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A decision model to allocate protective safety barriers and mitigate domino effects

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Abstract

In this paper, we present a model to support decision-makers about where to locate safety barriers and mitigate the consequences of an accident triggering cascade effects.

Based on the features of an industrial area that may be affected by domino accidents, and knowing the characteristics of the safety barriers that can be installed to stall the fire propagation between installations, the decision model can help practitioners in their decision-making. The model can be effectively used to decide how to allocate a limited budget in terms of safety barriers. The goal is to maximize the time-to-failure of a chemical installation ensuring a worst case scenario approach.

The model is mathematically stated and a flexible and effective solution approach, based on metaheuristics, is developed and tested on an illustrative case study representing a tank storage area of a chemical company. We show that a myopic optimization approach, which does not take into account knock-on effects possibly triggered by an accident, can lead to a distribution of safety barriers that are not effective in mitigating the consequences of a domino accident. Moreover, the optimal allocation of safety barriers, when domino effects are considered, may depend on the so-called cardinality of the domino effects.

Keywords: Domino effect, Metaheuristic, Risk management, Emergency, Safety barriers.

1. Introduction

Cascade events or domino effects truly are a timely topic. We live in a time where there is ever more industrial activity, especially within the chemical and process industry. This translates into a non-stop increase in amounts of hazardous materials being processed, stored, transported, etc. between chemical industrial parks worldwide. As a matter of fact, the need for more industrial activity is driven by the observation that

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population figures have been sharply increasing on a global scale since a century. Irrespective of the underlying reasons of both facts, taking the combination of both these facts into consideration, automatically leads to the question about their combined impact on societal risk and safety. In the chemical industry, an important aspect of this impact can be summarized by the potential of escalation of an industrial accident to a major disaster, or a so-called domino effect.

Although such events are less known than more "classic" major accidents such as for example vapour cloud explosions (VCEs), BLEVEs, and the alike, they may have even more disastrous consequences compared to those classic accidents. They are less recognized and studied by industry, academia and regulators due to the fact that their likelihood is even much lower than that of the better known major accident scenarios. Nonetheless, since they became an issue in the Seveso II Directive in 1996, and also because domino accidents do happen on a worldwide scale (even if they are extremely rare), ever more research is carried out by academics and industrials to further advance our knowledge on these obscure events.

Several lines of research have been initiated with respect to the domino effect topic. For example, indices have been suggested by [1, 2]. Tugnoli et al. [1] developed an index to assess the domino potential hazard including the effect of inherent and passive protection measures. Reniers and Audenaert [2] elaborated an index to rank chemical installations within any industrial area, and based on a their vulnerability for domino effects. Nguyen et al. [3] analysed the potential for domino effects produced by projectiles generated by explosions in industrial facilities. Salzano et al. [4] investigated domino effects related to home-made explosives. Landucci et al. [5] elaborated a quantitative risk assessment where domino effects are taken into account, and where events are triggered by fire. The model is based on an estimation of vessel time to failure. Cozzani et al. [6] studied inherent safety approaches providing the possibility to prevent knock-on events. Reniers [7] looked into the problem of cross-plant collaboration and the lack of sufficient information exchange to optimize protection against domino effects, employing game-theoretical modelling to do so. Darbra et al. [8] analysed 225 domino incidents during hazmat transportation. Reniers et al. [9] investigated the possibility of attenuation-based security within chemical industrial areas. Furthermore, in 2013, Reniers and Cozzani [10] edited a comprehensive volume on the modelling, prevention and management of domino effects in the process industries, providing the state-of-the-art at publication date and indicating the leeway for further exploration of the domino effects research area. As can be seen from this brief overview of important past research on domino effects, the subject is looked at from a safety as well as from a security point of view, and research efforts are ever more intensifying.

A lot of research is concerned with design-based safety with respect to domino effects, and hence, researchers mainly focus on managing domino effects in an inherent way. This is, of course, the most optimal way to deal with such potentially devastating events. However, this is not always possible. If installations (for example storage tanks) are present in a certain industrial setting, it is not easy to just replace them or to make major design-based (e.g. lay-out) changes. Therefore, it is also very important that research is aimed at optimizing add-on safety with respect to domino effects. The study explained and discussed in this paper is aimed at such optimization of safety barriers within existing industrial settings, and employs operational research techniques and

-science to do so.

The evolution of domino accidents, triggered by heat radiation, overpressure effects, or missile projection, depends on the presence (or absence) and the performance of safety barriers. Safety barriers may have the potential to prevent escalation, for example, in case of heat radiation, delaying or avoiding the heat-up of secondary targets. Thus, safety barriers play a crucial role in domino effect prevention and mitigation within existing industrial settings. More specifically, add-on safety barriers can indeed: (i) restrict the propagation of domino effects; (ii) mitigate the consequences of domino effect; and (iii) be extremely important in terms of increasing the time to failure of chemical installations.

