Research on the Personnel Shelter Location and Evacuation Route Model Planning under Emergent Events

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Abstract. Based on the reaction lag of emergency response, inadequate emergency rescue capacity and unreasonable emergency supply allocation and shelter location, it was of great significance to study the reasonable shelter locations and rapid evacuation route under major emergencies for the purpose of disaster prevention and mitigation. The Voronoi diagram partition method was carried out to determine the optimal layout and rational allocation of settlements based on the influence mode of emergency events and characteristics of personnel transfer and settlement, as well as the transfer distance impedance value was 2000 m. The possible population capacity of the settlement was used as weight of settlement planning selection, and a nonlinear full coverage solution model of settlements with shortest path was established. The solution method of the escape route for rapid personnel transfer under major emergencies was proposed to which according to the personnel settlement layout optimization model. Based on the poison gas diffusion simulation particle model and the risk assessment model of road section disaster of the cellular automaton, the path solving system of multi-source concurrent gas leakage and rapid diffusion of toxic gas under complex wind field conditions and dynamic prediction were also developed to predict disaster changes over time and provide technical support for early planning to avoid disasters and rapid personnel transfer.

1. Introduction
As the emergent events are considered as an unexpected events, which may cause serious social consequences, emergency response measures are required for natural disasters, accident disasters, public health events and social security events. Many emergencies such as earthquakes, leakage and spread of toxic and harmful gases are regular occurred in the form of coupled emergencies, because of its relevance, derivation and diversity. The impact on personnel safety, evacuation, and relocation is diverse and complicated. In recent years, various accidents are occurred frequently, such as the 5•12 Wenchuan Earthquake, 8•12 Tianjin Binhai New Area Explosion, and 11•13 Paris Terrorist Attack, etc., which leading to heavy losses of lives and property. On the other hand, with the rapid development of urbanization in China, emergency management problems which caused by traffic congestion have attracted widespread attention. And heavy traffic brings even greater difficulties of the crowd evacuation.

A lot of research have been conducted by domestic and foreign scholars in this field, which peaked in 1970s. The main focus of previous researches is the direction of personnel transfer planning, and the relationship between the location of the resettlement site and the time of personnel evacuation. Hanif D. Sherali et al. developed a planned and operation-based computer tool named transport evacuation DSS (TEDSS) which based on a specific location allocation model. The model develops an evacuation plan to minimize the total evacuation time associated with congestion, which by selecting a set of candidate shelters from an given set of allowable alternatives in a way that is feasible for available
resources. Paul Kailiponi et al.\textsuperscript{[4]} proposed a two-level planning model for the first time, and determined the best route for personnel transfer using genetic algorithms to determine the key influential factors of the site selection and resettlement plan. Nima Golshani et al.\textsuperscript{[5]} proposed a joint model for predicting the location and departure time of evacuees in the event of an emergency without notification, and deriving socioeconomic attributes, disaster characteristics, as well as building environmental factors of the evacuees. The evacuation order of government is a key determinant of these two decisions. Ammar W. Mohamed et al.\textsuperscript{[6]} proposed an optimal path with a good success rate which can be found based on the PSO method, and a closer suboptimal path with higher certainty was founded.

Domestic scholars have conducted extensive research on path optimization based on models and algorithms. Lu Guojun et al.\textsuperscript{[7]} proposed a two-way search algorithm for obtaining K optimal paths based on Dijkstra algorithm. And the specific escape paths of different disaster sites in the mine were obtained combined with VB programming language. Ding Chunhu\textsuperscript{[8]} proposed an optimization method for urban traffic emergency evacuation routes during peak pedestrian traffic, which based on ant colony algorithm. This method significantly improved evacuation route efficiency and channel utilization. Cao Huan et al.\textsuperscript{[9]} proposed a comprehensive emergency response model based on cellular automata(CA) in order to further improve the efficiency of emergency response to toxic gas leakage accidents, including accident dynamic assessment model and evacuation route selection model, including toxic gas diffusion model, accident dynamic assessment model and evacuation route selection model. Chen Yizhou et al.\textsuperscript{[10]} studied the optimization algorithm of crowd evacuation routes based on real-time poison gas which was effected by catastrophic models and algorithms. Liu Wenning et al.\textsuperscript{[11]} proposed a personnel evacuation model based on the cell fish school algorithm, which truly reflects the evacuation process of people when transferring in a comprehensive transportation hub, and optimizes the orderliness of crowd evacuation routes.

