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RESEARCH ARTICLE

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A graph-based optimization methodology for identifying firefighting strategies aimed at domino effects

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Abstract

Firefighting strategies at process plants would include simultaneous extinguishment of burning units and cooling of exposed units if firefighting resources are sufficient. This way, the fire can be contained and its propagation to the exposed units can be prevented, which would otherwise cause fire escalation and result in domino effects. However, when the firefighting resources are not sufficient to handle all the critical units—either burning or exposed—at once, firefighters need to decide which burning units to suppress first and which exposed units to cool first to minimize the risks. Making effective decisions in such situations becomes critical knowing that, by spreading the fire to adjacent units, the number of critical units grows exponentially, making the available firefighting resources even more insufficient. In the present study, after modelling fire spread in a tank terminal as a directed graph, closeness centrality—a graph centrality metric—is used to identify the critical units from the viewpoint of their contribution to potential domino effects. Knowing the critical units and considering available firefighting resources for suppression and cooling of these units, mathematical programming is applied for optimal allocation of firefighting resources. A comparison between the results of the present work and previous studies shows the effectiveness of the developed methodology.

KEYWORDS

closeness centrality, directed graph, domino effect, optimal firefighting, tank fire

1 | INTRODUCTION

Emergency response at chemical and process plants, particularly considering major fires and potential domino effects, has recently gained attention from the process safety and risk community. Among the emergency measures such as firefighting and evacuation, firefighting is the most complicated task as it starts shortly after the onset of fire and progresses toward the end until the fire is fully extinguished or controlled. So, compared with evacuation, which is usually conducted and finished within the first few minutes of fire onset and before it escalates into adjacent units,[1,2] firefighting is a much longer task (extinguishment of a full surface tank fire may take a few hours) and should adapt with the fire dynamics in order to be effective. Despite many studies devoted to the modelling and risk assessment of fire and potential domino effects in chemical and process plants,[3–14] work devoted to the modelling and optimization of firefighting strategies with the aim of preventing or delaying potential domino effects has been limited.

In an ideal firefighting strategy, burning tanks should be suppressed and the exposed tanks should be cooled all at the same time in order to control the fire and prevent its escalation until it is fully extinguished. However, firefighting resources which might be sufficient to handle a single tank fire can quickly become insufficient if fire propagates to adjacent tanks. As a result, the resources would no longer be sufficient to conduct ideal firefighting, and firefighters should decide which burning tank to suppress first and which exposed tanks to cool first to achieve optimal fire control.

Some general guidelines have been proposed in the literature for identification of firefighting strategies in process plants, but they cannot seem to effectively address the foregoing issue of resource scarcity. Lang et al.[15] proposed that, given a burning tank, all the tanks within 1.5 diameters of the impacted tank should be cooled, without prioritizing among the exposed tanks. In this regard, the works of Shelley[16] and D'Amico[17] are notable in that they have suggested some degree of prioritization regarding the cooling of exposed tanks. Shelley[16] suggested that exposed tanks downwind a burning tank should be cooled first, and then the ones to the left and right of the downwind tanks, if resources allow. D'Amico[17] suggested using fire simulation models to calculate the heat flux emitted from a burning tank and then prioritize the exposed tanks based on the magnitude of the heat flux they would receive: the exposed tanks that receive 19–35 kW/m^2 of heat flux should be cooled immediately (first priority) while the ones that receive 12–19 kW/m^2 of heat flux should be cooled within 1–3 h (second priority). The foregoing studies,[15–17] despite their merits, do not seem to consider the criticality of the tanks with respect to potential domino effects and further fine-tune the priority of the exposed tanks in the face of insufficient firefighting resources.

To address the drawbacks of the aforementioned studies, some researchers have proposed that domino effect modelling and risk assessment methodologies can be combined with decision making and optimization techniques to determine more effective firefighting strategies. In this regard, Zhou et al.[18–20] developed methodologies based on event sequence diagrams and Petri nets to increase the efficiency of firefighting schedules (deployment times) rather than identifying firefighting strategies (i.e., which tanks to be included in the firefighting plan).

The first notable work with respect to optimal firefighting strategies is that of Cincotta et al.,[21] where they developed a methodology based on Bayesian network and resilience theory to identify firefighting strategies that maximize the resiliency of the process plant in case of tank fires. Khakzad[22] used dynamic Bayesian networks (DBN) to calculate fire propagation probabilities in a tank farm and then combined these probabilities with information theory to compute mutual information between the burning and exposed tanks. He identified optimal firefighting strategies as ones that could minimize mutual information—flow of thermal energy—among the tanks. Later, Khakzad[23] developed two methodologies: one based on dynamic influence diagrams (DID), and another based on mathematical programming. In the first methodology, he developed a DBN to model fire propagation in a tank terminal and then converted the DBN into a DID to identify optimal firefighting strategies as the ones that would minimize internal risks. In the second methodology, the fire propagation probabilities were used to set up a mathematical programming model to identify optimal strategies. Both methodologies were demonstrated to result in the same optimal strategies. whereas the mathematical programming model was shown to be less cumbersome and time-consuming to set up than the DID model, especially in the case of large and versatile process plants. In similar efforts, Khakzad et al.[2] and Khakzad[24] and used fire propagation probabilities to set up goal programming models to identify firefighting strategies while considering a range of internal and external risks.

