INTERNATIONAL JOURNAL OF COMPUTERS COMMUNICATIONS & CONTROL
Online ISSN 1841-9844, ISSN-L 1841-9836, Volume: 17, Issue: 4, Month: August, Year: 2022
Article Number: 4749, https://doi.org/10.15837/ijccc.2022.4.4749

A Multi-objective Location Decision Making Model for Emergency Shelters Giving Priority to Subjective Evaluation of Residents

Yiying Wang, Zeshui Xu

Yiying Wang
Business School
Sichuan University
Chengdu, Sichuan, 610064, China
wanggyiying@163.com

Zeshui Xu*
Business School
Sichuan University
Chengdu, Sichuan, 610064, China
xuzeshui@263.net
*Corresponding author

Abstract

Earthquake is regarded as the most destructive and terrible disaster among all-natural disasters [1]. Experts agree that immediate emergency evacuation is the safest and most effective response to the earthquake disaster [2]. In the research of emergency evacuation planning, the influence of human subjectivity has gradually attracted researchers' attention. In this paper, we take the human subjectivity as one of the most important factors for emergency evacuation planning. Based on the preferences of the residents at each demand point for the attributes of every candidate emergency shelter, the subjective score of each candidate emergency shelter is obtained. The preferences of residents will change with the refuge time, so do the weights of residents' subjective scores of all attributes of candidate emergency shelters. Therefore, we use the subjective score function to describe the change of residents' evaluations for the emergency shelter over time, and take the average value of subjective scores at all refuge times as the primary basis for location decision making. On these bases, we build a multi-objective location decision making model for emergency shelters giving priority to subjective evaluation of residents. In the model, we consider transfer distance, the efficiency of construction funds and the distribution of people among emergency shelters. Considering fairness, we minimize the standard deviation of the scores and the standard deviation of the transfer distances in the model. This model is applied to a case, which verifies its feasibility and shows that human subjectivity plays an important role in emergency evacuation planning.

Keywords: Emergency shelter location; Multi-objective optimization; Multi-attribute; Subjective preference; Total refuge time.

1 Introduction

The frequent occurrence of natural disasters such as earthquakes has caused a large number of casualties and property losses [3], [4]. Therefore, emergency evacuation planning has attracted more and more attention. Emergency planning includes evacuation of disaster victims, site selection and construction of emergency shelters, etc. Next, we review the related literature.

The location problem originated from weber's study, which selected a position for the warehouse by minimizing the distance between the warehouse and all customers [5]. From then on, scholars have proposed models such as p-median problem [6], [7], set covering location problem [8] and maximal covering location problem [9]. However, the location of emergency shelters and evacuation of disaster victims are complex issues, involving many factors, while the single-objective model ignores some important objectives [10]. Therefore, the multi-objective model was put forward. Some scholars regarded minimizing the total evacuation distance and the total cost as the targets of emergency evacuation site selection [10], [11]. Coutinho-Rodrigues et al. presented a mixed integer linear programming model with such objectives as risks associated with paths and shelter locations, evacuation path lengths, and the final evacuation time [12]. Wang et al. proposed a model with three objectives to minimize construction cost, minimize traveling distance and maximize final number of survivors [13]. Wang et al. proposed a multi-objective optimization model, in which the first objective is to minimize the total service distance, the second objective is to maximize the network reliability level [14].

A central challenge in developing an evacuation plan is in determining the distribution of evacuees into the safe areas, that is, deciding where and from which road each evacuee should go [15]. Therefore, scholars have developed bilevel models with the multi-objective optimization in the upper-level problem or in the lower-level problem or both in the upper-level and lower-level problems. Xu et al. proposed scenario-based hybrid bilevel model that considers the dynamic number of evacuees and its implementation for earthquake emergency shelter location and allocation [10]. Kulshrestha et al. developed a bilevel model, in which the planning authority determines the shelter locations along with their capacities, whereas the evacuees choose the shelters and routes to evacuate [16].

From the previous literature review, we can see that scholars have begun to pay attention to residents' willingness to transfer, such as the choice of transfer route. In fact, the decision-making theory based on subjective preference has been widely studied and applied in many aspects, such as commodity selection [17], investment decision [18]. However, subjectivity associated with factors for shelter location decisions are not given much research attention [19]. Recent research considered self-interest (non-cooperative behavior) of evacuees during large evacuations [10], [20]. In this paper, the subjective willingness of the affected residents to move in an emergency is not only reflected in the choice of the transfer route, but also in their satisfaction with the emergency shelters, including their satisfaction with the types of emergency shelters, supporting facilities, accessibility, environment and so on. Only when we take into account the affected residents' willingness to transfer to emergency shelters, can they cooperate with the emergency management department to complete the implementation of various emergency management measures to the greatest extent.

In addition to paying attention to the satisfaction of residents with the emergency shelters, equity is another concern in emergency planning. However, there is not any common definition for equity [21]. Ng and Park proposed a model that yielded shelter assignments, which accounts for fairness in the sense that the algorithm assigns evacuees to shelters that are as close as possible to their points of origin [22]. Tsai and Yeh thought that the regional allocation of disaster evacuation/refuge shelters must consider timeliness and fairness. The indicator for fairness is the number of victims each single shelter can accommodate; the more the victims, the higher the service [23]. Sabouhi et al. developed a model, in which equity in relief provided for various affected areas is achieved by defining objective functions that minimize the maximum time for the transportation of evacuees to shelters, the transportation of injured people to hospitals, and the distribution of relief commodities [21]. In this paper, the residents of each demand point evaluate the attributes of emergency shelters according to their own preferences, and get the score of each emergency shelter. For the fairness, we assume that the residents in a demand point should be transferred only to their higher-scored emergency shelters that are within the service distance of this demand point. In addition, we take the standard deviation of the subjective scores and the standard deviation of the transfer distance as the factors to be considered, and minimize these two standard deviations as two goals in model, which is another embodiment of fairness. Therefore, in this paper the location planning and construction of emergency shelters proposed is based on the subjectivity of regional residents, and the construction of emergency shelters in our study is carried out in advance before the disaster, rather than the temporary planning and construction during and after the disaster [24].

In recent years, scholars have paid more and more attention to the standards of site selection and construction of emergency shelters. Nappi and Souza raised 10 possible criteria and their relevant aspects, including: location, optimal distribution, urban infrastructure, safety, physical adequacy, cultural adequacy, privacy, environmental comfort, universal accessibility and economic aspects [25]. Aman and Aytac defined 15 criteria to evaluate the suitability in terms of spatial, natural structure and accessibility of each potential open space for emergency gathering [26]. Wu et al. established an indicator system comprising five aspects: scale and location; risk of disaster; rescue facilities; feasibility; resident aspect [27]. Song et al. summarized the evaluation criteria for shelter-site selection, including location & logistic efficiency, costs, environmental conservation and social aspects [28]. In this paper, we combine the above-mentioned site selection and construction standards of emergency shelters, and refer to China Earthquake Administration's standard which is called Site and Supporting Facilities for Earthquake Emergency Shelter [29], and put forward six site selection and construction indexes of emergency shelters, including distance, accessibility, scale, supporting facilities, environment and type.

