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Application of event sequence diagram to evaluate emergency response actions during fire-induced domino effects

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ABSTRACT

Emergency response actions can significantly influence the propagation of domino effects, particularly those triggered by fires. Thus, the performance and efficiency of devised emergency response actions should be carefully evaluated and taken into account when analyzing the propagation of domino effects and their risk. In the present study, we have introduced a methodology based on Event Sequence Diagram (ESD) to evaluate and prioritize different emergency response actions based on their efficiency in preventing or delaying the propagation of domino effect. Using the developed methodology, the risk of domino effects under emergency response actions can be assessed, while considering factors such as sequence, duration, correctness, and mutual interaction of the emergency response actions. We demonstrated the application of the methodology in analyzing the effect of emergency response actions on fire-induced domino effects in a fuel storage plant; the comparison of the results with previous studies illustrates the efficacy and practicality of the developed methodology.

1. Introduction

Major industrial fires in the chemical and process industry can cause huge losses. In addition to inherent safety and add-on safety measures aimed at preventing or controlling of major fires, effective emergency response plans play a key role in preventing a major fire from causing secondary fires and thus forming a fire-induced domino effect. In order to ensure rapid, orderly and effective implementation of emergency response actions, emergency response plans are usually pre-established in chemical plants. Such plans arrange the structure of the emergency organization, personnel, technology, equipment, materials, actions, commands and coordination beforehand. However, whether these arrangements are reasonable and whether the actions and the coordination actions are effective or not are difficult to assess in the design stage of a plan. Some studies on the evaluation of emergency response plans have been carried out [4,5,12,15,29] most of these researches aimed to evaluate the emergency plans from robustness and integrity perspectives. However, the relevant studies in the field of emergency response actions are relatively limited. Nevertheless, the evaluation of emergency response actions has become an urgent requirement for improving emergency preparedness as the emergency actions responding to an accident can significantly affect the evolution of the accident. Different patterns of an accident evolution may lead to different consequences. As a result, the efficacy of the emergency response actions and their impact on both the evolution of the accident and the likelihood of the ensuing consequences should be effectively taken into account in the risk analysis of the accident.

Domino effects refer to a series of accidents triggered by an initial event/accident. In petrochemical storage areas, for example, there are many storage tanks containing large quantities of flammable substances. This makes these storage tanks potential sources of severe fires or explosions which could emerge as domino effects. Particularly, the large inventory of flammable chemicals along with the congestion of the storage tank area facilitates the escalation of an initial fire (primary fire) into a series of secondary and tertiary fires in the neighboring storage tanks-a so-called fire-induced domino.

Domino effects will cause more significant losses than a primary accident. Safety management often requires the risk assessment of domino effects; for example, the Seveso-III Directive requires the European member states to assess the risk of domino effects in their hazardous installations (Directive 2012/18/EU). Many researchers have studied the risk of domino effects and developed risk assessment methodologies [3,6,8,9,10,11,16–21,23,27,30–34]. Most of

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these methods analyze probabilities or consequences of domino events based on the escalation vectors.

For fire-induced domino effects in chemical plants, the major escalation vector is the thermal radiation. If the thermal radiation intensities received by neighboring tanks from a primary tank fire (or pool fire) both exceed a certain threshold and last for at least some specific time lapse, secondary fires or explosions may occur, and so on.

The emergency response actions can impact the propagation of a primary fire, thus affecting the possibilities and patterns of potential domino effects. Although the importance of emergency response actions in either preventing or controlling domino effects has previously been addressed by researchers [22,23], the impact of emergency response actions has not given due attention.

2. Emergency response

2.1. Definition

Emergency response is usually looked upon as a factor to mitigate the risk of accidents mainly by reducing the losses. However, actual emergency response actions do not necessarily reduce the losses, especially under wrong circumstances. After an accident occurs, different propagation patterns can be envisaged. The emergency response actions impact both the likelihood of the patterns and the respective consequences. In the present study, an emergency response evaluation methodology is introduced to investigate the foregoing impacts of emergency response actions.

The risk of an accident subject to an emergency response plan (hereafter emergency response risk) can be defined as:

$$ER_j = f\ (P_j, C_j) \quad \text{for } j = 1, 2, \ldots, M \tag{1}$$

where ER_j is the emergency response risk, that is, the risk resulting from the jth propagation pattern of the accident under the emergency response; P_j is the probability of the jth propagation pattern under the emergency response, and C_j is the consequence of the jth propagation pattern; M is the total number of possible patterns.