As can be noted, in the foregoing efforts,[2,21–24] fire propagation probabilities were required to feed or complement the employed decision making and optimization techniques. However, the calculation of such probabilities is usually challenging and error-prone, and needs sophisticated models such as DBN. Besides, such probabilities are usually calculated based on dose–response models,[25] where heat flux values received by exposed tanks are converted into failure probabilities. Such dose–response models have been developed only for a limited range of case studies and under some oversimplifying assumptions. This may introduce some degrees of uncertainty into the calculation of probabilities, which in turn may impact decision making and the resulting firefighting strategies.

Modelling fire propagation in tank terminals as directed graphs, Khakzad and Reniers[26] showed that some centrality metrics such as closeness and betweenness can be used to identify critical units with regards to their contribution to potential domino effects. Calculation of such centrality metrics does not require fire propagation probabilities and is only a function of the structural connectivity of the graph. Moreover, there are many algorithms that can quickly and accurately calculate the centrality metrics of graphs as soon as the structure of the graph (its nodes and edges) is defined.

In the present study, a mathematical programming model is developed based on graph centrality metrics rather than fire propagation probabilities for identification of firefighting strategies. The developed methodology is shown to be simple, effective, and in good agreement with the previous more sophisticated methodologies. Fundamentals of firefighting and graph centrality are reviewed in Section 2. Development and application of the methodology, along with the results, are shown in Section 3. The results are discussed with reference to the previous studies in Section 4. Section 5 summarizes the main outcomes and concludes the study.

2 | BACKGROUND

2.1 | Firefighting

When suppressing a tank fire, the heat emitted is assumed to decrease by a factor α $(0 < \alpha < 1)$, which is known as the suppression efficiency. The mitigated heat flux (q_m) is thus considered to be a fraction of the original heat flux q_o (unmitigated heat flux) as $q_m = \alpha \times q_o$. Similarly, when an exposed tank is cooled by firefighters (usually with water), the amount of heat flux received by the tank (q_c) would be decreased by a factor β $(0 < \beta < 1)$, which is known as the cooling efficiency. The reduced heat flux is thus considered to be a fraction of the original heat flux q_o the tank would have received had it not been cooled, that is, $q_c = \beta \times q_o$.[27,28]

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 that the exposed tank would receive from the suppressed tank fire can be modelled as follows:

$$q_{mc} = \alpha \times \beta \times q_o \quad (1)$$

Therefore, considering a burning tank Ti and an exposed tank Tj, the impact of different firefighting strategies on the magnitude of heat flux that Tj receives from Ti can be modelled as follows:

$$q'_{ij} = \alpha^{Xi} \times \beta^{Xj} \times q_{ij} \quad (2)$$

where q_{ij} is the heat flux Tj receives from Ti in the absence of any firefighting operations; q'_{ij} is the mitigated heat flux due to firefighting activities (either extinguishing Ti or cooling Tj); and Xi and Xj are binary variables {0, 1} to determine which tanks to include in the firefighting strategy. In this regard, Xi = 1 denotes that Ti should be suppressed, whereas Xi = 0 denotes that Ti should be left burning. Likewise, if Tj is exposed to heat, Xj = 1 denotes that Tj should be cooled, whereas Xj = 0 denotes that Tj should not be cooled.

2.2 | Closeness centrality in directed graphs

In a connected graph, closeness centrality (or simply, closeness) of a node is a measure of connectedness of the node in the graph, accounting for how many other nodes can be reached from the node of interest and within what distances. In other words, the more connected nodes and the shorter the connection distances, the higher the closeness of the node of interest. Closeness of a node is usually calculated as a variant of the reciprocal of the sum of the distances from the node. The distances are not arbitrary and should be the shortest paths possible between the nodes. In unweighted graphs, the shortest path between two connected nodes would be the smallest number of leaps (number of edges), whereas in a weighted graph it is the lowest sum of weights between the nodes. Closeness for a node can be calculated as follows:[29]

$$C_i = \sum_j \frac{n-1}{d(i.j)} \quad (3)$$

where C_i is the closeness of node i, n is the total number of nodes in the graph, and $d(i, j)$ is the shortest path from node i to node j. Having the closeness values of all the nodes in a graph, the graph closeness, or average closeness C_{avg}, can simply be calculated as the arithmetic average of the node closeness values.

Khakzad and Reniers[26] showed that closeness can effectively be used to identify critical units in a process plant with respect to their contribution to potential domino effects. In their approach, a process plant or tank terminal should first be modelled as a directed graph, with the units (e.g., storage tanks) as the nodes of the graph and the heat flux magnitudes as the edges connecting the adjacent nodes. For illustrative purposes, consider the four storage tanks, T1–T4, in Figure 1.

In the event of a tank fire at T1, T2 and T4 would receive 20 and 35 kW/m^2, respectively. If T2 catches fire,

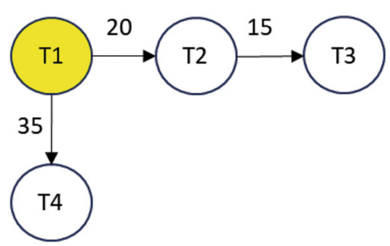

FIGURE 1 An example to show how the distance and closeness values can be calculated for a connected graph. T1–T4 are oil storage tanks, and the edges show the heat fluxes (kW/m^2) in case of a tank fire at T1 and its spread to T2 which can impact T3.

