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The Optimization of Emergency Evacuation from Nuclear Accidents in China

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Abstract: An emergency evacuation route is an important component of emergency rescue of for nuclear accidents. A reasonable evacuation route can reduce evacuation times and protect people's life. The evacuation route of the nuclear power plant is abstracted into a network diagram and a mathematical model of evacuation optimization route based on the graph theory and the parity of spot diagram method in this paper. Road traffic capacity and other external factors that may affect emergency evacuation are considered in the time weight factor for each road. Finally, an example is given to verify the feasibility of the model.

Keywords: nuclear accident; emergency evacuation; route optimization; the parity of spot diagram method

1. Introduction

The Daiichi Fukushima Disaster, coming 25 years after Chernobyl, emphasized that society must have robust, sensitive emergency management processes to respond to any future radiation accident, thus international agencies such as the International Commission on Radiation Protection (ICRP) and the International Atomic Energy Agency (IAEA), as well as national government organizations in nuclear countries made a serious of general guidance on nuclear emergency [1]. The National Nuclear Emergency Preparedness Plan [2] is a national plan for nuclear emergency preparedness work in China, which has clearly defined the targets, mechanism, main tasks, and safeguard measures for scientific and technological innovations in the field of nuclear emergency preparedness. The nuclear emergency status is divided into emergency standby, plant emergency, site emergency, and off-site emergency (general emergency), which correspond to IV, III, II, and I Level Response respectively) in the National Nuclear Emergency Preparedness Plan, according to the accident type, severity, and radiation effects. The I Level Response is the most serious accident condition in the four-level response, which is the status that the nuclear facilities release or intentionally release a large number of radioactive material, and the consequences of the accident beyond the site boundary that may seriously endanger public health and environmental security. The I Level Response involves the emergency response actions of the public and non-emergency personnel inside the nuclear power plant, and emergency evacuation is one of the emergency actions in the I Level Response.

Nuclear emergency evacuation is important for preventing radioactive harm by hazardous materials and for limiting the consequences of the accident. As a crucial component of nuclear emergency response and management, evacuation prior to the release of radioactive material is the only protection measure that can completely avoid all kinds of radiation caused by radioactive release. The nuclear power plant emergency evacuation decision-making mechanism mainly includes four main aspects: evacuation response action judgment criteria, evacuation timing option, evacuation scope, and the evacuation method. The evacuation timing option involves evacuation time estimation and evacuation route selection [3,4].

The evacuation can be divided into self-evacuation and organized evacuation referring to the nuclear emergency experience in other countries, and the emergency evacuation experience under other disasters [5]. It has been shown that compared with self-evacuation, organized emergency evacuations are more time-saving, with a lower traffic accident rate. In addition, the evacuation methods vary from country to country. For instance, in the U.S., due to most nuclear power plants being located in low-population areas and not having large-scale transport capacity [6], the evacuation method by private car is adopted. While in China, nuclear power plants are always close to densely populated areas, and the use of home-based evacuation methods is likely to cause traffic congestion and reduce evacuation efficiency. Therefore, unified and coordinated traffic organization and large-capacity public transport must be used in order to complete the emergency evacuation in the limited time. The Canadian Ontario Provincial Nuclear Emergency Response Plan consists of Unified Transportation Management Plans (UTMP) [7].

Evacuation route selection is a key factor affecting the estimation of emergency evacuation time. A reasonable evacuation route can save evacuation time, increase the success rate of emergency rescue, and reduce the loss of the nuclear accident. The objectives of the evacuation routing selection are to minimize travel time and individual radiation exposure along a path, which is a multi-objective decision problem. Multi-objective decision problems are widely used in various research fields, but it is difficult to solve directly due to its complexity; thus most of the multi-objective decision making problems are transformed into single objective problems. Goal Planning Method, Layered Sequence Method, and Main Object Method are common methods of transforming multiple targets into single objective solutions [8]. In the process of emergency evacuation, evacuation time and personnel security are both important. According to the dose standard of nuclear accidents emergency evacuation, as long as the effective dose obtained by the evacuated personnel is under the standard, the evacuation process is safe. Thus, the Main Objective Method adopted in this paper assumes that the evacuation began before the release of mass radioactive material, and the radiation dosage of the personnel is less than the standard value; therefore the problem of evacuation routing selection is transformed into a single objective optimization.

