Evacuation Shelter and Route Selection
Based on Multi-objective Optimization Approach

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ABSTRACT
Evacuation shelter and route selection are indispensable parts of emergency planning. An efficient plan can effectively evacuate people from a dangerous place to a safer location. Meanwhile, it is crucial to improve risk management. This article presents a multi-objective optimization algorithm based on social media and GIS to optimize shelter usage and personnel distribution considering social relationship. The proposed algorithm is examined using a case study for the Zhongguancun district in Beijing. The district is modeled by the graph theory. Traffic route data and population distribution are synthesized to form a risk map. Furthermore, the Floyd-Warshall algorithm is adopted to find a shortest path route in order to relocate evacuees to a safer place effectively. Efficiency, fairness and social relation are taken into consideration in this context.

Categories and Subject Descriptors
G.2.2 [Discrete Mathematics]: Graph Theory – graph algorithm, network problems, path and circuit problem.

General Terms

Keywords
evacuation; GIS; social media; multi-objective optimization; emergency management

1. INTRODUCTION
Over the past several decades, China had encountered many natural disasters and anthropogenic hazards during economic development. From 1980 to 2014, there has been more than 1611 disasters including complex disasters, natural and technology accidents happened. These disasters have brought tremendous life and economic losses to the affected areas.

Emergency evacuation is one of major activities in disaster response [1]. The purpose of emergency evacuation was to relocate crowded people from potential hazard areas to safe areas [2]. Emergency management researches can be applied to accident rescuing, logistic mission, hazard mitigation and risk management. Researches [3, 4] studied flood evacuation planning and logistics of hurricane evacuation. Investigators [5] provided a Protective Action Decision Model (PADM) to produce behavioral responses and advanced traveler information system (ATIS) was developed to guide evacuees to alternate routes in case of congestion on key roadways [6].

When facing natural hazard or human-made disaster, traffic network becomes vulnerable. In order to reflect the real road and traffic accurately, graph theory was employed [7]. Roads and intersections were specified as a sequence of edges and points. Traditionally, Dunn and Newton proposed a maximum flow algorithm applied to evacuation [8]. Yamada presented the minimal cost problem to optimize city emergency evacuation plan [9]. Campos et al suggested k-independent path for evacuation planning [10]. These researchers showed similarities, such as shortest path problem, which can be solved by the Dijkstra algorithm, Bellman-Ford algorithm or k-shortest algorithm. Heuristic algorithm, optimization approach and simplex method can also be applied to determine the evacuation route. The target of these methods was making full use of traffic network information, allocating traffic resources and evacuating residents effectively at the shortest time before disaster. Evacuation management agencies usually recommend alternative routes for evacuees to take [11]. However, people in the affected area would like to choose different routes or shelters according to their own understanding and social relationship. Sometimes, residents may change the routes or safety destination from initial. Under this circumstance, local administration needs to consider real-time path selection and social media.

Successful evacuation depends on many factors, such as vehicles usage, number of people evacuated, total evacuation time and shelter utilization. Li et al proposed a scenario-based location model to optimize a set of shelter locations [12]. Bayram et al proposed a constrained system optimal model to locate shelters and to assign evacuees to the nearest shelters with a given degree of tolerance [13]. However, few literatures traded off these conflicting objectives. For instance, user equilibrium was first formulated according to least travel time, and this sole criterion lasts for about forty years [14]. Therefore, multi-objective optimization approach is greatly needed. Stepanov and Smith presented an integrating programming formulation combining with routing model and GIS module for optimal route assignment [15]. Meanwhile, traffic congestion and time delay were taken into consideration. Saadatseresht et al proposed a three-step method including (a) safe area selecting, (b) optimal path finding,
optimal safe area selection by using multi-objective evolutionary optimization approach [16]. These three steps determined safety area designation and optimum path finding. After that, they presented the evacuation plan on a map.

Spatial decision support system (SDSS) is a new approach that integrates GIS and intelligent traffic system (ITS). de Silva and Eglese integrated simulation modelling and spatial technologies to produce a spatial decision tool for emergency planning [17]. GPS received the real time vehicle information through satellite or traffic camera, then transferred these data to ITS. Meanwhile, ITS recognized or predicted the optimal routes for drivers.

