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Emergency response for tackling major accidental toxic gas releases: what should be done and when?

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Abstract: When there are toxic gas leaks, rapid emergency response planning is vital to protect public safety. In this study an emergency response trade-off model to assist decision-makers in taking focused action for different personnel is developed. First, a modified Dijkstra algorithm and a minimum cost maximum flow algorithm are employed to determine the optimal evaluation routes, after which an as low as reasonably practical criterion is applied to evaluate the emergency response risk levels and identify the multiple emergency response windows of opportunity. Finally, a case study based on a real incident is given to illustrate the applicability of our method. It was found that an immediate evacuation of all members of the public in a target area would expose some of them to excessive risk. It was also discovered that there is a close and complex relationship between the emergency response risk and the shelter-in-place duration and the public emergency response. Another interesting finding is that the evacuation routes in the windows of opportunities differ significantly depending on the location, and the emergency response risks associated with using the same path to evacuate at different times. These interesting findings , which were based on the scientific assessment of emergency response risks, have a massive practical impact and could assist in more accurately formulating public protection strategies.

Keywords: emergency response; windows of opportunity; risk assessment; toxic gas release; evacuation; shelter-in-place

Nomenclature

$G\ (V, A)$	directed graph representing roadway network
V	the set of nodes in $G\ (V, A), V = V_s \cup V_d = \{v_1, v_2, \cdots, v_n\}$
V_s	the set of source nodes (the starting point for the evacuees), $V_s = \{v_d \mid d = 1, 2, \cdots, n_s\}$
V_d	the set of source nodes (the starting point for the evacuees), $V_d = \{v_d \mid d = 1, 2, \cdots, n_d\}$
A	the set of arcs， $A = \{(v_i, v_j) \mid v_i, v_j \in V\}$
Q	population size
Q_{ev}	number of evacuees
Q_{sh}	number of people sheltered in place
$Q_{v_i \to v_j}$	number of people traveling along the arc (v_i, v_j)
$t_{v_i \to v_j}$	the travel time going through the arc (v_i, v_j)
t_{v_i}	the time when evacuees reach nodes v_i along the arc (v_i, v_j)
$l_{v_i \to v_j}$	the length of arc (v_i, v_j)
$p_{v_s \to v_d}$	an efficient path from the evacuation source v_s node to the destination node v_d ,$p_{v_s \to v_d} = \{(v_s, v_{R_1}, \ldots, v_{R_K}, v_d) \big| v_s \in V_s$; $v_d \in V_d$; $v_{R_k} \in V - \{v_s\} - \{v_d\}$; $0 \le R_k \le n$ }. The feasibility of the evacuation path plans and the urgency of emergency response time must not be a loop.
$P_{v_s \to v_d}$	the set of efficient paths from the evacuation source v_s node to the destination node v_d , $P_{v_s \to v_d} = \{p^1_{v_s \to v_d}, p^2_{v_s \to v_d}, \cdots, p^m_{v_s \to v_d}\}$; where m is number of paths included in $P_{v_s \to v_d}$
$P(T_{v_s \to v_d}, P_{v_s \to v_d})$	the emergency response plan for evacuees from node v_s to node v_d
$T^*_{v_s \to v_d}$	the optimal duration of shelter-in-place at node v_s for evacuees on the path $p_{v_s \to v_d}$.
$P^*_{v_s \to v_d}$	the set of the optimal paths from the evacuation source v_s node to the destination node v_d
$f_{p_{v_s \to v_d}}$	number of evacuees going along path $p_{v_s \to v_d}$ per unit time.
$C^{outdoor}(v_s, t)$	the outdoor toxic gas concentration at node v_s at time t
$C^{indoor}(v_s, t)$	the indoor toxic gas concentration at node v_s at time t
$u_{v_i \to v_j}$	the capacity of the arc (v_i, v_j), which denotes the maximum pedestrian flow allowed per unit time step of the arc.
$d_{v_i \to v_j}$	the expected individual exposure dose when people travel along the arc (v_i, v_j).
$s^0_{v_i \to v_j}$	the speed of the people traveling along the arc (v_i, v_j) under normal circumstances.
α_{ij}, β_{ij}	attenuation coefficients for the individual speed on the arc section (v_i, v_j), $\alpha_{ij} \in (0,1]$, $\beta_{ij} \in (0, +\infty]$. α_{ij}, β_{ij} can be estimated according to the distance from arc (v_i, v_j) to the disaster center, the vulnerability of the arc (v_i, v_j) and the type of the disaster etc.
τ	the time step for calculating the toxic gas concentrations
ΔT	the time step for calculating the best evacuation plan

1. Introduction

When hazardous material accidents occur during transportation or usage or at fixed facilities, such as a chemical plant or a storage location, there is a risk that the surrounding area will be exposed to a toxic gas dispersion (Glickman and Ujihara, 1990). For example, on December 3, 1984, the methyl isocyanate leak from a pesticide plant in Bhopal, India, resulted in 8,000 deaths within a week, 10,000 permanent injuries, and 520,000 exposures to the poisonous gas (Dikshit et al., 2011a). Also on December 23, 2003, a blowout accident at the Luojia 16H well in Chuandongbei Gas Mine, Kaixian County, Chongqing, China, killed 243 people (Li et al., 2009). Although major toxic gas exposures can be prevented by learning from previous accidents (Yang, 2019), in the last 20 years, many accidental toxic gas releases have occurred in both developed and developing countries because of technology and management failures (Hou et al., 2021; Tenchov, 2021). Therefore, it is vital to develop effective emergency response plans to protect workers and the public when toxic gas leak accidents occur (Hosseinnia et al., 2018).

In toxic gas emergencies, there are two main protective actions that can be taken by emergency response decision-makers: shelter the workers and the public in one structure or location or evacuate everyone from the affected area (Glickman and Ujihara, 1990). The shelter-in-place strategy seeks to reduce human exposure to toxic gas leaks as it may be safer to seek shelter in the surrounding buildings than to go outdoors (Jetter and Whitfield, 2005; Zhang et al., 2017). However, when seeking to shelter the affected people, it is necessary to provide a relatively “clean” space until the danger passes, that is, to close all doors and windows and shut down all ventilation, heating, and cooling systems (Austin, 2008).

Therefore, as a shelter-in-place strategy requires significant pre-work to ensure that the chosen shelter is sufficiently protective (Wang, 2011), decision-makers should make shelter-in-place recommendations only if moving the people out of their homes, workplaces, or schools would present a greater danger to their health and safety than allowing them to remain in place. Further, the shelter-in-place structures may not be able to maintain personnel safety for a long time (Wilson, 1987) as shelter protection performance depends on the characteristics of the leaking chemicals, the meteorological conditions, the building's structure and age, and the effectiveness of the door and window seals to reduce/eliminate the toxic gas concentrations (Gettings, 2001; Wilson, 1988; Wilson and Morrison, 2000). While a general method for determining possible indoor toxic gas concentrations has been proposed (Chan, 2006; Glickman and Ujihara, 1990; JO and PARK, 2016), because the workers and public could be exposed to the toxic gases during an evacuation (Gai et al., 2018b; Rogers et al., 1990), which is often a lengthy process, in many cases it may be more effective for the public to shelter-in-place. However, as many people feel that the shelter-in-place strategy does not provide effective protection, they often resort to their basic psychological motivation to escape environmental hazards rather than to passively seek protection (Wilson, 1987).

1.1. Literature review

The protection strategy for the public in a major chemical accident is mainly shelter-in-place and evacuation (Sorensen et al., 2004a). Shelter-in-place means that evacuees enter a building or another facility and close all doors, windows, ventilation, heating and cooling systems until the danger has passed. Evacuation means moving all potentially threatened personnel from the hazard area to a safe area. In addition, there are some supplementary public protection measures, including respiratory protection, wearing protective clothing, using preventive medicines and antidotes, etc. (Bhuiyan et al., 2019).

Emergency evacuation involves moving people away from the areas that pose imminent or ongoing threats to lives or property (Ronchi and Nilsson, 2013). Emergency evacuation is a common public protection action to reduce/eliminate the possible health consequences of a major accident (Gai et al., 2018a). Therefore, effective emergency resident evacuation procedures have been heavily researched (Xu et al., 2021b), and several emergency micro- and macro-evacuation models proposed (Bayram, 2016; Campos et al., 1970; Farahmand et al., 2001; Gao and He, 2007; Hamacher et al., 2006; Helbing et al., 2000; Kirchner et al., 2003; Mizuta et al., 2020). The studies on emergency evacuations for toxic gas leak accidents that have been conducted have focused on predicting toxic dispersal areas, determining evacuation areas and routes, and carrying out the calculation of evacuation risks including factors such as possible health consequences and social impacts (Chen et al., 2018; Gai and Deng, 2019; Gai et al., 2018a, b; Law et al., 2019; Mizuta et al., 2020; Wang and Sun, 2014; Xu et al., 2021a; Yoo and Choi, 2019; Zhang et al., 2017). Compared to shelter-in-place strategies, emergency evacuation usually requires greater government emergency response capacity and cost to move many people from danger areas to safety.

Therefore, the first problem is to determine the public protection actions that need to be taken (Smith and Swacina, 2017). Although there are many decision-making aids to assist decision-makers in formulating emergency response plans, such as checklists, decision trees, and decision matrices (Baybutt, 2014; Markowski and Mannan, 2008; Sorensen et al., 2004b), to protect the public, most decision-makers usually only choose either shelter-in-place or evacuation strategies (Sorensen et al., 2004b; Zhang et al., 2017) rather than developing emergency response plans that combine the two methods. However, before making a judgment about whether to advise people to shelter-in-place, evacuate, or combine these two protective actions, a comprehensive analysis of the relevant factors is needed (Shimada et al., 2018). Previous research on the protection of the public from hazards (evacuation, shelter-in-place, or a combination of both) has mostly been based on particular frameworks rather than optimization methods. For example, China’s national standard, the "Method for the Division of Emergency Planning Areas for Major Toxic Gas Leakage Accidents (GB/T 35622-2017)", outlines the factors that need to be considered when selecting an emergency evacuation method, but it does not specify any specific technical methods. Also, the American Industrial Hygiene Association proposes a principle for determining public protection actions based on whether the onsite toxic gas concentrations exceeded their critical concentration, but fails to consider the impact of other factors, such as individual movement. Several optimization methods for the selection of public emergency refuge methods have also been put forward. For example, Georgiadou et al. (2010) propose a multi-objective optimization implementation strategy to protect the public from major accidents, such as fire, explosions, and toxic gas exposures. However, the strategy focuses on emergency response over a wide area and sets assumptions such as when the public should evacuate and the choice of evacuation routes. If sheltering-in-place is the chosen protective action in a specific area, the worst-case scenario is when the toxic gas plume spreads to the area. This means that if people stay in the structures for too long, they may have a cumulative inhaled toxic gas dose that exceeds acceptable human tolerance levels (Gai et al., 2020). In other words, the possibly exposed public may need to be to evacuated before this critical time. Therefore, determining when to terminate current protective actions and when other protective actions are required could be critical decision points.

