14thAnnual International Conference on Industrial Engineering and Operations Management
Dubai, United Arab Emirates (UAE), February 12-14, 2024
Publisher: IEOM Society International, USA
Published: February 12, 2024 DOI: 10.46254/AN14.20240293

Enhancing Process Industry Safety: Optimizing Safety Barrier Allocation to Prevent Domino Effects in Chemical Plants

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Abstract

The domino effect in the oil and gas industry can be attributed to the persistent need to store, transport, and process hazardous materials in equipment or storage facilities in close proximity to optimize operational efficiency and economic viability. Natural occurrences, such as floods, earthquakes, and typhoons, can also act as initiating factors for domino effects. In our current work, we have developed an enhanced model to optimize the allocation of safety barriers for stopping or delaying domino impacts in chemical plants. Mixed Integer Programming (MIP) is used to solve the optimal barrier allocation problem. The solution approach provides information on the minimum propagation times of various fire paths associated with all possible accident scenarios, which is directly related to the location of the selected safety barriers. Furthermore, the current work introduces a pioneering approach to barrier allocation based on nodes rather than the traditional focus on arcs. As a case study, the developed model simulates the Shibushi Storage Base in Japan, comprising forty-three oil storage tanks. The model provides a fast and effective solution to allocating safety barriers around the storage tanks within the allocated budget constraints.

Keywords
Domino effect, Mixed Integer Programming, Safety Barrier allocation, Chemical plants, Propagation Time

1. Introduction
In the chemical and process sectors, there is an ongoing and significant risk when it comes to fire incidents, particularly the activities of handling, storage, and transportation of hazardous materials across chemical industrial parks globally. The potential dangers of the escalation of an accident into a major catastrophe (representing a phenomenon called the domino effect) are more pronounced than ever. The term “domino effect” (also termed “knock-on effect”) refers to a scenario in which an event sets off a chain reaction of similar events. The general definition of the domino effect includes both pleasant and unpleasant occurrences. However, in the context of safety and security, it almost invariably accounts for an unfavorable incident that triggers a cascade of untoward incidents (or accidents). It is pertinent to mention that the original inadvertent or deliberate incident can propagate within the affected piece of equipment over time or affect the adjacent equipment simultaneously or in sequence. Most importantly, this change activates a single

or multiple secondary unfavorable incidents that, in turn, produce even higher-order events. Consequently, the severity of the devastation increases multi-fold compared to the original event.

The origins of the domino effect in the oil and gas industry can be attributed to the persistent need to store, transport, and process hazardous materials in equipment or storage facilities in close proximity to optimize operational efficiency and economic viability. This spatial proximity also increases the risks of accidents, such as fire, leaks, or explosions spreading from one facility to adjoining facilities. In other cases, natural occurrences, such as floods, earthquakes, and typhoons, can act as initiating factors for domino effect accidents. For instance, the 2011 Tohoku earthquake and the resulting tsunami inflicted severe damage on the Fukushima nuclear plant (John, 2011). Consequently, one-third of Japan's refining capacity had to be shut down. Likewise, in 2017, Harvey's record-breaking rainfall disrupted operations in over 40 industrial facilities and resulted in more than 100 accidents involving the spillage of toxic chemicals. Irrespective of the triggering cause (natural or human error), the domino effect accidents incur significant losses in financial resources, materials, infrastructure, and human lives. The associated expenditures for remediation, legal ramifications, and often fines levied by the government augment the adverse consequences, exacerbating the adverse impact on financial and societal aspects.

Although domino-effect incidents are low-frequency events, their repercussions are significantly more severe than conventional accidents. Consequently, the associated risks of the domino effect warrant a thorough investigation, leading to considerable attention from the scientific community. A pioneering work by Anderson et al. (1974) on a Domino accident can be traced back to a chemical-related accident caused by fire and explosion in Texas City in 1974. The catastrophic explosion triggered multiple fires and even gave rise to a 15-foot tidal wave, resulting in a tragic loss of approximately 400 to 600 human lives and injuring as many as 4000 people. Initially, research efforts primarily focused on modeling and controlling domino effects from accidental events. However, Reniers et al. (2008) proposed strategies to prevent and handle security-related domino effects in chemical clusters, leading researchers to take a keen interest in studying domino effects arising from intentional assaults (security-related domino effects). Additionally, there has been a notable increase in attention to domino effects triggered by natural disasters in recent years.

