} \cdot m^{-8/3} \cdot s$) received by a human can be expressed as[22]:

$$\text{Dose} = t_e \cdot q^{4/3} \qquad (1)$$

where q (kW/m^2) is the heat flux, and t_e (s) is the exposure time. For a fire, q at a distance can be calculated using a variety of analytical and numerical models. The Point

1. Identify major process vessels and their credible fire scenarios
2. Map the process plant into a 2D grid
3. Calculate heat flux at each node **q** of the grid
4. Modify the heat fluxes considering the impact of firefighting
   - 4.1. For adjacent vessels, modify **q** by considering the impact of suppression α & cooling β as $q^* = \alpha^{X_i} . \beta^{X_j} . q$
   - 4.2. For other nodes of the grid, modify **q** by considering the impact of suppression as $q^* = \alpha^{X_i} . q$
5. Considering potential domino effects, calculate fire spread probability to the i^th vessel P_i
6. For the nodes comprising the evacuation routes, calculate the total thermal dose as $Dose = \sum P_i . q^*$
7. Set the goals and constraints of the firefighting:
   - 7.1. Identify maximum allowable thermal dose for each evacuation route, for instance, using F-N curve
   - 7.2. Identify the maximum allowable risk of damage to the assets due to potential domino effects
   - 7.3. Identify available firefighting resources
8. Set the penalties for deviations from the goals and solve the goal programming

FIGURE 1 Steps taken in developing the methodology. q: original heat flux; q^*: mitigated heat flux; α and β: suppression and cooling efficiencies; P: probability of fire spread to an adjacent tank; X_i and X_j: optimization binary variables.

THE CANADIAN JOURNAL OF CHEMICAL ENGINEERING

Source model is a simple and easy-to-use analytical technique to calculate the heat flux. The Point Source model, however, cannot consider the shape or tilt of the flame due to the wind effect.[1] Nevertheless, the results of the model for far-field targets (i.e., targets at distances over 10 times the radius of fire) are assumed to be of acceptable accuracy. In the present study, the Point Source model, due to its simplicity, is used to demonstrate the development of the methodology though it can be replaced by more sophisticated models without loss of generality. Using the Point Source model, heat flux Q (kW) for a pool fire can be calculated as[22]:

$$Q = m'' \cdot \Delta H \cdot A \cdot \left(1 - e^{-k \cdot d}\right) \quad (2)$$

where m″ (kg/m^2 · s) is the burning rate of the fuel, ΔH (kJ/kg) is the heat of combustion of the fuel, A (m^2) is the surface area of the pool fire, k (m^{-1}) is an empirical constant, and d (m) is the diameter of the pool fire. For a target R meters away from the center of the pool fire, heat flux q (kW/m^2) can be calculated as[22]

$$q = \frac{f.Q}{4\pi R^2} \quad (3)$$

For high-sooting fuels such as hydrocarbons, $f = 0.6$, while for low-sooting fuels such as alcohols, $f = 0.15$. The exposure time t_e in Equation (1) can be calculated using the relationship below:

$$t_e = t_r + \frac{L}{u} \quad (4)$$

where t_r (s) is the reaction time, L (m) is the distance between the exposed person and the safe spot, and u (m/s) is the average speed of the person (~4 m/s). For trained personnel who expect fire and explosions at workplace, $t_r \sim 3$ s whereas for a lay person $t_r \sim 8$ s.

For a given fire scenario, such as a tank fire, a process plant can be modelled as a two-dimensional grid. The intensity of heat flux for each node of the grid can then be calculated using the Point Source model and be assigned as the weight of that node. Subsequently, by combining Equations (1) and (4), the thermal dose an evacuee may receive while escaping from their location at node $i = 0$ to a safe spot at node j can be calculated as[23]:

$$\text{Dose} = t_r q_0^{\frac{4}{3}} + \sum_{i=1}^{j} \left(\frac{q_i + q_{i-1}}{2}\right)^{\frac{4}{3}} \frac{\Delta l}{u} \quad (5)$$

[1]Due to the titling effect of wind on the flame, targets downwind receive larger heat fluxes than targets upwind. This, however, cannot be considered by the Point Source model.

where q_i and q_{i+1} are the heat fluxes at two adjacent nodes on the grid; Δl is the distance between the adjacent nodes; q_0 is the heat flux at the initial location of the evacuee (node $i = 0$). As an example, consider a thermal grid in Figure 2 where given a fire, an evacuee should leave their initial location at node $i = 0$ and seek shelter at a safe spot at node $i = 3$. In so doing, the evacuee decides to traverse nodes $i = 0$, 1, 2, and 3 in sequence. The heat flux intensity at each node has been calculated and shown as q inside the respective node.