To improve public protection, it is necessary to ensure that evacuation routes are properly planned (Xu et al., 2021a). Stepanov and Smith (2009) conclude that following two approaches are worth considering: (i) the first approach defines a set of optimal routes and evaluates performance measures simultaneously; and (ii) the second approach uses an analytical optimization technique to offer a routing policy, which is then evaluated with a suitable traffic simulation model (Stepanov and Smith, 2009). According to Stepanov and Smith (2009), the first approach is prevalent in practice. In recent years, with the maturity of computer technology and multi-intelligence modeling techniques, the second approach has gradually started to be widely used (Kim et al., 2017). However, regardless of which method is used to select evacuation routes, it is necessary to define the optimization objectives, such as health consequences, and thus select the best route. In other words, Emergency route planning requires identifying the routes that have a minimum weighted sum between the constituent arcs and the two nodes on a graph (composed of nodes and arcs) (Shimbel, 1953; Yadav and Biswas, 2010). In response, several network theory-based models and algorithms have been proposed (Bkp et al., 2019; Dave et al., 2006; Gai et al., 2015; Georgiadou et al., 2010; Xu et al., 2021a; Yong et al., 2017; Zhang et al., 2013), This includes the traditional algorithms like D*, Dijkstra and those intelligent evolutionary-based algorithms such as the ant colony algorithm and the genetic algorithm. Xu et al. (2021a) recently designed a modified Dijkstra algorithm to resolve a dynamic multi-objective route planning problem that overcame the weaknesses of the traditional Dijkstra algorithm. Besides, for the weighted sum objective function, it was able to determine a local optimum for small-scale road networks. This algorithm has a high accuracy and low time complexity. To avoid evacuees traveling from low-risk areas into high-risk areas, some studies (Liu et al., 2019) have proposed road risk assessment methods that compare the risk levels in all regions and develop road risk assessment matrices. From a practical viewpoint, it is very important to have emergency path planning (Wang and Sun, 2014), especially when a population needs to be urgently transferred after a major gas leak accident. If a population is not effectively transferred or is transferred in no particular order, the consequences may be catastrophic, as happened in the toxic chemical gas leak accident in Bhopal, India, in 1984 (Dikshit et al., 2011b). We would like to stress that the focus of this study is not to compare the advantages and disadvantages of path planning algorithms, but to analyse what and when people do in emergency situations. In other words, the choice of the algorithm to be used is not important as it does not affect our main research purpose, and hence a detailed analysis of the variability of different algorithms is not necessary.

1.2. Contribution and organization of the paper

Based on the above discussion, previous studies mainly focused on the issues of personnel evacuation area determination, path planning and risk assessment, but the research results were independent of each other and did not provide systematic guidance methods for decision makers. This results in the research work on emergency response risk assessment and control strategy optimization seriously lagging behind engineering applications. In this paper, we aim to propose a more flexible, detailed and practicable emergency response decision method: This is achieved by dividing emergency response scenarios according to the size of the population to be evacuated, using a minimum cost maximum flow path planning algorithm to calculate the optimal evacuation path in different environments, and combining the ALARP principle and WOs to find the best response behavior of evacuees at different moments. In other words, the aim of the study is to contribute towards providing emergency decisions by answering the following three critical questions:

i) When an accident occurs, should the population be threatened by the toxic gas shelter-in-place or evacuate the area?

ii) If the populations at risk of toxic gas exposure need to first take shelter-in-place actions, when should they be evacuated from the shelter-in-place to another safe location?

iii) What are the different evacuation route assignments needed for different populations at risk of toxic gas exposure?

The remainder of this paper is organized as follows. Based on an emergency response risk assessment, Section 2 proposes a decision-making response methodology for dealing with major accidental toxic gas releases, followed by Section 3 that studies a case based on a real accident using the proposed methodology. Section 4 presents and discusses the case study results while Section 5 summarizes the experimental results. Our final section outlines our conclusions and highlights some research avenues that we believe to be worthwhile exploring in the future.

2. Methodology

In this section, we discuss and study the emergency response risk assessment and trade-off between shelter in place and evaluation. We divide evacuation scenarios into two types according to scale, propose an emergency response trade-off (ERT) model between shelter-in-place and immediate evaluation, and give a solution method for the model.

2.1. Emergency response risk assessment

In this section, we define five items that are used in our study. These include the time estimation for people that travel through a selected route, the calculation of exposure dose, the evacuation risk and the shelter-in-place risk, and finally the determination of acceptable risk levels.

2.1.1. **Time estimation for people traveling through a route section**

Individual travel time depends on the individual movement speeds and the path length along the multiple arcs. The evacuees' travel speeds along the arc are mainly influenced by their physical conditions (Thompson et al., 2015). The road traffic capacity (Liu et al., 2021) is influenced by the road section length and the capacity attributes on each arc, that is, the ability to divert or handle the road traffic flow influencing factors, such as the road conditions (width, surface quality, etc.), number of intersections, traffic conditions, (traffic flow characteristics and traffic flow distribution), control conditions (the intersection, traffic, and signal controls), and the environmental conditions (wind, the transverse interference, and visibility). Toxic gas diffusions can also have a serious impact on evacuee health, which can also affect their evacuation speeds, with the extent of this impact being determined by the path node locations and the disaster grade, that is, the closer the evacuees are to the accident point and downwind direction, the greater the impact on their evacuation speeds. Depending on the accident's extension, the travel speeds on each arc in road networks for emergency evacuation can decrease with time and space (Yuan and Wang, 2007), and psychological factors can also have an effect; for example, moderate psychological pressure can increase people's walking speeds. However, as there has been little relevant research (Cao et al., 2021) on the impact of psychological factors on walking speeds, this was not considered in this study. To illustrate the applicability of the proposed model and solution method to dynamic road networks for emergency evacuations, the decrease function proposed by Yuan and Wang (2007) was used to describe this dynamic change (Yuan and Wang, 2007):

$$s_{ij}(t) = s_{ij}^{0} \cdot \alpha_{ij} \cdot e^{-\beta_{ij} t} \quad \forall i, j = 1,2,\ldots,n \tag{1}$$

To determine the emergency treatment at actual accidents, the real-time travel speeds can be obtained from road monitoring data. If the speed t_i when entering arc (v_i, v_j) and the arc length l_{ij} are already known, then Eqs. (1)-(3) can be used to estimate the time t_{ij} it takes for a person to travel through the arc:

$$t_{ij} = t_j - t_i \tag{2}$$

$$\int_{t_i}^{t_j} s_{ij}(t)dt = l_{ij} \quad \forall i, j = 1,2,\ldots,n \tag{3}$$

2.1.2. Exposure dose calculation

Major toxic gas leak accidents expose people to extreme phenomena such as toxic clouds, sedimentation, thermal radiation, overpressure, or debris caused by secondary disasters, all of which can adversely affect the health of the workers or the public in the affected areas (Georgiadou et al., 2007). The expected individual exposure dose $d_{v_i \to v_j}$ when people travel along the arc (v_i, v_j) can be calculated as follows:

$$d_{v_i \to v_j} = \int_{v_i}^{v_j} C^{\text{outdoor}}(v,t)\,dv \tag{4}$$

Because of the arc continuity, the individual evacuation process along the arc between the two nodes changes in time and space. Therefore, the toxic gas dose inhaled by the evacuees moving along this arc is difficult to calculate accurately. To solve this problem, the average value of the concentration changes at the start and endpoints of the arc is used to replace the concentration changes across the entire arc. Assuming a time step of τ, the time when the evacuees arrive at each point can be replaced by the time step, as follows.

$$x =< \frac{t_{v_i}}{\tau} > \tag{5}$$

$$y =< \frac{t_{v_j}}{\tau} > \tag{6}$$

When combined with the concentration changes at each time step at each node, the expected exposure dose $d_{v_i \to v_j}$ along the arc (v_i, v_j) can be estimated as follows (Xu et al., 2021a):

$$d_{v_i \to v_j} = \begin{cases} \left(\frac{1}{2}\left(\left(\frac{C_i^x + C_j^x}{2}\right) + \left(\frac{C_i^y + C_j^y}{2}\right)\right)\right)^n \cdot t_{v_i \to v_j}, & t_{v_i \to v_j} \le \tau \\ \sum_{k=x}^{y-2}\left(\frac{1}{2}\left(\left(\frac{C_i^k + C_j^k}{2}\right) + \left(\frac{C_i^{k+1} + C_j^{k+1}}{2}\right)\right)\right)^n \cdot \tau + \left(\frac{1}{2}\left(\left(\frac{C_i^{y-1} + C_j^{y-1}}{2}\right) + \left(\frac{C_i^y + C_j^y}{2}\right)\right)\right)^n \cdot \left(t_{v_i \to v_j} - \tau(y-x-1)\right), & \tau < t_{v_i \to v_j} \le \tau(y-x) \\ \sum_{k=x}^{y-1}\left(\frac{1}{2}\left(\left(\frac{C_i^k + C_j^k}{2}\right) + \left(\frac{C_i^{k+1} + C_j^{k+1}}{2}\right)\right)\right)^n \cdot \tau + \left(\frac{C_i^y + C_j^y}{2}\right)^n \cdot \left(t_{v_i \to v_j} - \tau(y-x)\right), & t_{v_i \to v_j} > \tau(y-x) \end{cases} \tag{7}$$

where C_i^k and C_j^k are the respective ppm toxic gas concentrations at nodes v_i and v_j at time step k, and n is a dimensionless parameter that depends on the type of toxic gas.

2.1.3. Evacuation risk calculation

If there are a small number of people to be evacuated, the length of time the population stays at the evacuation source node and waits for evacuation is not considered. The average risk $R_{\mathrm{ev}}^{1}\left(P_{v_s \to v_d}\right)$ of evacuation from node v_s to node v_d can be estimated as follows：

$$R_{\mathrm{ev}}^{1}\left(P_{v_s \to v_d}\right) = \frac{1}{Q_{\mathrm{ev}}} \sum_{(v_i, v_j) \in p_{v_s \to v_d}^{k}, k=1}^{m} Q_{v_i \to v_j} d_{v_s \to v_d} \qquad (8)$$

If there are a large number of people to be evacuated, when the higher the flow of the chosen path, the more people are evacuated at the right time, the lower the exposure risk $R_{\mathrm{ev}}^{2}\left(P_{v_s \to v_d}\right)$, while the opposite is true. $R_{\mathrm{ev}}^{2}\left(P_{v_s \to v_d}\right)$ of evacuation from node v_s to node v_d can be calculated as follows:

$$R_{\mathrm{ev}}^{2}\left(P_{v_s \to v_d}\right) = \left(\sum_{(v_i, v_j) \in p_{v_s \to v_d}^{k}, k=1}^{m} f_{v_i \to v_j}\right)^{-1} \qquad (9)$$

2.1.4. Shelter-in-place risk calculation

Well-insulated houses or buildings can provide excellent protection against toxic gas clouds for a limited time (Zhao, 2011) if people tightly seal doors and windows to reduce the penetration rate (Zhang et al., 2017). It is assumed that all the toxic gas permeance would occur evenly; that is, there would be no difference between the floor and the ceiling leakages. Given these assumptions, the toxic gas concentrations in the building can be calculated as follows (Xi, 2016):

$$\frac{dC^{indoor}(v_s, t)}{dt} = \frac{\left(C^{outdoor}(v_s, t) - C^{indoor}(v_s, t)\right)}{\tau_e} \qquad (10)$$

where τ_e is the penetration time constant.

Based on Eqs. (10), for path $p_{v_s \to v_d}$, assume that evacuees shelter in place at source node v_s for $T_{v_s \to v_d}$. The average exposure risk $R_{\mathrm{sh}}(T_{v_s \to v_d})$ of people sheltering-in-place on the path $p_{v_s \to v_d}$ after the accident can be estimated as follows:

$$R_{\mathrm{sh}}(T_{v_s \to v_d}) = \int_{0}^{T_{v_s \to v_d}} f_{v_s \to v_d} \frac{\left(C^{outdoor}(v_s, t) - C^{indoor}(v_s, t)\right)}{\tau_e} dt \qquad (11)$$

2.1.5. Acceptable risk levels

The “as low as reasonably practical” (ALARP) principle is a common risk division tool (Melchers, 2001) that divides emergency response risk levels into three zones; an unacceptable region, a broadly tolerable zone, and a zone in between called the "ALARP" zone. The upper and lower limit lines are defined, with the upper line being the maximum tolerable risk that cannot be exceeded and the lower line denoting the broadly tolerable risk (Baybutt, 2014). The term ALARP arises from UK legislation, particularly the Health and Safety at Work etc. Act 1974, which requires "Provision and maintenance of plant and systems of work that are, so far as is reasonably practicable, safe and without risks to health". The ALARP principle has been applied to urban planning (Zhou and Liu, 2012), the setting of numerical risk tolerance standards for individuals and groups (Baybutt, 2014), chemical industry safety management (Abrahamsen et al., 2018), fire probabilistic risk assessments (Van Coile et al., 2019), and many other fields.