At present, in industrial practice, the decision to take certain safety barriers for dealing with major accident scenarios does not take domino effects of a higher order into account. At most, possible direct escalation of major accident scenarios is considered (thus only possible domino events with cardinality 0, see Section 2). However, this is a myopic way of tackling domino effects within chemical parks. Especially with respect to security issues, this myopic approach may prove to be largely insufficient. Therefore, to optimize current practice, there is need for studying in what way higher order domino events can be taken into account in the decision-making process of investing in add-on safety barriers for existing industrial areas. Possibly, considering higher-order domino events in the safety barrier investment problem will lead to alternative decisions. Hence, an approach and a computer program to determine the most optimal safety barrier investment decision for dealing with domino effects in existing industrial settings, and thereby considering higher-order domino events, is currently non-existent in academic literature and lacking in industrial practice.

The remainder of the paper is organized as follows. In Section 2 the decisional model and it mathematical representation is presented. In Section 3 an effective solution algorithm based on a metaheuristic approach is developed. This solution method is tuned and tested on a realistic study case in Section 4. Section 5 concludes the paper and presents some suggestions for future research.

2. Problem description

In this section, the problem is described and mathematically stated. The main objective of the model is to support decision makers to optimally locate protective barriers within an industrial setting of chemical installations, to mitigate domino effects. Given a budget constraint, the optimal mix of protective barriers needs to be selected in order to delay the propagation of a major fire resulting from accident towards a chemical installation that might further trigger the failure of other chemical installations engendering thus escalation effects.

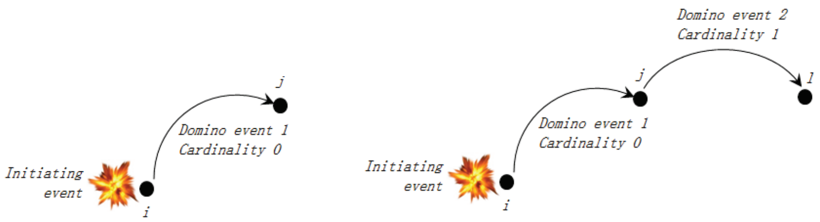
Depending on the intensity of the domino effects, the cardinality D can be used to denote how many domino events happen after the initiating failure/accident. We suppose that the initiating event always happens at a root installation and from it fire might propagate to neighbouring installations engendering thus a cascade effect.

In particular, domino events characterized with cardinality 0 represent the first cascade effect as a consequence e.g. of an accident to a chemical installation (the so-called “primary domino events”), whereas cardinality 1 refers to secondary domino events, cardinality 2 to tertiary domino events and so on [11]. It is worth noticing that when cardinality is equal to zero the first domino effect is produced. Using this taxonomy, it is possible to classify domino effects triggered by installation i and affecting:

(i) **Situation I**: a single neighbour installation j by means of fire propagating from i to j (in case $D = 0$);

(ii) **Situation II**: a neighbour installation j and an installation l, that is a neighbour of j, by means of fire propagating from i to j and subsequently from j to l (in case $D = 1$) and so on.

In Figure 1 both situations are shown. In the remainder of the paper, for the sake of clarity of exposition when we represent the initiating event resulting in the first domino event of cardinality 0 affecting the root node i, we implicitly assume that a major accident (e.g. a major fire) has already affected installation i.



(a) Situation I

(b) Situation II

Figure 1: Situation I and Situation II in terms of cardinality

In this paper, an industrial area that is potentially subjected to domino effects, such as a chemical plant, is modelled by using a graph, $\mathcal{G} = \{\mathcal{N}, \mathcal{A}\}$. $\mathcal{N}$ is the set of nodes representing the critical installation within the industrial area that, after an accident, may engender domino effects. $\mathcal{A}$ denotes the set of arcs (i, j) representing a fire propagation from node i to node j. As a consequence of a failure/accident happening to node $i \in \mathcal{N}$ fire propagates, along arc $(i.j) \in \mathcal{A}$, in a non negative *propagation time* pt_{ij}, triggering a failure/accident of a neighbouring node $j \in \mathcal{N}$.

A set, $\mathcal{M}_{ij}$, is defined for each arc (i, j) and comprises all the protective measures that are available for this arc. Each protective measure k for arc (i, j) presents a cost c_{ij}^k and a value of effectiveness e_{ij}^k in delaying the escalation and thus increasing the *propagation time* needed by fire to affect a neighbour facility j starting from node i. Both cost and effectiveness associated to each protective measure are based on information, such as number and type of protective barriers, thickness, equipments and used materials. These values are assumed to be predefined by a security risk assessment, carried out by the security management team.