Further, assume that the distances between the adjacent nodes are $\Delta l_{01} = 40$ m, $\Delta l_{12} = 20$ m, and $\Delta l_{23} = 40$ m. Assuming $t_r = 3$ s and $u = 4$ m/s, the total thermal dose the evacuee would receive while escaping from the 'initial location' to the 'safe spot' can be calculated as:

$$\text{Dose} = t_r\, q_0^{\frac{4}{3}} + \sum_{i=1}^{j} \left(\frac{q_i + q_{i-1}}{2}\right)^{\frac{4}{3}} \frac{\Delta l}{u} = 3(12{,}000)^{4/3} + \left(\frac{12{,}000 + 8000}{2}\right)^{4/3} \frac{40}{4} + \left(\frac{8000 + 8000}{2}\right)^{4/3} \frac{20}{4} + \left(\frac{8000 + 2000}{2}\right)^{4/3} \frac{40}{4} = 4{,}633{,}617\ \left(\text{W}^{4/3} \cdot \text{m}^{-8/3} \cdot \text{s}\right).$$

Given the thermal dose, dose–response relationships can be used to estimate the probability of injury (e.g., second-degree burns) or death due to heat exposure. The following probit function can be used to estimate the probability of death P_d[22]:

$$Y_1 = -36.38 + 2.56 \ln(\text{Dose}) \quad (6)$$

$$P_d = \Phi(Y_1 - 5) \quad (7)$$

where Y_1 is the probit value, and Φ (.) is the cumulative density function for standard normal distribution. For the

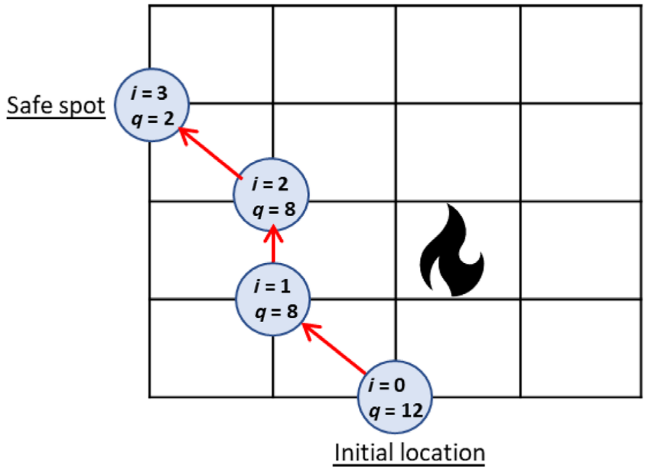

FIGURE 2 Thermal grid given a fire in the process plant. Each node is indicated with two indices: i refers to the node number and q (kW/m^2) shows the intensity of heat flux at that node. An evacuee is supposed to escape from their location at $i = 0$ to a safe spot at $i = 3$. The presented path here is for illustrative purposes and is not necessarily the shortest (safest) available path.

evacuee in Figure 2, who receives an accumulated thermal dose = 4,633,617 ($W^{4/3} \cdot m^{-8/3} \cdot s$), the probit value is calculated using Equation (6) as $Y_1 = 2.91$, which can be converted to a death probability $P_d = 0.02$ using Equation (7).

In case more than one person needs to be evacuated, F–N curves could be consulted to determine the maximum acceptable probability of fatality P_{d-max}. Subsequently, the maximum acceptable probit value Y_{1-max} and maximum acceptable accumulated thermal dose $Dose_{max}$ for each evacuation route can be calculated using Equations (6) and (7).

In the present study, the F–N curve adopted by the National Fire Protection Association (NFPA) in Figure 3 is referred to determine $Dose_{max}$ for evacuation routes.[24] According to Figure 3, for instance, if 10 people are to evacuate via an evacuation route, $P_{d-max} \leq 10^{-6}$. Using Equation (7), this maximum acceptable probability can be translated into $Y_{1-max} \leq 0.25$, and then using Equation (6) into $Dose_{max} \leq 1.64 \times 10^6$ ($W^{4/3} \cdot m^{-8/3} \cdot s$). The line presenting the maximum allowable probability of fatality in Figure 3 (e.g., the line denoting the upper boundary of the 'Tolerable risks' area) can be modelled as Equation (8) to facilitate the calculation of P_{d-max} for any other number of fatalities N:

$$P_{d-max} = -10^{-6} \times N + 11 \times 10^{-6} \quad (8)$$

2.2 | Firefighting in process plants

When suppressing a tank fire, the emitting heat gradually decreases until the fire is completely extinguished.

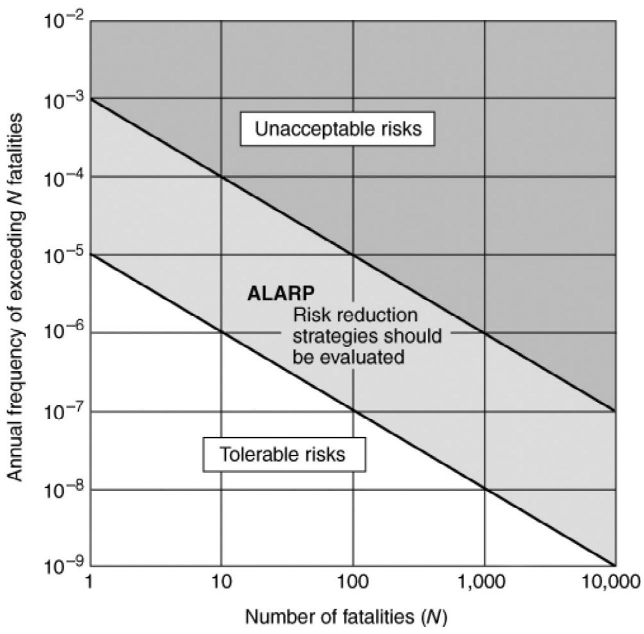

FIGURE 3 F–N curve for identification of acceptability regions of societal fatality risk.[24]

The average mitigated heat flux (q_m) can be considered as a fraction of the original heat flux q_o (unmitigated heat flux) as $q_m = \alpha\, q_o$, where α ($0.0 < \alpha < 1.0$) is the suppression efficiency. Likewise, when cooling an exposed tank, the amount of mitigated heat flux received by the tank (q_c) can be considered as a fraction of the original heat flux q_o it would have received had it not been cooled, that is, $q_c = \beta\, q_o$, where β ($0.0 < \beta < 1.0$) is the cooling efficiency.[7] As a result, when a burning tank is suppressed, and an exposed tank in its vicinity is being cooled at the same time, the reduced heat flux q' the cooled tank would receive from the burning tank under suppression would be $q' = \alpha\, \beta\, q_o$.