There are only a few studies on the establishment of the emergency evacuation model for nuclear power plants [5]. Zou et al. [9] studied plant field emergency evacuation and rescue routes under nuclear accident in a nuclear power plant based on A* algorithm with an improved sub-period BPR resistance function. In addition, some scholars have studied the different aspects of emergency evacuation from nuclear accidents. For example, Li et al. [6] used the emergency evacuation virtual reality simulation system to estimate the emergency evacuation time of Fuqing nuclear power plant. Xie et al. [10] set up an S-BOX model to coordinate the emergency resources of multiple departments to respond to the nuclear emergency. Urbanik II [11] put forward some analysis about evacuation time estimates.

After the nuclear accident, it is crucial to evacuate people from the plant site to safe areas safely and quickly. Suppose that there are a small number of people distributed in several temporary shelters in site and it is required to transport all the people to the safe area by bus. The bus starts from the safety point, traversing all temporary shelters and back to its safety points in the shortest possible time. Thus the evacuation situation in this paper is the shortest path problem. The shortest path problem is a typical problem in graph theory and Dijkstra algorithms, and the A* algorithm and the SPFA algorithm etc. are the most common methods for solving the shortest path problem [12]. The parity of the spot diagram method is a common method for the Chinese Post-line Problem (CPP) [13,14]. The evacuation route from the nuclear power plant is abstracted into a network diagram, then a mathematical model of evacuation optimization route based on the parity of spot diagram method is established, and the solving process of the model is demonstrated by an example that can provide ideas for the selection and planning of a nuclear emergency evacuation route.

2. Evacuation Path Network Model with Multiple Security Points

Some assumptions:

(1) The paths are the same if the vehicle's starting point and destination are the same;
(2) The evacuation vehicles are buses;
(3) There is an emergency vehicle garage at the farthest distance from the plant entrance inside the nuclear power plant. Once a serious nuclear accident has occurred and evacuation is needed, the vehicles start from the garage and travel through every temporary shelter to take people in the nuclear plant site to a safe area past the entrance.
(4) The radiation dose of the personnel on the driving path of the emergency vehicle is within a safe value.

It is necessary to evacuate personnel from temporary shelters in the site to the safe area. The sketch map of evacuation route network composed of the roads, road nodes, and temporary shelters, is shown in Figure 1. The buses start from the garage, traversing all temporary shelters, and take people to the safe area. The sketch map can be transformed into a connected undirected graph using graph theory, thus the basic description of the emergency evacuation route for nuclear accidents is as follows:

$$\begin{cases} G = (V, A) \\ V = \{v_i, 1 \le i \le n\} \\ A = \left\{(v_i v_j)\middle| v_i, v_j \in V, A(i,j)\right\} \end{cases} \quad (1)$$

In the above formula, G denotes the road network diagram in the nuclear power plant; V is the set of vertices belonging to G; A is the set of the edges (the lines connecting the vertices) used to denote the evacuation route. They can be drawn up as V (G) and A (G). It is assumed that the evacuation path of the nuclear power plant is an undirected network diagram; the roads are the edge of the network graph, and the junction points of the roads are the nodes of the network diagram. A series of node sequences $V = (V_1, V_2, V_3, \ldots, V_n)$ are used to represent the paths' junction points, and the paths between the junction points and V_j ($i \neq j$ and V_i, $V_j \in V$) can be expressed as V_iV_j. In particular, the garage in the factory is defined as V_0 and the entrance is defined as $V_{0'}$. Thus, the evacuation network model of nuclear emergency with six nodes and 10 paths is established as in Figure 2, which is based on Figure 1.

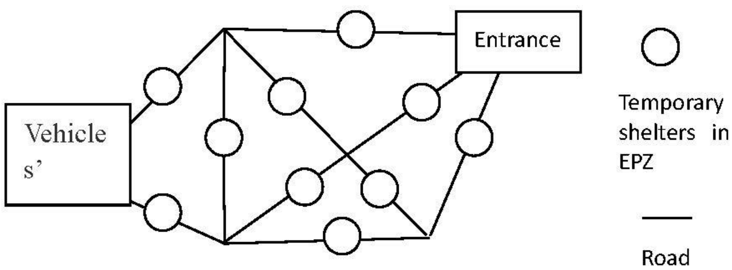

Figure 1. Sketch map of the evacuation route network.