Let B represent the maximum available budget to be invested in protective measures. For the sake of simplicity, for each arc (i, j), a dummy protective measure, having a cost $c_{ij}^0 = 0$ and an effectiveness $e_{ij}^0 = 0$, is defined. It represents a default

Table 1: Set of protective measures $\mathcal{M}_{ij}$ for arc (i, j)

Measure id	**Combination of protective barriers**	**Cost**	**Effectiveness**
0	-	0	0.0
1	A	100	0.5
2	B	150	0.45
3	C	200	0.4
4	A&B	250	0.32
5	B&C	300	0.25

state that indicates that no protective measure is applied on arc (i, j). Moreover, only one protective measure per arc can be applied. A protective measure can be a combination of single protective barriers presenting different capabilities, to stop or delay the fire propagation, depending on the characteristics of the barriers themselves. A combination of protective barriers can have a different effectiveness (greater or lower) than the sum of the impact of the individual protective barrier due to possible interaction effects. In some cases, specific combinations of single barriers might not be available due to possible incompatibility factors (see e.g., Table 1).

In order to make the notation used inside the mathematical model more readable, a set, $\mathcal{F}_i^D$ for each node $i \in \mathcal{N}$, is defined. Set $\mathcal{F}_i^D = \{P_1, P_2, \ldots, P_q\}$ contains a list of q *fire-paths* denoting all possible cascading effects of cardinality D that can be triggered by a failure/accident happened at root node i. The generic *fire-path* $P_k \in \mathcal{P}_i^D$ is composed by a sequence of $D + 1$ arcs starting from root node i (e.g. $(i.j), (j, l), (l, m), \ldots$) resulting in an escalation (i.e. accident/failure) that affects a sequence of $D + 2$ nodes of the graph $\mathcal{G}$ (i.e. nodes i and j in case of $D = 0$).

To mathematically state the problem, three families of decision variables are defined: (1) Let PT_{ij} be the *propagation time* of the fire along arc $(i.j)$ when at least one protective measure is used; (2) Let ET_i be the *escalation time* after which a domino effect of cardinality D is initiated as a consequence of a failure/accident happened at node i; Let x_{ij}^k be a binary decision variable that is equal to one if protective measure k for arc (i, j) is selected, zero otherwise. The decision problem is defined as follows:

$$\text{lexicographic max} \quad f(x) = (f_1(x), f_2(x)) \tag{1}$$

$$f_1(x) = \min_{i \in \mathcal{N}} ET_i \tag{2}$$

$$f_2(x) = \sum_{(i,j) \in P_i} PT_{ij} \qquad \forall P_i \in \mathcal{F}_i^D, \forall i \in \mathcal{N} \tag{3}$$

s.t.

$$\sum_{(i,j) \in \mathcal{A}} \sum_{k \in \mathcal{M}_{ij}} c_{ij}^k \cdot x_{ij}^k \leq B \tag{4}$$

$$PT_{ij} = \sum_{k \in \mathcal{M}_{ij}} pt_{ij}^k \cdot (1 + e_{ij}^k) \cdot x_{ij}^k \qquad \forall (i,j) \in \mathcal{A} \tag{5}$$

$$\sum_{k \in \mathcal{M}_{ij}} x_{ij}^k = 1 \qquad \forall (i,j) \in \mathcal{A} \tag{6}$$

$$ET_i \leq \sum_{(i,j) \in P_i} PT_{ij} \qquad \forall P_i \in \mathcal{F}_i^D, \forall i \in \mathcal{N} \tag{7}$$

$$x_{ij}^k \in \{0, 1\} \qquad \forall (i,j) \in \mathcal{A}, \forall k \in \mathcal{M}_{ij} \tag{8}$$