The contributions of this paper are as follows: we comprehensively use the methods of normal distribution, ordered weighted aggregation (OWA) operator [30], [31], [32] and analytic hierarchy process (AHP) [33] to form the subjective score and the initial weight of each attribute score; on the basis of reasonable assumptions, the dynamic weight of each attribute score is obtained; the concept of total refuge time is formed, and the subjective score function of each demand point for each candidate site is obtained with the total refuge time as the independent variable; and the average value of subjective scores at all refuge times is taken as the primary basis for location decision making. This paper expands the meaning of fairness in emergency shelter location, and brings the standard deviation of residents' subjective scores and the standard deviation of residents' transfer distances together into the scope of fairness in emergency shelter location. As human subjectivity is paid more and more attention, the model in this paper could be used as an important part of the government decision support system for emergency shelter location [34].

The rest of the paper is arranged as follows: Section 2 presents a methodology to determine the value and the weight of each attribute. Section 3 describes the formulation of the model. Then, in Section 4, the previous multi-objective model is applied to a case. Meanwhile, we conduct some analyses about the case. Finally, we make conclusions about our study in Section 5.

2 Methodology

2.1 Description of the problem and determining the value of each attribute

The candidate emergency shelters in this paper are the sites built for other purposes, such as the park, the green space, the square, the stadium and the indoor public place. If a site needs to be used as an emergency shelter, it needs to be constructed to improve the function, so as to meet the requirements of being an emergency shelter.

This paper focuses on people's subjective preferences for the attributes of the emergency shelters. Emergency shelter has many attributes. We select six attributes to analyze people's subjective preferences. These attributes include the distance from the demand point to the emergency shelter, the accessibility, scale, supporting facilities, environment and type of the emergency shelter. The first two are external attributes, and the last four are internal attributes. According to different evaluation methods, these attributes are divided into three categories: 1) the distance from the demand point to the emergency shelter; 2) the accessibility, the scale, the supporting facilities and the environment of the emergency shelters; 3) the types of the emergency shelters. Next, we discuss the subjective evaluation of these attributes by the affected residents in turn.

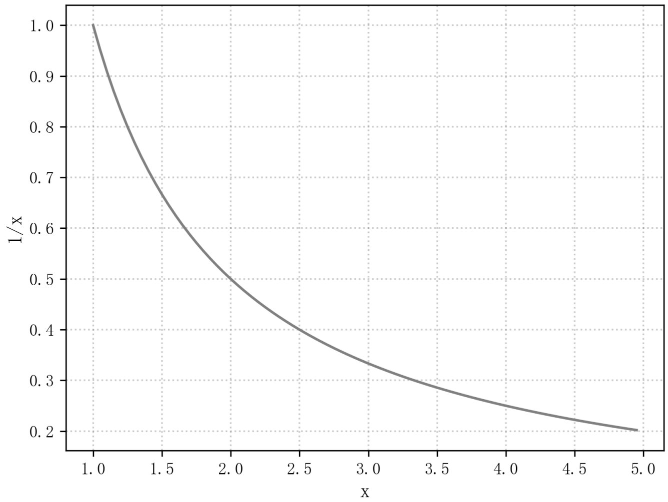

Figure 1: Graph of function $y = 1/x$.

1. **Evaluation of the distance attribute:**

   Some researchers studied people's behaviors under the condition that the travel cost is proportional to distance [35]. Usually, people's willingness to move to a place decreases with the increase of the distance, that is, the farther away the place is, the more reluctant people are to move, and people prefer to move to a place closer to themselves. This paper assumes that the score of the distance between the demand point i and the shelter j is inversely proportional to the distance between them, as shown in Fig 1.

   Let the distance between the demand point i and the shelter j be r_{ij}, and the distance between the demand point i and its nearest shelter be r_{i0}, then the distance score of the demand point i to the shelter j could be expressed as $x_{ij,d} = 100 \cdot \frac{r_{i0}}{r_{ij}}$.

2. **Evaluation of the accessibility, the scale, the supporting facilities and the environment:** Emergency shelters are distributed in various areas of the city. Due to different actual construction conditions, their attributes are at different levels. According to the construction standards, we suppose that the levels of the accessibility, the scale, the supporting facilities and the environment are divided into five grades. The scores from grade 1 to grade 5 are set sequentially to be: 100, 90, 80, 70 and 60. Then, the scores of the accessibility, the scale, the supporting facilities and the environment of the shelter j could be obtained, which are expressed as $x_{j,c}$, $x_{j,sc}$, $x_{j,su}$ and $x_{j,en}$ respectively.

   When a candidate emergency site is selected as the emergency site, we can take measures to improve the level of the attributes of this emergency site to obtain a higher score.

3. **Evaluation of the type:** Different residents have different preferences for different types of sites. We use the combination of normal distribution and the OWA operator to evaluate different types of sites [30], [31], [32]. The evaluation process is as follows:

   Residents evaluate the type of each shelter according to their preferences, and get the subjective score of type ranging from 1 to 100. The scores obtained are arranged in descending order. We use k to indicate the type of the emergency shelter, i.e., k represents the park (PA), the green space (GR), the square (SQ), the stadium (ST) and the indoor public place (ID). Let u be the number of residents participating in the evaluation, and the following evaluation matrix is obtained:

$$\begin{bmatrix} h_1^{PA} & h_1^{GR} & h_1^{SQ} & h_1^{ST} & h_1^{ID} \\ h_2^{PA} & h_2^{GR} & h_2^{SQ} & h_2^{ST} & h_2^{ID} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h_q^{PA} & h_q^{GR} & h_q^{SQ} & h_q^{ST} & h_q^{ID} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ h_{u-1}^{PA} & h_{u-1}^{GR} & h_{u-1}^{SQ} & h_{u-1}^{ST} & h_{u-1}^{ID} \\ h_u^{PA} & h_u^{GR} & h_u^{SQ} & h_u^{ST} & h_u^{ID} \end{bmatrix}$$

in which, h_q^{PA}, h_q^{GR}, h_q^{SQ}, h_q^{ST}, h_q^{ID} respectively represent the score of the ith resident for the Park (PA), the green space (GR), the square (SQ), the stadium (ST), the indoor public place (ID), which could be uniformly expressed as h_q^k.

The method of determining the OWA weight based on normal distribution refers to weighting those too large or too small data by small values to eliminate or reduce the impact of unfair evaluation on decision-making results [32]. The OWA weights of residents' scores are solved by using the method of normal distribution, so as to obtain residents' scores for different types of sites. Calculating the weight coefficient $\omega_{k,q}$, which is the evaluation of the resident q for the site type k ($q = 1, 2, 3, \ldots, u$):

$$\omega_{k,q} = \frac{e^{-\left[\left(h_q^k - \mu_k\right)^2 / 2\sigma_k{}^2\right]}}{\sum_{r=1}^{u} e^{-\left[\left(h_r^k - \mu_k\right)^2 / 2\sigma_k{}^2\right]}}, \mu_k = \frac{\sum_{q=1}^{u} h_q^k}{u}, \sigma_k = \sqrt{\frac{1}{u} \sum_{q=1}^{u} \left(h_q^k - \mu_k\right)^2},$$

in which, μ_k represents the average value of scores of all residents participating in the evaluation on the site type k; σ_k represents the standard deviation of scores of all residents participating in the evaluation on the site type k.