T3 would then receive 15 kW/m^2 from T2. Since a higher heat flux means a higher fire propagation probability[25] and thus a shorter distance (fire at T1 may propagate more quickly to T4 than T2, so T4 is closer to T1), the distance between two adjacent nodes i and j can be calculated as follows:

$$d(i,j) = \frac{100}{q_{ij}} \tag{4}$$

The number 100 in the numerator of Equation (4) is simply to result in distance and closeness values greater than unity, making the calculations more convenient. This way, the distance from T1 to the other nodes in Figure 1 can be calculated as: $d(1,2) = \frac{100}{20} = 5$; $d(1,3) = \frac{100}{20} + \frac{100}{15} = 11.67$, and $d(1,4) = \frac{100}{35} = 2.86$. Using this relationship for calculating the distance between two nodes has the benefit of accounting for not only the amount of heat flux but also the number of edges (leaps). For instance, although the sum of heat fluxes from T1 to T3 ($20 + 15 = 35$ kW/m^2) is equal to the heat flux between T1 and T4, the distance between T1 and T4, that is, $d(1,4) = 2.86$, is much shorter than the distance between T1 and T3, that is, $d(1,3) = 11.67$. For more complicated graphs, if the distance values between the adjacent nodes (i.e., nodes connected together via a single edge) are known, the shortest distance between any two connected nodes can be found and measured using a variety of shortest-path-finding algorithms such as Dijkstra's algorithm.[30] Having determined the shortest distances in Figure 1, the closeness centrality for T1 can be calculated using Equation (3) as: $C1 = \frac{3}{d(1,2)} + \frac{3}{d(1,3)} + \frac{3}{d(1,4)} = 3\left(\frac{1}{5} + \frac{1}{11.67} + \frac{1}{2.86}\right) = 1.91$.

Having all the shortest paths determined, Equations (2) and (3) can be combined to further account for the impact of firefighting on the distance and thus closeness as follows:

$$d'(i,j) = \frac{100}{\alpha^{Xi} \times \beta^{Xj} \times q_{ij}} \tag{5}$$

where $d'(i,j)$ is the modified distance between nodes i and j while considering the firefighting activities.

3 | APPLICATION OF THE METHODOLOGY

3.1 | Case study

Consider atypical oil tank terminal consisting of nine oil storage tanks T1–T9,[24] in which the heat fluxes between the adjacent tanks in case of tank fires have been calculated and presented as the edges of the graph in Figure 2. A heat flux threshold of 15 kW/m^2 is considered for fire propagation between the adjacent tanks.[31] Two fire scenarios are considered: (i) T4 catches fire, and (ii) fire propagates from T4 to T5.[24] As the edges in Figure 2 indicate the possibility of fire propagation between adjacent tanks, when a tank is already on fire, it is no longer being considered as a target by the other tanks, and thus the edges coming to it from the adjacent tanks should be deleted from the graph.

For instance, in Figure 2B, T1, T5, and T7 can no longer impact T4, and that is why the respective edges in Figure 2A have been removed in Figure 2B. As a result of this graph modification, the distances (and consequently, the closeness values) calculated for Figure 2B should be recalculated when fire spreads from T4 to T5 in Figure 2C due to the removal of incoming edges to T5. Due to implementing such changes, in Figure 2B, the shortest path from T4 to T6, for instance, would comprise T4 → T5 → T6, whereas in Figure 2C it would be modified as T4 → T1 → T2 → T3 → T6. As such, the

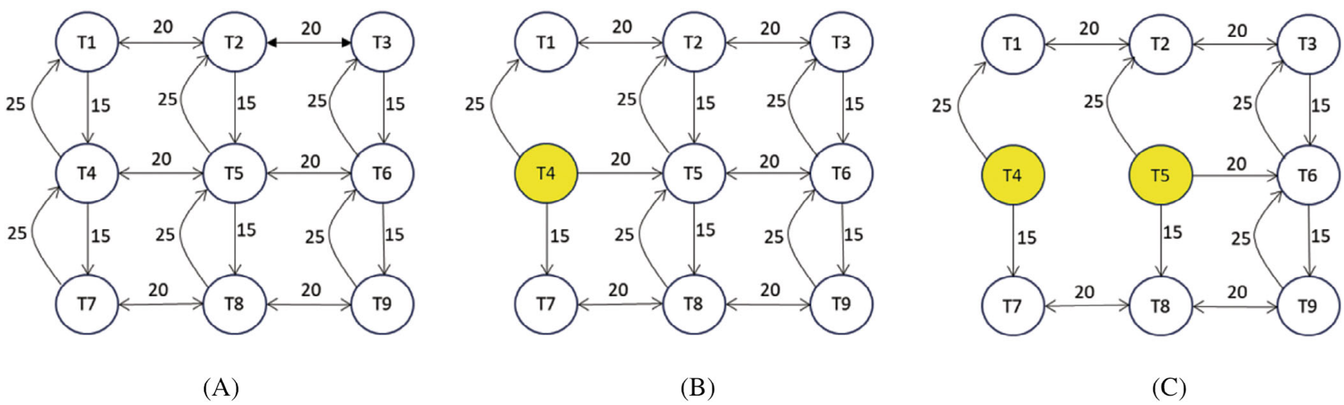

FIGURE 2 (A) Modelling fire propagation in a tank terminal as a directed graph. (B) A primary tank fire at T4 can initiate a domino effect. (C) Fire has propagated from T4 to T5, changing the connectivity and closeness of the nodes.

closeness values of T4 would not be the same in Figure 2B,C. Replacing $d(i,j)$ in Equation (3) with $d'(i,j)$ in Equation (5), the closeness values of the nodes in Figure 2B,C can readily be calculated.