Since the probability of fire spread from a burning tank T_i to an exposed tank T_j is dependent on the heat flux that T_j receives from T_i, the effect of firefighting on this probability can directly be taken into account by modifying the heat flux as:

$$q' = \beta^{X_j} \cdot \alpha^{X_i} \cdot q \quad (9)$$

where q is the heat flux that T_j receives from T_i in the absence of any firefighting operations; q' is the reduced heat flux due to firefighting; and X_i and X_j are binary variables {0, 1} to determine which tanks should be included in the firefighting strategy: If T_i is burning, $X_i = 1$ denotes that T_i should be suppressed whereas $X_i = 0$ denotes that T_i should be left burning. Likewise, if T_j is exposed to heat, $X_j = 1$ denotes that T_j should be cooled whereas $X_j = 0$ denotes that T_j should not be cooled. In case T_j is exposed to two tank fires T_i and T_k, the received heat flux by T_j can be modified as[5]:

$$q' = \beta^{X_j}\left(\alpha^{X_i} q_{ij} + \alpha^{X_k} q_{kj}\right) \quad (10)$$

where q_{ij} and q_{kj} are, respectively, the heat fluxes T_j receives from T_i and T_k in the absence of any firefighting operations.

2.3 | Goal programming

Goal programming is a multi-objective optimization technique that aims to find the best solution by minimizing the (weighted) sum of deviations for all the objectives.[25] In non-pre-emptive goal programming, all the objectives are considered to be of equal priority whereas in pre-emptive 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 pre-emptive goal programming, the more important an objective, the larger the penalty assigned to deviations from that objective.[26] A typical goal programming problem with N variables and M objective functions (M goals) can be illustrated as:

$$\text{Minimize} \sum_{j=1}^{M} w_j \cdot \left(d_j^+ \; or \; d_j^-\right) \tag{11}$$

$$\text{Subject to}: \left(\sum_{i=1}^{N} a_{ij} \cdot X_{ij} - \left(d_j^+ - d_j^-\right) = B_j\right)_{j=1}^{M} \tag{12}$$

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 the deviations above and below from the jth goal, respectively.

3 | METHODOLOGY

3.1 | Case study

To demonstrate the application of the methodology, consider an illustrative tank terminal in Figure 4, consisting of 10 identical crude atmospheric tanks, two operating units, and one safe spot. Units #1 and 2 accommodate, respectively, 10 and five workers. The nominal diameter and height of each tank are 19.8 and 6.1 m, respectively.[2] Considering the burning characteristics of crude oil as $m'' = 0.035\ \text{kg/m}^2 \cdot \text{s}$, $\Delta H = 42{,}600\ \text{kJ/kg}$, and $k = 2.8\ \text{m}^{-1}$, the heat flux that tank T_j may receive from a tank fire at T_i can be calculated using the Point Source model, as presented in Table 1.

Since all the tanks are atmospheric, a minimum heat flux of 15 kW/m^2 is considered as the threshold for causing damage and fire spread to an exposed tank.[9] Subsequently, the probability of fire spread can be calculated using the probit function below[7]:

$$Y_2 = 9.25 - 1.85\, ln(\text{ttf}) \tag{13}$$

$$ln(\text{ttf}) = -1.13 ln\left(\frac{q}{1000}\right) - 2.67 \times 10^{-5}\, V + 9.9 \tag{14}$$

$$P_f = \varphi(Y_2 - 5) \tag{15}$$

where Y_2 is the probit value, ttf (min) is the time-to-failure of the exposed tank; q (kW/m^2) is the heat flux the exposed tank receives from an external fire (e.g., from a nearby tank fire); V (m^3) is the volume of the exposed tank; $\varphi(.)$ is the cumulative density function of standard normal distribution, and P_f is the probability of fire spread to the exposed tank. To facilitate the calculation of fire spread probabilities, Khakzad,[5] used Equations (13)–(15) to draw a p–q diagram and fit a curve to directly relate the fire spread probability P_f to the received heat flux q. Following their approach, the p–q diagram for the tanks in Figure 4 can be drawn in Figure 5, and subsequently the approximate fire spread probability $\hat{p}_f$ as a function of q can be estimated as:

$$\hat{p}_f = f(q) = -0.0005\, q^2 + 0.051\, q - 0.4651 \tag{16}$$

3.2 | Domino effect modelling

To identify the firefighting strategies, consider tank fires at T1, T5, and T9. These tank fires could not only endanger the safety of personnel at Units #1 and 2, but also trigger domino effects and cause significant property damage in the plant. In this section, the probabilities of fire spread to the exposed tanks (i.e., the tanks adjacent to the tank fires) are developed. These probabilities, which are dependent on heat fluxes and firefighting strategies, are needed both to model potential domino effects and to identify evacuation routes in the next section.