There are a number of factors affecting the passage of time outside the site of the nuclear power plant, such as road traffic capacity, weather condition, the flow of traffic, the development of the nuclear accident, and the distance between two nodes [15], thus a time weight is added in each road in the evacuation as following, which is a function of the factors affecting efficient evacuation.

$$
\begin{cases}
G = (V, A, W) \\
V = \{v_i, 1 \leq i \leq n\} \\
A = \{(v_i, v_j) | v_i, v_j \in V, A(i, j)\} \\
W = f(k_i), 1 \leq i \leq n
\end{cases}
\tag{2}
$$

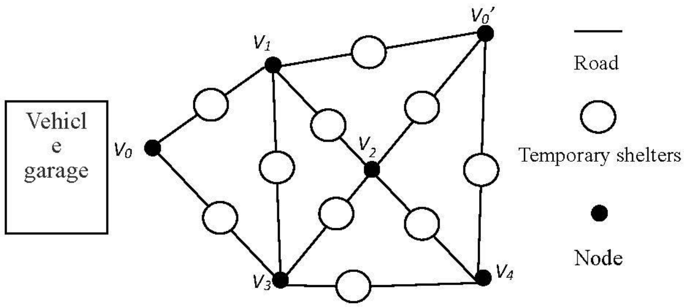

Figure 2. Evacuation network model.

However in the plant site, only the distance between nodes is considered, and the time weight in this study depends on the distance between nodes. According to the above formula, the network model can be established as showed in Figure 3.

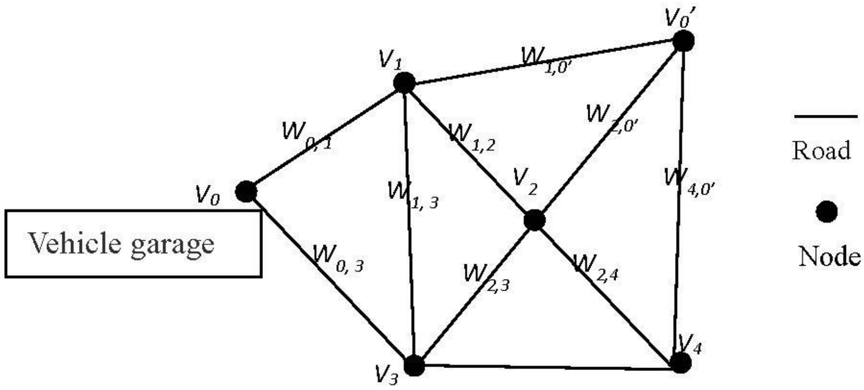

Figure 3. Evacuation network model with time weight.

Based on the parity-of-spot diagram method [13,14], the shortest evacuation route for nuclear emergency is obtained through following steps:

(1) Construct an evacuation network diagram and add weight for each edge.
(2) Find singularities (a singularity is the node for which the number of edges associated with it is odd).
(3) In the singularities above, find a node with the longest distance (largest weight) from the origin (V_0).
(4) Add a virtual origin V_t to the network diagram; connect the virtual origin V_t with a singularity found in the third step and the origin (V_0) separately, the weight of the connecting edges being zero.
(5) In addition to the singularity found in the third step, the number of singular points in the graph must be odd. Any singular point is paired with the origin (V_0), and the rest of the singularity is paired. A repeating edge is added between each pair of singularities (or between the singularity and the origin), then the number of edges associated with each node is even. At this time from the virtual origin V_t, going through the all edges (no repeat) can also return to V_t.

(6) A loop that contains a repeating edge is randomly selected, and the total weights of the loop are calculated. If the sum of the weight of the repeated edges in the loop is less than half of the loop's total weight, then the network model diagram is the optimal network, otherwise the repeating edge is adjusted until the repeated edges in the loop are less than half of the loop's total weight.

At this time, the path starts from the origin, and traversal of all of the lines in the diagram (not repeated) back to the virtual origin yields the optimal route. The virtual origin in the loop is deleted to obtain the shortest route.

3. Example Simulation

In the process of evacuation, the vehicles start from the unsafe area, transport to all the safe points in a zone, and eventually stop at the last safe point. The shortest time mainly depends on the route chosen, which is related to the location of temporary shelters as well as to the weight of each route. A network model is established based on the simplified diagram of a nuclear power plant's planar diagram. In this model, V_0 and $V_{0'}$ represent the vehicle garage and plant entrance separately. The weight of each path is the value of the length of the road, as shown in Figure 4.

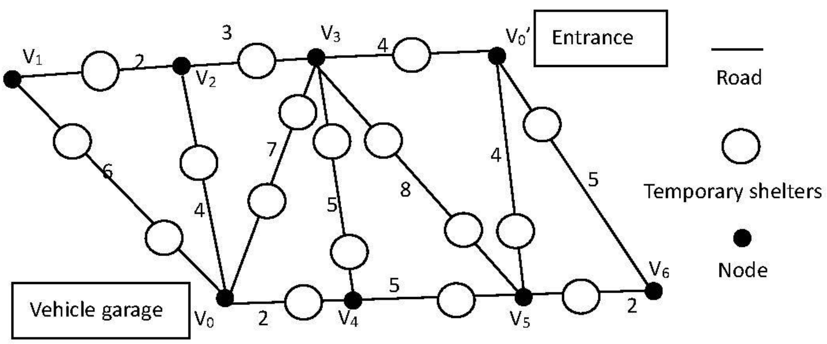

Figure 4. Evacuation network model.