The objective function $f(x)$ in Eq. (1) is used to evaluate the quality of feasible solutions. It is divided into two objectives $f_1(x)$, $f_2(x)$, to be both maximized in a lexicographic order. $f_1(x)$ and $f_2(x)$ are ordered by descending importance according to the decision maker's preferences. More specifically, the objective function $f(x)$ maximize in order: (i) function $f_1(x)$ (in Eq (2)) namely the escalation time associated to the worst case scenario presenting the lowest total escalation time considering a domino effect of cardinality D in which a sequence of D node accidents in cascade is triggered by a failure at root node i; (ii) function $f_2(x)$ (in Eq (3)) namely the sum of the propagation time associated to all possible scenarios with an accident in any of the nodes triggering a domino effect of cardinality D. This objective attempts to increase the effectiveness of the safety barriers considering not only the worst case scenario, but taking into account the mitigations of possible accidents affecting the overall industrial area. The ranking of solutions is based on a multi-objective lexicographic order, i.e. a solution x is considered better than x' if and only if, for some $i \in [1, 2]$, $f_i(x) > f_i(x')$ and for all j such that $j < i$, $j \geq 1$, $f_j(x) = f_j(x')$. In other words, a solution with a higher value of $f_1(x)$ is always preferred. In case of solutions with an equal value of $f_1(x)$, the one with the highest value of $f_2(x)$ is to be selected. Constraint (4) guarantees that the total cost associated to the selected protective barriers does not exceed a predefined budget B. Constraint (5) is used to define the propagation time PT_{ij} associated to arc (i, j) depending on the type of protective measures being installed on that arc. Constraint (6) forces the decision process to select at maximum one protective measure to increase the propagation time associated to arc (i, j). It should be noted that $x_{ij}^0 = 1$ means that for arc (i, j) no protective system of barriers has been applied. Constraint (7) is used to compute for each node the minimum escalation time given an accident that happens in node i and generate a domino effect with a cardinality D.

Finally, Constraint (8) represents the domain of the decision variable, which ensures that no partial protective measures are allowed.

3. Solution approach

The problem described in Eq.(1)-(8), belongs to the class of knapsack problems, also known as resource allocation problems. These well-known combinatorial optimisation problems have been widely studied in the literature (see e.g. [12]). In general, knapsack problems include a set of items each with a certain benefit and cost. The goal is to select a subset of these items in order to maximize the benefit within a certain budget.

As problem instances grow larger, an exact algorithm will require an exponential amount of time to solve them. Therefore, the optimality is sacrificed for near optimal solutions, that can be calculated in a very short amount of time. To achieve this goal, metaheuristics will be used. The solution approach developed in this paper is based on a tabu search heuristic hybridized with a iterated local search that makes use of a variable neighbourhood descent heuristic [13]. The overall structure of the metaheuristic is shown in Algorithm 1.

It is composed of 4 subsequent phases. In *phase 1*, some preliminary computations are made in order to speed up the solution process. In particular, given the cardinality of domino scenarios that need to be considered, the list of paths, trough which the accident originating in a given node can propagate, is generated. Moreover, for each of these paths the total escalation time without any protective measures is computed.

In *phase 2*, an initial solution for the problem is constructed step by step by using a GRASP heuristic [14]. This methods selects, in a greedy randomized fashion, one protective measure at each iteration until there is no more budget available. The selected measure must not be contained in the tabu list *TB* and there should be enough available budget to include it in the current solution. The paths are ordered by increasing total escalation time and then the first α arcs for which no protective measure is applied yet, are inserted in a restricted list *RL*. Next, an arc is randomly selected from this list and a protective measure, not in the tabu list and whose cost is lower than the remaining budget, is randomly selected and added to the current solution.

Phase 3 improves the current solution by the means of a variable neighbourhood descent. Three different neighbourhoods are defined as follows: (1) *Internal Swap* (N_1) replaces a protective measure for a given arc with another one, that is not contained in the tabu list, for which there is sufficient budget; (2) *External Swap* (N_2) substitutes a protective measure of one arc with another one, associated to a different arc that is not yet considered in the current solution. The substitution must be compatible with the budget constraint and allowed by the tabu list; (3) *Double Swap* (N_3), which is a variant of the *Internal Swap*, executes two moves simultaneously. Two arcs are selected and their protective measures removed from the current solution. The budget made available is summed with the remaining budget and used to add two new protective measures to those selected arcs.

A diversification mechanism is implemented in *phase 4* to let the metaheuristic escape from local optima and to explore different areas of the search space. If a maximum number of iterations without having improved the best known solution is not reached, a perturbation heuristic is applied, otherwise a new solution is built from scratch by reapplying the GRASP heuristic, which is described before. The perturbation partially removes a certain amount of protective measures from the current solution and adds them in the tabu list. If the remaining budget, after the removal operations, allows the introduction of new unexplored protective measures, they are added into the new current solution in a greedy random fashion as done in the GRASP heuristic.

As in the iterated local search framework (see [15]), phases 3 and 4 of the proposed metaheuristic are repeated until a stopping criterion is met. This criterion needs to be defined by the user and it is usually expressed either as a maximum number of repetitions or, alternatively, as a maximum allowed computation time.

