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The Decision-Making between Evacuation and Shelter-In-Place (SIP) in Case of Multi-Hazard Chemical Accidents

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One of the reasons for the shelter-in-place (SIP) strategy is not often adopted in chemical industries is the lack of methods that can effectively guide evacuees to make the optimal evacuation decision. Evacuees face the decision-making between direct evacuation and SIP in case of a chemical accident. This paper proposes a method for evacuees to make real-time decision between direct evacuation and SIP according to the dynamic risk assessment of fire, explosion, and toxic release multi-hazard chemical accidents. This method can guide evacuees to adjust their evacuation decisions according to the development of the accident, and guide the chemical industry to optimize the SIP location planning based on evacuees' decisions.

1. Introduction

Shelter-in-place (SIP) is an effective emergency response strategy for natural disasters (e.g. storms, lightnings) and technological accidents (e.g. fires, explosions). American Red Cross (2003) defined SIP as "selecting a small room and taking refuge there when an emergency happens". The SIP strategy has been promoted by the U.S. FEMA (2021) and the China's MEM (2023a), and widely adopted in communities (Hillsborough, 2024) and universities (Yale, 2024), especially in North America.

Scholars have also emphasized the necessity of the SIP strategy in emergency management. Natural disasters (Steer et al., 2017), epidemics (Berry et al., 2021), toxic releases (Gao et al., 2021), etc. are all considered emergency scenarios where SIP strategies are applicable. Specifically, Lyu and Wehby (2020) discussed the effects of SIP orders on reducing COVID-19 mortality. Chan et al. (2008) studied the effectiveness of SIP strategies in urban communities. Several companies had also designed protective buildings for SIP such as MineARC's shelter, BakerRisk's SIP haven, Fortress's protective building, etc.

However, the SIP strategy has not been widely adopted in hazardous material-related industries, such as the chemical industry. One of the important reasons lies in the uncertain decision-making between direct evacuation and SIP. Many scholars have discussed the comparison between strategies of direct evacuation and SIP (McLennan et al., 2022; Smith and Swacina, 2017), but few of them could support the "evacuate or SIP" real-time decision-making in emergencies, especially in fire, explosion, and toxic release multi-hazard chemical accidents. In actual chemical accident cases, due to the lack of effective evacuation decision-making methods, evacuees suffered casualties during the evacuation process. For example, in an explosion accident happened in Panjin, China in 2023, nine casualties all happened during the evacuation process (MEM, 2023b).

The multi-hazard and dynamic characteristics of chemical accidents are two major factors that bring difficulties to the research on the method for evacuation decision-making. Mutual influence and triggering relationships among fire, explosion, and toxic release accidents cause coupling effects and domino effects, respectively (He and Weng, 2020). The nonlinear additivity and dynamicity of the consequences of multi-hazard chemical accidents make the past research on evacuation decision-making methods for single-hazard accidents inapplicable.

This paper intends to propose an effective evacuation decision-making method for multi-hazard chemical accidents. The method is based on the cumulative individual risk (CIR) optimization criterion and intelligent path planning method, aiming to support the "evacuate or SIP" real-time decision-making of evacuees. The method

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applies the consequence assessment based on multi-physical field analysis and a self-developed software to conduct quantitative risk assessment (QRA) of multi-hazard chemical accidents. The nonlinear and dynamic QRA results are the basis of the proposed assistant decision-making algorithm. This method can not only support evacuees' decision-making during the evacuation process, but also improve the optimization algorithm for SIP locations based on genetic algorithm (GA) proposed in the author's past research (He et al., 2024).
This study is expected to improve the evacuation efficiency in multi-hazard chemical accidents by proposing an effective assistant decision-making method, thereby optimizing the emergency management strategy of the chemical industry. The goal of the research is to enhance the safety management capacities of the chemical industry, and prevent serious losses caused by multi-hazard chemical accidents.
Section 2 introduces the methodology of this research, including dynamic QRA methods, an improved GA-based SIP location planning method, and the real-time evacuation decision-making method. Sections 3 and 4 take a chemical cluster located in Guangzhou, China as a case study to verify the effectiveness of the methods for SIP location planning and evacuation decision-making. Section 5 provides some concluding remarks.