We calculate the type score h^k of the type k by the following formula: $h^k = \sum_{q=1}^{u} \omega_{k,q} h_q^k$. Therefore, the final evaluation matrix of each site type is:

$$\begin{bmatrix} h^{PA} & h^{GR} & h^{SQ} & h^{ST} & h^{ID} \end{bmatrix},$$

in which, h^{PA}, h^{GR}, h^{SQ}, h^{ST}, h^{ID} represent the final score of the park, the green space, the square, the stadium, the indoor public place respectively.

Through the above analysis, we have obtained all the attribute scores of the shelter j. The distance score, the accessibility score, the scale score, the supporting facilities score, the environment score and the type score are expressed as $x_{ij,d}$, $x_{j,c}$, $x_{j,sc}$, $x_{j,su}$, $x_{j,en}$, $x_{j,k}$ (here, $x_{j,k}$ is the above mentioned h^k) respectively.

2.2 Dynamic weights of the attributes

AHP can quantify people's experience judgment, and it is more practical when there are many and complicated factors [36]. Through AHP, the relative importance of pairwise attributes is judged, the weight judgment matrix is constructed, the consistency is checked, and the weights are normalized, so that the weight of each attribute can be obtained. Because this paper needs to deal with many attributes of the demand points, we use the AHP [33] to get the attribute weights of each demand point. In this paper, the attribute weight reflects the degree of resident's concern on the attribute of the candidate emergency shelter:

$$\boldsymbol{\omega_i(0)} = (\omega_{i,d}(0), \omega_{i,c}(0), \omega_{i,sc}(0), \omega_{i,su}(0), \omega_{i,en}(0), \omega_{i,k}(0)),$$

in which, $\omega_{i,d}(0)$, $\omega_{i,c}(0)$, $\omega_{i,sc}(0)$, $\omega_{i,su}(0)$, $\omega_{i,en}(0)$, $\omega_{i,k}(0)$ represent respectively the weight of the distance score, the accessibility score, the scale score, the supporting facilities score, the environment score and the type score that are evaluated by the demand point i, and meet:

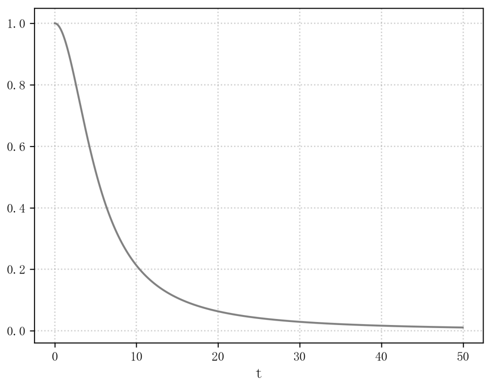

Figure 2: The graph of function $f_1(t)$.

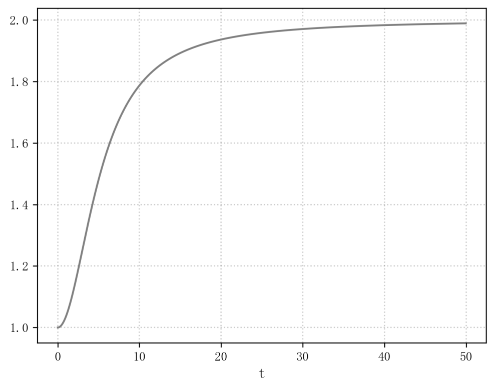

Figure 3: The graph of function $f_2(t)$.

$$\omega_{i,d}(0) + \omega_{i,c}(0) + \omega_{i,sc}(0) + \omega_{i,su}(0) + \omega_{i,en}(0) + \omega_{i,k}(0) = 1.$$

In fact, for different total refuge time (i.e., the total time that the residents stayed in an emergency shelter at one time of refuge), the resident's preference for each attribute of the emergency shelter is also different. That is, the weight of each attribute score of the emergency shelter will change with the total refuge time. Therefore, the weight obtained by the above AHP method is only taken as the initial weight. We use the dynamic weight to express the change of people's preference for the attributes of the emergency shelters for different total refuge times. Furthermore, people's preferences for external attributes and internal attributes change in the opposite direction with the change of the total refuge time. The longer the total refuge time, the more attention they pay to internal attributes, and the less attention they pay to external attributes. This paper assumes that the change of people's preferences for external attributes and internal attributes meets $f_1(t) = \frac{1}{1+\alpha t^2}$ and $f_2(t) = 2 - \frac{1}{1+\alpha t^2}$ respectively, where t $(t \geq 0)$ represents the total refuge time, α $(\alpha > 0)$ is a constant. The following two figures are the graphs of $f_1(t)$ and $f_2(t)$ respectively. From Fig 2 and Fig 3, we could see that $f_1(t)$ is a decreasing function and $f_2(t)$ is an increasing function, which satisfy the change of resident's external attribute preference and internal attribute preference respectively.

The first and second derivatives of $f_1(t) = \frac{1}{1+\alpha t^2}$ are:

$$f_1'(t) = -\frac{2\alpha t}{(1+\alpha t^2)^2}, f_1''(t) = \frac{2\alpha(3\alpha t^2 - 1)}{(1+\alpha t^2)^3}.$$

When $f_1''(t) = 0$, i.e., $\frac{2\alpha(3\alpha t^2-1)}{(1+\alpha t^2)^3} = 0$, we have $t = \frac{1}{\sqrt{3\alpha}}$.

When $t < \frac{1}{\sqrt{3\alpha}}$, we have $f_1''(t) < 0$; when $t > \frac{1}{\sqrt{3\alpha}}$, we have $f_1''(t) > 0$. Therefore, when $t = \frac{1}{\sqrt{3\alpha}}$, $f_1'(t)$ get the minimum value, and when $t = \frac{1}{\sqrt{3\alpha}}$, $f_1(t)$ decreases the fastest. In order to get the weight function of each attribute, it is necessary to determine the value of α. This paper assumes that $f_1(t)$ decreases the fastest when $t = 3$, then $\alpha = \frac{1}{27}$.

