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Firefighting Resources Optimization to Reduce Risk of Fire Dominoes in Process Industries

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Effective control of fires in process industries is essential due to their significant potential risk to both individuals and valuable assets. Insufficient firefighting resources can lead to irreversible consequences both onsite and offsite in case of major process fires. On the other hand, excessive firefighting resources may reduce firefighting efficiency, increase the risk of other accidents, present logistical challenges, and increase costs. Given the potential for the spread of fire among process units (i.e., domino fires), determining the optimal number of firefighting resources and their allocation to critical units become a challenging task for both facility designers and incident commanders. This paper presents an optimization model to find the minimum number of firefighting resources required to fight fire and prevent fire dominoes. The model strategically allocates firefighting resources to process units while prioritizing the preservation of lives both onsite and offsite. The developed model not only assists in identifying sufficient firefighting resources for adhering to regulatory requirements but also aids incident commanders in selecting the most effective firefighting strategies during a fire domino.

1. Introduction

Chemical plants have a high potential to threaten human lives and other valuable assets. Fire is one of the most important hazards of these plants that could endanger employees and people in the surrounding environment (Cheraghi et al., 2024). Fires in these plants are inevitable and still occur. For instance, the Buncefield fire in the United Kingdom in 2005 (Johnson, 2010) and the Jaipur oil depot fire in India in 2009 (Mishra et al., 2013) clearly demonstrated the importance of paying attention to fires in chemical plants, making it one of the most significant concerns for plant managers. In addition, fires in a chemical plant have the potential to spread among process units (i.e., domino fires) (Reniers and Cozzani, 2013). Thus, managing fires in chemical plants remains a challenge for plant owners.

In this way, facility designers should design a chemical plant considering the risk of fires. They consider fire risk-reducing measures such as maintaining safe distance between chemical units, installing automatic fire extinguishing systems, and applying fire-resistant coatings. Additionally, they should determine the required firefighting resources (e.g., firefighting water tanks and fire engines) to fight potential fires and prevent fire domino effects in the plant. Insufficient firefighting resources at chemical and process plants can lead to irreversible consequences both to employees and people in the surrounding environment in the event of major fires. On the other hand, unrequired firefighting resources increases costs and may decrease the efficiency. Therefore, answering the question "what is the optimal quantity of firefighting resources for a chemical plant?" is always challenging for designers and owners of the plant.

Furthermore, incident commanders often encounter similar challenges. One of the most crucial tasks for an incident commander at a fire scene is to effectively manage firefighting resources. While fighting a fire with insufficient resources is inefficient, unrequired deployment of resources at the incident scene may reduce firefighting efficiency, increase the risk of accidents, and present logistical challenges. For effective firefighting, determining the quantity of required firefighting resources is as important as selecting firefighting strategies. During a fire incident, the incident commander is responsible for requesting firefighting resources and selecting strategies to maximize the effective allocation of the resources to fight the fire, depending on its intensity and potential for domino effects. Therefore, determining the required firefighting resources and allocating them to

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critical units to implement firefighting strategies, including offensive firefighting operations (i.e., attacking units involved in fire to suppress them rapidly) and defensive firefighting operations (i.e., cooling exposed units to reduce the risk of fire spread), is crucial for incident commanders.

Numerous risk-based optimization models have been developed to evaluate and enhance plant safety (Cheraghi & Taghipour, 2024; Eslami Baladeh & Taghipour, 2022). In particular, mathematical optimization models have proven effective in finding optimal firefighting strategies aimed at minimizing the total cost of damage and risks to people. For instance, Khakzad (2021b) proposed an optimization model to identify the optimal firefighting strategies that aim to minimize the property damage inside a tank terminal. They compared the results of the optimization model with those of a dynamic influence diagram model and demonstrated the superior performance of the mathematical optimization model. Similarly, Khakzad (2023) developed a goal programming model to identify firefighting strategies that considers both risk of onsite property damage and risk of offsite casualties and property damage. As discussed above, both limited and excessive deployment of resources at the incident scene can lead to adverse consequences. Therefore, this paper is an attempt to propose an optimization model to determine the required firefighting resources and strategically allocate them to process units to fight fire and prevent fire dominoes while preserving lives both onsite and offsite. The remainder of the paper is organized as follows: Section 2 presents common firefighting operations in process plants and evaluates their effectiveness. The proposed optimization model is elaborated in Section 3. Section 4 demonstrates the capability of the proposed model in optimizing firefighting resources through an illustrative example. Section 5 summarizes the conclusions of our study.