At present, the UK Health and Safety Executive (HSE) calculates an unacceptable level of annual risk of death for people based on the severity and frequency of accidents (e.g. for the public, the annual risk of death is not allowed to be higher than 10^{-4}) from a society-wide perspective. However, it is clear that such level cannot be applied to the accident-specific emergency response risks that are the subject of this paper. The white paper "Risk Acceptance Criteria: Overview of ALARP and Similar Methodologies as Practiced Worldwide" released by Texas A&M Engineering Experiment Station (TEES) analyzed the acceptance criteria of individual and social risk in countries such as Australia, New Zealand, Norway and the United Kingdom, and found that "The risk level calculated for the same scenario in different countries varies with the underlying principles selected ". For example, New Zealand's "Health & safety at work act 2016 " gives a direct basis for judging the acceptable risk level: when the cost involved in reducing the risk further is grossly disproportionate to the benefit gained, the risk will be ALARP.

The above shows that the acceptable level of individual social risk is not fixed (Baybutt, 2014; Borghetti et al., 2019; Guan and Jiao, 2013). Then the acceptable level of risk for public emergency response risk for a specific accident that has occurred will be therefore variable depending on the different accident scenarios. That means that the accident severity and evacuation condition factors in emergencies must be judged on the actual situation. This shows that it is difficult to have fixed decision-making standards as decision-makers often need to select the acceptable risk levels based on the actual situation, even if the selected acceptable risk levels still seem very high. For example, if shelter-in-place is not possible because there are no available safe shelters (which was the situation in the “3.29” accident case), the risk for the calculated best evacuation plan may be higher than the generally accepted risk level. Under these circumstances, the decision-makers may have no choice but to raise the acceptable level of risk and evacuate the affected public as quickly as possible.

In summary, our aim is not to develop and apply precise emergency response risk criteria (as it is almost impossible to achieve), but to consider in our analysis the upper and lower limits, 9.02×10^{10} ppm^2 min and 1.75×10^{11} ppm^2 min., respectively. This strategy will make the three risk areas clearly separable, and provides a framework to demonstrate how our study can help decision makers to apply the ALARP criteria and WO theory to formulate refined emergency response plans.

2.2. Trade-off between shelter-in-place and evacuation

2.2.1. Main modeling process

When there is a major accidental toxic gas release, the authorities need to develop action plans for shelter-in-place, immediate evacuation, or a combination of these two protective actions. Decision makers are asked to weigh and decide on emergency response actions for evacuees at every moment after an accident: immediate evacuation or evacuation after sheltering in place first, i.e., the emergency response trade-off (ERT) process. When constructing the ERT model, three issues need to be considered: (i) the dynamic changes in the individual travel times on the road sections as the accident expands in time and space; (ii) the provision of highly individualized public emergency response guidelines for the two emergency scenarios; and (iii) the optimization of the public protective actions to control and manage the emergency response risk.

2.2.2. Problem formulation

In this section, two emergency scenarios are defined, one for small scale population which we name Scenario I and the other for large scale which we call Scenario II.

"Small scale population " means that one path in the network can be found to evacuate everyone safely and quickly, and "large scale population " means that multiple paths are needed to evacuate at the same time. Differences in population scale will lead to very different path planning plans. For small scale populations, the path with minimal health consequences can be found using the shortest path algorithm. While when the population scale is large, if the fewer people evacuate at the right time, the more people waiting for evacuation at the source node and the longer the stay time, the more serious the health consequences of the emergency response and often accompanied by potential risks such as panic and congestion. Therefore, in this paper, the selection of evacuation paths for large-scale population is considered as a multi-objective optimization problem with evacuation flow and health consequences as the optimization objectives, while the assignment of multiple evacuation paths in the affected area is solved using a minimum-cost maximum-flow algorithm.

Scenario I

This is an emergency response scenario for a small-scale population. In this scenario, an optimal evacuation route (i.e., m=1) with sufficient traffic capacity needs to be found to ensure the safe and rapid evacuation of all people who need to be evacuated. For example, if the accident affected area is sparsely populated, or an emergency response plan needs to be customized for a small number of special individuals (persons with mobility impairments, wounded, etc.). For a small population evacuated via path $P_{v_s \to v_d}$, the risk $R_{\mathrm{sh/ev}}\left(P\left(T^*_{v_s \to v_d}, P^*_{v_s \to v_d}\right)\right)$ of the optimal emergency response actions can be expressed as follows:

$$R_{\mathrm{sh/ev}}\left(P\left(T^*_{v_s \to v_d}, P^*_{v_s \to v_d}\right)\right) = Minimize\ (R_{\mathrm{sh}}(T_{v_s \to v_d}) + R^1_{\mathrm{ev}}(P_{v_s \to v_d})) \tag{12}$$

subject to Eqs. (1) –(5) and Eq.(13),

$$\underset{(v_i, v_j) \in P_{v_i \to v_j}, m=1}{\text{minimize}} u_{ij} \geq Q \tag{13}$$

Here, Eq. (12) ensures that the emergency response risk is minimized, and Eq. (13) guarantees that the traffic capacity of the single selected evacuation route meets the rapid evacuation needs of the affected population.

Scenario II

This is an emergency response scenario for a large-scale population. As the capacity of any single evacuation route is unable to meet the safe and rapid evacuation requirements, in this scenario, multiple evacuation routes need to be assigned in the affected area to ensure a safe, rapid evacuation for avoiding panic and congestion (Shiwakoti et al., 2014). Therefore, The risk $\left(P\left(T^*_{v_s\to v_d}, P^*_{v_s\to v_d}\right)\right)$ of the optimal emergency response action for large-scale population from source node v_s to target node v_d can be expressed as follows:

$$R_{\mathrm{sh/ev}}\left(P\left(T^*_{v_s\to v_d}, P^*_{v_s\to v_d}\right)\right) = Minimize\ \left(R_{\mathrm{sh}}(T_{v_s\to v_d}) + R^1_{\mathrm{ev}}(P_{v_s\to v_d})\right) \quad (12)$$

$$R^2_{\mathrm{ev}}\left(P_{v_s\to v_d}\right) = \left(\sum^{m}_{(v_i,v_j)\in p^k_{v_s\to v_d}, k=1} f_{v_i\to v_j}\right)^{-1} \quad (14)$$

subject to Eqs. (1)–(5) and Eq.(13).

$$\underset{(v_i,v_j)\in P_{v_i\to v_j}, m=1}{\text{minimize}}\ u_{ij} \geq Q \quad (15)$$

Here, Eqs. (12) and (14) work together to ensure that the emergency response risk is minimized. Eq. (14) ensures the rapid evacuation of the population while Eq. (15) indicates that the traffic capacity of any single selected evacuation route cannot meet the rapid evacuation needs of the affected population.

2.2.3. Solution method

As described in the previous sections, the travel risks during evacuations are related to both the arc length and the travel speeds on the arc, as the travel speed is a decreasing function with respect to distance. Therefore, the ERT model is a dynamic optimization problem. A modified Dijkstra algorithm (Xu et al., 2021a) and minimum cost maximum flow algorithm (Booth and Tarjan, 1993) are used to solve the ERT model in this paper. The solution method flow chart is shown in Fig. 1. It should be noted that since the VISIO software does not allow input “$P^*_{v_s \to v_d}$”, “P^*_{ev}” is used instead in Fig. 1.

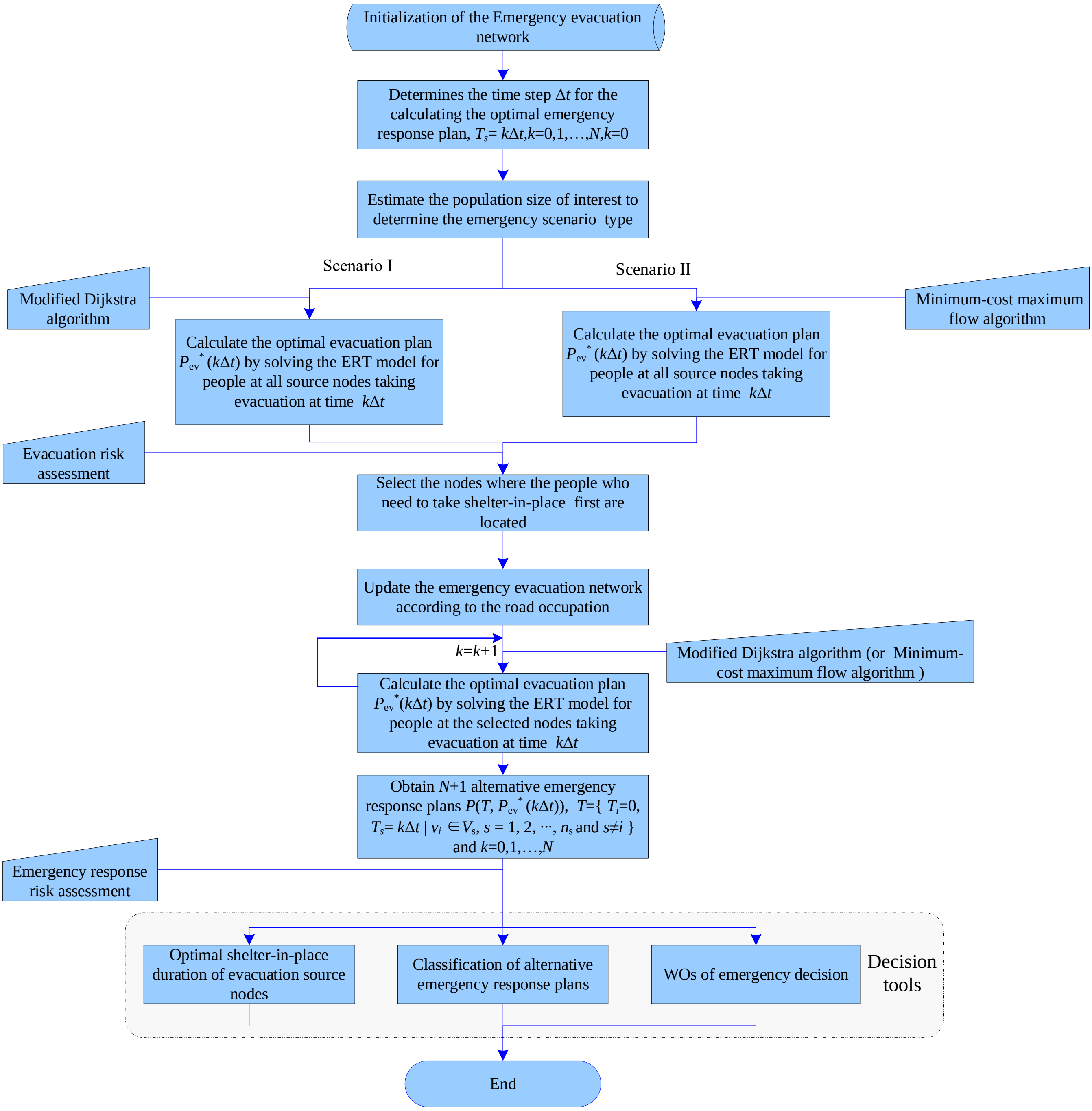


Figure 1 Flow chart for the proposed method

Let T_E denote the total emergency response time, and $T_E = N\Delta t$ with Δt being the time steps for calculating the optimal emergency response plan. When developing the Scenario Ⅰ emergency response plan, first let $T_s = k\Delta t$ and k=0, and then calculate the best evacuation plan for all nodes by solving the shortest path problem, which minimizes the evacuation risk $R_{\text{ev}}^{1}\left(P_{v_s \to v_d}\right)$ in the network. The modified Dijkstra algorithm is then used to solve the ERT model and determine the best evacuation plan $P_{v_s \to v_d}^{*}$ $(k\Delta t)$ for people at all source nodes v_s at time $k\Delta t$. The nodes for the people who need to first take shelter-in-place actions are then selected from the evaluation of the evacuation risks at each evacuation source node. Based on the optimal evacuation plans for the unselected nodes, the road occupation is analyzed and the road network for emergency evacuation updated.