To develop the fire spread probabilities, the most likely sequence of events during potential domino effects should be identified. Khakzad et al.[8] employed BN to model and assess 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 T_i to tank T_j only if the heat flux that T_j received from T_i was equal or greater than a threshold (e.g., 15 kW/m^2 for atmospheric tanks). In case of two or more tank fires, arcs should still be drawn from the tank fires to an adjacent tank if the total heat flux received by the adjacent tank is above the threshold value.[8]

Probit functions similar to the one presented in Equations (13)–(15) can be employed to calculate the fire spread probabilities (e.g., $P\,(T_j = \text{fire}|T_i = \text{fire})$ needed to populate the conditional probability tables of the BN. Following the methodology developed by Khakzad et al.,[8] the most likely sequence of events due to domino effects can be modelled as in Figure 6.

Considering the BNs in Figure 6, the probability of fire spread to each exposed tank can be calculated using the chain rule and the law of total probability as in Equations (17)–(23). In these equations, '$T_i = f$' means T_i is on fire whereas '$T_i = nf$' means otherwise.

[2]For nominal dimensions of crude storage tanks, see: https://petrowiki.spe.org/w/images/a/a4/Vol3_Page_508_Image_0001.png

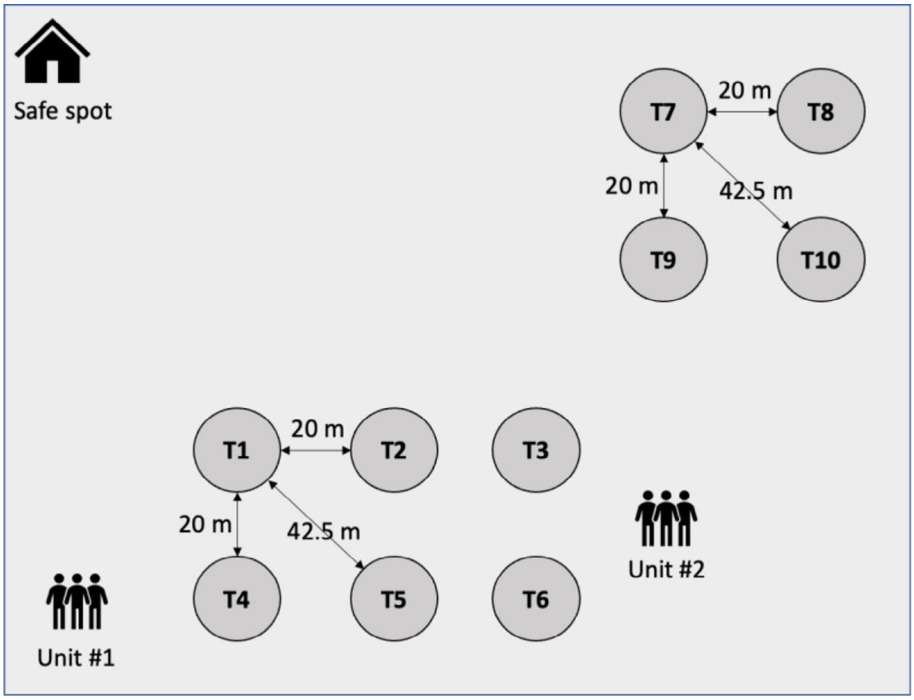

FIGURE 4 A tank terminal with 10 identical crude storage tanks, two operating units, and one safe spot.

TABLE 1 Heat flux (kW/m^2) received by an exposed tank (T_j) given tank fire at tank T_i in Figure 4.

	Heat flux received by T_j									
Fire at T_i	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10
T1	-	24.85	-	24.85	8.11	-	-	-	-	-
T2	24.85	-	24.85	8.11	24.85	8.11	-	-	-	-
T3	-	24.85	-	-	8.11	24.85	-	-	-	-
T4	24.85	8.11	-	-	24.85	-	-	-	-	-
T5	8.11	24.85	8.11	24.85	-	24.85	-	-	-	-
T6	-	8.11	24.85	-	24.85	-	-	-	-	-
T7	-	-	-	-	-	-	-	24.85	24.85	8.11
T8	-	-	-	-	-	-	24.85	-	8.11	24.85
T9	-	-	-	-	-	-	24.85	8.11	-	24.85
T10	-	-	-	-	-	-	8.11	24.85	24.85	-

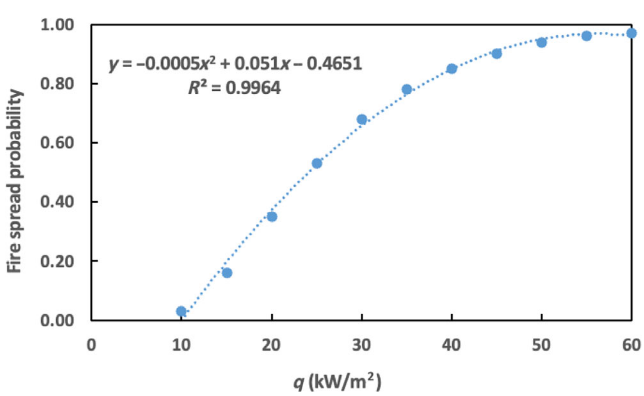

FIGURE 5 Probability of fire spread to the storage tanks as a function of received heat flux.