2. Firefighting operations and their effectiveness

For the sake of simplicity, this paper assumes there are only two common firefighting operations for fighting fires in a tank farm: (i) offensive firefighting operation, and (ii) defensive firefighting operation.

2.1 Offensive firefighting operation (suppression):

In the event of a fire in a tank farm, an offensive firefighting operation means attacking the tanks involved in the fire to suppress them as rapidly as possible. The effect of a suppression operation on the heat flux emitted from a burning tank can be quantified by a reduction factor, α, which reduces the heat flux received by receptors (i.e., tanks or people). Therefore, the reduction in heat flux resulting from the suppression operation can be expressed as (Landucci et al., 2015):

$$Q^{\text{Suppression}} = \alpha\, Q^{Original}, \quad 0 \leq \alpha \leq 1 \tag{1}$$

where α represents the suppression efficiency factor. In other words, the mitigated heat flux due to the suppression would be calculated as $Q_{ms} = Q^{Original} - Q^{Suppression} = (1-\alpha)\, Q^{Original}$.

2.2 Defensive firefighting operation (cooling):

A defensive firefighting operation involves cooling the exposed tanks to reduce the risk of fire spreading to which. Similarly to assessing the effectiveness of suppression, the reduction in heat flux resulting from the cooling operation can be calculated as (Landucci et al., 2015):

$$Q^{Cooling} = \beta\, Q^{Original}, \quad 0 \leq \beta \leq 1 \tag{2}$$

where β represents the cooling efficiency factor. As such, the mitigated heat flux due to the cooling would be calculated as $Q_{mc} = Q^{Original} - Q^{Cooling} = (1-\beta)\, Q^{Original}$.

3. Methodology

The main purpose of firefighting is to save human lives. Hence, risks exceeding tolerable levels must be mitigated to the tolerable levels. In the proposed model, the aim is to find the optimal combination of tanks for suppression or cooling while minimizing the total amount of firefighting resources. This must be achieved while ensuring that individual risks for both employees and people in the surrounding environment remain within the tolerable levels. Therefore, the decision variables x_i and y_k can be defined as:

$$x_i = \begin{cases} 1, & if\ burning\ tank\ i\ \ is\ selected\ for\ suppression\ operation \\ 0, & otherwise \end{cases} \tag{3}$$

$$y_k = \begin{cases} 1, & if\ \ exposed\ tank\ k\ \ is\ selected\ for\ cooling\ operation \\ 0, & otherwise \end{cases} \tag{4}$$

The proposed model can be mathematically presented as:

$$Minimize \longrightarrow The\ total\ amount\ of\ firefighting\ resources = \sum_{i=1}^{I} x_i w_i + \sum_{k=1}^{K} y_k w_k \tag{5}$$

Subject to:

$$TIR_j - IR_j \geq 0, \ \ \forall j, j = 1, \dots, J \tag{6}$$
$$x_i \in \{0, 1\}, \ \forall i, i = 1, \dots, I \tag{7}$$
$$y_k \in \{0, 1\}, \ \forall k, k = 1, \dots, K \tag{8}$$

where IR_j is the individual risk (i.e., the probability of death of a single person in a year) in the population j, TIR_j is the tolerable individual risk for population j, w_i is the required water for suppression of tank i, w_k is the required water for cooling tank k, I is the number of burning tanks, K is the number of exposed tanks, and J is the number of populations (e.g., people at a nearby school is considered as a single population).

As discussed above, while fighting a fire requires sufficient firefighting resources to meet the safety objectives, excessive deployment of firefighting resources may incur unnecessary costs and potential drawbacks. Thus, the objective function of the model in this paper is to minimize the total firefighting resources (i.e., total water usage in this paper). The constraint in the proposed model ensures that any feasible solution meets the tolerable individual risks for all the employees and people in the surrounding environment. In this paper, we assume that a tank fire has already occurred, and the probability of another tank fire at an adjacent tank due to accidental failures other than domino effect is negligible; thus, only the domino probabilities are accounted for. We also assume that this fire is the only accident in the year of calculation that threatens the lives of employees and people in the vicinity of the tank farm. Therefore, IR_j given a fire at tank i can be calculated as:

$$IR_j = 1 - \prod_{s=1}^{S} (1 - P(D_j \mid M_{ij,s})) \tag{9}$$

where D_j denotes the event that a person in population j is killed, and $M_{ij,s}$ is the s^{th} set consisting of any combination of fires that may originate from tank i that results in the emission of heat flux to population j. For example, consider a case where fire at tank i and spread of fire from tank i to tank k both can expose population j to heat flux. Thus, there are only two combinations from tank i to population j: (1) $M_{ij,1} = \{ij\}$, indicating the direct impact of tank i on population j with $P(D_j \mid M_{ij,1}) = P(D_j \mid T_i)$, and (2) $M_{ij,2} = \{ik, kj\}$, indicating the fire spread from tank i to tank k and then the combined impact of tanks i and k on population j with $P(D_j \mid M_{ij,2}) = P(T_k \mid T_i) P(D_j \mid T_k, T_i)$. It's worth mentioning that instead of using the Law of Total Probability and the Chain Rule, Equation (9) takes advantage of independency to reduce the number of required conditional probabilities, albeit resulting in slightly less precise probabilities (Khakzad, 2021a).

The probability of fire spreading from tank T_i to the exposed tank T_k as a consequence of thermal effect can be estimated using the following probit function (Landucci et al., 2009):

$$P(T_k \mid T_i) = \frac{1}{2} \left[1 + erf\left(\frac{Pr^T(ttf_{ik}) - 5}{\sqrt{2}}\right)\right] \tag{10}$$

where erf is the error function, and $Pr^T(ttf_{ik})$ is the tank damage probit value (see Equation (12)), and ttf_{ik} is the time to failure of tank k due to the heat flux it receives from tank i. ttf_{ik} is expressed in minutes and can be calculated as:

$$ttf_{ik} = 0.0167\, e^{(9.88 - 2.67 \times 10^{-5} V_k - 1.13\, ln\, Q_{ik})} \tag{11}$$
$$Pr^T(ttf_{ik}) = 9.26 - 1.85\, ln\, ttf_{ik} \tag{12}$$

where V_k is the volume of tank k (m^3), and Q_{ik} is the heat flux (kW/m^2) tank k receives from fire at tank i.

Similarly, the probability of death of a person in population j given the thermal dose $Dose_{ij}$ received from the fire at tank i can be calculated as (Assael & Kakosimos, 2010):

$$P(D_j \mid T_i) = \frac{1}{2} FC_j \left[1 + erf\left(\frac{Pr^D(Dose_{ij}) - 5}{\sqrt{2}}\right)\right] \tag{13}$$

where FC_j is the correction factor that represents the influence of the clothing worn by individuals in population j on the probability of death from a thermal dose. $Pr^D(Dose_{ij})$ is the lethality probit value for the thermal dose, $Dose_{ij}(W^{\frac{4}{3}}.s.m^{-\frac{8}{3}})$, which can be calculated as:

$$Pr^D(Dose_{ij}) = -36.38 + 2.56\, ln(Dose_{ij}) \tag{14}$$

$$Dose_{ij} = t_j^{exp}.(Q_{ij})^{\frac{4}{3}} \tag{15}$$

where $t_j^{exp}(s)$ is the exposure time for a person in population j to the heat flux $Q_{ij}(kW/m^2)$. In the case of a pool fire (e.g., full surface tank fires) the duration of the fire is longer than the escape time. Therefore, $t_j^{exp}(s)$ can be calculated as (Assael & Kakosimos, 2010):

$$t_j^{exp} = t_j^r + \frac{d_j}{u_j} \tag{16}$$

where t_j^r is the reaction time (s) of a person in population j; d_j is the distance (m) that an exposed person in population j should run to reach a safe spot (often considered as the position where $Q_{ij} < 1\ kW/m^2$), and $u_j\left(\frac{m}{s}\right)$ is the scape speed of the person in population j.

Given the effectiveness of firefighting operations in reducing the heat flux received by a receptor (i.e., a tank or a person), the mitigated received heat flux value should be used to calculate IR_j. Thus, the mitigated received heat flux value by tank k from the fires at tanks 1, 2, ..., I can be calculated as follows:

$$Q_{\{1,\ldots,I\}k}(x_i, y_k) = (1 - \beta_k y_k) \sum_{i\in\{1,\ldots,I\}} (1 - \alpha_i x_i)\, Q_{ik}^{Original} \tag{17}$$

For example, in order to calculate $P(T_k \mid T_m, T_n)$, we need to compute the mitigated received heat flux by tank k from the fires at tanks m and n as:

$$Q_{\{m,n\}k} = (1 - \beta_k y_k) \sum_{i\in\{m,n\}} (1 - \alpha_i x_i)\, Q_{ik}^{Original} = (1 - \beta_k y_k)[(1 - \alpha_m x_m)\, Q_{mk}^{Original} + (1 - \alpha_n x_n)\, Q_{nk}^{Original}] \tag{18}$$

where β_k is the cooling efficiency factor for tank k, α_i is the suppression efficiency factor for tank i, $Q_{ik}^{Original}$ is the heat flux received by tank k from tank i without any firefighting operations.