3.2 | Results

Given the closeness values developed in the previous section, mathematical programing can be used to find optimal firefighting strategies by minimizing the closeness. Between two nodes in a graph, the one with the lower closeness can reach out to a lower number of nodes or to a comparable number of nodes but only by traversing longer distances. This means that fire at a tank with a lower closeness would impact fewer adjacent tanks or would take longer to do so, thus providing firefighters with more time to control the fire. To set up the mathematical programming and compare the results with those reported by Khakzad,[24] firefighting efficiencies are chosen as $\alpha = \beta = 0.7$, and it is further assumed that the firefighting resources are only sufficient to handle three tanks (whether to suppress or cool). As an example, the mathematical programming for minimizing the closeness of T4 in Figure 2B can be developed as follows:

$$\text{Min C4}$$

$$\text{Subject to}: \begin{cases} \sum \text{X}i \le 3 \\ \text{X}i = \{0,1\} \text{ for } i = 1,2,\ldots,9 \end{cases} \quad (6)$$

The distances from T4 to the other nodes are presented below for clarity:

$$d(4,1) = \frac{100}{\alpha^{X4} \times \beta^{X1} \times 25}$$

$$d(4,2) = d(4,1) + d(1,2) = \frac{100}{\alpha^{X1} \times \beta^{X2} \times 20}$$

$$d(4,3) = d(4,2) + d(2,3) = d(4,2) + \frac{100}{\alpha^{X2} \times \beta^{X3} \times 20}$$

$$d(4,5) = \frac{100}{\alpha^{X4} \times \beta^{X5} \times 20}$$

$$d(4,6) = d(4,5) + d(5,6) = d(4,5) + \frac{100}{\alpha^{X5} \times \beta^{X6} \times 20}$$

$$d(4,7) = \frac{100}{\alpha^{X4} \times \beta^{X7} \times 15}$$

$$d(4,8) = d(4,5) + d(5,8) = d(4,5) + \frac{100}{\alpha^{X5} \times \beta^{X8} \times 15}$$

$$d(4,9) = d(4,6) + d(6,9) = d(4,6) + \frac{100}{\alpha^{X6} \times \beta^{X9} \times 15}$$

With the above distances, the closeness of T4 can be modelled using Equation (3).

The optimal values of firefighting variables, that is, Xi, have been presented in Table 1 for the two fire scenarios: (i) tank fire at T4 and (ii) fire propagation from T4 to T5, which results in two tank fires. For each fire scenario, two objective functions were examined to see which would provide more accurate results. The first objective function examined is 'minimizing the closeness of the tank(s) which was on fire.' This is Min C4 for the first fire scenario, and Min (C4 + C5) for the second fire scenario. The second objective function is 'minimizing the average closeness', that is, Min C_{avg}. For comparison purposes, the results reported in Khakzad[24] by minimizing the total probability of fire propagation, Min $\sum P$, are also presented in Table 1.

3.2.1 | First fire scenario: T4 is on fire

Based on the results reported in Table 1, Figure 3 shows the firefighting strategies for the first fire scenario for the three objective functions. Here we see that the optimal firefighting strategy identified by Khakzad[24] under Min $\sum P$ (Figure 3A) is the same as that identified under Min C4 (Figure 3B) in the present study, indicating the suppression of T4 (X4 = 1) and cooling of both T1 and T5 (X1 = X5 = 1). The optimal firefighting variables identified under Min C_{avg} (Figure 3C) are, however, totally different from the ones obtained via Min C4 and Min $\sum P$. According to this strategy, T4 should be left burning (X4 = 0) to allocate resources for the cooling of T2, T6, and T8 (X2 = X6 = X8) to prevent tank damage and fire spread to T3, T6, and T9.

Although the firefighting strategies identified via Min $\sum P$[24] (Figure 3A) and Min C4 (Figure 3B) are consistent, the results depicted in Figure 3B,C can be further discussed to determine which strategy is more effective, Min C4 or Min C_{avg}.

Figure 3B shows a case where T4 is being suppressed while T1 and T5 are being cooled. Considering the heat flux threshold 15 kW/m^2 for domino effects,[31] the heat flux emitted from T4 cannot damage T1 ($q_{41} = 0.7 \times 0.7 \times 25 = 12.25$ kW/m^2), T5 ($q_{45} = 0.7 \times 0.7 \times 20 = 9.8$ kW/m^2), or T7 ($q_{47} = 0.7 \times 15 = 10.5$ kW/m^2). As such, the domino effect toll for this firefighting strategy would be zero tanks (excluding T4, which is already

TABLE 1 A comparison between the optimal values for different objective functions for $\alpha = \beta = 0.7$.