In this article, GIS is integrated with traffic system and network prototype. Evacuation routing needs to be selected in advance when unexpected emergency happens. Location based service, such as real-time evacuation of urban dynamics [18] is required. Social relationship can also be considered as a constraint in the optimization problem. Communication tools like cell phones can provide a new insight for urban traffic management [19].

2. MODEL AND METHODOLOGY

2.1 Framework and Model Development

![Figure 1. Framework and model development](image)

The framework includes three submodules: (1) data and algorithm; (2) traffic networking modeling and (3) linear programming. By integrating three submodules, evacuation shelter and route selection can be realized and displayed on smart phones.

2.2 Traffic Network Modeling

Traffic network is an abstract undirected network. This network consists of series nodes and edges. Nodes and edges can be hypothesized as constant variables. In the network graph $G$, it contains three parameters: $N, E, \omega$. $N$ denotes node in the crossroad and each node has its degree and utilization. $E$ denotes the edge between two vertexes and each edge has its length, width and traffic capacity. $\omega$ denotes the weight on each edge according to the attributes. Three parameters together denote the topology of the whole network graph. By adopting this kind of measure, the entire traffic network’s information can be stored in advance.

2.3 Shortest Path Route Choice

Shortest path problem is an optimal routing problem. The optimal path is not always the same for different transportation problems. The weight on each edge changes its value from time to time depending on road condition. In this article, the weight is proportional to the corresponding road length. The Floyd-Warshall algorithm is employed to solve the shortest path problem. The following steps are used to obtain shortest path routes.

$Step~1$: Predetermine several shelters according to disaster scenarios. By using traffic network’s information, an original destination trip matrix (O-D trip matrix) can be initialized.

$Step~2$: Add new crossroad nodes into the O-D trip matrix and calculate the new path routes.

$Step~3$: Analyze the results and determine whether new paths are shorter than the formal ones.

$Step~4$: Continue Step 3 until all residual nodes are checked.

2.4 Multi-objective Optimization

Evacuation shelter and route selection are a linear-programming problem with limited resources. Most objectives contradict each other in multi-objective evacuation problem. To solve this dilemma, emergency evacuation shelters are designated by considering the number and location of rescue facilities such as nearby bus stop, subway station, the location of hospital [3, 6]. Meanwhile, two objective functions are made in [15] as follows:

$$U = \min \sum_{j} \frac{p_j}{C_j} - 1 \quad V = \min \sum_{j} \sum_{i} d_{ij} p_j$$

subject to:

$$d_{ij}^{(k)} = \min(d_{ij}^{(k-1)}, d_{ik}^{(k-1)} + d_{kj}^{(k-1)})$$

parameters

$i, k : \text{node ID, } i, k \in N$ ;

$j : \text{shelter ID, } j \in N$ ;

$p_j : \text{population of the } i\text{th node to the } j\text{th shelter;}$

$d_{ij} : \text{shortest path from the } i\text{th node to the } j\text{th shelter;}$
Two objectives are treated to choose the best shelters and evacuation routes for evacuees. $U$ optimizes the usage of shelters, 
$V$ minimizes the evacuee’s number multiplied by corresponding path distance which is the indicator of system optimum strategy. 
The Floyd-Warshall algorithm is used to calculate the shortest path $d_{ij}$ between each vertex to each shelter. Therefore, distance matrix $d_{ij}$ is obtained. The population distribution $p_i$ in each vertex can be considered as a constraint.

3. CASE STUDY

3.1 Study Area and Shelters Location

The Zhongguancun district is located in the northwestern Beijing. It consists of 5.28 km$^2$ area and 245 thousands residents. The district is divided into four subareas and the most dangerous area is selected for our research (26.8% of total area and people). Regional population distribution is hard to obtain. Instead, total construction area is used. The population distribution is considered to be proportional to the construction area. From an operational point of view, choosing a shelter makes a full use of resources in the urban area, such as, park, bus station, school and stadium. In this paper, five shelters are designated fairly uniform among the study area. There are 66 thousands people in a 1.42 km$^2$ area.