Similarly, the total received heat flux value by a person in population j should be modified before calculating the probability of death:

$$Q_{\{1,\ldots,I\}j}(x_i) = \sum_{i\in\{1,\ldots,I\}} (1 - \alpha_i x_i)\, Q_{ij}^{Original} \tag{19}$$

where $Q_{ij}^{Original}$ is the heat flux received by the person in population j from tank i without any firefighting operations.

4. Numerical example

To illustrate the capability of the proposed model in optimizing firefighting resources in a process plant, a hypothetical tank farm is considered as a case study. The tank farm consists of nine atmospheric storage tanks (T_l, where $l = 1,2,\ldots,9$). There is one onsite population and two offsite populations ($J = 3$) surrounding the tank farm: the office of employees (onsite, $j = 1$), a residential area (offsite, $j = 2$), and the railway station (offsite, $j = 3$). Figure 1 illustrates the layout of the tank farm and depicts the heat flux transfer between the tanks, as well as from the tanks to the surrounding populations in the event of fires. Also, Table 1 presents the volumes of the tanks and the required water for firefighting of these tanks.

In this example, we assume that the firefighting operations on all the tanks are carried out such that the suppression and cooling efficiency factors are 0.4 and 0.6 for all the tanks, respectively ($\alpha_i = 0.4$ and $\beta_i = 0.6$). We also consider the tolerable individual risk for employees as $TIR_1 = 10^{-4}$ and the tolerable individual risk for the public as $TIR_2 = 10^{-6}$ and $TIR_3 = 10^{-6}$. The influence of clothing is considered as negligible for all the populations ($FC_j = 1$). Also, the reaction time of a person is considered to be 5 s for all the populations ($t_j^r = 5$

s), the distance that a person should run to reach a safe spot is assumed to be 100 m for all the populations ($d_j = 100$ m), and the scape speed of a person is considered as 4 m/s for all the populations ($u_j = 4\ \frac{m}{s}$).