Therefore, the weight functions of the distance score, the accessibility score, the scale score, the supporting facilities score, the environment score and the type score are as follows:

$$\begin{aligned}
\omega_{i,d}(t) &= \omega_{i,d}(0)f_1(t) = \frac{27\omega_{i,d}(0)}{27+t^2},\\
\omega_{i,c}(t) &= \omega_{i,c}(0)f_1(t) = \frac{27\omega_{i,c}(0)}{27+t^2},\\
\omega_{i,sc}(t) &= \omega_{i,sc}(0)f_2(t) = \omega_{i,sc}(0)\left(2-\frac{27}{27+t^2}\right),\\
\omega_{i,su}(t) &= \omega_{i,su}(0)f_2(t) = \omega_{i,su}(0)\left(2-\frac{27}{27+t^2}\right),\\
\omega_{i,en}(t) &= \omega_{i,en}(0)f_2(t) = \omega_{i,en}(0)\left(2-\frac{27}{27+t^2}\right),\\
\omega_{i,k}(t) &= \omega_{i,k}(0)f_2(t) = \omega_{i,k}(0)\left(2-\frac{27}{27+t^2}\right).
\end{aligned}$$

When $t = 0$, we have $f_1(0) = f_2(0) = 1$, the weight of each attribute score is the initial weight under this condition. When $t > 0$, the sum of the attribute weights of the demand point i is:

$$\begin{aligned}
\omega_i(t) &= \omega_{i,d}(t)+\omega_{i,c}(t)+\omega_{i,sc}(t)+\omega_{i,su}(t)+\omega_{i,en}(t)+\omega_{i,k}(t)\\
&= f_1(t)(\omega_{i,d}(0)+\omega_{i,c}(0))+f_2(t)(\omega_{i,sc}(0)+\omega_{i,su}(0)+\omega_{i,en}(0)+\omega_{i,k}(0)).
\end{aligned}$$

Assume that $f_1(t) = f_1(0) - \Delta(t)$. Since $f_1(t) + f_2(t) = 2$, we have $f_2(t) = f_2(0) + \Delta(t)$. Then

$$\begin{aligned}
\omega_i(t) &= (f_1(0)-\Delta(t))(\omega_{i,d}(0)+\omega_{i,c}(0))+(f_2(0)+\Delta(t))(\omega_{i,sc}(0)+\omega_{i,su}(0)+\omega_{i,en}(0)+\omega_{i,k}(0))\\
&= f_1(0)(\omega_{i,d}(0)+\omega_{i,c}(0))-\Delta(t)(\omega_{i,d}(0)+\omega_{i,c}(0))+f_2(0)(\omega_{i,sc}(0)+\omega_{i,su}(0)+\omega_{i,en}(0)+\omega_{i,k}(0))\\
&\quad +\Delta(t)(\omega_{i,sc}(0)+\omega_{i,su}(0)+\omega_{i,en}(0)+\omega_{i,k}(0))\\
&= 1+\Delta(t)[(\omega_{i,sc}(0)+\omega_{i,su}(0)+\omega_{i,en}(0)+\omega_{i,k}(0))-(\omega_{i,d}(0)+\omega_{i,c}(0))].
\end{aligned}$$

When $(\omega_{i,sc}(0)+\omega_{i,su}(0)+\omega_{i,en}(0)+\omega_{i,k}(0))-(\omega_{i,d}(0)+\omega_{i,c}(0)) \neq 0$, we get $\omega_i(t) \neq 1$. Therefore, we need to normalize $\omega_i(t)$:

$$\overline{\omega_{i,d}(t)} = \omega_{i,d}(t)/\omega_i(t), \overline{\omega_{i,c}(t)} = \omega_{i,c}(t)/\omega_i(t), \overline{\omega_{i,sc}(t)} = \omega_{i,sc}(t)/\omega_i(t),$$

$$\overline{\omega_{i,su}(t)} = \omega_{i,su}(t)/\omega_i(t), \overline{\omega_{i,en}(t)} = \omega_{i,en}(t)/\omega_i(t), \overline{\omega_{i,k}(t)} = \omega_{i,k}(t)/\omega_i(t),$$

in which, $\overline{\omega_{i,d}(t)}$, $\overline{\omega_{i,c}(t)}$, $\overline{\omega_{i,sc}(t)}$, $\overline{\omega_{i,su}(t)}$, $\overline{\omega_{i,en}(t)}$, $\overline{\omega_{i,k}(t)}$ are the normalized weights of the distance score, the accessibility score, the scale score, the supporting facilities score, the environment score and the type score respectively. Here,

$$\overline{\omega_{i,d}(t)}+\overline{\omega_{i,c}(t)}+\overline{\omega_{i,sc}(t)}+\overline{\omega_{i,su}(t)}+\overline{\omega_{i,en}(t)}+\overline{\omega_{i,k}(t)} = 1.$$

3 The formulation of the model

3.1 The formulation of the score function and the standard deviation function

When the total refuge time is t, the distance score, the accessibility score, the scale score, the supporting facilities score, the environment score and the type score of the emergency shelter j that are evaluated by the demand point i could be expressed as follows:

$$y_{ij,d}(t) = \overline{\omega_{i,d}(t)} \cdot x_{ij,d}, y_{ij,c}(t) = \overline{\omega_{i,c}(t)} \cdot x_{j,c},$$

$$y_{ij,sc}(t) = \overline{\omega_{i,sc}(t)} \cdot x_{j,sc}, y_{ij,su}(t) = \overline{\omega_{i,su}(t)} \cdot x_{j,su},$$

$$y_{ij,en}(t) = \overline{\omega_{i,en}(t)} \cdot x_{j,en}, y_{ij,k}(t) = \overline{\omega_{i,k}(t)} \cdot x_{j,k}.$$

Therefore, when the total refuge time is t, the subjective score of the demand point i for the candidate shelter j is:

$$\begin{aligned} y_{ij}(t) &= y_{ij,d}(t) + y_{ij,c}(t) + y_{ij,sc}(t) + y_{ij,su}(t) + y_{ij,en}(t) + y_{ij,k}(t) \\ &= \overline{\omega_{i,d}(t)} \cdot x_{ij,d} + \overline{\omega_{i,c}(t)} \cdot x_{j,c} + \overline{\omega_{i,sc}(t)} \cdot x_{j,sc} + \overline{\omega_{i,su}(t)} \cdot x_{j,su} + \overline{\omega_{i,en}(t)} \cdot x_{j,en} + \overline{\omega_{i,k}(t)} \cdot x_{j,k}. \end{aligned}$$

Assume that $\overline{\boldsymbol{\omega_i(t)}} = (\overline{\omega_{i,d}(t)}, \overline{\omega_{i,c}(t)}, \overline{\omega_{i,sc}(t)}, \overline{\omega_{i,su}(t)}, \overline{\omega_{i,en}(t)}, \overline{\omega_{i,k}(t)})$, $\boldsymbol{x_j} = (x_{ij,d}, x_{j,c}, x_{j,sc}, x_{j,su}, x_{j,en}, x_{j,k})^T$, then we get: $y_{ij}(t) = \overline{\boldsymbol{\omega_i(t)}} \cdot \boldsymbol{x_j}$.

Assume that there are m ($i = 1, 2, \ldots, m$) demand points, and n ($j = 1, 2, \ldots, n$) candidate shelters.

Let $\boldsymbol{x = (x_1, x_2, \ldots, x_{n-1}, x_n)}$, $\overline{\boldsymbol{\omega(t)}} = \begin{pmatrix} \overline{\boldsymbol{\omega_1(t)}} \\ \overline{\boldsymbol{\omega_2(t)}} \\ \vdots \\ \overline{\boldsymbol{\omega_{m-1}(t)}} \\ \overline{\boldsymbol{\omega_m(t)}} \end{pmatrix}$,then the score matrix of all demand points for all candidate shelters is:

$$\boldsymbol{y(t)} = \overline{\boldsymbol{\omega(t)}} \cdot \boldsymbol{x} = \begin{pmatrix} \overline{\boldsymbol{\omega_1(t)}} \\ \overline{\boldsymbol{\omega_2(t)}} \\ \vdots \\ \overline{\boldsymbol{\omega_{m-1}(t)}} \\ \overline{\boldsymbol{\omega_m(t)}} \end{pmatrix} \boldsymbol{(x_1, x_2, \ldots, x_{n-1}, x_n)}$$

Notice that, $x_{ij,d}$ in $\boldsymbol{x_j}$ should change with $\overline{\boldsymbol{\omega_i(t)}}$. The total subjective score of the demand point i for all candidate emergency shelters is: $y_i^0(t) = \sum_{j=1}^{n} y_{ij}(t)$.