Since the emergency response risk is a function of the occurrence of emergency response actions, it can be defined dynamically by considering the influences of each specific emergency action:

$$ER_j^{\,i} = f(C_j^i, P_j^i) \quad \text{for } i = 1,\ 2, \ldots,\ N \quad \text{and} \quad j = 1,\ 2, \ldots,\ M \tag{2}$$

where $ER_j^{\,i}$ indicates the emergency response risk of the jth propagation pattern under the ith emergency response action; N is the number of emergency response actions. P_j^i represents the conditional probability of the jth propagation conditioned by the occurrence of the ith emergency response action. Likewise, C_j^i represents the consequence of the jth propagation conditioned by the occurrence of the ith emergency response action.

The conditional probability embedded in Eq. (2) can be used to evaluate the efficacy of each emergency response action.

Domino effects are results of accident propagation. So, to assess the risk of domino effects under emergency response, M in Eq. (2) can be considered as the total number of domino effects resulted from an initial accident; P_j^i is the conditional probability of the jth domino effect conditioned by the occurrence of the ith emergency action; C^ij is the consequence of the jth domino effect conditioned by the occurrence of the ith emergency action; and ER_j^i is the risk of the jth domino effect conditioned by the occurrence of the ith emergency action after the initial accident occurs.

During the emergency response to an accident, the factors such as the time of each action and the sequence of the actions can influence the propagation of the accident. Thus, to assess the emergency response risk, the following factors should be considered:

(i) Time of emergency response action. An action implemented at different times may lead to different results.

(ii) Sequence of emergency actions. A different sequence of emergency response actions can change the probability of the resulting events, and also influencing the consequences.

(iii) Mutual influence of the actions. Some emergency actions may interact with each other, leading to different results.

(iv) Correctness of the actions. Whether an emergency action is performed correctly will affect the propagation of the accident. The correctness of an emergency response action can be reflected by its states. Although an action may include several states, usually two basic states are considered for an action: correct action which means the action works well and produces the intended results according to the objective of the emergency response; incorrect action which cannot prevent the propagation of the accident or mitigate the losses.

(v) Relations of the process variables. Emergency actions are highly related to process variables.

2.2. ESD modeling of emergency response

2.2.1. ESD modeling approach

Event sequence diagram (ESD) is a graphical method for visualizing the sequence of related events. As an effective risk assessment method, it has been used in many different fields. Swaminathan and Smidts [35] expanded the ESD framework by introducing dynamic factors, so that it can be used for probability risk assessment of dynamic systems.

Applications of ESD have been reported in Abdolhamidzadeh et al. [1], Ale et al. [2], Groth et al. [14], Luo and Hu [24], and Mohaghegh et al. [25]. For assessing emergency response risk in the present study, ESD is defined based on the work of Swaminathan and Smidts [35]:

$$ESD = (E, Cd, G, Pr) \tag{3}$$

where E refers to the events, which in turn implies any changes from one state to another. This approach will be employed to describe the event sequence in a domino effect scenario and related emergency actions. Events are divided into four categories: (1) “Initial event” (IE), being the beginning event of an ESD, and starting the potential event sequence. (2) “Delay event” (DE), including ‘deterministic delay event’ and ‘random delay event’. The deterministic delay event indicates that no event occurs within a certain time. It is also used to describe the fixed time, for example, the time to complete a regular job. The random delay event indicates that the delay time is determined by a random number. (3) “Comment event” (CE), describing the development of an event sequence. (4) “Termination event” (TE), indicating the termination event of the ESD.

Cd indicates conditions, which represent the rules controlling the development of an event sequence into different branches. The event sequence will develop in different directions according to whether the conditions are satisfied. They can be used to describe the impacts of emergency response actions on the development of an event sequence.

G represents the logic gates, indicating the logical relationships among events. The basic gates are the AND gate and the OR gate, which can be further divided into four types according to event relationships: (1) “Output AND gate”, representing the logical relationship that the occurrence of an event will lead to multiple independent events occurring simultaneously; (2) “Input AND gate”, indicating that one event occurs only if multiple other events have occurred; (3) “Output OR gate”, representing multiple exclusive events occurring when one input event occurs;