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A Risk-Averse Methodology for Firefighting Optimization in Process Plants

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Despite the incorporation of fire preventive measures in the design and operation of process plants, the threat of fire still remains a significant concern in the chemical and process industry. As such, every process plant must be equipped with firefighting resources to effectively respond to and manage potential fire incidents. Firefighting resources often prove insufficient to adequately protect all endangered facilities during a fire incident. Consequently, effective allocation of these limited resources requires a predetermined strategy to increase the efficiency of firefighting.

Such firefighting strategies necessitate consideration of various factors, including the risk of fire spread through the plant, the risk of injuries, fatalities, and property losses both inside and outside the plant. Due to the complexity of integrating all these relevant aspects, risk-based decision-making approaches can be effective in designing firefighting strategies. However, given the nature of safety risks, the adoption of a risk-neutral or risk-taking approach is inappropriate in decision-making regarding firefighting. In the field of safety, it is widely accepted to be prepared for worst-case scenarios, as emphasized in numerous safety standards. In other words, no company seeks to profit by jeopardizing the lives of its employees. From a safety perspective, addressing the consequences of worst-case scenarios may offer more advantages than simply reducing the mean consequences in the system.

This paper introduces a novel risk-averse methodology for determining firefighting strategies aimed at minimizing the likelihood and consequences of potential worst-case scenarios in the event of major fires in process plants. The presented approach is applied to an illustrative tank terminal, and the subsequent results are thoroughly discussed.

1. Introduction

Today's systems are becoming increasingly complex, driven by rapid technological advancements, interconnected networks, and diverse operational environments. This complexity introduces new challenges and uncertainties, necessitating a higher level of safety to mitigate potential risks and ensure operational integrity (Coit and Zio, 2019). Furthermore, evolving regulatory standards, heightened public awareness, and stakeholder expectations place greater emphasis on organizations to adopt comprehensive safety strategies that integrate risk-based decision making(Cheraghi et al., 2024). Risk-based decision making can be categorized into three main strategies: risk-averse, risk-neutral, and risk-taking (Baladeh et al., 2017).

Risk-neutral decision-making focuses on balancing risks and rewards without significant bias towards risk avoidance or acceptance. This strategy makes decisions based on expected values, considering both the probability and consequences of different outcomes; conventional cost-benefit analysis is an example of such decision-makings. It aims to balance between different aspects such as risk, cost-effectiveness of safety measures, and performance of the system. However, the effectiveness of a risk-neutral strategy depends heavily on the accuracy of its input data, including risk identification and evaluation. There is a significant risk of misrepresenting the potential impacts of accidents if risk assessments are based on incomplete data. On the other hand, risk-taking decision-making tries to accept higher levels of risk in pursuit of greater rewards or benefits. This strategy prioritizes growth opportunities over potential risks, making it beneficial for prototype products or technology companies investing heavily in research and development. In contrast, risk-averse

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decision-making prioritizes minimizing risk exposure and aims to avoid or mitigate as much potential hazards as possible. This strategy emphasizes safety and reliability over other considerations and tends to choose options that have a lower probability of failure, even if they offer lower potential rewards. However, these strategies often come with higher upfront costs in the system. Risk-averse strategies are particularly suitable for systems where safety is paramount and the consequences of failures are severe or unacceptable as is the case for critical infrastructure systems such as power plants, air traffic control systems, dams, and bridges.

Fires in process plants can lead to catastrophic consequences, including loss of life, property damage, environmental pollution, and disruption of operations. The ability to respond effectively to fires not only protects personnel, assets, and the environment but also helps in maintaining business continuity, meeting regulatory requirements, and preserving the reputation and credibility of the organization within the industry and the community. Having firefighting teams ready to suppress fires and cool exposed units is a necessity in every process plant. However, assigning a firefighting team to every asset in the plant is often not feasible due to limited resources.

Hence, every plant requires a well-defined firefighting strategy to determine the roles of firefighting team during a fire incident. Given that every second counts during a fire, firefighting strategies should be established in advance for all possible fire scenarios to save time and respond effectively. By strategically planning and optimizing firefighting resources, process plants can minimize response times, contain fires effectively, mitigate potential hazards, and reduce the likelihood of catastrophic incidents. This proactive approach not only enhances the safety and resilience of process plants but also helps in meeting regulatory requirements, maintaining operational continuity, and safeguarding the surrounding community and environment.