Fire scenario	Objective function	X1	X2	X3	X4	X5	X6	X7	X8	X9
T4 is on fire	Min C4	1	0	0	1	1	0	0	0	0
	Min C_{avg}	0	1	0	0	1	0	0	1	0
	Min $\sum P$	1	0	0	1	1	0	0	0	0
T4 and T5 are on fire	Min (C4 + C5)	0	1	0	1	1	0	0	0	0
	Min C_{avg}	0	1	0	0	0	1	0	1	0
	Min $\sum P$	1	0	0	1	1	0	0	0	0

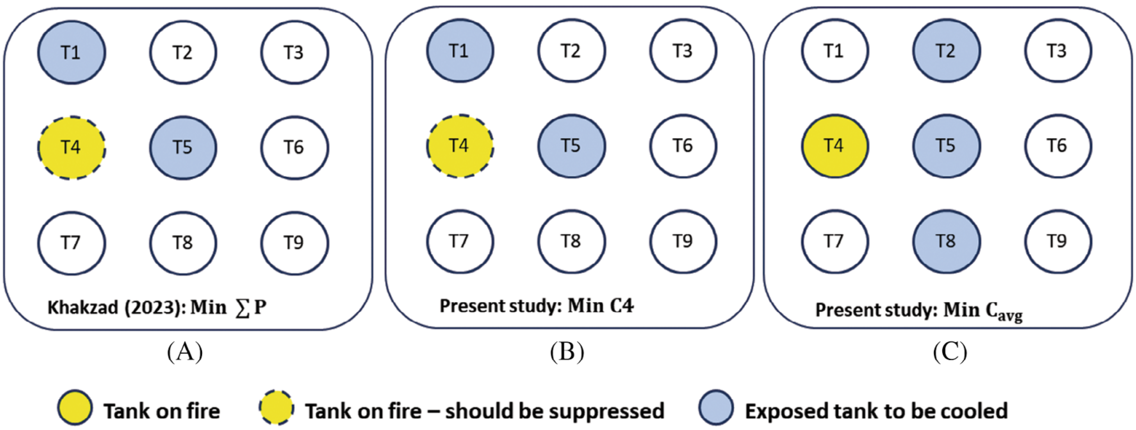

FIGURE 3 Comparison of firefighting strategies for the case where T4 is on fire.

burning). On the other hand, Figure 3C shows the case where T4 is not suppressed, nor are T1 and T7 cooled. Therefore, the heat flux emitted from T4 can cause damage to both T1 ($q_{41} = 25$ kW/m^2) and T7 ($q_{47} = 15$ kW/m^2) as both the heat fluxes are equal to or greater than the domino-effect threshold. However, since T2, T5, and T8 are being cooled, the heat fluxes they may receive from T1, T4, and T7 would be $0.7 \times 20 = 14$ kW/m^2 (less than the threshold); T2, T5, and T8 are thus not expected to be impacted. Having T1 and T7 as the only tanks being endangered by T4, the domino effect toll for the firefighting strategy in Figure 3C would be two tanks, T1 and T7 (excluding T4, which is already burning).

As can be seen, comparing the domino effect damages, the firefighting strategy shown in Figure 3B is more effective than the one presented in Figure 3C, implying that minimizing the closeness of the burning tank (Min C4) instead of minimizing the average closeness of the tank terminal (Min C_{avg}) would result in a more effective firefighting strategy.

3.2.2 | Second fire scenario: T4 and T5 are on fire

Figure 4 shows the firefighting strategies for the second fire scenario for the same three objective functions. While the strategies obtained via Min $\sum P$[24] (Figure 4A) and Min C4 (Figure 4B) are functionally consistent (although differing in terms of which tank should be cooled), the strategy obtained via Min C_{avg} (Figure 4C) is fundamentally different. To determine which strategy is more effective, their performance from a domino effect damage perspective can be examined in a manner similar to the first fire scenario in Section 3.2.1.

Considering Figure 4C, T4 and T5 should be left burning while T2, T6, and T8 should be cooled. This results in damage to T1 ($q_{41} = 25$ kW/m^2) and T7 ($q_{47} = 15$ kW/m^2) due to the heat flux emitted from T4 and also damage to T2 ($q_{52} = 0.7 \times 25 = 17.5$ kW/m^2) because of the heat flux emitted from T5. Also, if T2 catches fire, T3 can burn due to the heat flux from T2. For comparison purposes, however, we will limit the discussion only to the first stage of potential domino effects, disregarding T3 and other tanks that may be involved in the later domino stages. So, for the firefighting strategy shown in Figure 4C, the immediate damage potential of the domino effect would be three tanks: T1, T7, and T2 (excluding T4 and T5, which are already burning).

With respect to Figure 4B, suppression of T4 would slow, but not prevent, fire spread to T1 ($q_{41} = 0.7 \times 25 = 17.5$ kW/m^2) – although it would save T7 ($q_{47} = 0.7 \times 15 = 10.5$ kW/m^2). Simultaneous suppression