Algorithm 1: Metaheuristic structure

```
Phase 1: Pre-computation;
Define the list of paths of length D, for each node;
Compute the escalation time ET for each path;
Phase 2: Generation of initial solution;
let x be the current solution and f(x) its cost;
let x* be the best solution found so far and f(x*) its cost;
x*, x ← ∅, f(x*), f(x) ← ∞;
Initialize the tabu list TB, initially empty;
x ← GRASP Heuristic(TB);
Phase 3: Intensification stage;
while (stopping criterion not reached) do
    k ← 0;
    while (k < 3) do
        x' ← N_k(x);
        if ((f_1(x) < f_1(x')) || (f_1(x) = f_1(x') && f_2(x) < f_2(x'))) then
            x ← x';
        else
            k ← k + 1;
        end
    end
    if ((f_1(x*) < f_1(x)) || (f_1(x*) = f_1(x) && f_2(x*) < f_2(x))) then
        x* ← x, f(x*) ← f(x);
    end
    update number of iterations without improvement;
    Phase 4: Diversification stage;
    if (max number of iterations without improvement not reached) then
        x ← Perturbation(x);
        update TB;
    else
        x ← GRASP heuristic(TB);
    end
end
return x*
```

4. Computational Experiments

The metaheuristic, described in Section 3, has been coded in C++ language. After having tuned the solution approach, an illustrative case study has been solved. In Section 4.1, the characteristics of the problem instance are described, while Section 4.2 reports the main results of the experimental analysis. A machine with an Intel core i7-2760QM 2.40GHz processor and 8GB RAM has been used to run the tests.

4.1. Test instance

Both the decision model and its related solution approach are tested on a case study representing a storage park of a chemical company. We chose this industrial setting because it is a realistic representation of an actual chemical park concerned with potential cascade effects. Moreover, since we use this case study for illustrative purposes, to show the reader how our metaheuristic can be applied to the domino effect research problem, we kept the example as simple as needed.

To be concrete, this case study is an industrial park composed of 11 storage tanks with different characteristics such as floating roof or not, differing type of material, differing size and variable chemical substances. For illustrative reasons, we show a storage park and its schematic representation by using a network provided in Figure 2.

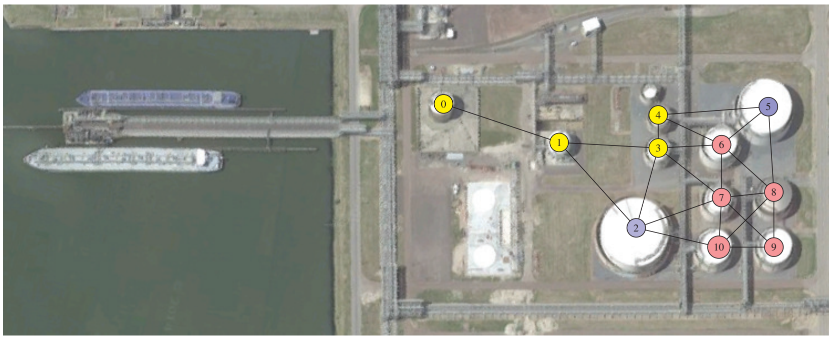


Figure 2: Network scheme overlayed on an image retrieved from Google maps showing a park of chemical storage tanks. For the sake of clarity bidirectional arcs (i.e. (i, j) and (j, i)) are represented by a segment between (i, j)

More specifically, a graph $G = (N, A)$ is used to model the storage park where N is the set of facility nodes (i.e. the storage tanks) and A is the set of arcs representing possible propagation links in case of accidents to a storage tank. For example, an accident to node A may trigger an accident to the neighbour facility B by means of the propagation of fire from A to B along arc (A, B).

The value associated to each arc $(i, j) \in A$ represents the time needed by the fire originated in node i to reach facility j and to determine its failure. The time for the fire to propagate from an installation to another one has been supposed proportional to the distance between nodes including also the impact of the average weather condition such as wind. The failure times associated with the installations in A are summarized in Table 2. The time to failure associated to a node can be expressed as the minimum time for the fire to get uncontrollable within the installation. These times are related both to the characteristics of the tanks and to real industrial information concerning the exposure of tanks to atmospheric conditions.

The values displayed in Table 2-3 and used to simulate an illustrative scenario in case of a domino accident, were validated by the head of the fire fighter department of a major chemical company. Therefore, the metaheuristic exercise on our illustrative case study can be considered to be realistic.

Table 2: Time to failure associated to the nodes

Facility	Description	Time to failure (min)
0-1-3-4	Small tanks without any protection (Diameter $\leqslant$25 meter)	20
2-5	Large tanks (Diameter$\geqslant$30 meter)	35
6-7-8-9-10	Small tanks with protection (Diameter $\leqslant$25 meter)	25

For each arc we considered a list of protective safety barriers that can be implemented to stall the fire spread. Each barrier is characterised by a capacity to delay the propagation of fire, as well as a cost, as shown in Table 3. A maximum budget has been considered in the remainder of the paper equal to 3.5 Million €.