It could be seen from the above analysis that when the total refuge time t changes, people's subjective score for the emergency shelters also changes. Obviously, it is not feasible to select emergency shelters once for each t. Assume that the maximum value of t is T, it is a feasible method to derive the average value of subjective scores for all t within the interval $[0, T]$, and use this average value to make location decision.

We divide the interval $[0, T]$ into N equal parts, and each equal part is Δt. Then, we take a value of t for every interval T/N from 0, and let $t_s = Ts/N$ ($s = 1, 2, \ldots, N$). If the probability of each t in the interval $[0, T]$ is the same, then, from 0 to T, the average value of the subjective scores for the emergency shelter j evaluated by the demand point i is:

$$\overline{y_{ij}}(T) = \frac{\sum_{s=1}^{N} y_{ij}(t_s)}{N} = \frac{\Delta t \cdot \sum_{s=1}^{N} y_{ij}(t_s)}{\Delta t \cdot N} = \frac{\sum_{s=1}^{N} y_{ij}(t_s) \cdot \Delta t}{\Delta t \cdot N}.$$

When $\Delta t \to 0$, the above formula becomes: $\overline{y_{ij}}(T) = \frac{\int_0^T y_{ij}(t)dt}{T}$.

The total subjective score for all candidate emergency shelters evaluated by the demand point i is:

$$y_i^0(T) = \sum_{j=1}^{n} \overline{y_{ij}}(T) = \sum_{j=1}^{n} \frac{1}{T} \int_0^T y_{ij}(t)dt = \frac{1}{T} \int_0^T (\sum_{j=1}^{n} y_{ij}(t))dt = \frac{1}{T} \int_0^T y_i^0(t)dt.$$

We define a binary variable Y_{ij}. When j provides service for the demand point i, $Y_{ij} = 1$; otherwise, $Y_{ij} = 0$. Then, the total subjective score of the demand point i for the selected shelters that provides services for i is:

$$y_i^1(T) = \sum_{j=1}^{n} \overline{y_{ij}}(T) Y_{ij} = \sum_{j=1}^{n} \frac{1}{T} \int_0^T y_{ij}(t) Y_{ij} dt = \frac{1}{T} \int_0^T (\sum_{j=1}^{n} y_{ij}(t) Y_{ij})dt.$$

Let $y_i^1(t) = \sum_{j=1}^{n} y_{ij}(t) Y_{ij}$, then $y_i^1(T) = \frac{1}{T} \int_0^T y_i^1(t)dt$.

Let $p_{ij} = \overline{y_{ij}}(T)Y_{ij}/y_i^1(t), y_{ij}^1(t) = y_{ij}(t)Y_{ij}$, then

$$p_{ij} = \frac{\frac{1}{T}\int_0^T y_{ij}(t)Y_{ij}dt}{\frac{1}{T}\int_0^T y_i^1(t)dt} = \frac{\int_0^T y_{ij}(t)Y_{ij}dt}{\int_0^T y_i^1(t)dt} = \frac{\int_0^T y_{ij}^1(t)dt}{\int_0^T y_i^1(t)dt}.$$

The larger the p_{ij} is, the more people transfer from the demand point i to the selected shelter j. We suppose that the number of people transferred from the demand point i to the selected shelter j is directly proportional to p_{ij}, so the number of people transferred from the demand point i to the selected shelter j is: $a_{ij} = p_{ij} \cdot a_i$, where, a_i represents the number of people at the demand point i. Here, $a_i = \sum_{j=1}^n a_{ij}$, which could be proven as follows:

$$\sum_{j=1}^n a_{ij} = \sum_{j=1}^n p_{ij}a_i = a_i\sum_{j=1}^n p_{ij} = a_i\sum_{j=1}^n \overline{y_{ij}}(T)Y_{ij}/y_i^1(T) = (a_i/y_i^1(T))\sum_{j=1}^n \overline{y_{ij}}(T)Y_{ij} = a_i,$$

then $a_i = \sum_{j=1}^n a_{ij}$ holds.

Let $Z_{i,s}^1$ be the number of the emergency shelters that provide services for the demand point i, then:

$$Z_{i,s}^1 = \sum_{j=1}^n Y_{ij}.$$

The average subjective score of the emergency shelters that provide services for the demand point i is:

$$\overline{y_i^1(T)} = \frac{y_i^1(T)}{Z_{i,s}^1}.$$

Let Z_s be the number of the selected sites, $y(T)^{Z_s}$ be the total subjective score of all selected emergency shelters evaluated by all demand points, then

$$y(T)^{Z_s} = \sum_{i=1}^m a_i\overline{y_i^1(T)}.$$

Let a be the total number of residents at all demand points, then per capita score for all selected shelters is:

$$\overline{y(T)}^{Z_s} = \left(\sum_{i=1}^m a_i\overline{y_i^1(T)}\right)/a = \left(\sum_{i=1}^m a_i\overline{y_i^1(T)}\right)/\sum_{i=1}^m a_i.$$

The variance of the subjective scores of residents at all demand points is:

$$f_y = \frac{1}{a}\sum_{i=1}^m a_i\left(\overline{y_i^1(T)} - \overline{y(T)}^{Z_s}\right)^2.$$

The standard deviation of the subjective scores of residents at all demand points is:

$$f_y' = \sqrt{\frac{1}{a}\sum_{i=1}^m a_i\left(\overline{y_i^1(T)} - \overline{y(T)}^{Z_s}\right)^2}.$$

3.2 The formulation of the transfer distance function and the standard deviation function

Let d_{ij} be the shortest distance from the demand point i to the emergency shelter j, then the transfer distance of residents at the demand point i to the selected shelters that provide services for i is $\sum_{j=1}^n a_{ij}d_{ij}$, and the total transfer distance of residents at all demand points is $\sum_{i=1}^m\sum_{j=1}^n a_{ij}d_{ij}$. So, the per capita transfer distance of residents at all demand points is:

$$d = \frac{1}{a}\sum_{i=1}^m\sum_{j=1}^n a_{ij}d_{ij}.$$

Therefore, the variance of the transfer distance of residents at all demand points is:

$$f_d = \frac{1}{a}\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}(d_{ij}-d)^2.$$

The standard deviation of the transfer distance of residents at all demand points is:

$$f_d' = \sqrt{\frac{1}{a}\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}(d_{ij}-d)^2}.$$

3.3 Cost and the formulation of the standard deviation function of the numbers of residents transferred to every emergency shelter