2. Methodology

This section intends to introduce the methodology of this research by dividing the method into three steps: the QRA of multi-hazard chemical accidents, the decision-based SIP location planning, and the real-time decision-making between direct evacuation and SIP.

2.1 Risk assessment of multi-hazard accidents

Individual risk (IR) is a widely adopted indicator which can comprehensively consider the consequence and frequency of the accident, and the exposure of victims, as indicated in Eq. (1). In chemical accidents, the human death rate caused by the accident is often regarded as the accident consequence, and the exposure is regarded as 1 during the evacuation process. The CIR optimization criterion can be calculated by integrating the IR of the evacuee along the evacuation path.

$$IR = frequency \times consequence \times exposure \quad (1)$$

The CIR optimization criterion is the basis of the proposed risk-driven decision-making process. This method utilizes a self-developed software to calculate the IR of accident according to the scenario. The software is divided into two modules: the consequences analysis module for fire, explosion and toxic release accidents, and the dynamic domino effect analysis module "Domino-MCS". The first module applies consequence analysis models (CCPS, 2000) to calculate the physical fields of single-hazard accidents, and the second module applies Monte Carlo simulation (MCS) to calculate the nonlinear dynamic multi-hazard risk.

2.2 Shelter-in-place location planning

The SIP location planning and evacuation decision-making influence each other, making the optimization of the SIP location into an *np* problem. The author has proposed a GA-based optimization method for SIP location planning in the past research (He et al., 2024). The method determines the SIP location with the minimum CIR through the process including fitness calculation, selection, crossover, mutation, and iteration. However, the method is based on the assumption that all evacuees will adopt SIP strategy rather than direct evacuation. To consider the alternatives of "evacuate or SIP" decision-making in SIP location planning, the GA process needs to add a CIR comparison process between direct evacuation and SIP strategies. The steps of the improved SIP location planning method are shown in Figure 1.

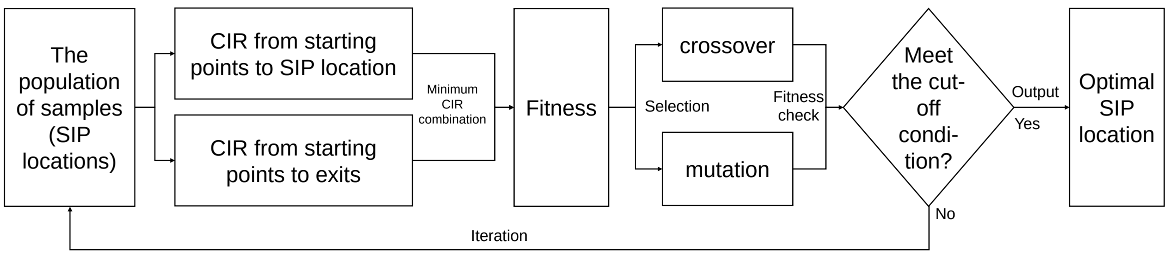

Figure 1. The steps of the improved GA-based SIP location planning method.

2.3 Decision-making between evacuation and SIP

The SIP location is determined by the QRA results of the multi-hazard accidents. However, the QRA based on MCS reflects the IR of the most-credible accident scenario and can not represent each possible scenario of the accident. The evacuees' decision between direct evacuation and SIP should be alterable according to the dynamic development process of the actual accident scenario.

The CIR calculation is based on the optimal evacuation path planned by the D* algorithm in the determination of the SIP location. The optimization criterion of the algorithm is the CIR indicator based on the accident QRA results. In actual accidents, evacuees' decision-making needs to be flexible enough to cope with the unpredictable dynamicity of the accident. The optimization criterion of the evacuation path planning algorithm needs to be adjusted according to the real-time accident risk, thereby achieving real-time decision-making between direct evacuation and SIP. The real-time decision-making process is shown in Figure 2.