Then, the assignments for k are updated in turn, $k = 1, \ldots, N$. For a defined value of k, the modified Dijkstra algorithm is applied to calculate the optimal evacuation plan $P_{v_s \to v_d}^{*}(k\Delta t)$ by solving the ERT model to evacuate the people at the selected nodes at time $k\Delta t$. Finally, N+1 alternative emergency response plans $P(T_{v_s \to v_d}, P_{v_s \to v_d}^{*}(k\Delta t))$ are determined, where $T = \{ T_i = 0, T_s = k\Delta t \mid v_i \in V_{\text{s}}, s = 1, 2, \cdots, n_{\text{s}}$ and $s \neq i\}$ and $k = 0,1,\ldots,N$.

Finally, we introduce the window of opportunity (WO) theory for decision-making. The concept was first introduced to the investment field. A WO is a short, often fleeting time period during which a rare and desired action can be taken. Once the window closes, the opportunity may never come again. It fits well with the urgency characteristics of emergency response actions. Combined with the optimal evacuation route, a set of emergency response plan is formed. For actual emergency response actions, it is often impossible to ensure rapid evacuation due to the unpredictability of accidents and the lag in rescue actions (including emergency notifications), and then it will be important to determine when people will terminate shelter-in-place. At this point, it is especially important for decision makers to quickly find the next WO. Combined with the ALARP criterion, three types of windows of opportunity (WOs) for evacuating people are provided to decision makers, corresponding to the three risk zones of the ALARP criterion.

In summary, there are three decision-making tools available for decision-makers. First, the optimal shelter-in-place duration at the evacuation source node is determined. Second, three types of WOs for evacuating people are provided to decision makers, to enable them to prepare more detailed emergency evacuation plans. Finally, due to the diffusion of toxic gases, it is likely that evacuees may have different optimal emergency response plans at different moments. According to the ALARP principle and the WO theory, for personnel in certain nodes, once they miss some suitable time, then their optimal emergency evacuation plan may become unacceptable. Therefore, there is a need to provide decision makers with an intuitive and flexible collection of emergency response plans. Corresponding to the three risk zones in the ALARP principle, the optimal emergency response plan for each node at different times can be classified into three categories, namely, high-priority group, reasonable and feasible group and unacceptable group.

Similar to Scenario I, various Scenario II emergency response plans $P(T_{v_s \to v_d}, P^*_{v_s \to v_d}(k\Delta t))$ can be obtained. However, the modified Dijkstra algorithm needs to be replaced with a minimum cost network flow to calculate the $P^*_{v_s \to v_d}(k\Delta t)$.

3. Case study setup based on the “3·29” liquid chlorine leakage accident in China

The Areal Locations of Hazardous Atmospheres (ALOHA) is an application jointly developed by the U.S. Environmental Protection Agency (EPA) and the National Oceanic and Atmospheric Administration (NOAA) that classifies three different hazard areas in red, orange, and yellow based on the Emergency Response Planning Guidelines (ERPGs) by entering environmental and accident parameters. The three ERPG tiers are defined as follows: ERPG-3 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing life-threatening health effects. ERPG-2 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing or developing irreversible or other serious health effects or symptoms which could impair an individual's ability to take protective action. ERPG-1 is the maximum airborne concentration below which nearly all individuals could be exposed for up to 1 hour without experiencing more than mild, transient adverse health effects or without perceiving a clearly defined objectionable odor. The three ERPG values of chlorine are 1ppm, 3ppm, and 20ppm, respectively, according to Database of Hazardous Materials.

In this section, we introduce the basic information of an actual accident, build an evacuation network by using the ALOHA, calculate the affected accident area, and give the parameter settings of the network.

3.1. The “3·29” leakage accident

On March 29, 2005, a tanker carrying about 40 tons of liquid chlorine collided with another truck on the Huai'an section of the Beijing-Shanghai Expressway, and a large amount of liquid chlorine leaked from the tank truck, leading to the evacuation of more than 10,000 villagers from a dozen villages around the accident site (Hou et al., 2020). The geographic information of the accident area is shown in Fig. 2.

Figure. 2 Geographic map of the accident area

3.2. Case study setup

3.2.1. Accident consequence calculation

The leakage parameters and weather conditions in Table 1 were determined from the information collected about the "3.29" leakage accident, and the ALOHA was used to calculate the affected accident area. Fig. 3 shows the affected area, the determination of which was based on the chlorine dispersion range and the geographic accident site information map.

Table 1 Leakage and meteorological parameters

Leakage parameters		Meteorological parameters	
type of leak source	recumbent	average	20

		temperature, ℃	
rip shape	circular	average wind speed, m/s	2
crack diameter, mm	100	prevailing wind direction	northwest
crack height (from the bottom of the tank), m	0.58	measuring height	10m above the ground
leakage source duration, min	12	relative humidity	70%
Mass of liquid chlorine in the storage tank, t	40		
filling ratio	44%		

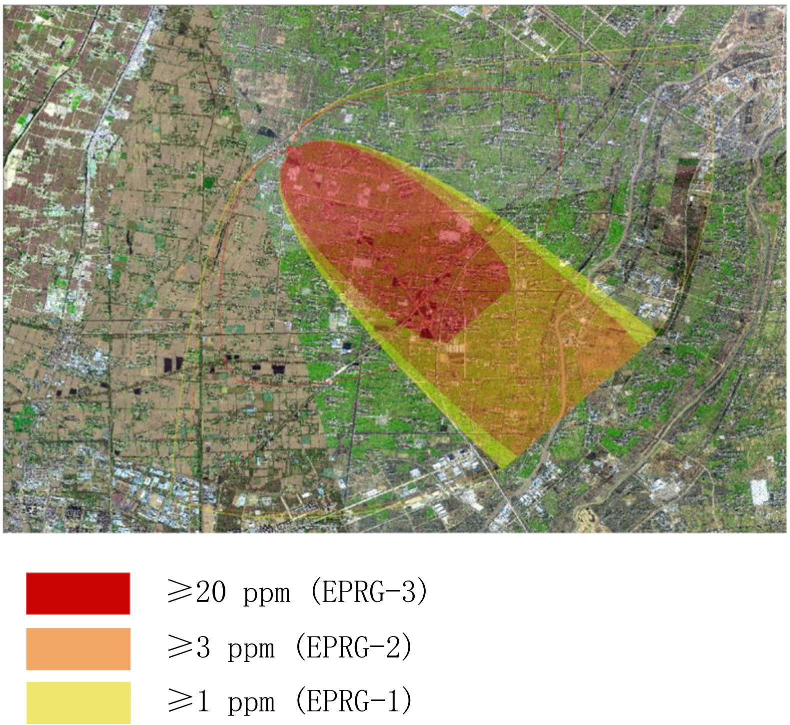


Figure 3 “3.29” leakage accident affected area

In this case study, the intersections and the road sections between them were respectively taken as the road network nodes and arcs, as shown in Fig. 4. We assume that node 53 outside the emergency response area is a safe node and does not limit its capacity. Using the downwind direction as a reference, only the west half of the emergency response area was selected for the testing. In an actual emergency decision-making situation, the eastern half area can be solved using the same method.

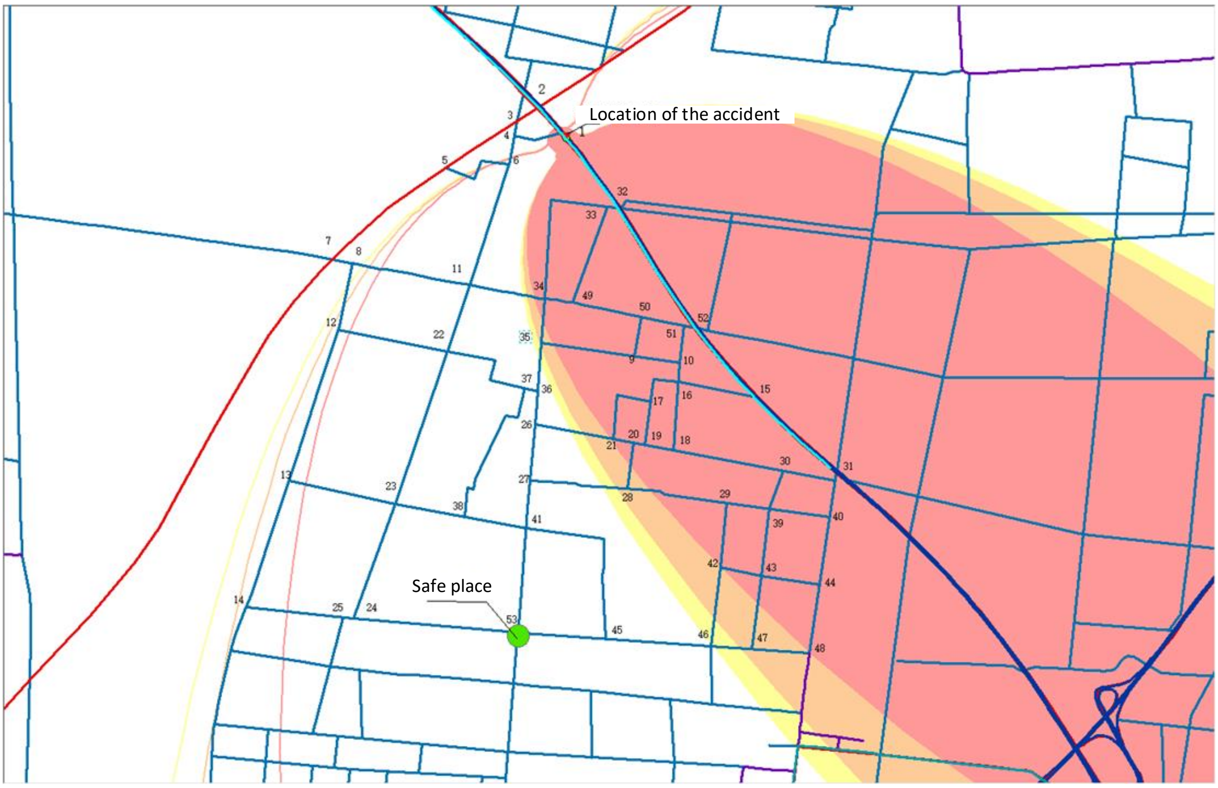


Figure. 4 Evacuation emergency network

3.2.2. Parameter settings

The research object was healthy young people, with the running economy speed of ordinary Chinese men aged 18–23 being the reference for setting s_{ij}^{0}. The evacuation network parameter settings are shown in Table 2. In this case study, the time step τ for the calculation of the chlorine concentration on the arcs was set to 5 minutes. However, as this study did not specifically set the penetration time constants of the buildings, ALOHA's default method was used to approximate the values (Sherman, 1980).