3.2 Produce Risk Maps Using GIS

Jenks natural breaks classification method is used to calculate the level of five different construction areas in ArcGIS because this method can minimize the interval error. Construction area is summed in the same level. Total construction areas of four zones are shown in figure 2.

It can be estimated that the greater total construction area is, the higher risk the area has. Therefore, Zone 2 and Zone 3 are more risker than Zone 1 and Zone 4 in figure 3. However, Zone 3 is identified as location that is more dangerous where red color means the most dangerous constructions. Finally, Zone 3 is chosen as the study area.

3.3 Get Population Data by Voronoi Diagram

In this paper, four map layers are used to calculate the population distribution data. Firstly, 189 crossroad points are gained through traffic network. These points are used to produce the Voronoi diagram, which contains 189 Thiessen polygons. Secondly, the Thiessen polygons are applied to cut the building construction layer. Each polygon contains different areas of construction. Lastly, the area multiplied by population density can calculate population data in these polygons. It can be presumed that each
3.4 Programming Realization

A two-staged method is used to handle the multi-objective function in section 2. On the one hand, total population in each of five shelters is calculated to optimize the usage of shelters. On the other hand, the multi-objective problem is seen as two single objective problems after the best population distribution is gained in each shelter. After that, the Floyd-Warshall algorithm is used to calculate the shortest route from 189 points to each of five shelters. Therefore, the population distribution problem is solved to make the evacuation procedure more efficiency. This problem is solved by programming on Matlab.

Programming result shows that 18 special points have two best choices to the shelters. Figure 5 shows the population distribution of these points. For example, point 115 has two choices to get to the shelter, namely, 267 people (75%) will evacuate to shelter 3 and another 89 people (25%) will evacuate to shelter 4. Presentative route selection is shown in figure 6 using ArcGIS.

We have developed a mobile phone application, EM-APP that aimed at improving emergency management. All results in this paper including evacuation and route selections can be realized using this mobile phone application (APP). Users can find their friends under conditions that both sides turned on the location-sharing function. When they find friends on the map, they can send a message for social activities or evacuation during disaster.

The EM-APP can be used in a large-scale activity, like sports events, music concerts etc. Registered users can meet their friends once emergency happens. The EM-APP provides the best route planning to his/her friend’s location. When they make an appointment to a location or the evacuation shelter, it can provide the route plan to both sides automatically. Meanwhile, the route plan contains three methods, bus, car or walking. The users can select one according to emergency scenario.

4. DISCUSSION

Evacuation plan is actually a liner-programming problem in operational research. Individuals may choose the nearest shelter if there is not sufficient information. Nevertheless, evacuees’ choice may destroy the equilibrium of the entire system. That is so called “the whole is greater than the sum of the parts”. At the same time, people may be evacuated to different shelters even if they are in...
the same place. Multi-objective evacuation routing in transportation network gives a useful algorithm when the administration begins to evacuate people in the affected area. Traditionally, government may evacuate all people to the nearest shelters. In this study, two important points can put forward.

(1) Evacuate people to the nearest shelter is not always a good method. Dynamic of disaster evolution should be considered.

(2) People in the same place may evacuate to different shelters. Part of people may be evacuated to different places. Social status and social relations play important roles in evacuation.

5. CONCLUSION

Risk map is presented at the beginning of this paper. The most dangerous part is chosen in our study. Through graph theory, nodes and edges are modeled in ArcGIS. By cutting construction area, people’s distribution in each point is calculated. After that, the multi-objective method is used to calculate the best population distribution to each shelter. This model can be used to make a full use of traffic network information, minimize the total distance for all affected people. Therefore, the total evacuation time can be decreased. The general steps of the best evacuees’ distribution plan is also given in this paper along with the multi-objective methods. Finally, two constructional suggestions illustrate with a case study in the Zhongguancun district and brief introduction for a mobile phone application named EM-APP are given.

In general, each type of disaster has repeatable characteristics, such as long duration, hard to predict and sudden rush. Disasters happened in the mega-cities may require immediate and quick response [20]. Relocating threatened population to safer area may be needed [21]. This study provides an effective method, which can be used to optimize the shelter locations and traffic usages.

6. ACKNOWLEDGMENTS

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7. REFERENCES