From the firefighting strategy perspective, there are three options for each vessel: (i) suppress the burning vessel, (ii) cool the exposed vessel, or (iii) leave the vessel without any intervention. Traditionally, firefighting strategies are primarily established based on generic standards and fire protection codes. However, these standards often overlook certain influencing factors such as the distance between vessels, their volume, wind speed and direction, the flammable chemicals involved, and the effectiveness of the firefighting. As a result, some researchers propose more comprehensive models for firefighting strategies by taking into account more parameters.

Due to resource limitations, it is not always feasible to assign a firefighting team to all assets simultaneously. This raises the challenge of setting up firefighting strategies and determining how to allocate resources to find an optimal approach. Given the complexity of firefighting analysis, a comprehensive approach is necessary to automatically determine and evaluate all credible firefighting strategies. In recent years, mathematical modelling has proven to be highly effective in optimizing system reliability and safety (Baladeh and Taghipour, 2022, Cheraghi and Taghipour, 2024). This approach can also effectively address the complexity of firefighting strategies identification by considering various parameters, ensuring robust and reliable firefighting strategies in challenging and dynamic environments. Subsequently, optimization models have been developed to select firefighting strategies that minimize the total expected cost of fires (Khakzad, 2021a) or their onsite and offsite risks (Khakzad, 2023, Khakzad et al., 2023) under limited resources.

Considering process plants as critical infrastructure systems with potentially significant safety risks, including loss of life, environmental damage, and economic impacts, a risk-averse strategy is suitable to minimize the risk of catastrophic failures. This paper introduces a novel risk-averse mathematical model for optimizing firefighting strategies in process plants. The proposed risk-averse model ensures that the optimization process focuses on mitigating high-impact risks and all available resources are allocated to minimizing the worst possible risks. The model evaluates firefighting strategies in a comprehensive manner, taking into account factors such as fire spread, resource allocation, firefighting effectiveness, and the risk of fatalities.

The rest of the paper is structured into two main sections. In Section 2, the mathematical model for risk-averse optimization of firefighting strategies is developed. Section 3 demonstrates the application of the proposed model to an exemplary tank terminal. The main outcomes of the study are summarized in Section 4.

2. Methodology

Due to resource limitations, it is not feasible to assign a firefighting truck to cool or suppress every vessel in the plant. Therefore, the safety manager faces the challenging task of allocating resources. This task is highly complex, as it involves evaluating various factors such as fire spread potential, available resources, and the likelihood of death in determining which vessels should be cooled and which ones should be suppressed. To deal with this complexity, this paper proposes a mathematical model to determine the optimal firefighting strategy. However, the challenge lies in the fact that different residential areas can be affected differently by fire, and certain strategies may be more effective in some areas than others. Furthermore, the number of people occupying each location can vary in different residential areas, and this variation should be taken into account.

Therefore, since the death of individuals has the most serious impact as a consequence of fire, resource allocation should prioritize minimizing the expected number of deaths in all residential areas. The expected number of deaths in each area can be calculated by the multiplying the number of people by the individual risk (IR) in that area. In other words, considering the objective function as a total expected number of deaths makes the model allocates more resources to areas where more population and protection has is easier. The proposed mathematical model, aiming to minimize the total expected number of deaths in all residential areas is represented by Equations (1)-(5).

$$objective\ function\text{: } \min \sum_{j=1}^{J} P_j . \sum_{i=1}^{I} IR_{ji} \tag{1}$$

$$\sum_{i=1}^{I} x_i \leq L \tag{2}$$

$$\sum_{i=1}^{I} IR_{ji} \leq IR_{min} \qquad ,\forall j \tag{3}$$

$$\sum_{i=1}^{I} x_i w_i \leq W_{max} \tag{4}$$

$$x_i \in \{0\ ,1\} \quad \forall\, i = 1,2,\dots,I \tag{5}$$

Where:

x_i	Decision vector, which indicates the strategy for *i*th vessel
L	Number of firefighting trucks which can be afforded by the firefighters
w_i	Required water for suppression/ cooling of the i^{th} vessel
P_j	The number of people in the j^{th} residential area
IR_{min}	minimum acceptable Individual Risk for the j^{th} residential area
w_{max}	Total available water for firefighting
IR_{ji}	Probability of death for the j^{th} residential area from the i^{th} vessel

The decision variables x_i can be defined as:

$$x_i = \begin{cases} 1, & if\ \ i^{th}\ vessel\ is\ selected\ for\ cooling/suppressing\ operation \\ 0, & \qquad\qquad otherwise \end{cases}$$

The model's objective is to minimize the summation of expected number of deaths in all residential areas, as expressed by Equation (1). The constraint presented in Equation (2) represents the maximum number of fire trucks afforded by the plant. To comply with the land use development regulations, Equation (3) ensures that the individual risk (IR) of offsite risks should be less than the values specified in the regulations, which are determined based on the type and population of the area. Each vessel requires a specific amount of water for cooling or suppression, and since there is a finite amount of water available for firefighting in the plant, the constraint in Equation (4) ensures that any feasible solution remains consistent with this limitation.