Table 2 Road network parameters

(v_i,v_j)	$(l_{ij},s_{ij}^0,\alpha_{ij},\beta_{ij},u_{ij})$(m,m/min,-,-,-)	(v_i,v_j)	$(l_{ij},s_{ij}^0,\alpha_{ij},\beta_{ij},u_{ij})$(m,m/min,-,-,-)
(1,2)	(286.32681,190,0.99,0,1440)	(23,38)	(435.56359,110,1,0,460)
(1,4)	(367.20546,120,0.99,0.01,910)	(24,53)	(1008.00913,150,1,0,560)
(1,32)	(597.15027,190,0.95,0,2110)	(25,24)	(59.99057,160,1,0,590)
(2,3)	(173.92984,190,1,0,650)	(26,27)	(410.24342,180,1,0,890)
(3,4)	(109.55304,120,1,0,300)	(27,41)	(348.65250,140,1,0,560)
(3,5)	(553.70152,180,1,0,1550)	(28,27)	(598.62371,130,1,0,740)
(4,6)	(211.12522,150,1,0,660)	(29,28)	(606.88416,140,1,0,560)
(5,7)	(956.90338,185,1,0,1300)	(29,42)	(470.96930,140,1,0,850)
(6,5)	(504.71955,130,1,0,400)	(30,18)	(679.75084,150,1,0,420)
(6,11)	(909.94133,140,1,0,700)	(30,39)	(289.94535,170,0.99,0,370)
(7,8)	(122.60102,130,1,0,700)	(31,30)	(325.76753,180,0.98,0,670)
(8,11)	(729.16458,160,1,0,740)	(31,40)	(269.14740,130,0.97,0,290)
(8,12)	(492.27343,116,1,0,650)	(32,33)	(73.04237,170,0.97,0,750)

(9,35)	(575.94907,180,0.99,0.01,420)	(32,52)	(994.32954,190,0.98,0,830)
(10,9)	(280.44022,120,0.99,0,360)	(33,34)	(1077.85422,160,0.99,0,710)
(10,16)	(141.89670,150,0.99,0,450)	(33,49)	(732.87947,140,0.97,0,560)
(11,22)	(504.34889,170,1,0,760)	(34,35)	(322.07300,130,1,0,610)
(11,24)	(469.56047,160,1,0,480)	(35,36)	(356.57849,150,0.99,0,640)
(12,13)	(1145.37846,170,1,0,890)	(36,26)	(241.78566,120,1,0,590)
(12,23)	(683.26093,140,1,0,690)	(37,36)	(83.75431,160,1,0,840)
(13,14)	(959.88100,170,1,0,750)	(37,38)	(1122.24720,110,1,0,350)
(13,23)	(665.37094,160,1,0,570)	(38,41)	(383.19700,140,1,0,470)
(14,25)	(595.16574,180,1,0,980)	(39,29)	(265.43429,170,1,0,490)
(15,16)	(468.78614,170,1,0,620)	(39,43)	(495.14070,140,1,0,650)
(15,31)	(748.61551,190,0.99,0.01,780)	(40,39)	(372.47701,180,0.99,0,490)
(16,17)	(318.09096,150,1,0,400)	(40,44)	(496.38234,120,1,0,480)
(16,18)	(500.07983,140,1,0,430)	(41,45)	(1212.81213,160,1,0,790)
(17,19)	(316.40131,130,0.98,0,230)	(41,53)	(764.67953,140,1,0,490)
(17,21)	(531.51184,140,0.97,0,260)	(42,46)	(580.07031,140,1,0,340)
(18,19)	(184.62159,140,1,0,410)	(43,42)	(257.26739,170,1,0,420)
(19,20)	(68.88968,160,1,0,610)	(43,47)	(536.25956,130,1,0,580)

(20,21)	(124.57359,130,1,0,220)	(44,43)	(361.27772,140,0.99,0,690)
(20,28)	(336.72868,160,1,0,590)	(44,48)	(506.61166,190,1,0.01,670)
(21,26)	(487.83417,160,1,0,750)	(45,53)	(538.33302,170,1,0,530)
(22,23)	(1162.79551,130,1,0,360)	(46,45)	(643.17056,140,1,0,480)
(22,37)	(665.48405,140,1,0,360)	(47,46)	(246.31909,160,1,0,370)
(23,24)	(873.86544,175,1,0,380)	(48,47)	(353.32435,140,1,0,380)
(49,34)	(171.81215,130,1,0,740)	(51,10)	(273.94159,140,1,0.01,730)
(49,50)	(427.08411,170,1,0,490)	(51,50)	(267.72206,130,1,0,450)
(50,9)	(289.22846,160,0.99,0,570)	(52,15)	(621.24714,190,0.98,0,870)
(52,51)	(68.25439,180,0.98,0,770)		

4. Case study results and discussion

In this section, we analyse the result for emergency Response planning of Scenario Ⅰ and scenario Ⅱ respectively for the above accidents. It includes the optimal evacuation path planning under the condition of immediate evacuation, the impact of shelter-in-place duration on emergency response risk, and the optimal emergency response WOs and planning.

4.1. Results for the Scenario Ⅰ emergency response planning

4.1.1. Optimal evacuation path assignment under an immediate evacuation condition

Nodes 1, 31, 32, and 52 in the downwind direction were selected as the source evacuation nodes for the independent testing. It was assumed that the population at these nodes started to evacuate immediately after the accident; that is, the duration of the shelter-in-place was 0, and the population size was smaller than the road capacity limit. According to the risk assessment method in section 2.1, the evacuation risk of the population when escaping along the path can be calculated. Using the model and the algorithm proposed in subsection 2.2, the path with the minimum evacuation risk can be obtained, as shown in Table 3.

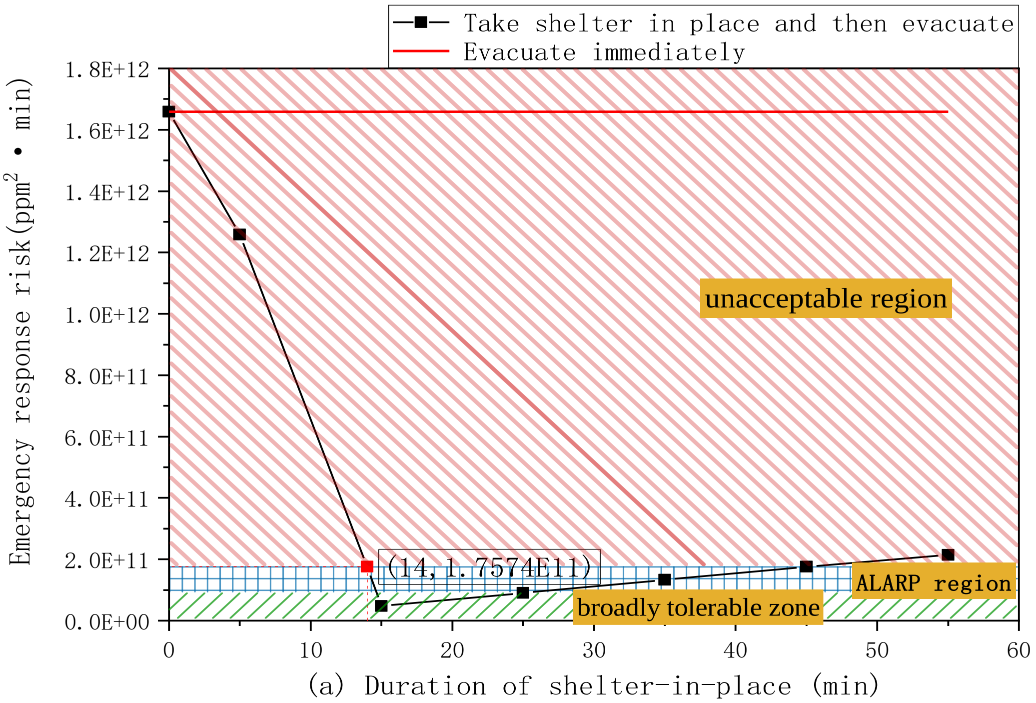
Table 3 Optimal evacuation paths and corresponding emergency response risks

node	$P^*_{v_s \to v_d}$	$R^1_{\mathrm{ev}}\left(P_{v_s \to v_d}\right)$, (ppm^2 · min)
1	1→2→3→5→7→8→12→13→23→24→53	1.66×10^{12}
32	32→52→51→10→16→18→19→20→28→27→41→53	3.56×10^{3}
52	52→51→10→16→17→19→20→21→26→41→53	5.11×10^{-6}
31	31→30→39→29→42→46→45→53	0

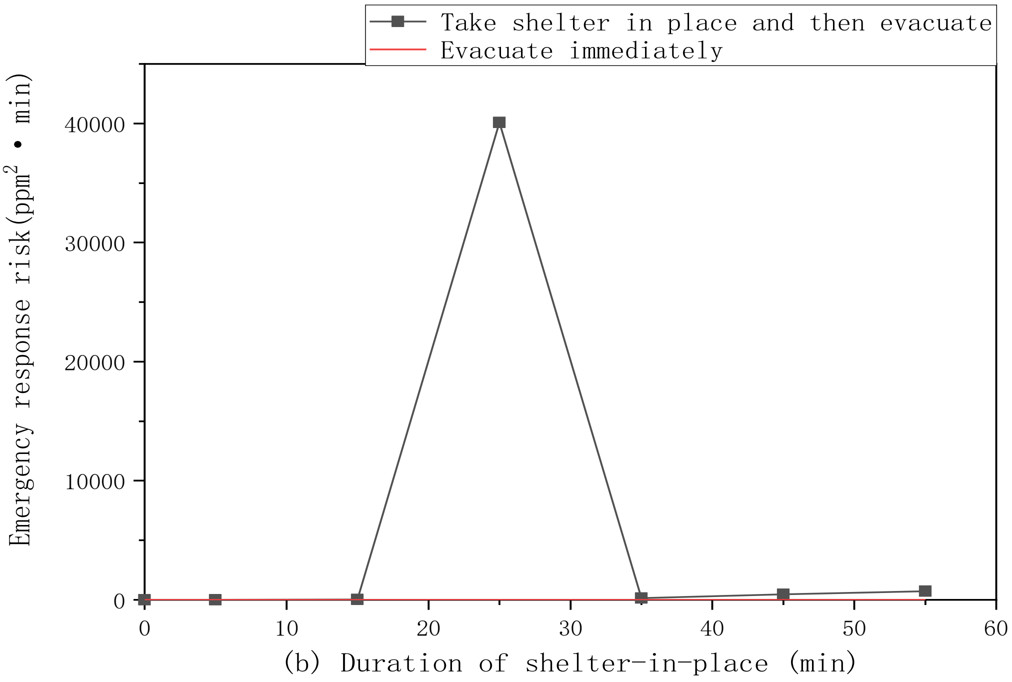
However, Table 3 shows that even if people at some nodes (such as node 1) evacuated along the optimal evacuation route, their emergency response risk would still be very high. This was mainly related to the time the population began to evacuate. Enabling people to complete their evacuation before being exposed to highly toxic gas concentrations can significantly reduce the emergency response risk, as verified by the results for nodes 52 and 31, where the emergency response risks are negligible. While timely and effective evacuation notification can help people escape from the risk areas in time (Gai and Deng, 2019), there are many influencing factors, such as the complexity of the accident, the emergency decision-making efficiency, the concealment of the accident perpetrators, and the ability of the people to act. As evacuating the local population is not enough to protect the safety of all people in this situation, some affected people may need to be sheltered in an appropriate place to wait for the best evacuation time.