Currently, the research on the settings and allocation models of personnel resettlement sites are rarely include the design and planning of emergency evacuation sites or resettlement sites at domestic and abroad. Much more research are on the single objective function focusing on the safety of the resettlement sites. The overall evacuation distance or time of the needy people is usually used as the planning goal of the resettlement site or shelter, and the route risks and safety factors around the site are ignored during the disaster avoidance process. The plan and design regarding secondary disasters which affecting the safety of transfer routes or resettlement sites need to be investigated when the different disasters occur. The impact of disaster avoidance paths based on real-time disaster have introduced catastrophic models and algorithms, but the models fail to take into account the real-time and future disaster impact transfer avoidance path optimization algorithms and evolution trends, which induce effect of disaster avoidance is missing for the models\textsuperscript{[12]}. Therefore, the study on integrated optimization of shelter location and evacuation route under major emergencies is of great significance for rapid disaster response.

The remainder is organized as follows. Section 1 introduces the technical methods for resettlement site planning. Section 2 constructs personnel transfer techniques. Section 3 constructs an Optimization model for planning disaster avoidance path. Finally, a brief summary in the section 4 is provided.

1.1. Overview

In terms of planning and selection of urban disaster prevention and evacuation sites, there are currently two main types of methods, which is location models and GIS-based Voronoi map methods. Common location model methods at domestic and abroad are mainly divided into four categories: P-median Problem, P-center Problem, Location Set Covering Problem(LSCP),Maximal Covering Location Problem(MCLP).Other location issues are mostly proposed based on these four categories.\textsuperscript{[13]}The location method of location model need to include huge amounts of data information. Therefore, with the continuous development of GIS, some scholars have also effectively combined the location model with GIS technology to develop the corresponding facility location analysis system, Visual representation of the model's solution structure and the final solution can be achieved with spatial data.
1.2. Voronoi diagram principle

Voronoi diagram principle is defined based on following hypothesis\(^{[13]}\). There is a set of growth points \( P \) on the two-dimensional Euclidean plane, and a Delaunay triangle network is produced from the set points on the plane. The points and the formed triangles are numbered to record the three discrete points of each triangle. And search for two points closest to it to form a seed triangle. Then, each side of the triangle is searched separately to ensure the distance to the two vertices of the edge and the smallest third point, and a new triangle is formed. Finally, the polygons of the Voronoi diagram can be obtained by connecting the circumscribed circles of adjacent triangles, ensuring that there is only one \( P \) point in each of the Vino polygons. As shown in Figure 1.

The following requirements should be satisfied. In the control point set \( P = \{p_1, p_2, \ldots, p_n\} \), any two points are not co-located, and any four points are not co-circular. In any convex polygon, the distance from any internal point to the control point \( p_i \) is the minimum comparing to the distance from the point to any other control point \( p_j \).

![Figure 1 Voronoi diagram for generation principle](image)

1.3. Principle of Multiplicative Weighted Voronoi Diagram

The principle of multiplicative weighted Voronoi diagram is based on the following assumptions\(^{[13]}\). The set of discrete growth points on the two-dimensional Euclidean plane \( P \), \( P = \{p_1, p_2, \ldots, p_i, \ldots, p_j, \ldots, p_n\} \), \( 2 \leq n < \infty \). \( W_i \) is the weight of \( P_i \), \( W_i > 0 \), and \( (P, P_i) \) is the Euclidean distance between point \( P \) and \( P_i \).

\[
V_w(p_i) = \left\{ p \left| \frac{d(p, p_i)}{W_i} \leq \frac{d(p, p_j)}{W_j}, \; j \neq i, \; j = 1, 2, \ldots, n \right\} \right. (1)
\]

The region is called the multiplication weighted Voronoi diagram of the growth point \( P_i \). Where, \( d(P, P_i) / W_i \) is the weighted distance. For a weighted Voronoi diagram, a Voronoi polygon with a large weight has a larger area and a stronger influence. According to the characteristics and constraints of the evacuation site, different weighting factors are determined, which makes the planning and selection of the evacuation site more reasonable and economical.