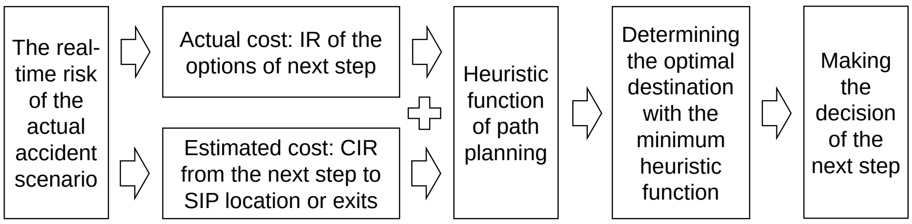

Figure 2. The process of real-time decision-making between direct evacuation and SIP.

3. Case study: the optimal SIP location

This paper takes a chemical cluster located on Xiaohu Island in China as a case study to verify the effectiveness of the proposed evacuation decision-making method. Hazardous materials such as gasoline and hydrogen chloride are stored in tanks on this island, resulting in the potential risks of fire, explosion, and toxic release multi-hazard chemical accidents. Figure 3 shows the overlook of the chemical cluster.

Figure 3. The overlook of the chemical cluster.

3.1 Quantitative risk assessment

Based on the storage and types of chemicals of each tank in the chemical cluster, the accident consequence analysis module is applied to calculate the physical fields (radiation intensity, overpressure, concentration) of fires, explosions, and toxic releases. The Domino-MCS module is used to calculate the dynamic risks of multi-hazard domino accident scenarios in this chemical cluster. Figure 4 uses a color map to show the IR of multi-hazard chemical accidents in this area. The locations of evacuees are shown at Locations 1-5 (triangles).

3.2 Decision-based SIP location planning

In the past research, a GA-based SIP location planning method has been proposed based on the CIR optimization of all evacuation paths from starting points to the SIP location. However, in some circumstances, direct evacuation can be a better decision for evacuees who are close to the exit. The case study adds a decision-making process between direct evacuation and SIP for each evacuee, and optimized the location of SIP based on the evacuees' decisions, as shown in Figure 4. The figure shows that the evacuees at Locations 1 and 5 prefer to directly evacuate rather than SIP. The optimal location for SIP is changed according to the changes of evacuees' decisions. The new SIP location is near the Location 2 of evacuees, and the evacuation paths for evacuees at Locations 3 and 4 are also changed.

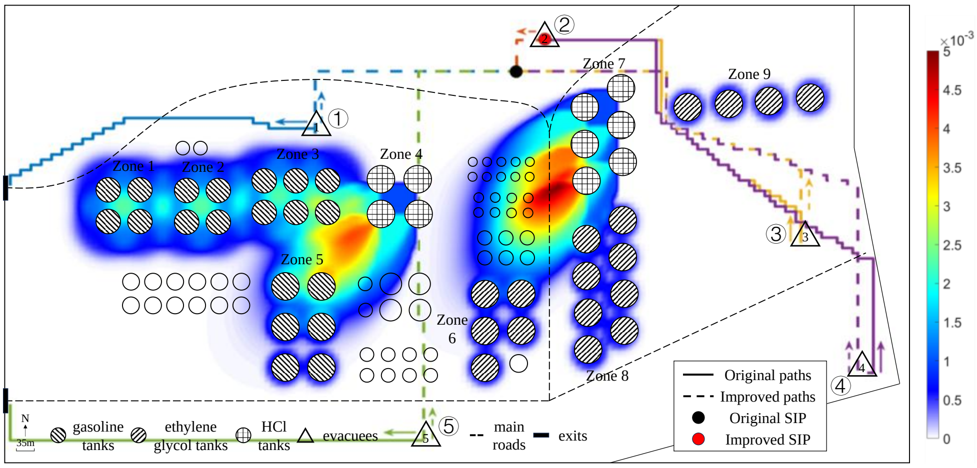

Figure 4. The improvement of the SIP location planning method. (Background is the IR of accident)

Figure 5(a) and 5(b) show the CIR of each evacuation path calculated by the original GA-based location planning method and the improved decision-based method, respectively. Figure 5(c) shows the total CIRs of the original and improved SIP location planning methods. The total CIR of the decision of direct evacuation for all evacuees is also shown in Figure 5(c) for comparison (green). The figures show that the improvement on the SIP location planning method effectively reduces the CIRs of evacuees from most starting points, and reduces the total CIR of evacuees from 0.1422 to 0.1224 (13.9% lower).