4.1.2. Impact of shelter-in-place duration on emergency response risk

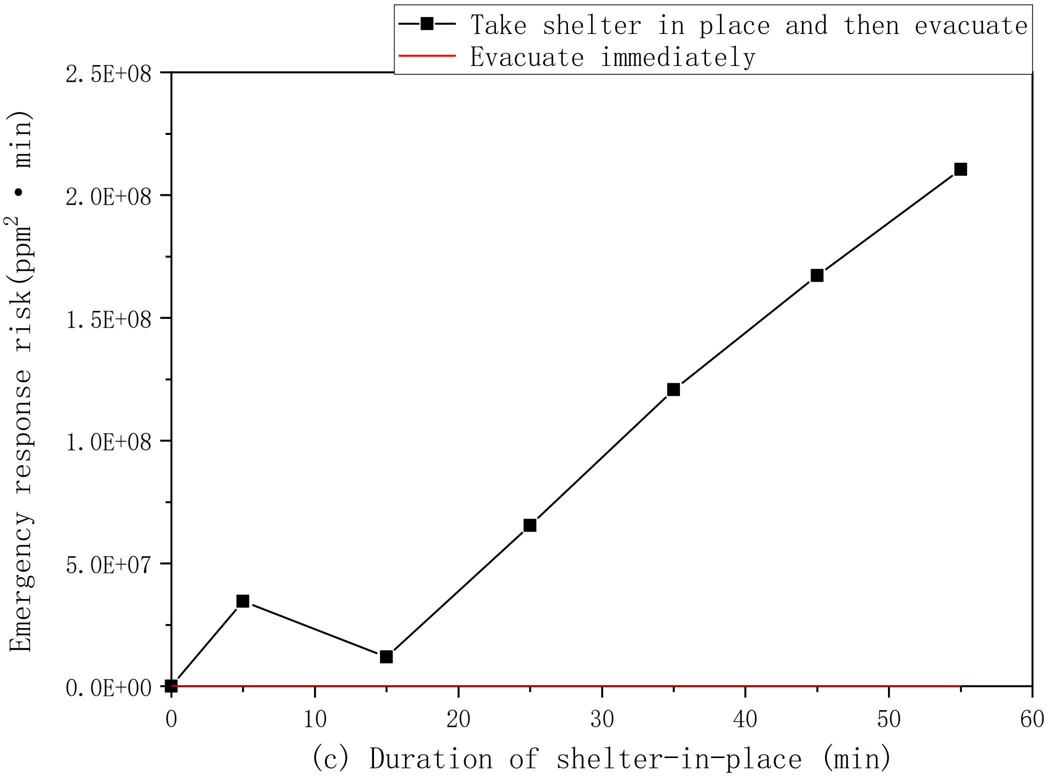
In this section, the question of "how long is the optimal duration to shelter-in-place?" is explored. Using the proposed method in Section 2, the relationship between the emergency response risk and the shelter-in-place durations for the people at nodes 1, 31, 32, and 52 were obtained (Fig. 5).


Take shelter in place and then evacuate
Evacuate immediately
Emergency response risk (ppm^2 • min)
1.8E+12
1.6E+12
1.4E+12
1.2E+12
1.0E+12
8.0E+11
6.0E+11
4.0E+11
2.0E+11
0.0E+00
unacceptable region
(14, 1.7574E11)
ALARP region
broadly tolerable zone
0
10
20
30
40
50
60
(a) Duration of shelter-in-place (min)

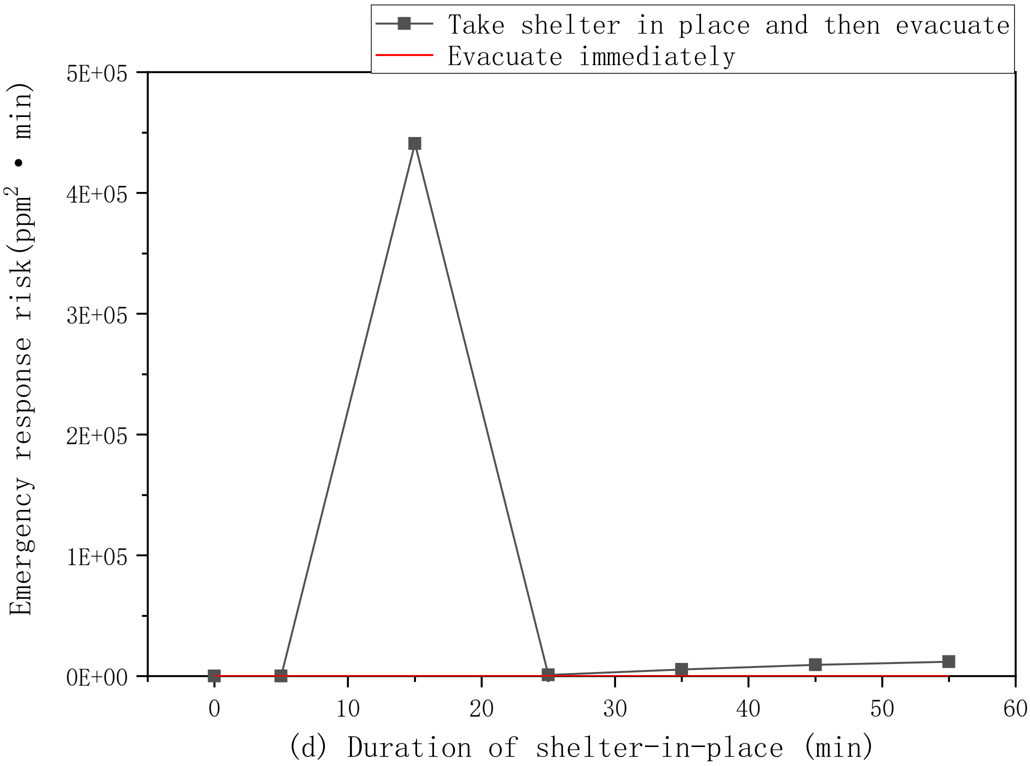
（a）


Take shelter in place and then evacuate
Evacuate immediately
Emergency response risk(ppm^2 • min)
40000
30000
20000
10000
0
0
10
20
30
40
50
60
(b) Duration of shelter-in-place (min)

(b)


Take shelter in place and then evacuate
Evacuate immediately
Emergency response risk(ppm^2 • min)
2.5E+08
2.0E+08
1.5E+08
1.0E+08
5.0E+07
0.0E+00
0
10
20
30
40
50
60
(c) Duration of shelter-in-place (min)

（c）



(d)

Figure 5 Change in the emergency response risks at each node after sheltering-in-place for different times: (a) Node 1; (b) Node 31; (c) Node 32; (d) Node 52

As shown in Fig. 5, the emergency response risks at nodes 31, 32, and 52 all first increased, then decreased, and then increased again with an increase in the shelter-in-place refuge duration. This was because it took some time for the toxic gas to spread to these nodes; therefore, in the early stage of the accident, the emergency response risk was relatively low regardless of whether there was an evacuation. However, when the toxic gas diffused to these nodes, the outside toxic gas concentrations were very high; therefore, if the shelter-in-place actions were terminated at this time, the emergency response risk would have been extremely high, as shown in the peaks in Figure 5 (b), (c), and (d). If people stayed in the shelter for a long time, due to the differences in the indoor and outdoor gas concentrations and the closure of the shelter itself, the high indoor gas concentrations would not be able to effectively diffuse to the outside, which could cause greater harm to the people and increase the emergency response risk. In particular, as node 32 is relatively close to the accident site (relative to nodes 31 and 52), the toxic gas would reach node 32 sooner. Therefore, if the people sheltering-in-place at node 32 stayed in the shelter, the highly toxic gas concentrations would cause a peak in the emergency response risk; that is, the emergency response risk rising period is relatively short. As the toxic gas concentration passing through node 32 is relatively high, the highly toxic gas concentration level means that the risk of shelter penetration would also be high, which means that the minimum emergency response risk (when sheltering-in-place for only 15 minutes) would still be high (compared to nodes 31 and 52). Because the outdoor toxic gas concentration would be very high at the early stage at node 1, which is close to the accident center, the emergency response risk related to immediate evacuation would also be extremely high; the emergency response risk change trend first peaks then declines and then rises, as shown in Figure 5(a).

However, the emergency response risk for evacuation at node 1 after sheltering-in-place for a period of time would always be lower than if there had been an immediate evacuation, whereas at nodes 31, 32, and 52, an immediate evacuation would significantly reduce the emergency response risk. As mentioned, individual differences and other factors can make it difficult for all people in the affected area to evacuate immediately. If those who have not been evacuated in time shelter-in-place for a certain duration, depending on the specific accident circumstances, the accident consequences could be reduced.

4.1.3. Optimal emergency response plans and the WOs for the emergency response

From Fig. 5 and the proposed method outlined in Section 2.3, the optimal emergency response plans for each evacuation source node were determined and are shown in Table 4.

Table 4 Optimal emergency response plan for each evacuation source node

Evacuation source node	Time interval of $T^*_{v_s \to v_d}$ (min)	Optimal emergency response plan $P(T^*_{v_s \to v_d}, P^*_{v_s \to v_d})$		Evacuation pedestrian flow (persons/ 5 minutes)	Emergency response risk, (ppm^2 · min)
		$T^*_{v_s \to v_d}$ (min)	$P^*_{v_s \to v_d}$		
1	15	15	1→2→3→5→7→8→12→13→23→24→53	380	4.75×10^{10}
31	[0,15], 35	0	31→30→39→29→42→46→45→53	340	0
32	0	0	32→52→51→10→16→18→19→20→28→27→41→53	410	0
52	[0,5], 25	0	52→51→10→16→17→19→20→21→26→41→53	230	5.11×10^{-6}

Table 4 indicates that the optimal emergency response plans are different at different times and at different nodes. For the population to be evacuated from node 1, which is near the accident location, the lowest risk emergency response plan is to shelter-in-place for 15 minutes and then evacuate along the path 1→2→3→5→7→8→12→13→23→24→53. However, the people at nodes 31 and 52 have two WOs. For example, the two WOs for node 31 are in the first 15 minutes and in the 35th minute after the accident. Of course, the optimal emergency response plan for each WO is different. The significance of determining multiple

WOs and their corresponding optimal emergency evacuation routes is to enable those who have not been able to be evacuated in time to have another WO to complete the evacuation and minimize the emergency response risk.

It is assumed at node 1 that the emergency response risk can be ignored when it is lower than 9.02×10^{10} ppm^2 min but is unacceptable when it is higher than 1.75×10^{11} ppm^2 min. Therefore, based on the ALARP principle, the emergency response risk can be divided into the three levels shown in Fig. 5 (a). Table 5 shows the WO and gives some emergency response plan examples that correspond to the different risk levels at node 1 shown in Table 5.

Table 5 WO and some examples of emergency response plans corresponding to different risk levels for node 1

Risk level	Time interval of $T_{v_s \to v_d}$ (min)	Type of WO	Example of emergency response plan $P(T_{v_s \to v_d}, P^*_{v_s \to v_d})$		Evacuation pedestrian flow (persons/ 5 minutes)	Emergency response risk, (ppm^2 · min)
			$T_{v_s \to v_d}$ (min)	$P^*_{v_s \to v_d}$		
broadly tolerable	[15,25)	optimum	15	1→2→3→5→7→8→12→13→23→24→53	380	4.75×10^{10}
ALARP	[14,15), [25,45)	reasonable	35	1→2→3→5→7→8→12→13→23→24→53	380	1.33×10^{11}

unacceptable	[0,14), [45,55)	unacceptable	5	1→4→6→5→7→8→12→13→23→24→53	380	1.26×10^{12}
			55	1→2→3→5→7→8→12→13→23→24→53	380	2.14×10^{12}

As shown in Table 5, the optimal evacuation routes for the various shelter-in-place durations generally differ. Depending on the given acceptable risk level, when a toxic gas release occurs, the emergency risk of evacuating the affected population along the designated optimal route after 15–25 minutes of sheltering-in-place is negligible. However, to reduce the emergency response risk to a negligible level, significant emergency resource investments are needed in the emergency preparedness phase. For example, frequent exercises would need to be conducted to improve the public’s risk perception and response capabilities, or basic communication facilities would need to be improved so that emergency warnings could be more quickly, widely, and accurately transmitted to the affected public after the accident. When decision-makers consider that the cost of reducing the emergency risks is unacceptable, the risks can be controlled in the ALARP region. In other words, with acceptable emergency resource inputs, the emergency response capacity would be adequate if the expected populations are able to evacuate along the designated optimal route no earlier than 14 minutes and no later than 45 minutes after the accident. If the risk cannot be contained within the ALARP region, that is, people have to be evacuated earlier than 14 minutes or later than 45 minutes after the accident, and then decision-makers must put mandatory measures in place to minimize the risk, such as providing protective respiratory devices and dispatching additional evacuation rescue vehicles.

4.2. Results of the emergency response planning for scenario Ⅱ

4.2.1. Optimal evacuation plan under an immediate evacuation condition

Nodes 1 and 52 were selected as the evacuation source nodes for Scenario II, and it was assumed that the people at these two nodes would all start to evacuate immediately after the accident. As there is large population is to be evacuated at each node, the optimal evacuation route assignment plan that satisfied the ERT model was then determined, as shown in Table 6. Table 6 shows that the maximum evacuation road network capacity was 1580 people per 5 minutes, with 560 people allocated to node 1 and 1020 people allocated to node 52. Based on the evacuation pedestrian flow allocation, when the people evacuated along the optimal evacuation paths shown in Table 6, the overall emergency response risk was the lowest.