Table 3: List of protective safety barriers

id	Barrier	Cost	Effectiveness
0	No Barrier	0K€	0%
1	Automatic sprinkler installation with additional foam	350K€	75%
2	Automatic sprinkler installation without additional foam	250 K€	65%
3	Deluge system (water spray system opened as signalled by a fire alarm system)	200 K€	50%
4	Fire-resistant coating	180K€	45%
5	Concrete wall surrounding tank + sprinkler without additional foam	2.250 K€	100%

4.2. Results

Based on the realistic test case, discussed before, we tested the metaheuristic described in Section 3. The goal is to shown that it is a flexible and effective decision tool especially when domino effects need to be considered. Some pilot experiments have been run to tune the metaheuristic. After these preliminary study test, the internal parameters of the metaheuristic have been set to the values reported in Table 4.

Table 4: Metaheuristic parameters

Parameter	Description	Value
`Repetition`	Number of times the whole metaheuristic is repeated	50
`IterNoImprovement`	Maximum number of iterations without improvements	10
`Alpha`	Size of the restricted candidate list in the GRASP heuristic	5
`TabuTenure`	Number of iterations that a barrier is kept in the tabu list	30
`Perturbation`	Percentage number of barriers to be removed from the current solution during the perturbation phase	10%

The metaheuristic converges towards stable solutions in a relative small number of iterations. In particular, the time needed to solve the instance, slightly increases with the cardinality of the domino effects that the user wants to analyse and in the worst case takes less than 1 second.

We solved the case study, testing different values of cardinality for the domino effects. As expected, the allocation of the protective safety barriers differs while domino effects having different cardinality are taken into account. In a myopic optimization approach, in which there is only one domino event, as shown in Situation I described in Figure 1(a), (i.e. the case in which the cardinality of the domino effects is set to 0), the goal is to allocate safety barriers to stop the escalation and thus the arise of secondary (tertiary, . . .) accidents triggered by a failure of an installation. However, in reality, domino effects cannot always be prevented from happening. Therefore, a specific allocation of protective safety barriers may be more suitable to stall the escalation and mitigate the consequence of cascade effects even further.

In a planning phase, when the design of an industrial area should be defined to cope with domino effects, several scenarios can be tested by the decision maker. Optimized allocations of safety barriers for each domino scenario can be evaluated in order to increase the time needed by the domino accident of a given cardinality to propagate. In Figure 3 several allocations of the available safety barriers are proposed for different values of the domino cardinality.

Despite the barrier type 5 is the most effective, it has not been selected in the solutions provided by the metaheuristic. This result seems counter-intuitive, but one should analyse this outcome in the light of the implementation cost. As a matter of fact, barriers of type 5 barrier is the most expensive having a cost close to the maximum allowed budget. For this reason, its implementation on an arc would allow from the one hand a large increase in propagation time associated to that arc, but on the other hand, it could limit the implementation of other barriers to other fire-paths which, in the meanwhile, as a result of that allocation, might become the most critical scenarios.