Sequential calculation of the probabilities assures that the conditional probabilities required to calculate a probability are already calculated in the previous steps:

$$P_2 = P\,(\mathrm{T2} = f | \mathrm{T1} = f, \mathrm{T5} = f) \tag{17}$$

$$P_4 = P\,(\mathrm{T4} = f | \,\mathrm{T1} = f, \mathrm{T5} = f) \tag{18}$$

$$P_6 = P\,(\mathrm{T6} = f | \mathrm{T5} = f) \tag{19}$$

$$\begin{aligned} P_3 = {} & P_2\,P_6\,P(\mathrm{T3} = f | \mathrm{T2} = f, \mathrm{T5} = f, \mathrm{T6} = f) \\ & + P_2\,(1 - P_6)\,P(\mathrm{T3} = f | \mathrm{T2} = f, \mathrm{T5} = f, \mathrm{T6} = nf) \\ & + (1 - P_2)\,P_6\,P(\mathrm{T3} = f | \mathrm{T2} = nf, \mathrm{T5} = f, \mathrm{T6} = f) \end{aligned} \tag{20}$$

THE CANADIAN JOURNAL OF CHEMICAL ENGINEERING

$$P_7 = P(\text{T7}=f|\text{T9}=f) \tag{21}$$

$$P_{10} = P(\text{T10}=f|\text{T9}=f) \tag{22}$$

$$\begin{aligned} P_8 = {} & P_7 P_{10} P(\text{T8}=f|\text{T7}=f,\text{T9}=f,\text{T10}=f) \\ & + P_7(1-P_{10}) P(\text{T8}=f|\text{T7}=f,\text{T9}=f,\text{T10}=nf) \\ & + (1-P_7) P_{10} P(\text{T8}=f|\text{T7}=nf,\text{T9}=f,\text{T10}=f) \end{aligned} \tag{23}$$

The conditional probabilities in Equations (17)–(23) can be calculated by entering the heat fluxes given in Table 1 in Equation (16) while considering the effect of firefighting strategies as in Equations (9) and (10). For instance, to calculate $P(\text{T2}=f|\text{T1}=f,\text{T5}=f)$ in Equation (17), the following modified heat flux needs to be used in Equation (16):

$$q' = \beta^{X_2}\left(\alpha^{X_1} 24.85 + \alpha^{X_5} 24.85\right) \tag{24}$$

According to Equation (24), if T2 is being cooled (i.e., $X_2 = 1$), T1 is suppressed (i.e., $X_1 = 1$) but T5 is left burning (i.e., $X_5 = 0$), the total heat flux T2 receives would be $q' = \beta\,(\alpha\, 24.85 + 24.85)$.

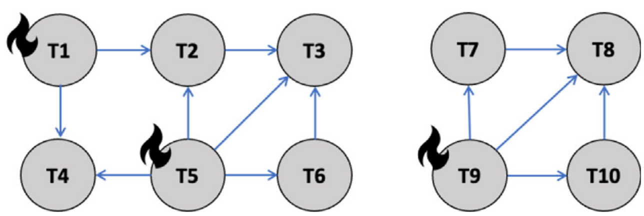

FIGURE 6 Bayesian network models to model potential domino effects given tank fires at T1, T5, and T9.

3.3 | Modelling the process as a thermal grid

The process plant can be modelled as a two-dimensional square mesh 20 × 20 m in Figure 7. The nodes of the mesh have been numbered from 1 to 135 with the tank numbers T1–T10 showing the center of each tank. The operating Units #1 and #2 are at nodes $i = 107$ and 102, respectively, and the fire shelter (safe spot) is at $i = 17$.

Given the tank fires at T1, T5, and T9, the magnitude of heat flux at node i can be calculated as:

$$q_i = q_{1i} + q_{5i} + q_{9i} + \sum_{j=2,3,4,6,7,8,10} P_j . q_{ji} \tag{25}$$

where q_{ji} is the heat flux that node i receives from tank fire at T_j, which can be calculated using Equation (3). P_j is the probability of fire spread to T_j, which can be calculated using Equations (17)–(23). To account for the impact of firefighting on the heat flux at node i, Equation (25) can be modified as:

$$q'_i = \alpha^{X_1} q_{1i} + \alpha^{X_5} q_{5i} + \alpha^{X_9} q_{9i} + \sum_{j=2,3,4,6,7,8,10} P_j \cdot \alpha^{X_j} q_{ji} \tag{26}$$

Given the evacuation routes identified in Figure 7 and knowing the heat fluxes at the nodes via Equation (26), the accumulated thermal dose an evacuee would receive while escaping from Unit# 1 or Unit #2 to the safe spot, i.e., Dose_1 or Dose_2, can be calculated using Equation (5). The evacuation routes are the shortest paths from the units to the shelter, presuming that evacuees would not run toward the tank fires and also avoid the exposed tanks for fear of potential domino effects. Such evacuation routes can be identified, for instance, using Dijkstra's algorithm.[23]

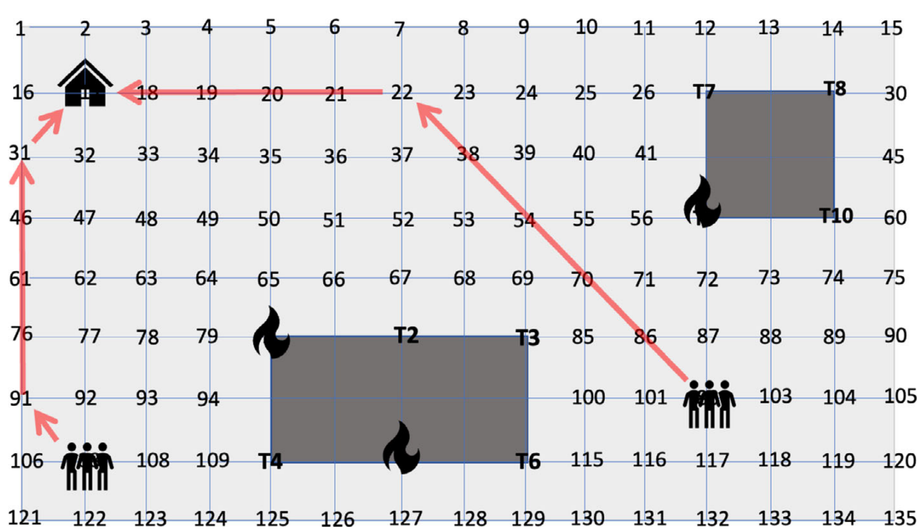

FIGURE 7 Modelling the process plant as a thermal grid given tank fires at T1, T5, and T9. Evacuation routes have been identified with red arrows for each operating unit.