3. Application of the methodology to a tank terminal

Consider an illustrative tank terminal with nine atmospheric tanks Ti (i = 1, …, 9) located near three residential areas, a warehouse (j = 1), a residential community (j = 2), and a rail station (j = 3). The layout and location of the tanks and heat fluxes from tanks received by the residential areas in the event of tank fire at adjacent tanks are illustrated in Figure 1. The safety manager has decided to prepare a firefighting strategy for a future scenario in case of tank fire at tank T5 when there are three available firefighting trucks (L=4) and a total of 19,000 m^3 of water available for firefighting (W_{max}). There are 5 people in the warehouse ($p_1 = 5$), 100 people in the rail station ($p_2 = 100$) and 50 people in the residential community ($p_3 = 50$). The land use development regulations in this region (1995) imply that the individual risk for the warehouse should be less than 1E-04, for the rail station less than 1E-06, and for the residential area less than 1E-05. The safety manager is seeking the best strategy to effectively allocate firefighting resources in order to minimize the total expected number of deaths in the three residential areas. Even though the fire is currently confined to tank T5, there is a risk that it could spread to other nearby tanks, triggering a domino effect. To calculate the probability of fire spread to the other tanks, the law of total probability and the chain rule (Khakzad, 2021a) or the Noisy-OR techniques (Khakzad, 2021b) can be utilized. However, compared with the former approach, the Noisy-OR technique extensively simplifies probability calculations but at the cost of resulting in less precise probabilities.

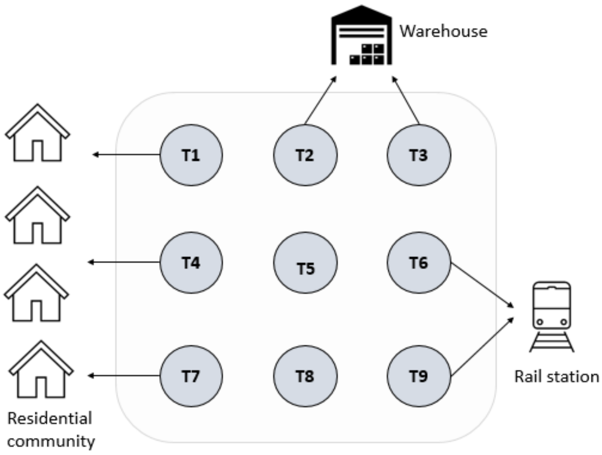

Figure 1. The layout and location of tanks in the tank terminal and offsite targets

Ignoring the fire spread paths which consist of more than two tanks, due to their low probabilities, the conditional fire spread probabilities given the tank fires at T5 can be calculated as:

$$P_1 = 1 - \left\{P(\overline{T_1}|T_5) \times \left(1 - P(T_2|T_5)P(T_1|T_2, T_5)\right) \times \left(1 - P(T_4|T_5)P(T_1|T_4, T_5)\right)\right\}$$

$$\begin{aligned} P_2 = 1 - \{&P(\overline{T_2}|T_5) \times \left(1 - P(T_3|T_5)P(T_2|T_3, T_5)\right) \times \left(1 - P(T_1|T_5)P(T_2|T_1, T_5)\right) \times \left(1 - P(T_6|T_5)P(T_2|T_6, T_5)\right) \\ &\times \left(1 - P(T_4|T_5)P(T_2|T_4, T_5)\right)\} \end{aligned}$$

$$P_3 = 1 - \left\{P(\overline{T_3}|T_5) \times \left(1 - P(T_2|T_5)P(T_3|T_2, T_5)\right) \times \left(1 - P(T_6|T_5)P(T_3|T_6, T_5)\right)\right\}$$