Researchers in the field of domino effects have conducted various studies, including past accident investigations (Shaluf et al., 2003; Clini et al., 2010; Darbra et al., 2010; Abdolhamidzadeh et al., 2011), bibliometric analysis (Li et al., 2017), and historical accounts (Swuste et al., 2019). A pioneering study by Bagster / Pitblado (1991) was based on building a program that predicted the recurrence rate and probability of domino accidents. In the survey of Kourniotis et al. (2000) documented 207 mishaps. Out of 207 accidents, 80 accidents included the domino effect. The researchers investigated the order of occurrence of these accidents and their impact on the population. Moreover, Ronza et al. (2003) analyzed 828 accidents in port areas and used event trees to predict the probability of recurrence of numerous accidents.

A comprehensive study on the domino effect accidents was conducted by Darbra et al. (2010). An examination of 225 mishaps since 1961 involving the domino effect revealed the most important characteristics of accidents in process/storage facilities and during the transportation of hazardous chemicals. The accident situation, nature of the accident, materials, causes and effects, and most typical accident sequences were all examined in this study. According to the findings, external events (31%) and mechanical failures are the most common underlying reasons (29%). There are a lot of domino incidents in storage areas (35%) and in process plants (28%). LPG was the most common combustible substance involved in 89% of the mishaps. The researchers used relative probability event trees to evaluate the domino effect sequences in their study. Their findings suggested that 27.6% of accidents involving accidents resulted in fire, 27.6% of fire-related accidents ended in an explosion, and 17.8% gave rise to other fire-related accidents. Abdolhamidzadeh et al. (2011) documented 224 domino effect mishaps from 1910 to 2008. According to them, fires were responsible for 43 percent of the reported accidents, while explosions caused 53% of those accidents.

Although the subject has been widely studied, a systematic study is still needed to identify the sources of the domino effect and propose mechanisms to mitigate its harmful effects. Nonetheless, there is still a need to learn more about the models and procedures utilized and how these models and methods have developed over time, determining the most crucial area of concern and which concerns require greater attention in the future. Therefore, in the current work, we extended the work performed by Janssens et al. (2015a) to enhance the problem formulation and propose novel optimization heuristics.

The remainder of the paper is organized as follows: Section 2 introduces the problem and presents its mathematical representation. A realistic study case is constructed in Section 3. Section 4 presents the results obtained in the current numerical model and suggests future research.

2. Problem Statement and Formulation

In this work, we developed a mathematical model using the optimization technique called Mixed Integer Programming (MIP) to assist the decision authorities in allocating protective barriers, ideally in an industrial context with chemical installations (e.g., in the case of a chemical storage tank park) to reduce domino effects as much as possible. The barriers are installed directly around the installations (nodes) or in the path between the two installations (arcs). Given the financial constraints, an ideal combination of protective barriers must be determined to prevent the spread of a mishap (such as a fire) from an accident towards a chemical installation that might further cause the collapse of additional chemical installations, resulting in escalation effects. As described by Janssens et al. (2015a), the importance of this problem stems from the fact that myopic optimization may lead to a distribution of safety barriers that are ineffective in minimizing the consequences of a domino disaster, as it does not take into consideration the possible domino effects of an accident. Since the decision variables are constrained to binary values, the MIP approach correctly addresses the optimization problem while considering barrier costs. This approach provides clear solution boundaries and can ensure accuracy.

Additionally, we extended our study by performing the barrier allocation directly based on the nodes, marking a pioneering contribution to the field. Prior investigations in the literature primarily focused on barrier allocation based on arcs. This novel approach provides a more comprehensive understanding of safety strategies. Furthermore, our developed model is versatile and offers more flexibility. Its application extends beyond the domain of chemical plants to encompass a wide range of scenarios. This includes safeguarding electrical systems, mitigating domino effects in rotating systems, enhancing the resilience of interconnected systems, and fortifying communication systems, thus demonstrating the adaptability and potential impact of our research across various industries. Nevertheless, the numerical studies presented here are based on barrier allocation in an oil and gas storage facility. Finally, we expanded the experimental works by adding more details, such as sensitivity analyses and managerial insights. After a first failure or accident, the cardinality D may indicate how many subsequent domino events occur. Causing a cascade effect, we assume that the first event always happens at a root installation, from which fire might spread to surrounding installations.