3.4 | Goal programming modelling

Having the thermal doses attributed to the evacuation routes along with probabilities for modelling the domino effects in the process plant, the objectives of the firefighting strategy would be to (i) minimize the risk of fatalities during the evacuation while trying to (ii) minimize the probability of domino effects at the same time, with the former being the first priority. However, after the evacuation is complete, the only objective of the firefighting would shift toward minimizing the probability of domino effects.

Considering 10 and 5 evacuees at Unit #1 and 2, respectively, the upper limits of the accumulated thermal dose for evacuation route #1 (from Unit #1 to the safe spot) and for route #2 (from Unit #2 to the safe spot) can be identified as $\text{Dose}_1 \leq 1.64 \times 10^6$ ($W^{4/3} \cdot m^{-8/3} \cdot s$) and $\text{Dose}_2 \leq 2 \times 10^6$ ($W^{4/3} \cdot m^{-8/3} \cdot s$), respectively.

Further, assume that each tank cost \$1 M (C_i = \$1 M, for $i = 1, \ldots, 10$), and the total risk of damage due to fire and potential domino effects should not exceed \$3.5 M. Subsequently, the firefighting objectives can be specified as in Equations (27)–(29), with the first two objectives being equally of the highest priority:

$$\text{Dose}_1 \leq 1.64 \times 10^6 \tag{27}$$

$$\text{Dose}_2 \leq 2 \times 10^6 \tag{28}$$

$$R_{\text{domino}} = \sum_{i=1}^{10} P_i \cdot C_i \leq 3.5 \times 10^6 \tag{29}$$

In addition to the objective functions, the constraints of the model need to be identified to complete the goal programming. For illustrative purposes, assume that the available firefighting resources are only sufficient to work on four tanks at a time. This constraint can mathematically be expressed as:

$$\sum_{i=1}^{10} X_i = 4 \tag{30}$$

$$X_i = \{0,1\} \quad \text{for } i = 1, \ldots, 10 \tag{31}$$

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

$$\text{Dose}_1 = 1.64 \times 10^6 + y_1^+ - y_1^- \tag{32}$$

$$\text{Dose}_2 = 2 \times 10^6 + y_2^+ - y_2^- \tag{33}$$

$$R_{\text{domino}} = 3.5 \times 10^6 + y_3^+ - y_3^- \tag{34}$$

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 Dose_1 above 1.64×10^6, which is unwanted and should be penalized. Subsequently, the single objective function and the constraints can be specified as:

$$\text{Minimize } Z = M y_1^+ + M y_2^+ + y_3^+ \tag{35}$$

$$\text{Subject to}: \begin{cases} \text{Dose}_1 - y_1^+ + y_1^- = 1.64 \times 10^6 \\ \text{Dose}_2 - y_2^+ + y_2^- = 2 \times 10^6 \\ R_{\text{domino}} - y_3^+ + y_3^- = 3.5 \times 10^6 \\ \sum_{i=1}^{10} X_i \leq 4 \\ X_i = \{0,1\} \quad \text{for } i = 1, \ldots, 10 \\ y_i^+ \geq 0 \text{ and } y_i^- \geq 0 \text{ for } \; i = 1,2,3 \end{cases} \tag{36}$$

In Equation (35), M is a very large number to penalize upper deviations from the goals of the highest priority. In the present study, we take M = 1.0 E12. After the evacuation is completed, the main goal could be switched to minimizing the risk of domino effect via a conventional linear programming instead of goal programming:

$$\text{Minimize } Z = \sum_{i=1}^{10} P_i \cdot C_i \tag{37}$$

$$\text{Subject to}: \begin{cases} \sum_{i=1}^{10} X_i \leq 4 \\ X_i = \{0,1\} \quad \text{for } i = 1, \ldots, 10 \end{cases} \tag{38}$$

4 | RESULTS AND DISCUSSION

4.1 | Results

We solve the system of equations using the Microsoft Excel® Solver Toolpak for three cases, each with different values for firefighting efficiencies α and β and under two situations: When the evacuation is still 'Underway,' and when it is 'Completed'. The optimal values of X_i are listed in Table 2 for combinations of these three cases and two situations.

4.1.1 | Case 1: $\alpha = 0.7$ & $\beta = 0.4$

As can be seen from Table 2, for Case 1, solving Equations (35) and (36) does not result in any feasible solutions for the variables (i.e., no integer values for X_i) when evacuation is underway. In other words, considering

TABLE 2 Optimal firefighting variables. The maximum allowable values for Dose_1 and Dose_2 are 1.64 E + 6 and 2.0 E + 6, respectively. The maximum allowable value for R_{domino} is 3.5 E + 6. Goals not met are in bold.