Table 6 Optimal evacuation path assignment plan

Evacuation source node	$P^{*}_{v_s \to v_d}$	Evacuation pedestrian flow (persons/ 5 minutes)	Emergency response risk, (ppm^2 · min)
1	1→2→3→5→7→8→12→13→14→25→24→53	560	1.66×10^{12}
52	1→52→15→16→18→19→20→21→26→27→41→53	220	1.60
	1→52→51→10→16→17→21→26→27→41→53	260	5.11×10^{-6}

1→52→51→10→16→17→19→20→28→41→53	10	1.07×10^{-4}
1→52→51→10→16→17→19→20→28→27→41→45→53	70	1.07×10^{-4}
1→52→15→31→40→44→48→47→46→45→53	290	3.61×10^{-3}
1→52→15→31→30→39→43→47→46→45→53	80	7.85×10^{-3}
1→52→15→31→30→39→29→42→46→45→53	90	1.49×10^{-2}
Total	1580	1.66×10^{12}

The results in Table 6 were similar to those in Section 4.1.1. Although the route allocation plan minimized the overall emergency response risk, the emergency response risks at the two evacuation source nodes were quite different for immediate evacuation; that is, the risk of immediate evacuation was high at node 1 but was negligible at node 52, which indicated that when an immediate evacuation is ordered for the accident affected population, the emergency response risks at some nodes may be too high. To solve this problem, it is necessary for the people in the different areas to take different public protective emergency response actions.

4.2.2. Impact of differentiated emergency response plan configurations on the emergency response risk

This section discusses the differentiated emergency response plan configurations for different nodes and analyzes whether the risk reduction effects are significant. From the upper and lower ALARP region lines set in Section 4.1.2 and the results in Section 4.2.1, the immediate evacuation emergency response risk was intolerable for node 1 and negligible for node 52. Therefore, it is assumed that the people at node 1 would have to evacuate after a period of sheltering-in-place, while the people at node 52 would evacuate immediately. The other assumptions are similar to those in Section 4.1.2. Fig. 6 shows the changes in the node 1 emergency response risk by shelter-in-place duration (0–20 minutes).

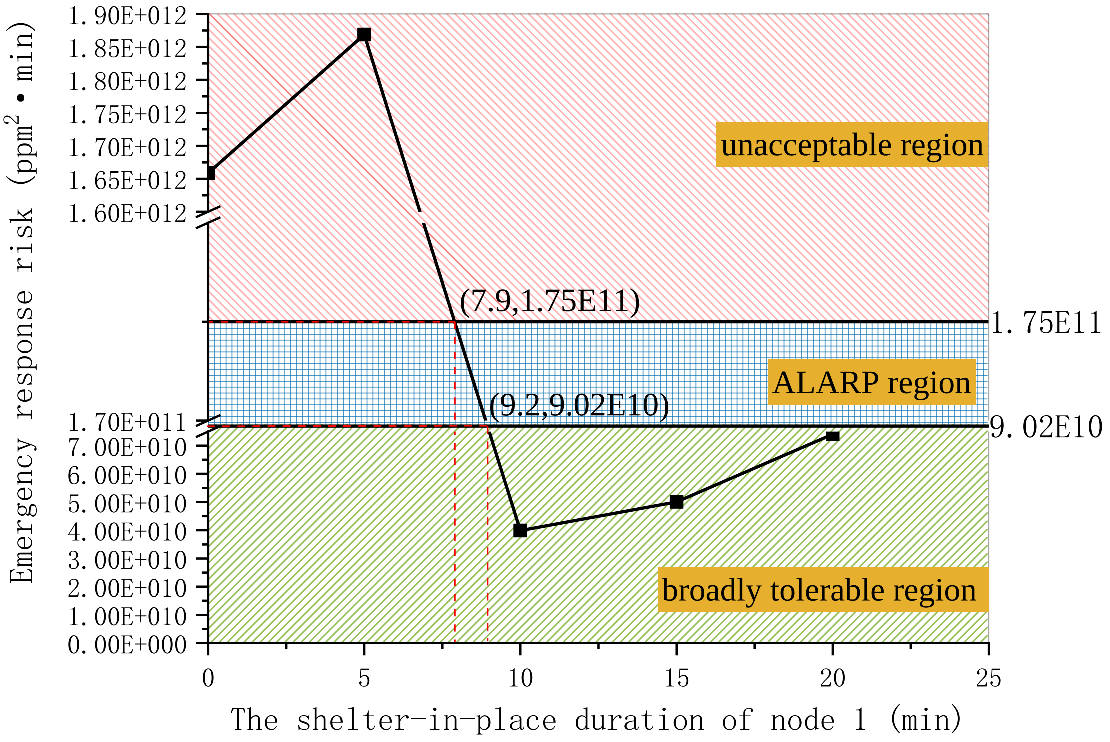


Figure 6 Emergency response risk changes at node 1 for shelter-in-place durations

Fig. 6 shows that the evacuation emergency response risk at node 1 is negligible within

9.8–20 minutes after the accident, and if the evacuation started at 10 minutes, the emergency response risk would be the lowest. Therefore, sheltering-in-place for an appropriate period of time (about 7.9–20 minutes) before evacuating could significantly reduce the emergency response risk at node 1, which is consistent with the conclusion in Section 4.1.2. In addition, these differentiated emergency response plans could assist in controlling the population size on the evacuation network and ease the congestion in the links.

4.2.3. Optimal emergency response plans and WOs for emergency response

Table 7 shows the evacuation action WO at various risk levels and some of the best possible evacuation routes. Similar to the conclusion in Section 4.1.2, it can be seen that the emergency response risks on the same evacuation route vary at different times. Combined with the results shown in Fig. 6 and Table 7, the best emergency response plan for people at node 1 would therefore be to shelter-in-place for 10 minutes and then evacuate along route 1 → 32 → 52 → 15 → 16 → 17 → 19 → 20 → 21 → 26 → 27 → 41 → 53 (220 people) and 1 → 4 → 6 → 5 → 7 → 8 → 12 → 13 → 23 → 24 → 53 (380 people).

Table 7 WO and some emergency response plan examples for node 1

Risk level	Time interval of $T_{v_s \to v_d}$ (min)	Type of WO	Example of emergency response plan $P(T_{v_s \to v_d}, P^*_{v_s \to v_d})$		Evacuation pedestrian flow (persons/ 5 minutes)	Emergency response risk, (ppm^2 · min)
			$T_{v_s \to v_d}$ (min)	$P^*_{v_s \to v_d}$		

broadly tolerable	(9.8,20)	optimum	10	1→4→6→5→7→8→12→13→23→24→53	380	1.38×10^{10}
				1→32→52→15→16→17→19→20→21→26→27→41→53	220	
ALARP	(7.9,9.2)	reasonable	9	1→2→3→5→7→8→12→13→14→25→24→53	560	1.0×10^{11}
unacceptable	(0,7.9),	unacceptable	5	1→2→3→5→7→8→12→13→14→25→24→53	560	1.86×10^{12}

If the decision-makers believe that it is not possible to reduce the emergency response risk to a negligible level or the cost is unacceptable, they could try to control the risk into the ALARP area, at which time there would be an evacuation WO, that is, within 7.9–9.2 minutes after the accident. As shown in Table 7, a suitable emergency response plan would be to let people evacuate along the path 1→2→3→5→7→8→12→13→14→25→24→53 after they shelter-in-place for 9 minutes. If decision-makers are unable to control the risk in the ALARP region, that is, the evacuees have to be evacuated within 7.9 minutes after the accident, then individual protective measures would need to be provided to minimize the risk of toxic gas exposure.

5. Conclusions, Limitations and Suggestions

This study found that making people threatened by a toxic gas leak evacuate or shelter-in-place may not be the most effective measures. When all people at risk are evacuated immediately after a gas leak, the people at some nodes may have a very high emergency response risk. However, if these people were to shelter-in-place for a certain time during the high gas concentration period, this could relieve the road network and significantly reduce the emergency response risk.

This paper presented an ERT toxic gas release problem from the decision-makers' perspective. Based on ALARP and WO theory, the needed protection measures were analyzed to determine when to terminate the current protection actions. The methodology presented in this paper contributes to the scientific knowledge in this field mainly as follows:

i) This paper demonstrates that it is nearly impossible to determine an acceptable level of emergency response risk.

ii) In this paper, we consider mass crowd evacuation as a multi-objective optimization problem with evacuation flow and health consequences as the optimization objectives, taking into account, for example, the impact of disaster expansion on pedestrian speed and road capacity, and obtain the optimal evacuation route for each node at each time step with the help of the minimum cost maximum flow algorithm proposed by (Xu et al., 2021a).

iii) The Window of Opportunity (WO) theory is introduced for decision-makers to solve the ERT problem. The WO indicates the time period when evacuees start evacuation actions. Combined with the optimal evacuation route, a set of emergency response plan is formed.

iv) The proposed methodology is evaluated using a real life case with interesting results.

For decision-makers, the optimal emergency response outcome is to ensure as low an emergency response risk as possible; that is, people need to be evacuated within the best possible response times, which may mean that decision-makers need to invest significant resources in emergency preparedness by conducting frequent exercises to improve the public's risk perception and response capabilities or improving basic communication facilities so that emergency warnings can be more quickly, widely and accurately transmitted to the public. If decision-makers believe that these requirements cannot be met, they could either extend or shorten the shelter-in-place durations to control the risk in the ALARP region, which usually reduces the emergency risks and can be more reliably implemented.

In short, compared with traditional "one size fits all" emergency response plans, the ERT plan developed in this paper could significantly reduce toxic gas emergency response risks and provide decision-makers with a greater range of response options. Further, as the WOs and evacuation routes for people in different locations may be very different, decision-makers could use ERT plans to develop personalized emergency response plans. The method proposed in this paper can systematically help decision makers deal with real-world decision problems and has good prospects for engineering practice.

It is also important to stress that this study has some limitations. For instance, we assume that the concentration of toxic gas at each location will not change temporarily and the personnel behavior is unified, so as to simplify the calculation of the dose of toxic gas inhaled by the public. We eliminate most of the uncertainty about accidents and emergency response. While in fact, a leakage accident may cause a fire or an explosion, evacuees may be unable to move due to panic, etc. We also simplify evacuees' movement process in the paper and did not consider the interaction between evacuees, such as the interaction between different groups following different evacuation routes. In addition, we use the ALOHA default values to approximately set the building permeability, which may be related to many factors, such as house age.

The following research aspects may be worthwhile examining. For example, there are many other key indicators to be considered in addition to the risk of toxic gas inhalation and the evacuation rate, such as the evacuation times and evacuation path complexity. A way forward would be to bring the emergency response process closer to reality by considering the impact of human emotions, emergency information dissemination and pedestrian-vehicle mixed-flow networks. To speed up the search process, metaheuristics that use learning (Salhi, 2017) could also be incorporated into the search so to produce an effective decision support system that can assist decision maker in their strategies as well as their rescue operations. From a practical view point, it could be interesting to adapt and use the emergency decision method proposed in this paper to other accident scenarios so to assess its robustness and wider applicability.

Acknowledgments

The work was partially supported by the National Natural Science Foundation of China (Nos. 72074196 and 71603017), Fundamental Research Funds for the Central Universities (Nos. 3-7-6-2021-09 and 2652019066), and the National Key R&D Program of China (No. 2017YFC0804706). Some of the work was also carried out during Dr. Gai's research visit to Professor Salhi at the Centre for Logistics & Heuristic Optimisation (CLHO) in Kent, UK.

References

Abrahamsen, Abrahamsen, Milazzo, Selvik, 2018. Using the ALARP principle for safety management in the energy production sector of chemical industry. Reliability Engineering & System Safety 169, 160-165.