1.4. Realization of Weighted Voronoi Diagram Based on GIS

(1) The smallest rectangle of all point sets in the area is obtained, and a certain range outward is expanded. According to the ID number in the graph, the point with ID 0 is selected and recorded as \( P_0 \), and the area current outsourced is divided into \( P_0 \). It is considered that the original area is recorded as \( R_0 \).

(2) The point with ID 1 is obtained, recorded as \( P_1 \). A Voronoi boundary of two points (the boundary is an arc, and the unweight Voronoi diagram is the vertical bisector) is generated by calculating the weight relationship between \( P_0 \) and \( P_1 \). It is recorded as \( L_1 \). And \( R_0 \) is divide into two parts with \( L_1 \). The attributes of the area that intersects \( P_0 \) are unchanged, and it is still recorded as \( R_0 \). But the area that intersects \( P_1 \) is denoted as \( R_1 \).
(3) The point with ID 2 is obtained, recorded as P2. The Voronoi boundary between P2 and P0 is first calculated, and the R0 area is divided into two new areas using this boundary. Then the Ri area is divided using the Voronoi boundary generated between P2 and Pi. The Pi region is divided into area R1, area R2, and finally the two R2 regions are merged.

(4) Sequentially, ID n is received, and use the method of the previous steps to process all the points to the end.

2. Personnel transfer techniques

2.1. Road accessibility satisfaction under the influence of an emergency
Taking poisonous gas as an example, according to the area affected by the spread of poisonous and harmful gases, a linear time is introduced for the layout of the resettlement sites to evaluate the probability of road safety pass ability from the transfer demand point to the resettlement point \(^{[14]}\).

\[
f(t_{ij}) = \begin{cases} 
0 & \text{when } t_{ij} > u_i \\
u_i-t_{ij} & \text{when } t_{ij} \in [L_i, u_i) \\
u_i-L_i & \text{when } t_{ij} < L_i 
\end{cases}
\]
where: \( U_i(s) \) is the critical maximum time, beyond which the toxic gas concentration will harm the health of the person beyond the tolerance range of the human body; \( L_i(s) \) is the maximum time (path) required for a successful transfer of personnel; \( t_i(s) \) is the actual time at which the person at \( i \) reaches the resettlement point \( j \).

According to the requirements of the resettlement site, at least two roads can reach to the resettlement site, and the passing probability of the two paths needs to be calculated. Area total traffic probability is defined as:

\[
u_i = u_i^1 + u_i^2 \tag{3}\]

\( u_i^1 \) is the passing probability of the shortest path from the affected area \( i \) to the settlement point, \( u_i^2 \) is the passing probability of the next shortest path from the affected area \( i \) to the settlement point.

In order to take into account the best reconciliation of human vulnerability, time satisfaction and traffic probability, that is, considering human vulnerability, the total time satisfaction during the transfer process is the largest:

\[
\text{Max: } w_T \sum_{i \in I} \sum_{j \in J} Y_{ij} f(t_{ij}) Z_{ij} + w_r \sum_{i=1}^n u_i \tag{4}\]

\( Z_{ij} \) is the decision coefficient, if the person in area \( i \) is transferred to the settlement point \( j \), then \( Z_{ij} = 1 \), otherwise \( Z_{ij} = 0 \).

\( w_T, w_r \) are weight coefficients determined by the decision maker.

2.2. Resettlement site planning and solution

(1) Spatial analysis of resettlement sites

Based on the topological overlay analysis of geographic information system and the impact criteria of various factors on the resettlement site, discrete topological influence areas are analyzed, including point, line, and area influence modes to superimpose and analyze the impact of each factor on the resettlement site. The red block in the figure below indicates that the resettlement site is in an unsafe area.
(2) Maximize coverage model

The existing resettlement sites and the planned resettlement sites are selected as optional facilities, and the transfer distance impedance value of 2000m is used to calculate the number and location of facilities required to cover all demand points or to cover all demand points to the greatest extent.