It is important to note that domino events described by cardinality 0 reflect the initial cascade effect (the so-called "primary domino events") due to an accident in a chemical installation. In contrast, cardinality 1 relates to the second and so on. It's worth noting that the first domino effect occurs when cardinality is zero. Classifying domino effects generated by installation i and influencing other systems may be done using this taxonomy. Using this taxonomy of cardinality, we can classify the incidents in terms of cardinality as follows: in the case of $D = 0$, an installation j next to i has been damaged by a fire that has spread from i. In the case of $D = 1$, fire propagates from i to j and then from j to l between a neighboring installation $(i - j)$ and a neighboring installation $(j - l)$. A visual representation adapted from Janssens et al. (2015a) is presented in Figure 1.

Fire or heat radiation propagates across a chemical system due to an initial event that damages an installation. These so-called "point-source" situations give rise to many of the domino consequences examined in this research proposal. The cardinality of the domino effects and the physical position of the adjacent installations play an essential role in the distribution of safety barriers in these situations. Refinement of the presented model to consider geometry can add significant value when simulating the problem; however, this shall come later in the research to enhance the obtained results. In the example presented here, when an accident occurs in an industrial region, the nodes N indicate the nodes of the essential installations inside the industrial area, which may result in domino consequences following an accident. A describes the grouping of all arcs that make up the fire propagation from a point i to another j. An accident/failure at node $i \in N$ causes a fire to travel down an arc to the next node j, which causes a failure or accident at the next node $j \in N$. If no safety measures are employed, the time it takes for the fire to spread from node i to the next, and for the failure of the next node to be determined, is propagation time pt_{ij}.
Protective measures accessible for each arc (i,j) are included in a single set, M_{ij}. Since fire propagates further and

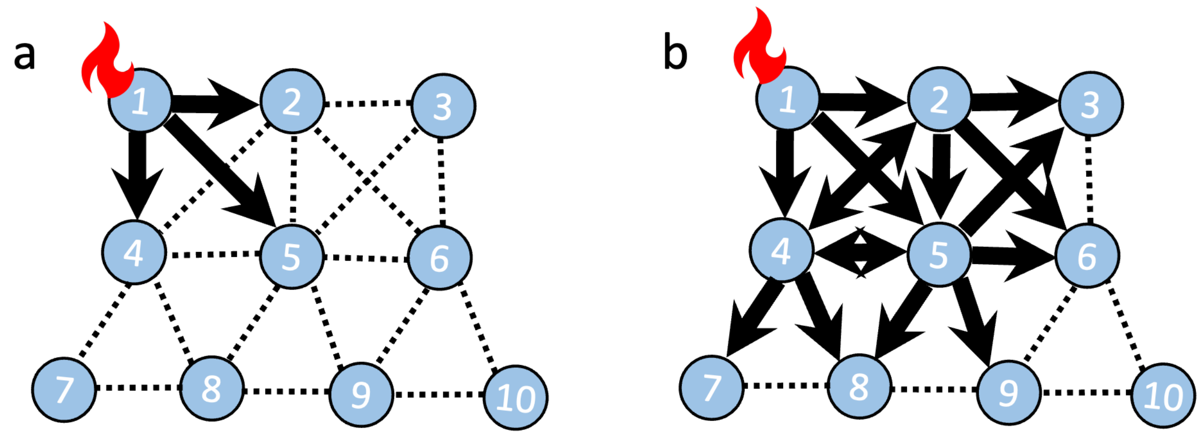

Figure 1: (a) Cardinality $D = 0$ and (b) cardinality $D = 1$

faster as it moves away from its original point of origin, any preventive step k that may be taken to slow its progress has an associated cost, and this, in turn, increases the time it takes for it to reach its next neighboring facility, in this case, facility j from facility i. Each protective measure's cost c_{ij}^{k} and efficacy e_{ij}^{k} depend on various factors, including the number and kind of protective barriers, thickness, equipment, and materials. It is anticipated that the security risk assessment carried out by the security management team has established these values.

B is the maximum amount of money that may be used to implement security measures. For clarity, each arc (i,j) is assigned a dummy protective measure with a cost $c^0_{ij} = 0$ and an efficacy $e^0_{ij} = 0$. Because there's no preventive mechanism, it's considered the default condition in arc (i,j). Furthermore, only one protective measure may be implemented for each arc. As a protective measure, a combination of single protective barriers with differing capacities can halt or delay the spread of the fire. For example, when multiple protective barriers are activated in the event of an explosion, the combined effect may be more significant or less influential than the sum of their individual effects. This is due to the possible interaction effects, such as increased complexity in activating the combined barriers or material and construction constraints that limit their performance.