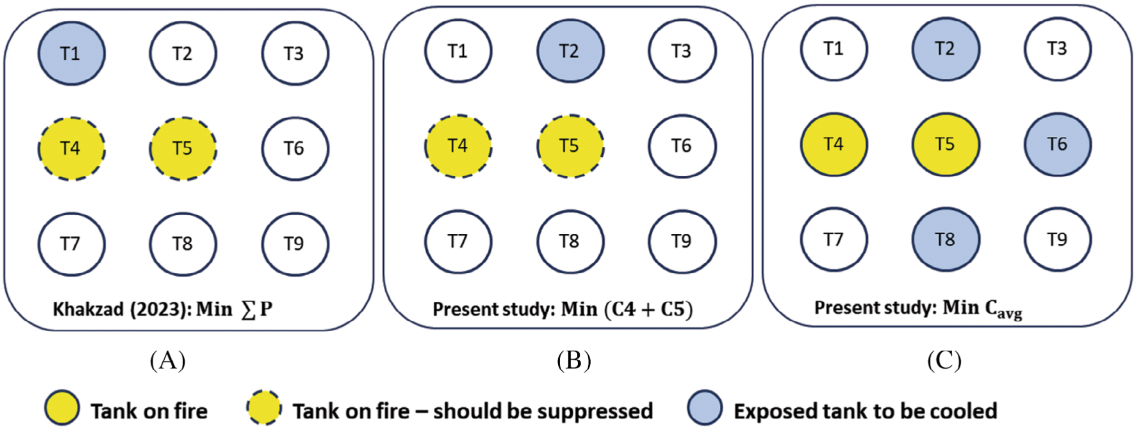

FIGURE 4 Comparison of firefighting strategies for a case where T4 and T5 are on fire.

of T5 and cooling of T2 would prevent fire spread to T2 ($q_{52} = 0.7 \times 0.7 \times 25 = 12.25$ kW/m^2) and would also save T6 ($q_{56} = 0.7 \times 20 = 14$ kW/m^2) and T8 ($q_{58} = 0.7 \times 15 = 10.5$ kW/m^2). Considering the immediate damage potential of the domino effect, only one tank, T1, would be in danger. So far, the comparison between the domino effect tolls in Figure 4B,C has demonstrated the better performance of the objective function Min (C4 + C5) over Min C_{avg}.

Figure 4A depicts the strategy identified under Min $\sum P$.[24] Suppression of T4 and cooling of T1 at the same time could prevent fire spread to T1 ($q_{41} = 0.7 \times 0.7 \times 25 = 12.25$ kW/m^2) and to T7 ($q_{47} = 0.7 \times 15 = 10.5$ kW/m^2). However, suppression of T5 cannot prevent fire spread to T2 ($q_{52} = 0.7 \times 25 = 17.5$ kW/m^2) whereas it could save T6 ($q_{56} = 0.7 \times 20 = 14$ kW/m^2) and T8 ($q_{58} = 0.7 \times 15 = 10.5$ kW/m^2). Thus, based on the immediate damage potential of domino effects in Figure 4A,B, both firefighting strategies seem equally effective as they both result in one tank being damaged (excluding the ones already on fire)—that is, T1 in Figure 4B versus T2 in Figure 4A. However, considering the damage caused by domino effects in later stages, damage to T2 in Figure 4A can cause damage to T3, but damage to T1 in Figure 4B cannot cause damage to any other tank. (In Figure 4B, T1 and T5 can cause damage to T2 via synergistic effects. This is beyond the scope of the present study as the equation for closeness calculation in its current form cannot account for synergistic effects.) This demonstrates the better performance of the strategy in Figure 4B over that in Figure 4A.

4 | DISCUSSION

In this section, the performance of the developed methodology is evaluated with reference to the guidelines proposed in previous studies.[15–17] It is worth noting that while all the foregoing studies have specified the exposed tanks that should be cooled, they have not provided guidance on which burning tanks to suppress. As such, to make a comparison between previous work and the present study, it is assumed that all the tank fires should first be suppressed to prevent further fire spread, and then as many of the exposed tanks that resources permit should be cooled. This assumption is consistent with the work of Nash,[32] which emphasized that burning tanks should not be left burning due to a high risk of fire spread and the large quantity of water required for cooling the exposed tanks in the vicinity.

4.1 | Tank fire at T4

Figure 5 depicts the strategies proposed in the previous studies and the one identified in the present study for the first fire scenario: according to Lang et al.,[15] T1, T5, and T7 should be cooled as these tanks are within 1.5 diameters of T4 (Figure 5A).[24] Assuming that T4 should be suppressed, only two of the exposed tanks could be cooled given that resources are sufficient only to handle three tanks. However, since Lang et al.[15] do not provide any further recommendation as to the criticality of the exposed tanks, it is left to the firefighters to decide which tanks to cool. Considering the wind direction (south to north),[24] firefighters may decide to give priority to T1 and T5 as these tanks are downwind and would thus receive higher heat fluxes. Thus, this firefighting strategy may coincide with the one identified in the present study.

D'Amico[17] provides a clearer guideline considering the criticality of the exposed tanks, which is also consistent with the strategy proposed in the present study: as T1 and T5 receive higher heat fluxes from T4, they should be given priority over T7 (Figure 5B). Among the