Aiming at the large-scale urban migration, Berman et al. [15] improved the traditional maximum coverage model and introduced the concepts of population coverage and distance coverage. Under conditions of limited resources, blocked roads, and uneven distribution of personnel, it is required that all demand points can be covered to varying degrees. The goal is to maximize the weighted sum of the covered demand points. 

\[
\max \sum_{i \in I} \sum_{j \in J} d_{ij} w_i y_{ij} - x_{js0} (i \in I, j \in J) \tag{5}
\]

\[
\sum_{j \in J} x_j = N (7)
\]

\[
\sum_{i \in I} y_{ij} = 1 (i \in I) \tag{8}
\]

\[
d_{ij} - 2000y_{ij} \leq 0 (9)
\]

\[
x_j \in \{0,1\} (j \in J)
\]

\[
y_{ij} \in \{0,1\} (i \in I, j \in J)
\]

where: \(x_j\) — j is 1 when the placement point is selected, otherwise it is 0.
\(d_{ij}\) is the coverage of the demand point i corresponds to the placement point j, which is related to the distance.
\(w_i\) is the population is used as a weight for the model and is related to the population.
Objective function (5) is to maximize the population of the demand points covered;
Constraint formula (6) indicates that the demand point i can be covered by the candidate point j only when the alternative placement point j is selected;
Constraint Condition (7) indicates that N placement points are to be selected from candidate points;
Constraint condition (8) defines that each demand point i is covered by 1 or more reset points multiple times and is 1;
Constraint Equation (9) is the limit the maximum distance covered by each settlement point to 2,000 meters.
According to the above iterative analysis, the results are shown: under the conditions of increasing the coverage population, coverage distance, etc., and taking the 2000m coverage distance of the resettlement point as the boundary condition, as well as considering the impact of population capacity weights, at least 4 settlement points are planned to achieve the optimal solution of the full coverage of the assembly point, which has one more settlement point comparing with only the settlement point planning under the minimum impedance of the coverage distance. And the ownership coverage relationship between assembly points and resettlement points has also been adjusted locally.

2.3. Personnel transfer resettlement allocation method

Different resettlement sites may use different transfer tools, and personnel resettlement allocation and transfer strategies at each resettlement site can be planned and formulated[16].

If the number of resettlement personnel is $Q_i(1,2,3,\ldots,p)$, then $\sum_{i=1}^{p} Q_i \leq q$ and $Q_i \leq \sum_{j=1}^{m} E_{ij}$ and. It is assumed that each resettlement point adopts a combination of vehicle lane transfer and pedestrian transfer. Among them, the disaster-stricken area to the meeting point adopts the method of walking by risk-averse personnel, and the meeting point of the resettlement point adopts the vehicle transfer mode. It is assumed that each type of resettlement site can use m-type vehicle transfer modes to transfer distressed people. The one-way time to the resettlement point is $t_i$, and the proportion of transferred personnel is $g_i$. According to the effective safety time conditions of personnel transfer, the relationship model between $q$ and $T$ can be established, that is, the transfer allocation model is established as shown below.

$$
\frac{2g_iQ_i}{f_{is}} - 1 \leq \left[ \frac{\sum_{s=i}^{p} t_{is}}{q} \right] (s=1,2,\ldots,m; i=1,2,\ldots,p)(10)
$$

Because of $\sum_{i=1}^{p} g_i \leq 1$ and $\sum_{i=1}^{p} Q_i = q$, the relationship between $Q$ and $T$ can be simplified as:
$$Q_i = \sum_{t=1}^{p} \left( \left[ \frac{T}{T_{ls}} \right] + 1 \right) \frac{f_{is}}{2}$$

$$q = \sum_{i=1}^{p} \sum_{s=1}^{S} \left( \left[ \frac{T}{T_{ls}} \right] + 1 \right) \frac{f_{is}}{2} \quad (11)$$

Where, $Q_i$ is the amount of personnel assigned to each resettlement site; $E_{ij}$ is the number of persons resettled at the $j$-th resettlement facility in the $i$-th resettlement site; $I$ is the number of categories of transfer tools; $T$ is the minimum time required for the transfer task, that is, the minimum security time required for the transfer of personnel; $q$ is the total number of personnel to be transferred; $g_{ks}$ is the proportion of personnel transferred by the $s$-th tool; $f_{is}$ is the number of people evacuated at the $s$ type of one-time vehicle; $k$ is the type of transfer tool.