A set, F_i^D, for each node $i \in N$, is defined. All conceivable cascading consequences of cardinality D may be denoted by the set of fire paths q in $F_i^D = \{P_1, P_2, ..., P_q\}$. These fire paths can be initiated by a failure or accident at root node i. When a fire spreads from the root node i (e.g., (i,j), (j,l), (l,m),....), which is a sequence of $D + 1$ arcs along a fire path $P_k \in P_i^D$. It causes an increase in the number of nodes in graph G, which impacts a series of $D + 2$ nodes in the network G (i.e., i and j in the instance of $D = 0$).

The risk expert identifies the cardinality of the domino accident D during the preliminary hazard identification phase, which is utilized as an input parameter in the model. A risk analyst might utilize the model provided in this study as a decision-support tool during the hazard identification phase, simulating and evaluating the effect of various D values. The domino effect problem defined in this paper can be described mathematically as a knapsack problem or resource allocation problem. We adopt Janssens et al. (2015b) mathematical model in explaining the problem and seek to enhance the solution obtained in the same paper by accomplishing the goals described later in the research objectives. In this section, we define three types of decision variables: First, let PT_{ij} be the propagation time of the fire when at least one protective measure is used; second, let ET_i be the escalation time after which the domino effect of cardinality D is initiated as a result of a failure/accident at node i; let x_{ij}^{k} be the binary decision variable that is equal to one if the arc's (i,j) protective measure k is selected, and zero otherwise. According to this definition, the problem is described as follows:

$$f(x) = (f_1(x), f_2(x)) \tag{1}$$

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

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

s.t.

$$\sum_{(i,j)\in A}\sum_{k\in M_{ij}} c_{kij} \cdot x_{kij} \leq B \quad (4)$$

$$PT_{ij} = \sum_{k\in M_{ij}} pt_{ij} \cdot (1 + e^{k}_{ij}) \cdot x^{k}_{ij} \qquad \forall (i,j) \in A \quad (5)$$

$$\sum_{k\in M_{ij}} x^{k}_{ij} = 1 \qquad \forall (i,j) \in A \quad (6)$$

$$ET_i \leq \sum_{(i,j)\in P_i} PT_{ij} \qquad \forall P_i \in F_i^D, \forall i \in N \quad (7)$$

$$x^{k}_{ij} \in \{0,1\} \qquad \forall (i,j) \in A, \forall k \in M_{ij} \quad (8)$$

The objective function in Eq. (1) assesses the quality of possible solutions. Both $f_1(x)$ and $f_2(x)$ are separated into two goals to be maximized in lexicographic order. The lexicographic ordering presupposes that the decision-maker can rank the goals $f_1(x)$ and $f_2(x)$ in order of priority. We assume that the decision maker's preferences rank the objective functions $f_1(x)$ and $f_2(x)$ in order of importance, with $f_1(x)$ ranking highest and $f_2(x)$ ranking lowest.

The objective function $f(x)$ maximizes (according to lexicographic order): (i) escalation time in Eq. (2) associated with the worst-case scenario presenting the lowest total escalation time due to a domino effect of cardinality D, which causes an accumulation of D node accidents in cascade when the root node i fails, (ii) the sum of the propagation times associated with all possible scenarios with an accident triggering a domino effect of cardinality D in any of the nodes as per Eq. (3). The goal of this objective is to improve the safety barriers' efficacy by taking into consideration not only the worst-case scenario but also the mitigations of potential accidents that impact the whole industrial region.

For the specified protective barriers, constraint (4) ensures that the overall cost does not surpass a predetermined budget B. The propagation time PT_{ij} associated with arc (i,j) is defined by constraint (5), which accounts for the type of protective measures implemented on that arc. Only one protective measure may be selected to enhance the propagation time associated with arcs (i,j), as enforced by constraint (6). It is essential to notice that ($x^0_{ij} = 1$) indicates that no protective barriers have been placed for the arc (i,j). The minimal escalation time for each node is computed using constraint (7), which results in a domino effect with a cardinality of D. Finally, the decision variable's domain is represented by constraint (8), which assures that no partial protection is permitted.

3. Case Study

To gauge the accuracy of our decision model and the solution approach, we applied it to a case study that simulates an oil storage park operated by a petroleum company. The study was mainly selected due to its accuracy in representing a chemical/oil storage park and its potential for cascade effects. This industrial setting ensured a realistic portrayal of the issue at hand. The objective of the case study was to illustrate how our model utilizing the MIP method can be applied to address the domino effect research problem.

