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A Macro-systematic Accident Propagation Analysis for Preventing Natural Hazard-induced Domino Chain in Chemical Industrial Parks

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Chemical industrial park (CIP) is a typical accident-prone safety-critical system, which is usually congested with high-density hazardous installation units. Domino effects triggered by natural hazards are one of the emerging threats in CIPs, imposing tremendous challenges on society, environment, and economy. This work focuses on analysing the evolution mechanism of natural hazard-induced domino chain (NHDC) from a macro-systematic perspective. Based on the disaster chain theory and the thought of system science, a disaster chain evolution system (DCES) is developed to clarify the accident propagation characteristics. Inspired by the multi-source multi-level propagation pattern of NHDC, the Na-tech layer, the domino layer and the destruction layer are used to form the specific system structure of DCES. A Markov process-based accident propagation (MPAP) model is proposed to cope with the uncertain and complex accident scenarios associated with the evolution process of NHDC. Through formulating the system response process, the proposed MPAP model can reveal the general law of accident evolution. Finally, a general system dynamic response process of DCES is provided to reveal the propagation law of domino effects triggered by natural disaster from a macro-systematic perspective.

1. Introduction

Natural hazards such as hurricanes, lightning, earthquakes and floods may rapidly lead to a series of loss of containment (LOC) events in chemical industrial parks (CIPs), causing fires, explosions, or toxic cloud emissions (Reniers et al., 2018). These technological accidents triggered by natural disasters are termed as Na-tech events (Showalter and Myers, 1994). Numerous previous studies (Ricci et al., 2021; Sengul et al., 2012; Young et al., 2004) have shown that there appears to be an increase in frequency and severity of Na-tech events. The typical examples of Na-tech events include: the Great East Japan Earthquake in 2011, caused serious fires and explosions in Sendai and Chiba (Huang et al., 2020); the Wenchuan earthquake in 2008, caused the release of over 100 tons of liquid ammonia in Shifang city (Cruz and Suarez-Paba, 2019); hurricanes “Katrina” and “Rita” in 2005, caused multiple damages to about 611 industrial installations in Gulf of Mexico (Ruckart et al., 2008).

(Showalter and Myers, 1994) first coined the term “Na-tech” in 1994. Since then, the increasing catastrophic destruction associated with Na-tech events has quickly raised the awareness of industries, government and academia (Camila et al., 2019). The accident statistics (CHEN and ZOU, 2018) show that the most frequent technological scenarios in CIPs caused by natural disasters include fires and explosions, of which domino effects are easily triggered. However, most of research only focuses on installation failures caused by natural disasters and their secondary technological accidents, and rarely considers the propagation of subsequent domino accidents. The main characteristic of domino effects is the expansion and escalation of accident scenarios, linking a primary scenario with one or several higher level scenarios (Chen et al., 2018). The traditional quantitative domino risk assessment framework (Cozzani et al., 2005) only considers the first propagation level of domino effects. (Chen and Reniers, 2020) have pointed out however that the risk of high-

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level domino propagation cannot be ignored. The escalation of domino accidents may result in multiple higher order scenarios, which can be seen as parallel effects. Accordingly, the escalation factors associated with multiple failure units may exacerbate the expansion of accident scenarios, and synergistic effects are defined (Reniers and Cozzani, 2013b). (Zhang et al., 2018) proposed an agent-based model to analyze the temporal dependencies of domino chains. (Chen et al., 2018) proposed a domino evolution graph model to capture the spatial-temporal evolution of domino accidents triggered by fire. In their follow-up study (Chen et al., 2021), a dynamic multi-agent approach was proposed to analyse the evolution of cascading technological accidents. (Huang et al., 2021) developed a dynamic analysis for domino chains under fire scenarios.
This paper aims to reveal the propagation law of domino effects triggered by natural disaster from a macro-systematic perspective. Specifically, a disaster chain evolution system (DCES) is developed to clarify the accident propagation characteristics. The various features of DCES designs are given, including the system units, the system states, the system activation conditions, the system structure. A Markov process-based accident propagation (MPAP) model is proposed to formulate system response behaviors during the evolution process of NHDC. Through analyzing the evolution mechanism of NHDC, a conceptual loss prevention framework is established to guide the prevention and the mitigation of the domino effects triggered by natural hazards.