Austin, 2008. Emergency Response Guidebook. Sandia National Lab.(SNL-NM), Albuquerque, NM (United States).

Baybutt, 2014. The ALARP principle in process safety. Process Safety Progress 33, 36-40.

Bayram, 2016. Optimization models for large scale network evacuation planning and management: A literature review. Surveys in Operations Research and Management Science 21, 63-84.

Bhuiyan, Wang, Shaid, Shanks, Ding, 2019. Advances and applications of chemical protective clothing system. Journal of Industrial Textiles 49, 97-138.

Bkp, Gbl, Ap, Drkp, Aj, 2019. A review: On path planning strategies for navigation of mobile robot. Defence Technology（防务技术） 15, 25.

Booth, Tarjan, 1993. Finding the minimum-cost maximum flow in a series-parallel network. Journal of Algorithms 15, 416-446.

Borghetti, Cerean, Derudi, Frassoldati, 2019. Calculation of the FN Curve and the Expected Damage Value, Road Tunnels. Springer, pp. 81-83.

Campos, da Silva, Netto, 1970. Evacuation transportation planning: a method of identify optimal independent routes. WIT Transactions on The Built Environment 44.

Cao, Lee, Yuen, Chan, Xie, Shi, Yeoh, 2021. Development of an evacuation model considering the impact of stress variation on evacuees under fire emergency. Safety science 138, 105232.

Chan, 2006. Assessing the effectiveness of shelter-in-place as an emergency response to large-scale outdoor chemical releases. University of California, Berkeley.

Chen, Chen, Wang, Reniers, 2018. Optimizing emergency rescue and evacuation planning with intelligent obstacle avoidance in a chemical industrial park. Journal of Loss Prevention in the Process Industries 56, 119-127.

Dave, Ferguson, Anthony, Stentz, 2006. Using interpolation to improve path planning: The Field D* algorithm. Journal of Field Robotics.

Dikshit, Kanhere, Surange, 2011a. Cancer survival in Bhopal, India, 1991-1995. IARC Sci Publ 162, 107-113.

Dikshit, Kanhere, Surange, 2011b. Cancer survival in Bhopal, India, 1991-1995. IARC Sci Publ 162, 107-113.

Farahmand, Garetto, Bellotti, Brennan, Goano, Ghillino, Ghione, Albrecht, Ruden, 2001. Monte Carlo simulation of electron transport in the III-nitride wurtzite phase materials system: binaries and ternaries. IEEE Transactions on electron devices 48, 535-542.

Gai, Deng, 2019. Survey-based analysis on the diffusion of evacuation advisory warnings during regional evacuations for accidents that release toxic vapors: a case study. Journal of Loss Prevention in the Process Industries 57, 174-185.

Gai, Du, Deng, 2018a. Evacuation risk assessment of regional evacuation for major accidents and its application in emergency planning: A case study. Safety science 106, 203-218.

Gai, Du, Deng, 2018b. Regional evacuation modeling for toxic-cloud releases and its application in strategy assessment of evacuation warning. Safety science 109, 256-269.

Gai, Jia, Xi, Deng, 2020. Shelter-in-place risk assessment for high-pressure natural gas wells with hydrogen sulphide and its application in emergency management. Journal of Loss Prevention in the Process Industries 63, 103993.

Gai, Jiang, Deng, Li, Du, 2015. Multiobjective Route Planning Model and Algorithm for Emergency Management. Mathematical Problems in Engineering 2015, 565403.

Gao, He, 2007. Optimization of evacuation routes considering movements at intersections. Tumu Gongcheng Xuebao 40, 80-83.

Georgiadou, Papazoglou, Kiranoudis, Markatos, 2007. Modeling emergency evacuation for major hazard industrial sites. Reliability Engineering & System Safety 92, 1388-1402.

Georgiadou, Papazoglou, Kiranoudis, Markatos, 2010. Multi-objective evolutionary emergency response optimization for major accidents. Journal of hazardous materials 178, 792-803.

Gettings, 2001. Field Test Evaluation of Conservation Retrofits of Low-Income, Single-Family Buildings in Wisconsin: Blower-Door-Directed Infiltration Reduction Procedure, Field Test Implementation and Results; TOPICAL. Oak Ridge National Lab.

Glickman, Ujihara, 1990. Deciding between in-place protection and evacuation in toxic vapor cloud emergencies. Journal of Hazardous materials 23, 57-72.

Guan, Jiao, 2013. A novel risk assessment technology based on ALARP criterion, 2013 Proceedings Annual Reliability and Maintainability Symposium (RAMS). IEEE, pp. 1-5.

Hamacher, Ruzika, Tjandra, 2006. Algorithms for time-dependent bicriteria shortest path problems. Discrete optimization 3, 238-254.

Helbing, Farkas, Vicsek, 2000. Simulating dynamical features of escape panic. nature 407, 487-490.

Hosseinnia, Khakzad, Reniers, 2018. Multi-plant emergency response for tackling major accidents in chemical industrial areas. Safety science 102, 275-289.

Hou, Gai, Cheng, Deng, 2020. Prediction model of traffic loading rate for large-scale evacuations in unconventional emergencies: A real case survey. Process Safety and Environmental Protection 144, 166-176.

Hou, Gai, Cheng, Deng, 2021. Hazardous chemical leakage accidents and emergency evacuation response from 2009 to 2018 in China: A review. Safety science 135, 105101.

Jetter, Whitfield, 2005. Effectiveness of expedient sheltering in place in a residence. Journal of hazardous materials 119, 31-40.

JO, PARK, 2016. Emergency response plane of toxic gas releases with considering ventilation ratio and meteorological conditions. International Journal of Safety and Security Engineering 6, 229-237.

Kim, Lee, Lee, 2017. An evacuation route choice model based on multi-agent simulation in order to prepare Tsunami disasters. Transportmetrica B: transport dynamics 5, 385-401.

Kirchner, Nishinari, Schadschneider, 2003. Friction effects and clogging in a cellular automaton model for pedestrian dynamics. Physical Review E 67, 056122.

Law, Erain, Ramli, Gimbun, 2019. Assessment of chlorine leak dispersion around Gebeng industrial area and potential evacuation route. Atmospheric Research 216, 117-129.

Li, Bin, Yang, Mao, 2009. The unfolding of ‘12.23’Kaixian blowout accident in China. Safety science 47, 1107-1117.

Liu, Li, Chen, 2019. Evacuation traffic management under diffusion of toxic gas based on an improved road risk level assessment method. Complexity 2019.

Liu, Li, Jiang, Jia, 2021. Evacuation traffic management under low visibility and toxic-gas leakage disasters. Journal of transportation engineering, Part A: Systems 147, 04020146.

Markowski, Mannan, 2008. Fuzzy risk matrix. Journal of Hazardous materials 159, 152-157.

Melchers, 2001. On the ALARP approach to risk management. Reliability Engineering & System Safety 71, 201-208.

Mizuta, Sumino, Kunito, Shiota, Izato, Miyake, 2020. Emergency evacuation model assuming leakage of toxic substances in a chemical plant. Journal of Loss Prevention in the Process Industries 68, 104287.

Rogers, Watson, Sorensen, Sharp, Carnes, 1990. Evaluating protective actions for chemical agent emergencies. Oak Ridge National Lab., TN (USA).

Ronchi, Nilsson, 2013. Fire evacuation in high-rise buildings: a review of human behaviour and modelling research. Fire science reviews 2, 1-21.

Salhi, 2017. Heuristic Search: The Emerging Science of Problem Solving. Palgrave, Cham.

Sherman, 1980. Air infiltration in buildings. University of California, Berkeley.

Shimada, Nomura, Ozaki, Higuchi, Hori, Sonoda, Yamamoto, Yoshida, Tsubokura, 2018. Balancing the risk of the evacuation and sheltering-in-place options: a survival study following Japan’s 2011 Fukushima nuclear incident. BMJ open 8, e021482.

Shimbel, 1953. Structural parameters of communication networks. The bulletin of mathematical biophysics 15, 501-507.

Shiwakoti, Sarvi, Dias, Burd, 2014. Understanding crowd panic at turning and intersection through model organisms, Pedestrian and Evacuation Dynamics 2012. Springer, pp. 1175-1183.

Smith, Swacina, 2017. The disaster evacuation or shelter-in-place decision: who will decide? Journal of the American Medical Directors Association 18, 646-647.

Sorensen, Shumpert, Vogt, 2004a. Planning for protective action decision making: evacuate or shelter-in-place. Journal of Hazardous materials 109, 1-11.

Sorensen, Shumpert, Vogt, 2004b. Planning for protective action decision making: evacuate or shelter-in-place. Journal of hazardous materials 109, 1-11.

Stepanov, Smith, 2009. Multi-objective evacuation routing in transportation networks. European journal of operational research 198, 435-446.

Tenchov, 2021. Ammonium nitrate explosions: lessons learned. https://www.cas.org/resources/whitepapers/ammonium-nitrate.

Thompson, Nilsson, Boyce, McGrath, 2015. Evacuation models are running out of time. Fire Safety Journal 78, 251-261.

Van Coile, Jomaas, Bisby, 2019. Defining ALARP for fire safety engineering design via the Life Quality Index. Fire Safety Journal 107, 1-14.

Wang, 2011. Multi level decision analysis of emergency protection action for hazardous chemicals leakage based on decision tree. 2010 International Symposium on Emergency Management, 843-849.

Wang, Sun, 2014. Principal aspects regarding to the emergency evacuation of large-scale crowds: a brief review of literatures until 2010. Procedia engineering 71, 1-6.

Wilson, 1987. Stay indoors or evacuate to avoid exposure to toxic gas. Emergency Preparedness Digest 14, 19-24.

Wilson, 1988. Variation of indoor shelter effectiveness caused by air leakage variability of houses in Canada and the USA, USEPA/FEMA Conference on Sheltering In Place During Chemical Emergencies, Nov.

Wilson, Morrison, 2000. Ordering Shelter or Evacuation During an Outdoor Toxic Gas Release Incident: the CAFC Decision Flow Chart, presented at Fire-Rescue Canada 2000, Annual Meeting of the Canadian Association of Fire Chiefs.

Xi, 2016. An evaluation method on effect of shelter in toxic gas accident. Journal of Safety Science and Technology, 65-69.

Xu, Gai, Salhi, 2021a. Dynamic emergency route planning for major chemical accidents: Models and application. Safety science 135, 105113.

Xu, Wang, Li, Wang, Wang, 2021b. System dynamics research of non-adaptive evacuation psychology in toxic gas leakage emergencies of chemical park. Journal of Loss Prevention in the Process Industries, 104556.

Yadav, Biswas, 2010. An intelligent search path. International Journal of Intelligent Systems 25, 970-980.

Yang, 2019. Internationalize hazard management of China's chemical plants. nature 569, 192-193.

Yong, Wang, Heng, Zhou, Ying, Wang, 2017. Mobile robot dynamic path planning based on improved genetic algorithm. Aip Conference Proceedings.

Yoo, Choi, 2019. Emergency evacuation plan for hazardous chemicals leakage accidents using GIS-based risk analysis techniques in South Korea. International journal of environmental research and public health 16, 1948.

Yuan, Wang, 2007. Multi-objective path selection model and algorithm for emergency evacuation, 2007 IEEE international conference on automation and logistics. IEEE, pp. 340-344.

Zhang, Ni, Huang, Duarte, 2017. Risk-based personal emergency response plan under hazardous gas leakage: Optimal information dissemination and regional evacuation in metropolises. Physica A: Statistical Mechanics and its Applications 473, 237-250.

Zhang, Zhang, Zhang, Wei, Deng, 2013. Route selection for emergency logistics management: A bio-inspired algorithm. Safety science 54, 87-91.

Zhao, 2011. An evaluation method on effect of shelter in toxic gas accident. China Safety Science

Journal 21, 131-137.

Zhou, Liu, 2012. Risk assessment of major hazards and its application in urban planning: A case study. Risk Analysis: An International Journal 32, 566-577.