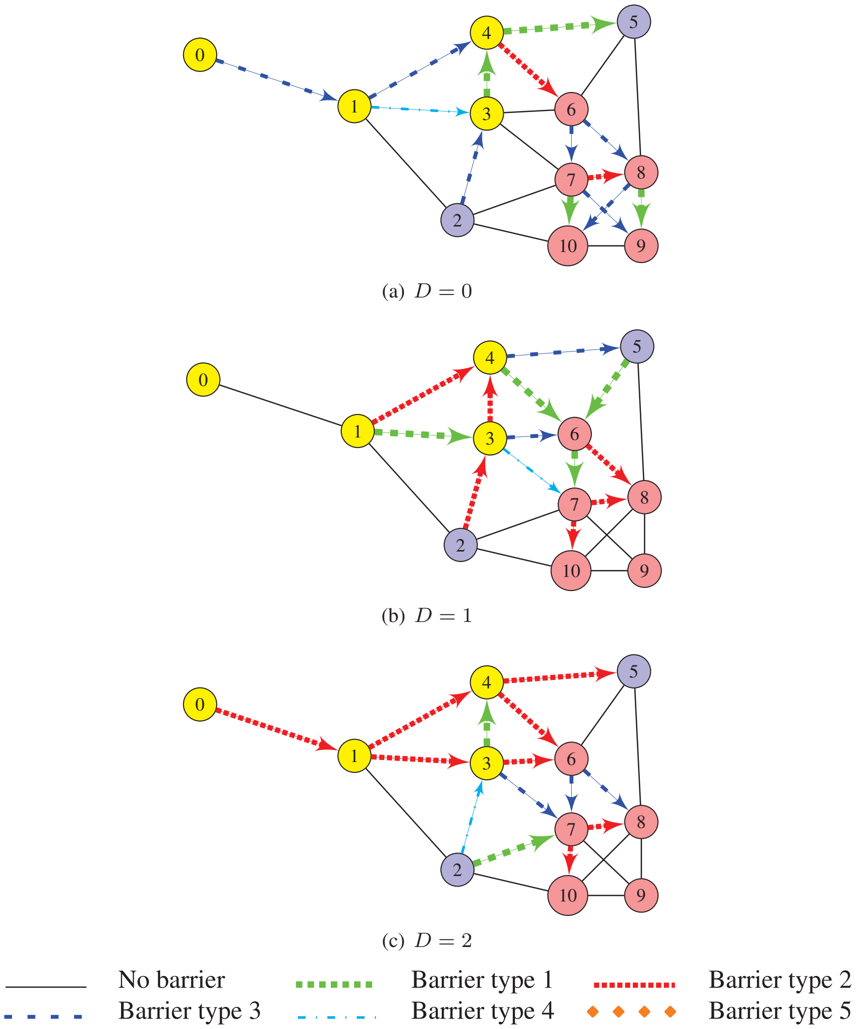
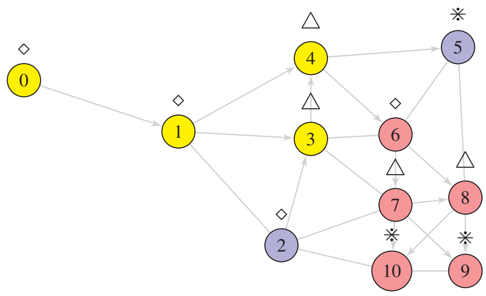


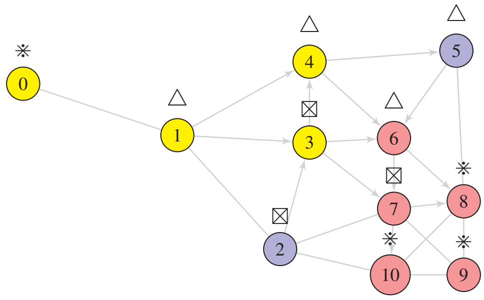
Figure 3: Barriers allocation for different values of D. The tickness of each arc is proportional to the effectiveness of safety barriers allocated on that arc. For the sake of clarity bidirectional arcs (i.e. (i, j) and (j, i)) are represented by a segment between (i, j)

To translate Figure 3 into a real industrial practice, the safety barriers which are now linked to arcs in the figure, need to be related with nodes, or, in other words, with chemical installations. Indeed, barriers such as sprinkler systems, water deluges, or a concrete wall surrounding a tank, are applied to installations (i.e., storage tanks in our example) and not to the pipework connecting the installations. Therefore, we chose the following approach. We looked at every node i (with $i \in 0, \ldots, 10$) and all its outgoing arcs. We then applied the most effective safety barrier on i considering the safety barriers of all the outgoing arcs of i. This way, Figure 4 was developed.

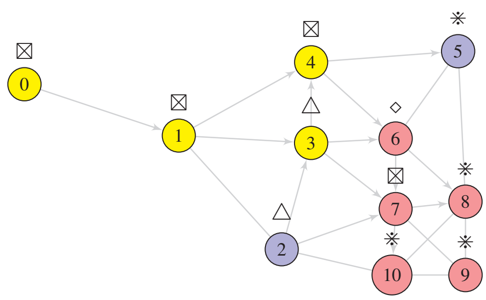
As can be seen in Figure 4, depending on the cardinality, different safety barriers are chosen for the same installations. Also, depending on the cardinality, a different total budget is needed: €2,2 million in case of $D = 0$; €2,15 million in case of $D = 1$; and €1,9 million in case of $D = 2$. This results from the fact that one barrier linked to an installation serves several barriers linked to several arcs.



(a) $D = 0$



(b) $D = 1$



(c) $D = 2$

⋇	No barrier	△	Barrier type 1	⊠	Barrier type 2
◇	Barrier type 3	⊚	Barrier type 4	⋈	Barrier type 5

Figure 4: Barriers allocation on each installation for different values of D. The symbol above each node represents the type of barrier allocated on that installation. For the sake of clarity bidirectional arcs (i.e. (i, j) and (j, i)) are represented by a segment between (i, j)

Finally, the solution approach can be also used to retrieve some information concerning the resulting minimum propagation times of different fire-paths which are associated to all possible accident scenarios. As expected, the values of these times are directly connected to the characteristics of the installations and the location of the selected safety barriers.