2. Disaster Chain Evolution System

The general system response process of DCES is demonstrated in Figure 1. To analyze the propagation characteristics of domino effects triggered by natural hazards, a DCES is proposed in this section. The various features of DCES designs are stated in next sub-sections, including the system units in Section 2.1, the system activation conditions in Section 2.2, the system structure in Section 2.3, the system response process in Section 2.4.

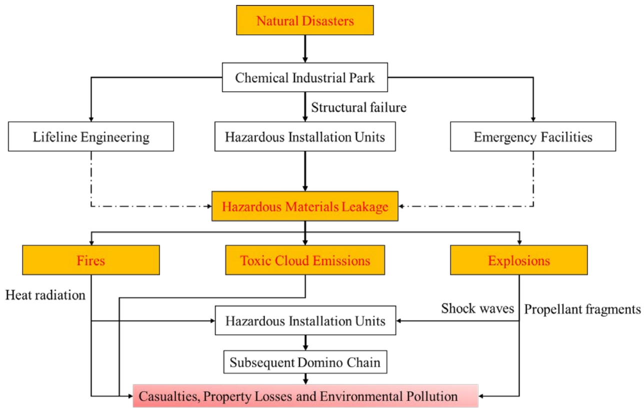

Figure 1: The general system dynamic response process

2.1 System Units

The proposed DCES consists of hazard unit set (H), environment unit set (E) and vulnerable unit set (V), i.e.:

$$DCES = < H, V, E > \quad (1)$$

where H refers to the hazard units that can cause adverse effects to vulnerable units. In CIPs, H can be divided into natural hazards and technological hazards. Vulnerable units refer to the objectives affected and damaged by hazards, which mainly includes various HIUs. Environment unit is closely related to the derivation of hazards, which refer to the relationship among natural environment, human environment, and industrial environment, such as meteorological conditions, personnel distribution, management factors, and land-use layout.

2.2 System Activation Conditions

The system activation conditions of DCES is equivalent to the occurrence conditions of NHDC. Based on the accident-causing theory (Chi and Han, 2013), the occurrence and development process of industrial accidents affected by natural disasters are analyzed, and the system activation conditions are stated as follows:

- Natural hazards are regarded as the primary disasters causing failures of vulnerable units and generating secondary technological hazards;
- Secondary technological hazards cause adverse effects to new vulnerable units;
- The failure energy of hazard units exceeds the failure threshold of vulnerable units.

2.3 System Structure

Usually, domino chains are propagated level by level (Reniers and Cozzani, 2013a). The propagation pattern of domino effects triggered by natural hazards is regarded as a multi-source multi-level parallel disaster chain. According to the propagation characteristics, a three-layer system structure is developed to identify the triggering relations among three system units, which mainly includes the Na-tech layer, the domino layer and the destruction layer. The following *Figure 2* is adopted to demonstrate the structure of proposed system. In the Na-tech layer, hazard units are mainly composed of extreme natural phenomena caused by various natural disasters, which may trigger multiple failures of HIUs (Yang et al., 2020). In the domino layer, hazard units are converted into the technological hazards generated by the failures of HIUs. When the failure energy exceeds the failure threshold of the current vulnerable unit, domino accident may be triggered. In the destruction layer, the uncontrolled energy generated by various hazard units can spread to vulnerable units outside the system, causing serious accident consequences.