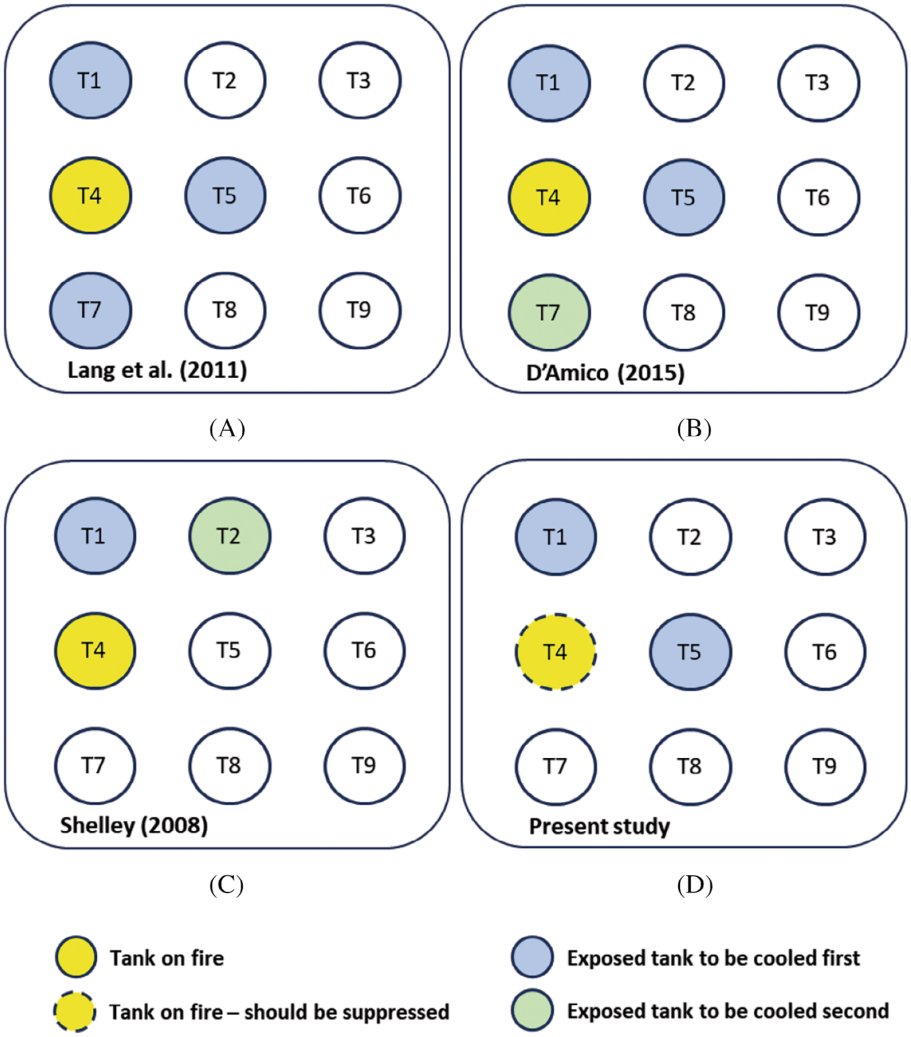

FIGURE 5 Comparison among the firefighting strategies given a tank fire at T4. The previous studies[15–17] have specified the exposed tanks that should be cooled, without providing guidance on which tank fires to suppress.

previous studies, the work of Shelley[16] seems to result in a less favourable firefighting strategy, in which first T1 (tank downwind of fire) and then T2 (tanks to the left and right of the previous downwind tank) should be cooled (Figure 5C). This strategy is less effective than the others as it would likely not prevent fire spread from T4 to T5 ($q_{45} = 0.7 \times 20 = 14$ kW/m^2 < 15 kW/m^2) and from T5 to the other tanks. In summary, considering the tank fire at T4, the strategy of Lang et al.[15] is the most conservative in confining the fire spread (assuming that resources are sufficient to suppress the tank fire and cool the three exposed tanks). The strategies proposed by D'Amico[17] (Figure 5B) and in the present study (Figure 5D) are the most efficient (considering the available resources), and the one by Shelley[16] seems to be the least efficient.

4.2 | Fire spreads from T4 to T5

As depicted in Figure 6A, when fire spreads from T4 to T5, according to Lang et al.,[15] five tanks should be cooled: T1, T2, T6, T7, and T8. Again, however, fire suppression at T4 and T5 allows only one tank to be cooled. Lang et al.[15] do not offer guidance on which tank to cool, and firefighters may decide it should be either T1 or T2 due to the larger heat flux these tanks might receive. With further consideration, firefighters may decide it is more efficient to cool T2 as by so doing, they would save T2 from T5 and prevent (or at least delay) fire spread from T2 to T3. In this manner, the strategy proposed by Lang et al.[15] may coincide with the present study, although not without some scrutiny and modification.

In the two-tank fire scenario, the strategies proposed by D'Amico[17] (Figure 6B) and Shelley[16] (Figure 6C) do not seem to outperform the one recommended by Lang et al.[15] (Figure 6A) because they also require deliberation as to which tank should be cooled: T1 or T2 in the case of Shelley,[16] and T1, T2, or T6 in the case of D'Amico.[17] Applying the same rationale as for Lang et al.,[15] the firefighters may decide to cool T2 in both cases. Similar to the first fire scenario, for this second fire scenario the strategy suggested by Lang et al.[15] seems to