For each each root node where the initiating event is localized, the fire-path of cardinality D presenting the minimum escalation time can be retrieved. This information is crucial for fire brigades, rescue and emergency teams since the time associated to each worst case fire-path (in term of escalation times) represents the requested maximum intervention time to stall the fire and avoid the propagation of the domino accident even further (i.e. domino events $> D$). An example is reported in Table 5 where for each installation the fire-path originating in that node with the minimum escalation time is reported.

Table 5: Escalation Time for all fire-paths in case of different domino effects cardinality

Node	$D = 0$	$D = 1$	$D = 2$
	Min ET (min)	**Min ET (min)**	**Min ET (min)**
0	28.05	54.45	71.95
1	26.40	43.90	79.20
2	37.70	55.20	81.60
3	17.50	43.90	71.95
4	26.25	52.65	80.70
5	42.90	69.15	95.55
6	18.15	44.40	70.80
7	31.50	49.00	75.40
8	39.00	57.15	83.40
9	41.25	74.40	91.90
10	41.25	74.40	91.90

Depending on this information the fire brigades can arrange specific trainings and decide, in their turn, where to locate emergency facilities to reduce the intervention time and increase their effectiveness.

5. Conclusions

In this paper, a model to support decision makers has been presented. The goal is to increase the total failure time associated to a domino event of a given cardinality which may be triggered by an accident happening to a chemical installation within a chemical plant. This is possible by investing a limited budget in safety barriers which may delay the propagation of the accident within a plant. The problem of selecting and allocating safety barriers given a limited budget represents a complex combinatorial optimization problem that can be tackled effectively by using efficient metaheuristic solution approaches.

An iterative local search is developed to support decision makers to quickly design and solve possible accident scenarios presenting different values of domino cardinality.

Depending on the cardinality of the domino event, the optimal allocation of safety barriers will change, allowing a delay of the failure time associated to the worst-case domino scenario.

The metaheuristic is applied to a realistic case study that has been designed to illustrate and prove the effectiveness of the proposed solution approach. The risk that an accident, which occurs at an installation, can trigger a propagation of that accident to other installations within the same industrial setting or to neighbouring industrial settings engendering thus in domino effects, has a significant impact on the optimal allocation of safety barriers.

We tested our model and its related solution approach to an illustrative case study of a storage tanks storage. This example is intended to show the effectiveness of the proposed decision model and the flexibility of our solution approach. The instance has been designed on the basis of validated and hence realistic data.

The decision model has been proven to be a valuable support tool to allocate protective safety barriers and mitigate the consequences of an accident engendering domino effects. Differently from a myopic optimization, where barriers are allocated to simply prevent domino accidents, the model proposed in this paper can be used to analyse more realistic scenarios in which domino effects need to be considered since they may have a significant impact on the allocation of protective safety barriers. The general optimization approach, proposed in this paper. can guide the decision maker to allocate a limited budget in order to increase the time needed to stop the escalation of an accident whose domino effects of a certain cardinality may determine the failures of other installations within the same plant or located in neighbouring plants.

The method thus can provide a valuable contribution in case of emergencies where rescue teams of fire brigades need to know the maximum intervention time that they have at their disposal to stop the escalation of the accident. The solution approach, developed in this paper, not only is able to determine the ideal allocation of safety barriers to increase the intervention time in case of a domino accident of a given cardinality associated to the worst case scenario, but it can provide useful information of the maximum intervention times to stop the escalation depending on the installation where the domino accident has originated.

The results obtained on a study case were quite encouraging both in term of quality of solutions and in term of flexibility. In fact, the metaheuristic can provide near-optimal solution in a limited amount of time and a large number of scenarios can be simulated by varying: (a) the cardinality of the domino accidents; (b) the available budget; (c) the features of the critical installations; (d) the number and the characteristics of the available protective barriers. For these reasons we believe that it can be effectively used as a powerful decision support tool not only by the decision makers to design an industrial setting considering domino effects, but also by emergency and rescue teams to evaluate the minimum time to stall the propagation of the accident depending on the features of the setting affected by the accident and the type of accident itself. In this latter case, the minimum time to intervene in case of major accident can provide valuable information on how to locate emergency or rescue facilities in order to minimize their intervention time.

Future works can be aimed at including in the proposed decision model better and/or additional data concerning probabilities and frequencies of accidents generating domino effects. Finally, the metaheuristic decision tool, proposed in this paper, might be also integrated in a game theory decision model to generate more realistic scenarios.

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