Let $b_{j,1}$ be the supporting construction cost of the emergency shelter j, $b_{j,2}$ be the upgrading construction cost of the emergency shelter j, b_1 be the total cost, then

$$b_1 = \sum_{j=1}^{n}(b_{j,1}+b_{j,2})Y_j,$$

in which, Y_j is a binary variable. When j is selected, $Y_j = 1$; otherwise, $Y_j = 0$.
The variance of the numbers of residents that transfer to every selected shelter is:

$$f_p = \frac{1}{Z_s}\sum_{j=1}^{n}\left(\sum_{i=1}^{m} a_{ij} - \frac{a}{Z_s}\right)^2.$$

The standard deviation of the numbers of residents that transfer to every selected shelter is:

$$f_p' = \sqrt{\frac{1}{Z_s}\sum_{j=1}^{n}\left(\sum_{i=1}^{m} a_{ij} - \frac{a}{Z_s}\right)^2}.$$

3.4 Goals and constraints

The research shows that in the process of the large-scale emergency evacuation, the affected residents do not transfer completely according to the government planning, and they follow self-interests [10], [20]. This paper comprehensively considers the subjective and objective factors affecting the location of emergency shelters. The subjective evaluation of residents at the demand point for the emergency shelter reflects their satisfaction with the emergency shelters. Therefore, the subjective evaluation of the residents will be reflected in their emergency transfer behavior. So, this paper takes the residents' subjective evaluation for the emergency shelter as an important basis for location decision making, this is an aspect of humanistic consideration. On the other hand, in order to ensure fairness, we take the standard deviation of the scores of the residents and the standard deviation of the transfer distance as the factors for emergency shelter planning. To further ensure fairness, in the following model, we assume that a demand point can only be served by the emergency shelters that are within the service distance r_d of this demand point. Among the selected emergency shelters, only those emergency shelters that meet this requirement can provide services for the corresponding demand points.

In order to improve the efficiency of the emergency evacuation and save the transfer cost, we take the minimization of the transfer distance of the residents as a goal. In fact, minimizing the transfer distance is also the overall desire of the residents at all demand points in the region. In order to avoid residents' excessive gathering in the emergency shelters, we also take the minimization of the standard deviation of the numbers of the residents that transfer to every selected emergency shelter as a goal in the model, which is a consideration of safety.

In terms of the construction cost, previous studies mainly focused on planning new shelters [20]. This paper considers providing the supporting facilities and upgrading the site level on the basis of the existing sites, so as to make full use of the existing resources and save the construction funds. Therefore, the cost in the model includes the cost of the supporting construction and the cost for upgrading the site level as analysis in Section 3.3.

- Assumptions - in addition to some assumptions put forward in the previous analysis, the model also includes the following assumptions:
  1. The candidate sites and the demand points are two different finite point sets in spatial network;
  2. The spatial distribution and the number of the candidate sites are known;
  3. Based on the road network, the shortest distance between any candidate site and demand point is known;
  4. A candidate site can provide services for multiple demand points;
  5. The candidate site has no capacity constraint.
- Sets

  M: The set of the demand points in the network $\{i|i = 1, 2, 3, \ldots, m\}$.

  N: The set of the candidate sites $\{j|j = 1, 2, 3, \ldots, n\}$.
- Parameters

  $\overline{y(T)}^{Z_s}$: The per capita score of all residents for all selected shelters.

  $\overline{y_i^1(T)}$: The average subjective score of the sites that provide services for the demand point i.

  a: The total number of the residents at all demand points.

  a_i: The number of residents at the demand point i, $\forall i \in M$.

  a_{ij}: The number of people transferred from the demand point i to the shelter j.

  d_{ij}: The shortest distance between the demand point i and the candidate site j, $\forall i \in M$, $\forall j \in N$.

  d: The per capita transfer distance of residents at all demand points.

  f'_d: The standard deviation of the transfer distance of residents at all demand points.

  f'_y: The standard deviation of the subjective scores of residents at all demand points.

  f'_p: The standard deviation of the numbers of residents that transfer to every selected shelter.

  r_d: The service distance.

  b: The total cost.

  $b_{j,1}$: The supporting construction cost of the site j.

  $b_{j,2}$: The upgrading construction cost of the site j.

  Z_s: The total number of the selected sites.

  $Z_{i,s}^0$: The maximal number of the selected sites that provide service for the demand point i.

  $Z_{i,s}^1$: The actual number of the selected sites that provide service for the demand point i.
- Decision variables

$$Y_j = \begin{cases} 1, & \text{if the site is located at } j, \forall j \in N. \\ 0, & \text{otherwise.} \end{cases}$$

$$Y_{ij} = \begin{cases} 1, & \text{if the site } j \text{ provide service for the demand point } i, \forall i \in M, \forall j \in N. \\ 0, & \text{otherwise.} \end{cases}$$

Objectives:

$$MAX\ \overline{y(T)}^{Z_s} = \frac{\sum_{i=1}^{m} a_i \overline{y_i^1(T)}}{a} = \frac{\sum_{i=1}^{m} a_i \overline{y_i^1(T)}}{\sum_{i=1}^{m} a_i} \tag{1}$$

$$MIN\ f'_y = \sqrt{\frac{1}{a}\sum_{i=1}^{m} a_i \left(\overline{y_i^1(T)} - \overline{y(T)}^{Z_s}\right)^2} \tag{2}$$

$$MIN\ d = \frac{1}{a}\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij} d_{ij} \tag{3}$$

$$MIN\ f'_d = \sqrt{\frac{1}{a}\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}(d_{ij} - d)^2} \tag{4}$$

$$MIN\ b_1 = \sum_{j=1}^{n}(b_{j,1} + b_{j,2})Y_j \tag{5}$$

$$MIN\ f'_p = \sqrt{\frac{1}{Z_s}\sum_{j=1}^{n}\left(\sum_{i=1}^{m} a_{ij} - \frac{a}{Z_s}\right)^2} \tag{6}$$

Subject to:

$$d_{ij} \le r_d Y_{ij}, \forall i \in M, \forall j \in N \tag{7}$$

$$Z_s = \sum_{j=1}^{n} Y_j, \forall j \in N \tag{8}$$

$$1 \le \sum_{j=1}^{n} Y_{ij} \le Z_{i,s}^0, \forall i \in M \tag{9}$$

$$Y_{ij} \le Y_j, \forall i \in M, \forall j \in M \tag{10}$$

$$Y_i, Y_{ij} \in \{0, 1\},\ \text{for } \forall i \in M, \forall j \in M \tag{11}$$

Objectives (1)-(6) have already been analyzed above. Constraint (7) means that a demand point can only be served by the emergency shelters that are within the service distance r_d of this demand point. Constraint (8) requires that the total number of selected emergency sites is Z_s. Constraint (9) requires that the number of the emergency shelters serving a demand point is at least 1 and at most $Z_{i,s}^0$. Constraint (10) means that a site could provide service for a demand point only when this site is selected. Constraint (11) means that both Y_j and Y_{ij} are binary variables.