The shortest time $T$ required to complete the transfer task is obtained according to the maximum transfer time in the impact of the accident. And taking $T$ into the above formula, $Q_i$, $g_{is}$ are calculated to get the number of tasks that need to be completed in different transfer methods at each settlement point. Then the optimal number of resettlement sites to be transferred is obtained.

3. Optimization of disaster avoidance path

Based on the resettlement site planning, planning technology and disaster simulation, this paper analyzes the accessibility of people's transfer network traffic and the evolution mechanism of disaster risk, and then studies the solution and optimization of the fast-moving disaster avoidance path for people.

3.1. Optimization of personnel transfer path considering real-time disaster impact

In the process of emergency personnel transfer, not only the time factor, but also the level of disaster risk of each section of the evacuation network must be considered. The solution of the personnel transfer and disaster avoidance path requires not only high-speed, but also high disaster avoidance. Therefore, the planning of personnel transfer and disaster avoidance paths is to determine a path with the shortest total transit time from the assembly point to the resettlement point and the lowest level of disaster risk. And taking the shortest total transfer time required to pass the route and the lowest level of disaster risk as the optimization objectives, a model for selecting the transfer route of personnel considering the real-time impact of disaster spread is established:

$$\min \sum_{i=1}^{n} \sum_{j=1}^{n} (t_{ij} + \lambda r_{ij}^t) x_{ij} \quad (12)$$

$$\sum_{j=1}^{n} x_{ij} - \sum_{j=1}^{n} x_{ji} = \begin{cases} 1 & i = 1 \\ -1 & i = n \\ 0 & \text{other} \end{cases} \quad (13)$$

$$\sum_{j=1}^{n} x_{ij} \left\{ \begin{array}{cl} \leq 1 & i \neq n \\ = 0 & i = n \end{array} \right. \quad (14)$$

$$x_{ij} = 0, 1, i = 1, 2, ..., n, j = 1, 2, ..., n \quad (15)$$

Where, $t_{ij}$ is the time that the evacuee pass through the arc; $r_{ij}^t$ is disaster risk value at time $t$.

Constraint (13) indicates that the value of $x_{ij}$ constituting a feasible evacuation path from the source node to the destination node;

Constraint (14) indicates no loop in the evacuation path;

Constraint (15) is the type constraint of decision variables.
3.2. Optimization of disaster avoidance paths based on disaster prediction

Based on the simulation methods, it is possible to predict the disaster changes in the future. And based on this forecast scenario, a path that avoids disasters with shortest human transfer time can be planned.

For a known person transfer path:

\[ P = (v_{p_1}, v_{p_2}, ..., v_{p_k}, ..., v_{p_K}) \]

there is:

\[ r_{pkk+1}^p = \int_{t_k}^{t_{k+1}} r_{pk}^p dt \] (16)

\[ r^p = \sum_{k=1}^{K-1} r_{pkk+1}^p \] (17)

Formula (16) represents the total disaster risk when a person passes a road section; formula (17) represents the total disaster risk when a person passes the entire transfer line. A disaster avoidance route optimization model based on disaster prediction was established based on the disaster risk assessment of road sections.

\[ \min \sum_{i=1}^{n} \sum_{j=1}^{n} (t_{ij} + \lambda \int_{t_i}^{t_j} r_{ij}^p dt) x_{ij} \] (18)

\[ \sum_{j=1}^{n} x_{ij} - \sum_{j=1}^{n} x_{ij} \neq i = \begin{cases} 1, & i = n \\ 0, & \text{other} \end{cases} \] (13)

\[ \sum_{j=1}^{n} x_{ij} \leq 1 \neq i = \begin{cases} 0, & i = n \\ 1, & \text{other} \end{cases} \] (14)

\[ x_{ij} = 0, 1, i = 1, 2, ..., n; j = 1, 2, ..., n \] (19)

3.3. Dynamic planning mechanism for personnel transfer

Traffic management under emergency conditions is a multi-stage, multi-tasking decision-making and dispatching process. There are different traffic management activities and their influences at different stages. An event trigger mechanism need to be established to control the update of personnel transfer instructions. The process is shown in Figure 9.