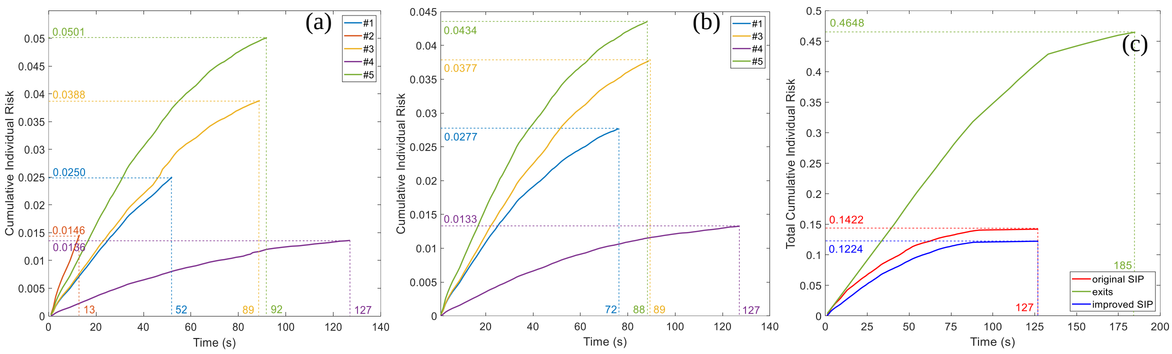

Figure 5. The CIRs of evacuees determined by the original and improved SIP location planning methods.

4. Case study: evacuation or SIP decision-making

To verify the effectiveness of the "evacuate or SIP" decision-making method, the case study assumes a dynamic domino chemical accident scenario: The primary accident is a fire happens in Zone 9 of the chemical cluster. The fire causes an explosion at the tanks nearby at the 38th second after the primary accident. The explosion causes fire accidents in Zone 6 and Zone 8, and toxic release accidents in Zone 7. Figure 6 shows the dynamic IR of this domino accident scenario.

The decision-making method introduced in Section 2.3 is based on the path planning algorithm with the real-time accident risk as the heuristic function. The IR shown in Figure 6(a) will drive the evacuees at starting points 3 and 4 to directly evacuate to the exits rather than to the SIP location. However, the secondary accidents happen after 38 second increase the expected CIR of the direct evacuation. The method will dynamically change the evacuees' decisions and drive them to escape in the direction of the SIP location with the lower CIR. The alterable decision-making process is shown as red lines in Figure 7. As a contrast, the blue and yellow lines in Figure 7 show the evacuation paths according to evacuees' unalterable decisions of direct evacuation and SIP, respectively.

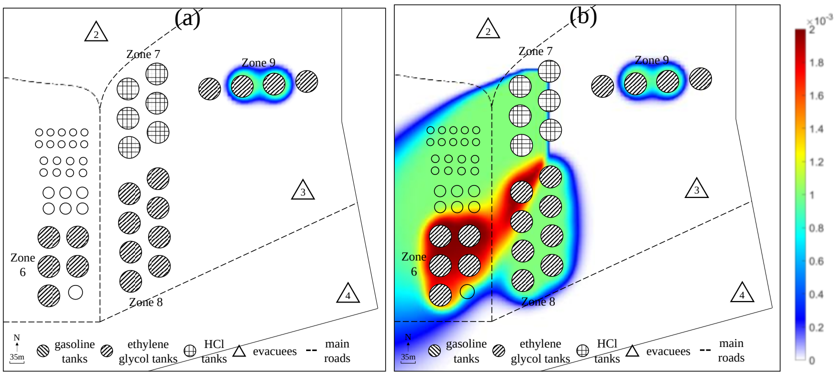

Figure 6. The IR of the domino accident scenario: (a) the primary accident, (b) after the 38th second.