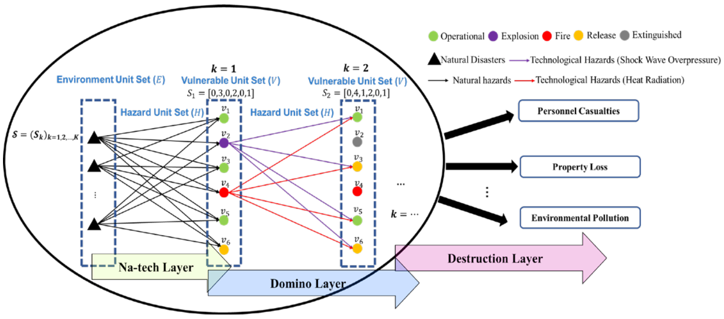

Figure 2: Three-layer system structure of the disaster chain evolution system

3. Markov process-based accident propagation

The core of the NHDC is the expansion and escalation of accident scenarios (Reniers and Cozzani, 2013a). The potential simultaneous damages caused by natural hazards lead to the complex and uncertain evolution process of NHDC. To facilitate the analysis of accident evolution mechanism, a reasonable assumption is established, that is, the accident scenario of the next accident expansion level is only related to the current accident scenario. Thus, the evolution process of NHDCs is regarded as a Markov process (Wang et al., 2020). In this work, the changes of system units during the system response process are used to describe the evolution of NHDC. The proposed MPAP model is stated as follows:

$$MPAP = < \boldsymbol{S}, \boldsymbol{P} > \quad (2)$$

where S is the state space of system units; P is the transition probability space. The formulation of MPAP are stated in the following sub-sections.

3.1 State Space

In CIPs, domino effects are mainly propagated among the HIUs (Zhang et al., 2019). According to the potential technological hazards associated with HIUs, five states of HIUs are shown in Table 1. Suppose that $V = \{v_i | i = 1,2, \dots |V|\}$ is a vulnerable set containing $|V|$ HIUs. The state of system units for kth-level accident scenario can be expressed by a state matrix $\boldsymbol{S_k} = (s_{k1}, s_{k2}, \dots, s_{k|V|})$.

$$s_i = \begin{cases} 0, the\ state\ of\ v_i\ is\ "operational" \\ 1, the\ state\ of\ v_i\ is\ "Release" \\ 2, the\ state\ of\ v_i\ is\ "Fire" \\ 3, the\ state\ of\ v_i\ is\ "Explosion" \\ 4, the\ state\ of\ v_i\ is\ "Extinguished" \end{cases}, i = 1,2,..,|V| \quad (3)$$

Table 1: Five states of HIUs

State Type	State Description
Operational	The HIU is not failed.
Release	The HIU is physically damaged, resulting in the release of hazardous materials.
Fire	The HIU is on fire, causing heat radiation
Explosion	The LOC event of the HIU induces an explosion, causing heat radiation, causing shock wave overpressure and propellant fragments.
Extinguished	The HIU is failed but does not produce any technological hazards.

3.2 Transition Probability Space: Na-tech layer

In the Na-tech layer, vulnerable units suffer from negative effects imposed by natural hazards. Suppose that $V = \{v_i | i = 1,2, \ldots |V|\}$ is a vulnerable unit set containing $|V|$ HIUs, $\mathcal{N}$ is a natural hazard unit $\mathcal{N}$. The failure probability of HIU v_i under the influence of natural hazard $\mathcal{N}$ is given as follows:

$$P_F^1(v_i) = f_{\mathcal{N}} P(v_i | \mathcal{N}) \quad (4)$$

where $f_{\mathcal{N}}$ is the frequency of the occurrence of $\mathcal{N}$, $P(v_i|\mathcal{N})$ is the failure probability derived from the vulnerability assessment model. Generally, the vulnerability assessment model (Yang et al., 2020) is determined by comparing the relationship between the intensity of natural hazards and the resistance of HIUs, which can be expressed as follows:

$$P(v_i|\mathcal{N}) = \phi(I(\mathcal{N}) > R(v_i)) \quad (5)$$

where $\phi(\cdot)$ is the mapping relation of the vulnerability model; $I(\mathcal{N})$ is the intensity of natural hazard unit $\mathcal{N}$; $R(v_i)$ is the resistance of HIU v_i. The probabilities of v_i being in five predefined states in Na-tech layer is given as follows:

$$P_{Na}(\boldsymbol{S_1}(\boldsymbol{i})) = \begin{cases} 1 - P_F^1(v_i), \boldsymbol{S_1}(\boldsymbol{i}) = \boldsymbol{0} \\ P_F^1(v_i) P_T(v_i|R), \boldsymbol{S_1}(\boldsymbol{i}) = \boldsymbol{1} \\ P_F^1(v_i) P_T(v_i|F), \boldsymbol{S_1}(\boldsymbol{i}) = \boldsymbol{2} \\ P_F^1(v_i) P_T(v_i|E), \boldsymbol{S_1}(\boldsymbol{i}) = \boldsymbol{3} \\ 0, \boldsymbol{S_1}(\boldsymbol{i}) = \boldsymbol{4} \end{cases} \quad (6)$$

where $P_{Na}(\boldsymbol{S_1}(i))$ gives the probabilities of v_i being in five predefined states in Na-tech layer; $P_T(v_i|R)$, $P_T(v_i|F)$ and $P_T(v_i|E)$ are the probabilities of three accident scenarios (release, fire and explosion) after installation failure. In practical engineering application, $P_T(v_i|R)$, $P_T(v_i|F)$ and $P_T(v_i|E)$ can be obtained by the event tree analysis (Vilchez et al., 2011). According to the system activation conditions, it is assumed that the initial state of the system is safe, i.e.:

$$\boldsymbol{S_0} = \boldsymbol{O_{1 \times |V|}} \quad (7)$$

where all the entries in the matrix $\boldsymbol{S_0}$ are 0. To sum up, the transition probability of the Na-tech layer can be formulated as follows:

$$P(\boldsymbol{S_0}, \boldsymbol{S_1}) = \prod_{i}^{|V|} P_{Na}(\boldsymbol{S_1}(i)) \quad (8)$$

3.3 **Transition Probability Space:** *Domino layer*

The technological hazards that can trigger the domino effects are mainly thermal radiation and shock wave overpressure generated by fires and explosions. The domino extension probability can be obtained by the classical Probit model (Cozzani et al., 2005). In the Domino layer ($k \geq 2$), for $\forall\, v_i \in V_k$, its failure probability $P_D(v_i)$ can be calculated as follows:

$$P_D(v_i) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} e^{-\frac{x^2}{2}} dx \quad (9)$$

where Y is the probit variable, the probit variables of common installation are provided by (Cozzani et al., 2005).

Similarly, the probabilities of v_i being in five predefined states in next level accident scenario can be calculated as follows:

$$P_{Do}(\boldsymbol{S_{k+1}}(i)) = \begin{cases} 1 - P_F^k(v_j), \boldsymbol{S_{k+1}}(i) = 0 \\ P_F^k(v_j) P_T(v_i|R), \boldsymbol{S_{k+1}}(i) = 1 \\ P_F^k(v_j) P_T(v_i|F), \boldsymbol{S_{k+1}}(i) = 2 \\ P_F^k(v_j) P_T(v_i|E), \boldsymbol{S_{k+1}}(i) = 3 \\ 0, \boldsymbol{S_{k+1}}(i) = 4 \end{cases}, k \geq 1 \quad (13)$$

where $P_F^k(v_j)$ is the failure probability of HIU v_j in kth-level accident scenario. The transition probability of the Domino layer ($k \geq 1$) can be formulated as follows:

$$P(\boldsymbol{S_k}, \boldsymbol{S_{k+1}}) = \prod_{v_i \in V_k} P_{Do}(\boldsymbol{S_{k+1}}(i)) \quad (14)$$

It is worth mentioning that the shock wave overpressure caused by the explosion is a kind of instantaneous damage. For the unit in the explosion state, it will be directly converted to the extinguished state in the next level of accident scenario, and it will no longer participate in the subsequent accident evolution process.