Variables	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	Dose_1	Dose_2	R_{domino}
Case 1: $\alpha = 0.7$ & $\beta = 0.4$ Evacuation?													
Underway	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS
Completed	0	1	0	0	0	1	1	0	0	1	-	-	**4.36 E + 6**
Case 2: $\alpha = 0.4$ & $\beta = 0.7$ Evacuation?													
Underway	1	1	0	0	1	0	0	0	1	0	1.31 E + 6	**2.92 E + 6**	**3.52 E + 6**
Completed	1	1	0	0	1	0	0	0	1	0	-	-	**3.52 E + 6**
Case 3: $\alpha = 0.4$ & $\beta = 0.4$ Evacuation?													
Underway	1	1	0	0	1	0	0	0	1	0	1.26 E + 6	**2.64 E + 6**	3.35 E + 6
Completed	1	0	0	1	1	0	0	0	1	0	-	-	3.31 E + 6
Case 4: $\alpha = 0.3$ & $\beta = 0.3$ Evacuation?													
Underway	1	1	0	0	1	0	0	0	1	0	7.36 E + 5	1.71 E + 6	3.18 E + 6
Completed	0	1	0	1	1	0	0	0	1	0	-	-	3.00 E + 6

Abbreviation: NFS, no feasible solution.

that suppression of a tank fire may reduce the emitted heat flux by 30% (i.e., $1 - \alpha = 0.3$) and cooling of an exposed tank may reduce the received heat flux by 60% (i.e., $1 - \beta = 0.6$), no firefighting strategy could seem to reduce the accumulated thermal dose below the maximum allowable dose for the evacuation routes and also keep the risk of domino effect under \$3.5 M. However, solving Equations (37) and (38) shows that cooling the exposed tanks T2, T6, T7, and T10 (since $X_2 = X_6 = X_7 = X_{10} = 1$) would be the most effective strategy in reducing the risk of domino effect (given the available resources and the fact that cooling is more effective than suppressing). This outcome is intuitive as by cooling T2 and T6, not only T2 and T6 but T3 could also be saved. Likewise, by cooling T7 and T10, both of which along with T8 could be saved. This strategy, despite being more effective than the other strategies, results in \$4.36 M for the risk of domino effect, which is larger than the desired goal of \$3.5 M.

4.1.2 | Case 2: $\alpha = 0.4$ & $\beta = 0.7$

Unlike Case 1, which did not render any feasible solution, when the suppression efficiency is higher than that of cooling,[3] the strategy 'Suppress T1, T5, and T9 and cool T2' turns out as the most effective strategy in Case 2. This strategy seems to successfully provide for the safety of evacuees at Unit #1 (1.31 E + 6 < 1.64 E + 6) and barely satisfy the domino effect risk objective (\$3.52 M > \$3.5 M) though it fails to meet the safe evacuation goal for people at Unit #2 (2.92 E+6 > 2.0 E + 6). When the evacuation is completed, and the main goal is shifted to minimizing the risk of domino effect, the previous optimal strategy does not change, still keeping the risk of domino effect near the desired goal (\$3.52 M > \$3.5 M). The results show that for the case study of interest and under the available firefighting resources, a higher suppression efficiency (Case 2) better satisfies the safety goals than does a higher cooling efficiency (Case 1).

4.1.3 | Case 3: $\alpha = 0.4$ & $\beta = 0.4$

Compared with the previous cases, Case 3 has a higher efficiency for both suppression and cooling. As can be seen from Table 2, under this case, when the evacuation is underway, the optimal strategy is the same as the one under Case 2, that is, 'Suppress T1, T5, and T9 and cool T2'. This strategy successfully meets the safety goals for evacuees at Unit #1 (1.26 E + 6 < 1.64 E + 6) and the domino effect risk (\$3.35 M < \$3.5 M) but still fails to meet the safe evacuation goal for the personnel at Unit #2 (2.64 E+6 > 2.0 E + 6). However, compared with Case 2, as could be expected, Case 3 results in a smaller

[3]The lower α and β, the higher the suppression and cooling efficiencies, respectively. α = 0.4 means that emitted heat flux is reduced by 60%, while β = 0.7 means received heat flux is mitigated only by 30%.

TABLE 3 Optimal firefighting variables. The maximum allowable values for $Dose_1$ and $Dose_2$ are 1.64 E + 6 and 2.0 E + 6, respectively. The maximum allowable value for R_{domino} is 3.5 E + 6. Goals not met are in bold.

Variables	X_1	X_2	X_3	X_4	X_5	X_6	X_7	X_8	X_9	X_{10}	$Dose_1$	$Dose_2$	R_{domino}
Case 1: $\alpha = 0.7$ & $\beta = 0.4$													
Multi-objective	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS	NFS
Min R_{domino}	0	1	0	0	0	1	1	0	0	1	**4.55 E + 6**	**1.14 E + 7**	**4.36 E + 6**
Case 2: $\alpha = 0.4$ & $\beta = 0.7$													
Multi-objective	1	1	0	0	1	0	0	0	1	0	1.31 E + 6	**2.92 E + 6**	**3.52 E + 6**
Min R_{domino}	1	1	0	0	1	0	0	0	1	0	1.31 E + 6	**2.92 E + 6**	**3.52 E + 6**
Case 3: $\alpha = 0.4$ & $\beta = 0.4$													
Multi-objective	1	1	0	0	1	0	0	0	1	0	1.26 E + 6	**2.64 E + 6**	3.35 E + 6
Min R_{domino}	1	0	0	1	1	0	0	0	1	0	1.47 E + 6	**2.78 E + 6**	3.31 E + 6
Case 4: $\alpha = 0.3$ & $\beta = 0.3$													
Multi-objective	1	1	0	0	1	0	0	0	1	0	7.36 E + 5	1.71 E + 6	3.18 E + 6
Min R_{domino}	0	1	0	1	1	0	0	0	1	0	1.41 E + 6	**2.5 E + 6**	3.00 E + 6