As shown in Figure 7, the paths of direct evacuation (blue) will encounter the high-risk area of secondary accidents during the evacuation process. The direct paths to the SIP location (yellow) may make the evacuees suffer casualties in the explosion accident that happens in Zone 9. Figure 8 show the CIRs of evacuees from starting points 3 and 4 with different evacuation decisions. The figures show that the CIR of the unalterable decision of direct evacuation is the highest, and the CIR of the unalterable decision of SIP is second. The CIR of the alterable decision-making process is the lowest.

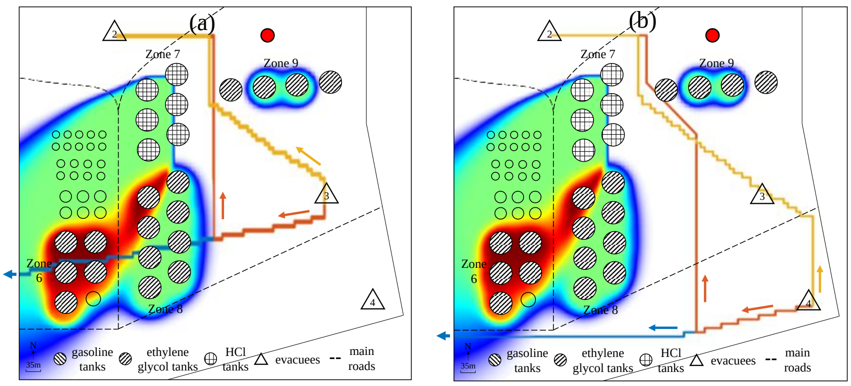

Figure 7. The evacuation paths based on different evacuation decisions from starting points (a) 3 and (b) 4.

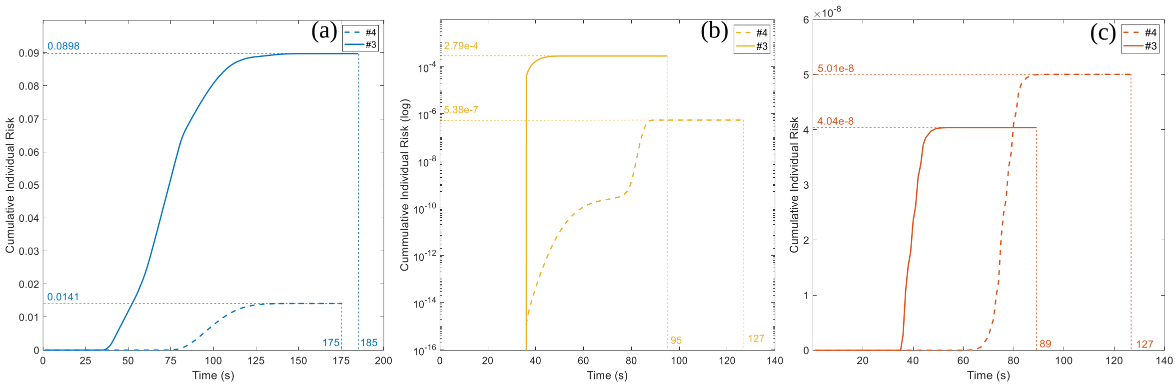

Figure 8. The CIRs of evacuation decisions: directly (a) to exit, (b) to SIP, and (c) alterable decision-making.

5. Conclusion

In order to solve the problem that evacuees have difficulty in decision-making between direct evacuation and shelter-in-place in chemical accidents, this paper proposes an assistant decision-making method based on the quantitative risk assessment of multi-hazard chemical accidents. A chemical cluster in Guangzhou, China is taken as a case study to verify the effectiveness of the proposed method. The case shows that the evacuees' correct escape decisions can optimize the location of shelter-in-place and reduce the total cumulative individual risk of the evacuation process. It is also important for evacuees to dynamically adjust their decisions between direct evacuation and shelter-in-place according to the real-time development of the multi-hazard accident to reduce the evacuation risk. This research is expected to enhance the emergency management of the chemical industry, and support the loss prevention of multi-hazard chemical accidents.

Acknowledgments

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