4. Methodology illustration

The following ***illustration*** shown in Figure 3 is adopted to demonstrate the transition probability space of the domino layer. Suppose that $V = \{v_1, v_2, v_3, v_4\}$ is a vulnerable unit set containing four HIUs. All HIUs are pressure vessels. F_k and E_k are used to express the fire-related hazard units and the explosion-related hazard units corresponding to $\boldsymbol{S_k}$. For the primary accident scenario, its system units are stated as follows:

$$\begin{cases} \boldsymbol{S_1} = (\boldsymbol{2\ 0\ 0\ 0}) \\ V_1 = \{v_2, v_3, v_4\} \\ F_1 = \{v_1\} \\ E_1 = \emptyset \end{cases} \tag{15}$$

The fire domino effect propagation probability P_{fi}^1 of v_2 can be obtained as follows:

$$\begin{cases} P_{fi}^1(v_2) = \dfrac{1}{\sqrt{2\pi}} \displaystyle\int_{-\infty}^{Y(v_2)-5} e^{-\frac{x^2}{2}} dx \\ Y(v_2) = 16.82 - 1.847 D_2\,(tff) \\ D_2(tff) = -0.97\, ln\left(\mu_f^1(v_2)\right) - 8.835 {V_2}^{0.032} \end{cases} \tag{16}$$

where $\mu_f^1(v_2) = f_{12}$; V_2 is the volume of HIU v_2. Since the primary accident scenario contains only one fire accident, the failure probability of HIU v_2 in primary accident scenario is equivalent to $P_{fi}^1(v_2)$, $P_F^1(v_2) = P_{fi}^1(v_2)$. The failure probabilities of HIUs v_3 and v_4 in primary accident scenario can be obtained in the same way. Since the vulnerable unit set $V_4 = \emptyset$, the termination state condition is satisfied. Thus, $\boldsymbol{S_4}$ is the termination state of the above NHDC. The transition probabilities are given as follows:

$$P(\boldsymbol{S_1}, \boldsymbol{S_2}) = \left(1 - P_F^1(v_2)\right) P_F^1(v_3) P_T(v_3|E) \left(1 - P_F^1(v_4)\right) \tag{17}$$

$$P(\boldsymbol{S_2}, \boldsymbol{S_3}) = P_F^2(v_2) P_T(v_2|F) \left(1 - P_F^2(v_4)\right) \tag{18}$$

$$P(\boldsymbol{S_3}, \boldsymbol{S_4}) = P_F^3(v_4) P_T(v_4|F) \tag{19}$$

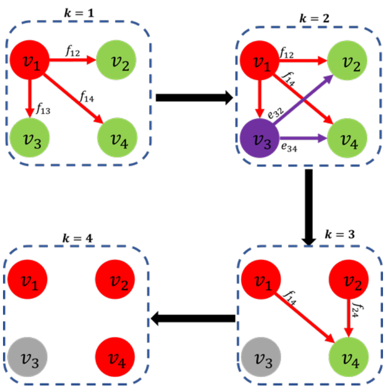

Figure 3: An illustration of state transition

5. Conclusions

Natural hazards and their secondary fires and explosions may damage HIUs in chemical industrial parks, resulting in domino effects and enlarging the consequences of accidents. This work focuses on the multi-source multi-level domino accident chain induced by typical natural disasters such as lightning, floods, and earthquakes in chemical industrial parks. A disaster chain evolution system is developed to clarify the accident propagation characteristics. A Markov process-based accident propagation is proposed to formulate the system response behaviour during the evolution process of natural hazard-induced domino chain. The proposed MPAP model can quantify the possibility and uncertainty associated of the expansion of the accident scenario through the state transition probability, identify the most likely propagation chain and the most dangerous vulnerable unit. Natural hazards can produce LOC events in HIUs that store hazardous materials causing fires, explosions, or toxic cloud emissions. The technological hazards such as heat radiation, shock waves, and propellant fragments generated by fires and explosions can easily cause damage to the adjacent HIUs, triggering the domino chain. With the expansion and escalation of accident scenario, the hazard units and the vulnerable units are updated level by level.

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