(1) Finding all the singularities in Figure 4: V_2, V_3, V_4, $V_{0'}$. Among all the singularities, a point with the longest path with V_0 is found, and $V_{0'}$ is the point to find ($V_0V_4 = 2$, $V_0V_2 = 4$, $V_0V_3 = 7$, $V_0V_{0'} = 11$). A virtual origin V_t is added; V_t is connected to V_0 and $V_{0'}$ separately.

(2) Duplicate edges are added, so that each node in the graph has an even number of degrees. From node V_t, all the edges of the graph are traced through at least once, returning to V_t. There are two duplicate edges added in the network diagram, which is shown in Figure 5.

(3) In the loop of $V_0V_2V_3V_4$, the total loop weight = $V_0V_2 + V_2V_3 + V_3V_4 + V_4V_0$. The weight of the duplicate edges (5 + 4) is greater than half of the total loop weight (7). So, the duplicate edges in $V_0V_2V_3V_4$ loop should be changed, and we can adjust the duplicate edges as shown in Figure 6:

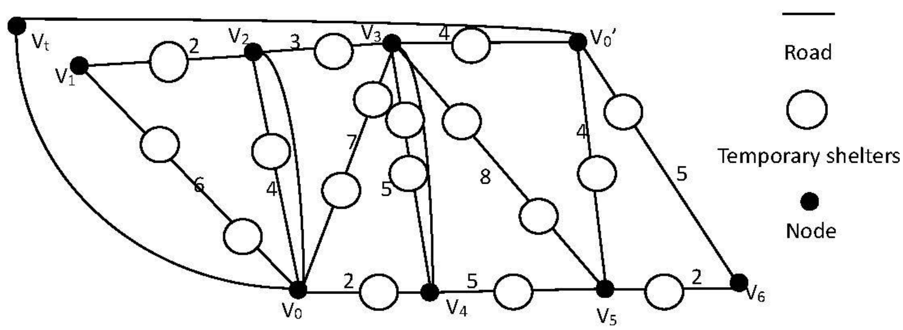

Figure 5. The evacuation network model with the virtual source and repeat edges.

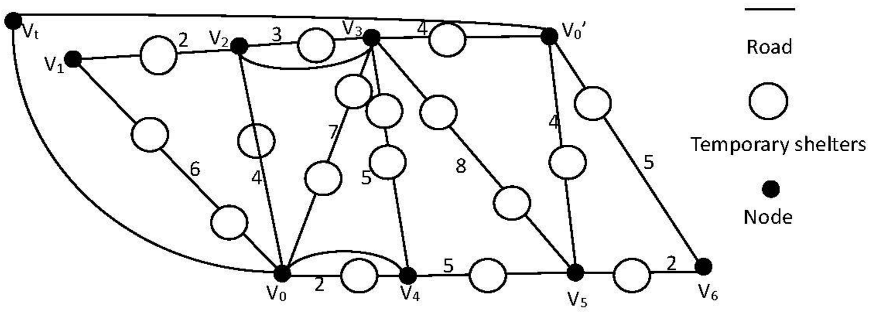

Figure 6. Revised evacuation network model.

A loop begins from the point V_t, travels through all of the points, and returns back to point V_t:

$$V_t \to V_0 \to V_1 \to V_2 \to V_0 \to V_4 \to V_0 \to V_3 \to V_2 \to V_3 \to V_4 \to V_5 \to V_3 \to V_{0'} \to V_5 \to V_6 \to V_{0'} \to V_t$$

The virtual origins are removed from the above loop, then the shortest route is:

$$V_0 \to V_1 \to V_2 \to V_0 \to V_4 \to V_0 \to V_3 \to V_2 \to V_3 \to V_4 \to V_5 \to V_3 \to V_{0'} \to V_5 \to V_6 \to V_{0'}$$

4. Conclusions

The selection of an emergency evacuation route in the nuclear accident is very important because it bears upon people's lives and property safety. Positive and correct organization, command, and scheduling can effectively reduce the threat of nuclear radiation. Supposing that there are a number of temporary shelters in-site and that people should go to the safe area by the evacuation vehicles in time, the vehicles need to go through every temporary shelter. Therefore, it is vital to find the right route in a limited time. A solution model for solving the shortest evacuation path problem is set up based on graph theory and the parity of the spot diagram method, considering the weight of a variety of factors, which can provide a decision basis for the nuclear emergency evacuation route.

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