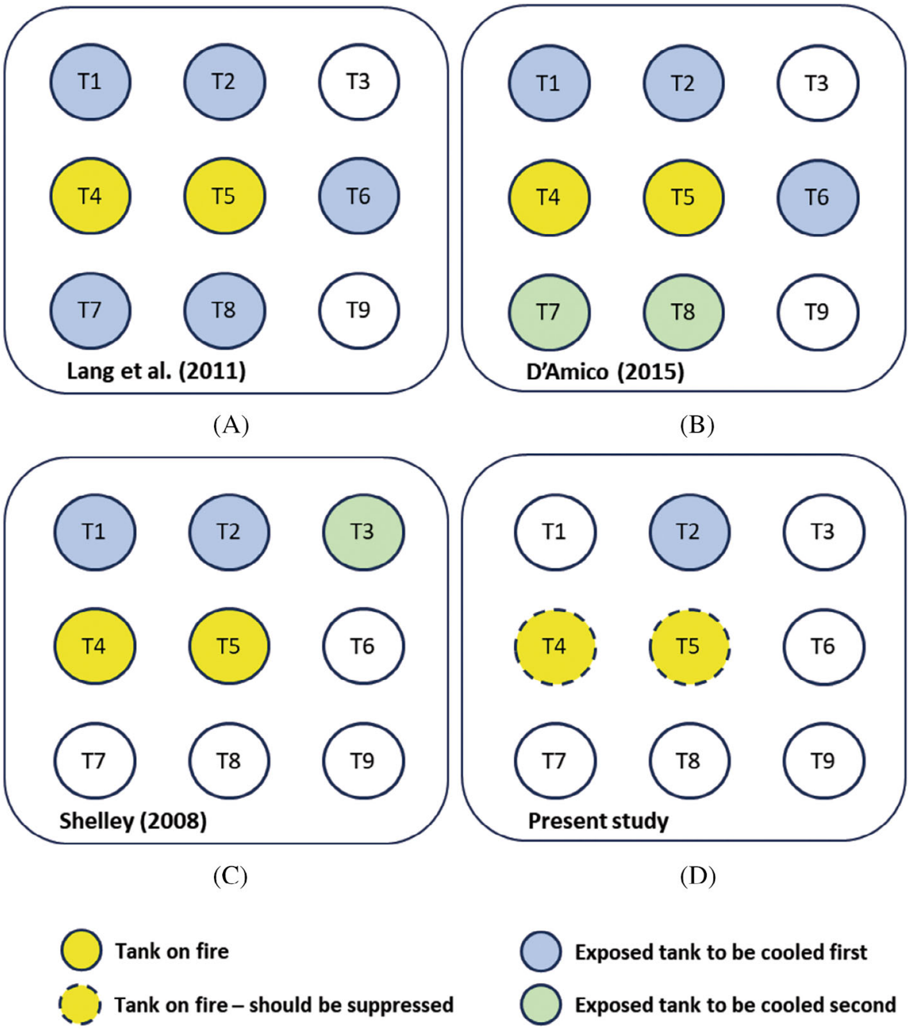

FIGURE 6 Comparison among the firefighting strategies given fire spread from T4 to T5. The previous studies[15–17] have specified the exposed tanks that should be cooled, without providing guidance on which tank fires to suppress.

be the most conservative strategy in limiting the fire and potential domino effects (assuming that resources are sufficient to suppress the two tank fires and cool the five exposed tanks), The strategies suggested by Shelley[16] and D'Amico[17] are more resourceful, but not as efficient as the one proposed in the present study (Figure 6D) given that they rely heavily on firefighter scrutiny and ad hoc prioritization.

5 | CONCLUSION

Firefighting at chemical and process plants is a last resort to control fire spread and prevent potential domino effects. When resources are sufficient, all the burning vessels should be suppressed and all the exposed vessels should be cooled, all at the same time. However, when resources are insufficient, decision-making methodologies are required to assist firefighters to prioritize the vessels and shift their resources toward the most critical ones. Selecting the vessels only based on their vulnerability while neglecting their criticality (i.e., their contribution to potential domino effects) may lead to ineffective firefighting strategies. So, among the vulnerable vessels (the ones closest to a burning vessel), the ones that can also make significant contributions to potential domino effects (i.e., the most critical ones) should be included in firefighting. Considering these two features, that is, vulnerability and criticality, the former may be more obvious and thus more easily recognizable. However, criticality is a feature that demands dedicated techniques and methodologies to determine.

In the present study, we demonstrated that if fire propagation through a tank terminal can be modelled as a weighted directed graph (with units as the nodes and heat fluxes as the edges of the graph), by minimizing the closeness centrality score of the burning tanks, the optimal firefighting strategies can be determined. A comparison between the results of the present study with previous studies demonstrated the effectiveness and satisfactory performance of the developed methodology.

The fact that the methodology does not require calculating fire propagation probabilities and can be developed by knowing only the heat fluxes makes it an easy-to-use and effective methodology, alleviating the need for sophisticated techniques such as Bayesian networks to estimate the probabilities. The developed methodology was also shown to be capable of considering changes in fire scenarios (e.g., spread of fire from one tank to another), dynamically optimizing firefighting strategies as per the fire propagation in the tank terminal. To further verify the effectiveness and accuracy of the methodology, it should be tested on a variety of case studies with more complicated plant layouts and fire scenarios. Moreover, a comparison between the optimal firefighting strategies determined in the present study and those practiced by firefighters in reality could further help assess the effectiveness of the developed methodology. This will be investigated in our future research.

AUTHOR CONTRIBUTIONS

Nima Khakzad: Writing – original draft; methodology; funding acquisition. **Ernesto Salzano:** Writing – review and editing; validation. **Paul Amyotte:** Writing – review and editing; validation.

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DATA AVAILABILITY STATEMENT

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

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