Step1, transfer termination judgment
The transfer process is generally limited by the number of arrivals or a specified time to limit whether the transfer is terminated. If the termination condition is reached, the result is output and the simulation ends.

Step2, implement monitoring
Changes in the resources of the resettlement site during the transfer process is taken real-time monitoring. Updates will be initiated when the number of transferees reaches the limit of resettlement.
site resources; And changes in the availability of road network infrastructure under disaster conditions is taken real-time monitoring. Then instruction updates is started when road capacity changes suddenly.

Step 3, dynamic traffic demand forecast

By predicting the current demand for people to transfer the road network traffic flow, the traffic distributed on the entire road network can be virtually gathered at each node of the road network along its flow direction, and the line traffic demand can be converted into point traffic demand. Through the analysis of real-time traffic data, the traffic demand at each node on the road network, that is, the demand for the transfer of people in the traffic flow is obtained.

Step 4, branch instruction generation

The input factors required for the transfer instruction generation algorithm are the structure of the road network, the transfer requirements of each node, the resource situation of the resettlement site, the transfer time limit, and the disaster situation; the output is composed of five elements: time, number of people, starting point, transfer path, and specific instructions of resettlement site.

Step 5, instruction update

By various means, new transfer instructions are issued and updated at the downstream nodes where the traffic flow will reach. Then, the dynamic traffic flow model during the transfer process was simulated by the "Link-node" model under the emergency conditions. The realization of traffic flow constraints on road sections and nodes. Finally, return to Step 1.

3.4. System implementation and example verification

Based on the above model algorithm, the platform is developed using C# programming language and Visualstudio2013, which is a path solving system that considers the effects of toxic gas real-time diffusion and dynamic prediction is developed, mainly including the following functional modules:

(1) Rapid simulation module for toxic gas diffusion. It is used to quickly simulate the diffusion process of various toxic gases under different winds. It can be set the type of toxic gas, the amount of toxic gas leakage over time, and the location of the leakage source through the human-computer interface. Multiple toxic gas leaks can be added to the source, and the wind direction can be set or adjusted at any time during the simulation.

(2) Personnel transfer network disaster risk assessment module. It is used for real-time dynamic assessment of the disaster risk of each road section in the human transfer network; the corresponding relationship between the road section and the grid is established. The disaster risk value of the road section is calculated according to the concentration of toxic gas in the grid.

(3) The solution module of personnel transfer path. It is used to calculate the optimal transfer path from the rendezvous point to the resettlement point. The optimal transfer path from the rendezvous point to the resettlement point will be dynamically calculated based on the disaster risk and transfer time of each road section.

(4) Visualization module. Real-time diffusion of poison gas, disaster risk status of routes, and evacuation routes can be mapped.
This paper selects a city's oil depot as the research object, a virtual scene for the rapid transfer of people to avoid disaster was constructed combining the actual data and data of hazardous chemicals, meteorology, geography, hydrology, transportation, population distribution in the vicinity of the oil depot. The results of personnel transfer placement and route optimization are analyzed in the case of oil depot explosion and the diffusion of toxic gases such as CO, as shown in Figures 10 and 11.

Figure 10 Schematic diagram of the solution of the personnel transfer path.

Figure 11 Simulation of personnel transfer placement.

4. Conclusion
(1) In consideration of meeting the basic needs of risk aversion, the attraction weights of resettlement sites are introduced, and the weighted coverage impact radius of resettlement sites is proposed. The Voronoi diagram division method is used to determine the responsibility service area of each resettlement site to facilitate regional personnel transfer scheduling and resettlement decisions. The capacity-based personnel transfer allocation model for regional population transfers is analyzed. The number of transfer tools to be equipped can be determined based on constraints such as population size and safe transfer time to facilitate the preparation and dispatch of emergency resources.

(2) The optimization mode of the rapid transfer disaster avoidance path under the influence of emergencies was established based on the resettlement site planning and road section disaster risk assessment results with cellular automata-based toxic gas diffusion simulation particle model and road section disaster risk assessment model. And the path optimization model not only realizes the path planning under the influence of the current real-time disaster, but also implements the path planning under the consideration of future disaster deduction and prediction, and decision support is provided for the rapid transfer of personnel under emergency events and the dynamic solution optimization of traffic disaster avoidance routes.

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