4 Case study

4.1 Basic data

Some scholars have used the Sioux Falls Network (or a simplified Sioux Falls Network) to conduct research [37], [38]. The simplified Sioux Falls network is shown in Fig 4. In our case, we also use a simplified Sioux Falls Network (undirected) to test our model, and the number marked next to each side is the length of the side. Table 1 is the initial value of the attribute weight of each demand point for each attribute of the shelter. Table 2 shows the number of the residents at each demand point. Table 3 shows the supporting construction cost (SCC) and the upgrading construction cost (UCC) of each candidate site. Table 4 shows the attribute grade and score of each candidate site after upgrading. Table 5 shows the distance between each demand point and each candidate site and the corresponding distance score.

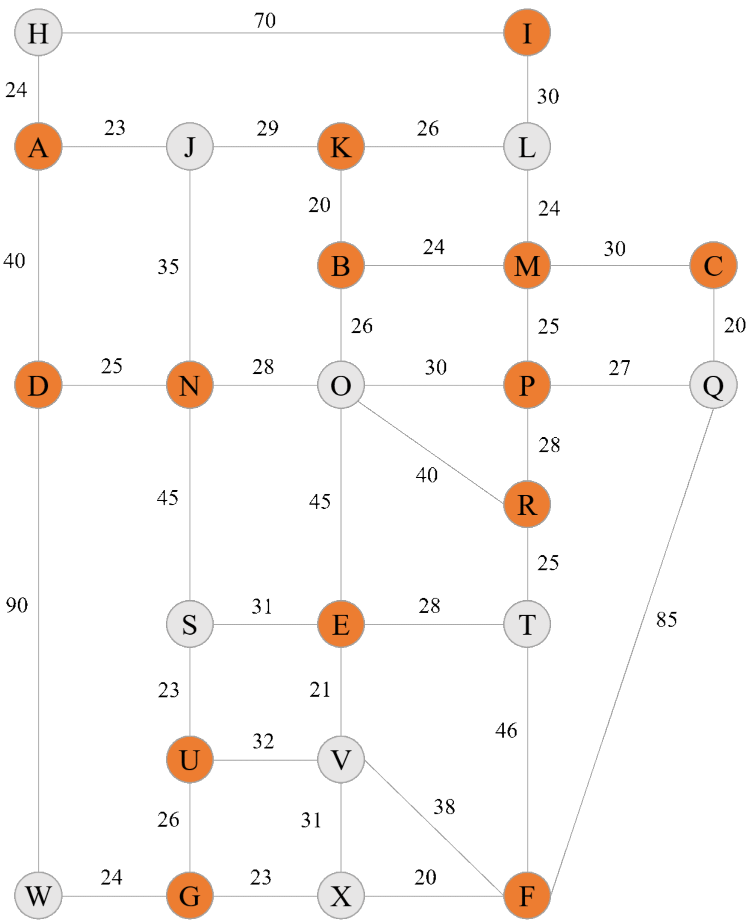

Figure 4: The network.

Demand point	External attributes		Internal attributes			
	Distance	Accessibility	Scale	Supporting facilities	Environment	Type
A	0.50	0.02	0.07	0.20	0.09	0.12
B	0.51	0.05	0.06	0.15	0.08	0.15
C	0.49	0.04	0.08	0.17	0.11	0.11
D	0.50	0.07	0.06	0.18	0.06	0.13
E	0.44	0.04	0.10	0.14	0.08	0.20
F	0.48	0.03	0.09	0.16	0.12	0.12
G	0.53	0.06	0.07	0.13	0.10	0.11
I	0.42	0.10	0.09	0.15	0.07	0.17
K	0.52	0.08	0.07	0.14	0.11	0.08
M	0.43	0.03	0.11	0.16	0.13	0.14
N	0.47	0.05	0.12	0.20	0.07	0.09
P	0.39	0.11	0.09	0.22	0.11	0.08
R	0.55	0.07	0.05	0.15	0.11	0.07
U	0.44	0.08	0.10	0.12	0.13	0.13

Table 1: The initial value of the attribute weight of each demand point for each attribute of the shelter.

Demand point	The number of the residents	Demand point	The number of the residents
A	1500	I	900
B	2000	K	1800
C	800	M	2000
D	900	N	1700
E	2500	P	2300
F	500	R	1800
G	1000	U	1100

Table 2: The number of the residents at each demand point.

Candidate site	SCC	UCC	Candidate site	SCC	UCC
H	110	180	S	95	70
J	120	60	T	60	20
L	90	40	V	70	24
O	130	30	W	125	160
Q	105	100	X	85	30

Table 3: The supporting construction cost (SCC) and the upgrading construction cost (UCC) of each candidate site.

Candidate site	Accessibility		Scale		Supporting facilities		Environment		Type	
	Grade	Score	Grade	Score	Grade	Score	Grade	Score	Name	Score
H	2	90	2	90	3	80	2	90	GR	68
J	1	100	2	90	3	80	2	90	SQ	72
L	2	90	4	70	2	90	2	90	ST	83
O	1	100	1	100	2	90	2	90	SQ	72
Q	2	90	3	80	3	80	2	90	GR	68
S	1	100	1	100	3	80	2	90	PA	78
T	2	90	2	90	1	100	1	100	ID	92
V	1	100	2	90	2	90	1	100	ID	92
W	4	70	3	80	3	80	2	90	GR	68
X	2	90	3	80	3	80	2	90	ST	83

Table 4: The attribute grade and score of each candidate site after upgrading.

$i \setminus j$	H	J	L	O	Q	S	T	V	W
A	24, 96	23, 100	78, 29	86, 27	143, 16	103, 22	151, 15	152, 15	130, 18
B	96, 27	49, 53	46, 57	26, 100	74, 35	99, 26	91, 29	92, 28	169, 15
C	150, 13	103, 19	54, 37	77, 26	20, 100	150, 13	100, 20	143, 14	172, 12
D	64, 83	60, 88	115, 46	53, 100	110, 48	70, 76	118, 45	119, 45	90, 59
E	155, 14	108, 19	117, 18	45, 47	102, 21	31, 68	28, 75	21, 100	99, 21
F	214, 9	167, 12	148, 14	104, 19	85, 24	90, 22	46, 43	38, 53	67, 30
G	176, 13	129, 18	184, 12	120, 19	128, 18	49, 47	89, 26	54, 43	24, 96
I	70, 43	85, 35	30, 100	102, 29	104, 29	165, 18	132, 23	168, 18	224, 13
K	76, 34	29, 90	26, 100	46, 57	94, 28	109, 24	111, 23	112, 23	179, 15
M	120, 20	73, 33	24, 100	50, 48	50, 48	123, 20	78, 31	116, 21	191, 13
N	82, 34	35, 80	90, 31	28, 100	85, 33	45, 62	93, 30	94, 30	115, 24
P	140, 19	93, 29	49, 55	30, 90	27, 100	103, 26	53, 51	96, 28	166, 16
R	150, 17	103, 24	77, 32	40, 63	55, 45	84, 30	25, 100	74, 34	138, 18
U	150, 15	103, 22	158, 15	96, 24	153, 15	23, 100	81, 28	32, 72	50, 46

Table 5: The distance between each demand point and each candidate site and the corresponding distance score. (Note: The first number in the table represents the distance and the last number represents the distance score.)