$$\begin{aligned} P_4 = 1 - \{&P(\overline{T_4}|T_5) \times \left(1 - P(T_1|T_5)P(T_4|T_1, T_5)\right) \times \left(1 - P(T_7|T_5)P(T_4|T_7, T_5)\right) \times \left(1 - P(T_2|T_5)P(T_4|T_2, T_5)\right) \\ &\times \left(1 - P(T_8|T_5)P(T_4|T_8, T_5)\right)\} \end{aligned}$$

$$\begin{aligned} P_6 = 1 - \{&P(\overline{T_6}|T_5) \times \left(1 - P(T_3|T_5)P(T_6|T_3, T_5)\right) \times \left(1 - P(T_9|T_5)P(T_6|T_9, T_5)\right) \times \left(1 - P(T_2|T_5)P(T_6|T_2, T_5)\right) \\ &\times \left(1 - P(T_8|T_5)P(T_6|T_8, T_5)\right)\} \end{aligned}$$

$$P_7 = 1 - \left\{P(\overline{T_7}|T_5) \times \left(1 - P(T_8|T_5)P(T_7|T_8, T_5)\right) \times \left(1 - P(T_4|T_5)P(T_7|T_4, T_5)\right)\right\}$$

$$\begin{aligned} P_8 = 1 - \{&P(\overline{T_8}|T_5) \times \left(1 - P(T_9|T_5)P(T_8|T_9, T_5)\right) \times \left(1 - P(T_7|T_5)P(T_8|T_7, T_5)\right) \times \left(1 - P(T_6|T_5)P(T_8|T_6, T_5)\right) \\ &\times \left(1 - P(T_4|T_5)P(T_8|T_4, T_5)\right)\} \end{aligned}$$

$$P_9 = 1 - \left\{P(\overline{T_9}|T_5) \times \left(1 - P(T_8|T_5)P(T_9|T_8, T_5)\right) \times \left(1 - P(T_6|T_5)P(T_9|T_6, T_5)\right)\right\}$$

Where, $P\left(\overline{T_i}|T_j\right) = 1 - P\left(T_i|T_j\right)$ is the probability of fire not spreading from T_j to T_i. It is worth noting that since T5 are burning: $P_5 = 1$.

The probability of fire spread to an exposed tank can be estimated using dose-effect relationships such as probit functions as (Landucci et al., 2009):

$$ttf_{iz} = 0.0167\, e^{(9.88 - 2.67 \times 10^{-5} V_i - 1.13 \ln Q_{iz})} \tag{6}$$

$$Y_{iz}^{d} = 9.26 - 1.85 \ln ttf_{iz} \tag{7}$$

$$\mathrm{P}(T_i|T_z) = \phi(Y_{iz}^{d} - 5) \tag{8}$$

where Q_{iz} (kW/m^2) is the heat radiation tank T_i receives from tank T_z, V_i (m^3) is the volume of the tank T_i, ttf_{iz} is the time to failure (min) of the tank T_i, Y^d is the damage probit value, and $\mathrm{P}(T_i|T_z)$ is the probability of fire spread to the tank T_i from tank T_z. $\phi(.)$ is the cumulative density function of standard normal distribution.

The probability of death for an individual, Individual Risk (IR_{ji}) in residential area of j due to the tank fire at tank T_i can be calculated through the following probit function (Assael and Kakosimos, 2010) :

$$Y_{ji}^{f} = -36.38 + 2.56 \ln\left(t_e . Q_{ji}\right) \tag{9}$$

$$IR_{ji} = \phi(Y_{ij}^{f} - 5) \tag{10}$$

where Q_{ji} (kW/m^2) is the received heat radiation to residential j from tank T_i, and Y_{ji}^{f} is the fatality probit value, and $t_e(s)$ is the exposure time of the individual (set as 60 s).
When suppressing a burning tank, the emitting heat flux from the tank would be a factor of the original heat and the suppression inefficiency as $Q_{modified} = (1-\alpha)\, Q_{original}$. Likewise, when cooling an exposed tank, the amount of heat radiation received by the tank would be a factor of the original heat and cooling inefficiency as $Q_{modified} = (1-\beta)\, Q_{original}$ (Landucci et al., 2015) . Therefore, to use Equation (5) for calculation of fire spread probabilities between two adjacent tanks, T_l & T_k, the received heat radiation to tank T_i should be modified as:

$$Q_i = (1-\beta x_i)\{(1-\alpha x_l)\, q_{li} + \big((1-\alpha x_k)\, q_{ki}\big)\} \tag{11}$$

In this example, the suppression and cooling efficiencies are assumed to be α = 0.4 and β = 0.6. The volume of tanks T1, T4, T5, T7, and T8 is 50,000 m^3, while the volume of T2, T3, T6 and T9 is 80,000 m^3. The required water for cooling tanks T1, T4, T7 and T8 is 3,000 m^3, for tanks T2, T3, T6, and T9 it 5,000 m^3, and the required water for suppression tank T5 is 6,000 m^3. The heat fluxes received by the tanks T_z or residential areas in the event of tank fire at tank T_i are listed in Table 1.