In particular, the selected case study for this research is the Shibushi Storage Base in Japan, which consists of an oil stockpile base comprising forty-three (43) storage tanks, as shown in Figure 2. Each storage tank has the same size and material and has a floating roof. To model the storage park and the potential propagation of accidents, a graph $G = (N,A)$ was employed. The set of facility nodes, or storage tanks, is represented by N, while A denotes the set of

Figure 2. The aerial photo of the Shibushi national petroleum stockpiling base in Kagoshima Prefecture. (Mainichi).

Figure 3. The Satellite photo of the plant to identify the location of each node

arcs that signify the possible propagation links from one storage tank to another in case of an accident. In the event of an accident at node *A*, a neighboring facility, *B*, may also be affected due to the fire spreading from *A* to B along the arc (*A,B*). The value assigned to each arc (*i,j*) belonging to set *A* represents the time the fire takes to travel from node *i* to facility *j* and cause it to fail (refer to Figure 3). The propagation time is assumed to be proportionate to the distance between the nodes and the impact of average weather conditions, including wind. The duration of time for failure that is attributed to each node can be described as the minimum period for which the mishap becomes uncontrollable within the installation. These time periods depend on the tanks' unique characteristics and actual industrial data regarding the tanks' exposure to atmospheric conditions. The types of barriers are adapted from Janssens et al. (2015a). As a result, the MIP-based model conducted in our illustrative case study may be deemed realistic.

For every arc, we have examined a compilation of safety barriers that can be enforced to impede the spread of the calamity. Each barrier possesses the ability to retard the progression of the accident and is accompanied by an associated cost. Throughout the remainder of this document, we have established a maximum budget of 3.5 million Euros.

4. Results and Discussion

This section discusses the results achieved through our model. One of the primary objectives of our study was to demonstrate the flexibility and effectiveness of our proposed model as a decision-making tool, especially when dealing with domino effects. We conducted several pilot experiments to fine-tune the model. After these initial tests, we established the internal parameters of the model. The simulation quickly converges towards stable solutions within a relatively small number of iterations. Furthermore, the time required to solve the instance gradually increases with the cardinality of the domino effects analyzed by the user. Still, it takes less than 40 seconds even in the worst case. We tested various cardinalities for the domino effects in our case study. As anticipated, the allocation of protective safety barriers differed depending on the cardinality of the domino effects considered.

In a myopic optimization approach, wherein only one domino event is analyzed, wherein the cardinality of the domino effects is zero, the primary objective is to allocate safety barriers to prevent the escalation and the emergence of secondary or tertiary accidents that could result from the failure of an installation. However, domino effects cannot always be prevented, so a specific allocation of protective safety barriers may be more appropriate to limit the escalation and mitigate the consequences of cascade effects even further. During the planning phase of an industrial area's design, decision-makers can evaluate various scenarios by testing different optimized allocations of safety barriers for each domino effect. This approach can increase the time required for a domino accident of a particular cardinality to propagate.

The optimum solution is demonstrated in Figure 4. Since type 5 is the most effective at impeding the spread of fire, it has been utilized at the center of the storage tank cluster. This finding appears logical since it is the most effective way to isolate the seemingly two groups of tanks in the figure. It should also be kept in mind that the cost of deploying type 5 barriers is considerably higher than other barrier types. Hence, allocating other barriers does not make the allocated budget exceed the maximum value.

Additionally, the solution approach provides information on the minimum propagation times of various fire paths associated with all possible accident scenarios, which is directly related to the location of the selected safety barriers. This is essential for fire brigades, rescue, and emergency teams since the escalation time of the worst-case fire path (in terms of escalation times) represents the maximum intervention time required to stop the fire and prevent the further spread of the domino accident.

Figure 4. Barrier type optimum allocation solution

5. Conclusion

A comprehensive mathematical model is developed using Mixed Integer Programming (MIP) to improve chemical plant safety barrier allocation, addressing the domino effect in industrial facilities. This novel model incorporates nodes and arcs, expanding on the classic arc-based barrier allocation technique. We used lexicographic optimization to minimize escalation time and analyze the sum of propagation durations for different fire pathways. This dual-objective optimization lets decision-makers intelligently manage resources to reduce domino effects. The model's capacity to provide optimum answers in an acceptable computing time makes it more applicable in real-world situations. The research focused on chemical facilities, but the concept may be applied to other sectors, underscoring its potential to improve safety in linked systems. The model will be modified to account for geometric aspects in future work, and more industrial experiments will be performed to enhance our technique. This study improves process industry safety and lays the groundwork for domino effects and safety barrier optimization studies.

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