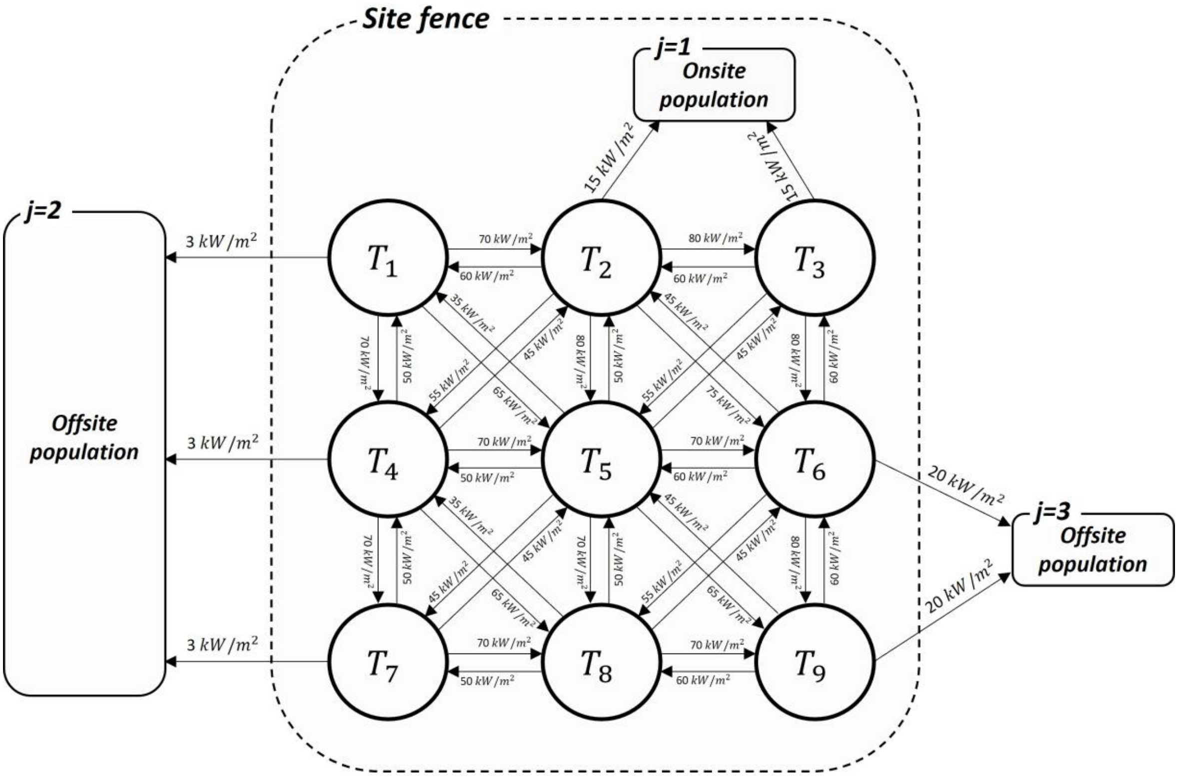

Figure 1: Schematic of the tank farm and heat flux transfers.

Table 1: Tank volumes and required water for firefighting operations.

Tank No., l	Volume of tank, V_k ($\times 10^4\ m^3$)	Required water for suppression of tank, w_i ($\times 10^3\ m^3$)	Required water for cooling of tank, w_k ($\times 10^3\ m^3$)
1	5	3	3
2	8	5	4
3	8	5	4
4	5	3	3
5	5	3	3
6	8	5	4
7	5	3	3
8	5	3	3
9	8	5	4

Let's consider a fire scenario involving T_4 and T_5. We aim to determine the minimum required firefighting resources and strategically allocate them to the tanks to ensure that the individual risks for the onsite and offsite populations remain within tolerable levels. An optimization model for this example is developed according to Equations (5)-(8). Table 2 compares the results of the proposed model with the situation where firefighting operations are not performed. As presented in Table 2, without performing any firefighting operations, the individual risk for population 1 exceeds the tolerable level (i.e., 10^{-4}), and similarly, the individual risk for population 3 is greater than the tolerable level (i.e., 10^{-6}). Therefore, firefighting resources must be deployed at this tank farm to reduce escalation probabilities and mitigate individual risks to adhere to the regulatory requirements. According to Table 2, the minimum required water for reducing individual risks to the tolerable levels for this tank farm is 11000 m^3. This amount of water should be allocated for suppressing T_5, and cooling T_6 and T_9. By suppressing T_5, and cooling T_6 and T_9, even without suppressing T_4, the probability of fire spread to other tanks can be significantly reduced, resulting in lower individual risks for all the three populations below the tolerable levels.

Table 2: The results of the proposed model.

Without firefighting operations										
$P(T_1)$	$P(T_2)$	$P(T_3)$	$P(T_6)$	$P(T_7)$	$P(T_8)$	$P(T_9)$	IR_1	IR_2	IR_3	Water usage ($\times 10^3\ m^3$)
2.55×10^{-2}	3.32×10^{-1}	8.48×10^{-2}	1.64×10^{-1}	5.66×10^{-2}	6.21×10^{-2}	1.48×10^{-1}	2.34×10^{-2}	4.53×10^{-8}	9.66×10^{-2}	0
With optimal firefighting operations: Suppressing T_5, cooling T_6 and T_9										
$P(T_1)$	$P(T_2)$	$P(T_3)$	$P(T_6)$	$P(T_7)$	$P(T_8)$	$P(T_9)$	IR_1	IR_2	IR_3	Water usage ($\times 10^3\ m^3$)
3.33×10^{-3}	8.28×10^{-2}	4.22×10^{-5}	1.66×10^{-5}	1.43×10^{-2}	1.05×10^{-2}	6.36×10^{-6}	4.60×10^{-5}	4.53×10^{-8}	2.86×10^{-7}	11

5. Conclusions

In this paper, an innovative optimization model was developed to determine the required firefighting resources and strategically allocate them to process units to fight fires and prevent fire dominoes ensuring that individual risks for both employees and people in the surrounding environment remain within tolerable levels. The application of the model to determine the required firefighting resources for a hypothetical tank farm and their allocation to the tanks in the event of a fire demonstrated the effectiveness of the proposed model. The developed methodology can assist facility designers in determining the minimum required firefighting resources that a facility should be equipped with. Also, incident commanders can utilize this model to effectively manage available firefighting resources and identify the need for additional resources for adhering to regulatory requirements. Future research could expand upon this model by exploring other objective functions such as minimizing the total cost. However, the drawbacks of excessive deployment of firefighting resources, such as increased risk of other accidents, reduced firefighting efficiency, and logistical challenges, should be included in the future models.

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