Table 1. Heat radiation $Q_{iz}$to tank T_i (kW/m^2) if tank fire at tank T_z

i z	T1	T2	T3	T4	T5	T6	T7	T8	T9	Residential community	warehouse	Rail station
T1	-	70	-	70	65	0	-	-	-	3	-	-
T2	60	-	80	55	80	75	-	-	-	-	15	-
T3	0	60	-	-	55	80	-	-	-	-	15	-
T4	50	45	-	-	70	-	70	65	-	3	-	-
T5	35	50	45	50	-	70	45	70	65	-	-	-
T6	-	45	60	-	60	-	-	55	80	-	-	20
T7	-	-	-	50	45	-	-	70	-	3	-	-
T8	-	-	-	35	50	45	50	-	70	-	-	-
T9	-	-	-	-	45	60	-	60	-	-	-	20

Based on the proposed model, the optimal firefighting strategy when tank T5 is on fire would be to cool tanks T4, T6, and T9 while suppressing T5. This approach aims to prevent the spread of fire to tanks located closer to the public areas, thereby minimizing the probability of fatalities in those areas. The individual risks under the optimal strategy for each residential area are provided in Table 2. In the optimal solution, suppressing tank T5 is crucial since it is a burning tank, leaving us with only 3 trucks and 13,000 m^3 of water for cooling the other tanks. Given that the occupancy of the warehouse is just 5 people, cooling of tanks T2 and T3 would be of a lower priority. Additionally, by comparing the required water for tanks T1, T4, and T7 (3,000 m^3) with that for tanks T6 and T9 (5,000 m^3), it is noted that protecting the residential community requires less water than the rail station. As a result, tanks T1, T4, and T7 are selected for cooling in the optimal solution to protect the residential community from possible fire spread to the other tanks. The total of 19,000 m^3 of water used in this strategy meets the model's requirements.

Table 2. Optimal firefighting strategies for different models

Residential area	Individual risk (IR_j)
Warehouse (j = 1)	4.60E-05
Residential community (j = 2)	6.66E-16
Rail station (j = 3)	2.86E-07

4. Conclusions

This paper presents a risk-averse mathematical model to optimize firefighting strategies at process plants. The model prioritizes risk of death over other consequences of fire, reflecting the belief that in the process industry, companies should prioritize public safety over other safety objectives in the event of major accidents such as tank fire. Moreover, the model's capacity to handle large-scale problems makes it applicable across a wide range of chemical and process plants. It offers a robust tool for decision-making to enhance system safety and minimize the fatalities. By determining the optimal strategies for every possible fire scenario, firefighting teams can respond promptly and effectively during a fire incident. As further research, considering the cost of damage could be valuable extensions to this work, enhancing the model's applicability and impact in real-world firefighting operations.

Nomenclature

IR_{ji} – probability of death for the j^{th} residential area from the i^{th} vessel
IR_{min} – minimum acceptable Individual Risk for the j^{th} residential area
L – number of available firefighting trucks
$\mathrm{P}(T_i|T_z)$ – probability of fire spread to the tank T_i from tank T_z
P_j – number of people in the j^{th} residential area
Q_{ji} – received heat radiation to residential j from tankT_i, kW/m2
Q_{iz} – heat radiation tank T_i receives from tank T_z,kW/m2
$\phi(.)$ – cumulative density function of standard normal distribution
$t_e(s)$ – exposure time of the individual
ttf_{iz} – time to failure (min) of the tank T_i
V_i – volume of the tankT_i, m3
w_i – required water for suppression/ cooling of the i^{th} vessel
w_{max} – total available water for firefighting
x_i – decision vector, which indicates the strategy for i^{th} vessel
Y_{ji}^{f} – fatality probit value of the heat radiation to residential j from tank T_i
Y^{d} – damage probit value

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