Abbreviations: NFS, no feasible solution.

deviation above the safe evacuation goal due to its higher suppression and cooling efficiencies. Under this case, after the evacuation is completed, the firefighting strategy should be updated to 'Cool T2 and T4 and suppress T5 and T9' to further reduce the risk of domino effect from \$3.35 to \$3.31 M.

4.1.4 | Case 4: $\alpha = 0.3$ & $\beta = 0.3$

By further improving the firefighting efficiencies to $\alpha = 0.3$ and $\beta = 0.3$, the optimal firefighting strategy 'Suppress T1, T5, and T9, and cool T2' seems to satisfy all the safety objectives, resulting in $Dose_1 = 7.36$ E + 5 (<1.64 E + 6), $Dose_2 = 1.71$ E + 6 (<2.0 E + 6), and domino risk = \$3.18 M (<\$3.5 M). Similar to the previous cases, after the evacuation was completed and all the firefighting resources were focused on domino effects, the risk of domino effect could be further reduced from \$3.18 to \$3 M.

4.2 | Discussion

As previously discussed, the majority of previous studies considered only one objective in optimizing the firefighting strategies: Minimizing the risk of fire spread, or minimizing the risk of property loss due to potential domino effects.[5,17,18,20] In case of remote tank farms that are being operated by a few staff and are sufficiently far from onsite and offsite assets, such single-objective optimization procedures may be effective. However, for storage tanks that are within densely populated industrial areas or tank farms that are in proximity of residential areas, a single-objective optimization approach cannot seem to be effective due to several onsite and offsite safety goals to meet.[27,28] To demonstrate the outperformance of multi-objective optimization over single-objective optimization in such cases, optimal values of the firefighting variables along with the safety goals for both optimization approaches are presented in Table 3 for comparison.

In Table 3, under each case, the row headed 'Multi-objective' presents the results of multi-objective optimization using the goal programming. The row headed 'Min R_{domino}' presents the results of single-objective optimization where minimizing the risk of domino effect has been the only objective, disregarding the safe evacuation goals. As can be seen from the results, except for Case 1[4] and Case 2, the single-objective optimization resulted in higher (worse) values for $Dose_1$ and $Dose_2$ despite lower (better) values for R_{domino}.

For Case 2, the single-objective optimization resulted in the same optimal values as the ones obtained from the goal programming, and for Cases 3 and 4 it managed to satisfy two of safety goals, $Dose_1$ and R_{domino}. This is because the onset and development of domino effects increase the thermal doses received by the evacuees, and thus minimizing the risk of domino effects would decrease the risk of fatalities to some extent. However, such a decrease cannot be controlled or forced to drop below a predefined threshold, which is the case with the goal programming. The advantage of multi-objective optimization in identifying firefighting strategies (and safety

[4]It was not possible to compare the results for Case 1 as the goal programming did not render any feasible solution for this case.

measures allocation, in general) becomes more prominent knowing that failures to comply with onsite and offsite safety objectives set out by enforcing safety acts and directives may jeopardize the permit of a process plant.[29]

5 | CONCLUSION

Optimal allocation of firefighting resources in process plants is very crucial particularly when the extent of fire and the number of assets (personnel, properties, etc.) to protect exceed the available resources. While an ideal firefighting strategy aims to contain and fully suppress the burning vessels before fire spreads to other vessels, an optimal firefighting strategy aims to limit the extent and pace of fire spread until more firefighting resources become available. This would delay potential domino effects and help buy time for emergency measures such as evacuation.

In the present study, a methodology was developed by combining domino effect models and goal programming for identifying optimal firefighting strategies under limited resources. We demonstrated the application of the methodology for two main safety goals (safe evacuation of personnel while reducing the risk of domino effect) and one constraint (only four tanks could be afforded by firefighters at a time). However, the developed methodology is sufficiently flexible to accommodate a variety of safety goals (e.g., safety of offsite people and assets) and constraints (e.g., limited available water, limited capacity of safe spots and evacuation routes) depending on fire scenarios, operational and environmental characteristics of tank farms, assets to protect, and enforcing safety acts and directives.

The generality and practicability of the methodology can further be improved by considering, among others, (i) the possibility of boil over in prolonged tank fires, which may demand updating the priorities during the firefighting,[30] (ii) the possibility of burnout or extinguishment of burning tanks so that the assigned firefighting resources could be released and reassigned to other tanks, and (iii) the possibility of explosions and fireballs, which are not credible scenarios for atmospheric tanks but could be of concern regarding pressurized cylinders and tanks in process plants. These are the improvements to be considered in future studies.

AUTHOR CONTRIBUTIONS

Nima Khakzad: Formal analysis; methodology; writing – original draft. **Chao Chen:** Validation; writing – review and editing. **Genserik Reniers:** Validation; writing – review and editing. **Paul Amyotte:** Validation; writing – review and editing.

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DATA AVAILABILITY STATEMENT

Data sharing not applicable to this article as no datasets were generated or analysed during the current study

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