4.2 Analysis and discussions

4.2.1 Analysis

In this case, we set $r_d = 120$, $Z^0_{i,s} = 2$. We set $min\ Z_s = 2$, and solve the model respectively under the condition of $Z_s = 2, 3, \dots, 10$. Since the emergency evacuation time may be short-term or long-term [39], we set the maximum value of T be 20, and solve the model respectively under the condition of $T = 1, 2, 3, \dots, 20$.

We set the priority of the objectives in the order of $\overline{y(T)}^{Z_s}$, f'_y, d, f'_d, b and f'_p to solve the model. Table 6 to Table 9 are the solutions of the model. Fig 5 is the three-dimensional figure of the $\overline{y(T)}^{Z_s}$, in which T and Z_s are both independent variables. Fig 6 is a figure which reflects the $\overline{y(T)}^{Z_s}$ changes with Z_s, when $T = 4, 8, 12, 16, 20$.

From Table 6, we could see that $\overline{y(T)}^{Z_s}$ shows an upward trend with the increase of T, when Z_s remains unchanged; $\overline{y(T)}^{Z_s}$ shows an upward trend with the increase of Z_s, when T remains unchanged. From Table 7, we could see that d shows an upward trend with the increase of T, when Z_s remains unchanged; d shows a downward trend with the increase of Z_s, when T remains unchanged.

From Table 6, f'_y shows an overall downward trend with the increase of Z_s, when T remains unchanged. From Table 7, f'_d shows an overall downward trend with the increase of Z_s, when T remains unchanged.

From Table 6, Fig 5 and Fig 6, we notice that when T is constant, the increment of $\overline{y(T)}^{Z_s}$ is fast first and then slow with the increase of Z_s, on the whole. This indicate that, when T is constant, the utilization efficiency of costs is different with the change of Z_s. Next, we analyze the utilization efficiency of the costs under the condition of constant T, based on the cost and the per capita score when Z_s is 2. Let $b_1^{Z_s}(T)$ be the total cost, $\overline{y(T)}^{Z_s}$ be the per capita score, and $\beta^{Z_s}(T)$ be the increment of $\overline{y(T)}^{Z_s}$ generated by the unit increment of the cost when the biggest total refuge time is T and the number of selected sites is Z_s. Then $\beta^{Z_s}(T) = \left(\overline{y(T)}^{Z_s} - \overline{y(T)}^{2}\right) / \left(b_1^{Z_s}(T) - b_1^2(T)\right)$, in which, $Z_s = 3, 4, \dots, 10$.

For example, when $T = 4$, from Table 8, we have $b_1^2(4) = 240$, $b_1^3(4) = 370$, $b_1^6(4) = 934$, $b_1^9(4) = 1419$.

$T \setminus Z_s$	2		3		4		5		6		7		8		9		10	
	y	f'_y	y	f'_y	y	f'_y	y	f'_y	y	f'_y	y	f'_y	y	f'_y	y	f'_y	y	f'_y
1	72.77	9.96	76.56	9.86	79.39	9.4	82.20	8.33	83.37	7.56	84.51	7.23	85.62	5.06	86.29	4.60	86.78	4.43
2	73.35	9.68	76.95	9.52	79.71	9.10	82.41	8.06	83.50	7.32	84.60	6.98	85.65	4.92	86.30	4.50	86.76	4.32
3	74.19	9.28	77.51	9.04	80.18	8.67	82.72	7.67	83.74	7.49	84.72	6.06	85.69	4.73	86.31	4.34	86.74	4.18
4	75.15	8.81	78.17	8.62	80.73	8.32	83.08	7.22	84.02	7.01	84.89	5.72	85.74	4.52	86.32	4.18	86.72	4.02
5	76.16	8.32	78.88	8.10	81.32	7.86	83.44	6.76	84.30	6.52	85.09	5.37	85.79	4.29	86.34	4.02	86.69	3.87
6	77.13	7.85	79.57	7.60	81.9	7.41	83.81	6.32	84.59	6.05	85.29	5.03	85.88	4.03	86.37	3.83	86.68	3.69
7	78.04	7.41	80.28	7.92	82.47	7.00	84.17	5.92	84.88	5.62	85.52	4.70	86.00	3.77	86.44	3.63	86.71	3.50
8	78.88	7.00	81.02	7.49	83.00	6.63	84.50	5.55	85.15	5.23	85.72	4.42	86.11	4.39	86.50	3.47	86.73	3.35
9	79.65	6.63	81.70	7.11	83.47	6.30	84.81	5.23	85.40	4.89	85.90	4.19	86.26	4.17	86.55	3.33	86.75	3.22
10	80.34	6.29	82.32	6.76	83.9	6.01	85.08	4.96	85.62	4.60	86.07	3.99	86.39	3.99	86.66	3.25	86.82	3.15
11	80.96	5.99	82.87	6.45	84.29	5.75	85.33	4.72	85.82	4.35	86.22	3.82	86.50	3.84	86.75	3.19	86.89	3.10
12	81.53	5.72	83.37	6.17	84.65	5.51	85.56	4.51	86.02	4.13	86.36	3.68	86.62	3.71	86.85	3.13	86.96	3.05
13	82.04	5.47	83.83	5.92	85.00	5.30	85.79	4.32	86.21	3.94	86.52	3.55	86.74	3.59	86.96	3.07	87.05	3.00
14	82.50	5.25	84.24	5.69	85.31	5.12	86.02	4.17	86.40	3.78	86.67	3.45	86.86	2.99	87.07	3.02	87.14	2.97
15	82.93	5.05	84.62	5.48	85.59	4.95	86.22	4.03	86.58	3.65	86.81	3.36	86.99	2.95	87.17	2.99	87.22	2.95
16	83.31	4.87	84.96	5.30	85.85	4.80	86.44	3.92	86.76	3.54	86.96	3.30	87.13	2.92	87.29	2.96	87.33	2.94
17	83.66	4.70	85.28	5.12	86.09	4.66	86.63	3.82	86.93	3.45	87.11	3.24	87.26	2.91	87.40	2.95	87.42	2.93
18	83.99	4.55	85.58	4.96	86.31	4.54	86.81	3.73	87.09	3.36	87.23	3.09	87.38	2.90	87.50	2.93	87.50	2.93
19	84.28	4.41	85.86	4.82	86.51	4.42	86.98	3.65	87.23	3.30	87.36	3.05	87.49	2.89	87.60	2.93	87.60	2.93
20	84.56	4.28	86.11	4.69	86.7	4.32	87.13	3.58	87.37	3.24	87.48	3.03	87.59	2.89	87.68	2.93	87.68	2.93

Table 6: The per capita score and the standard deviation of the subjective scores of the residents. (Note: here, y represents $\overline{y(T)}^{Z_s}$.)

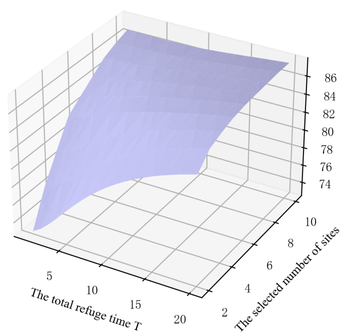

Figure 5: The three-dimensional figure of the per capita score.

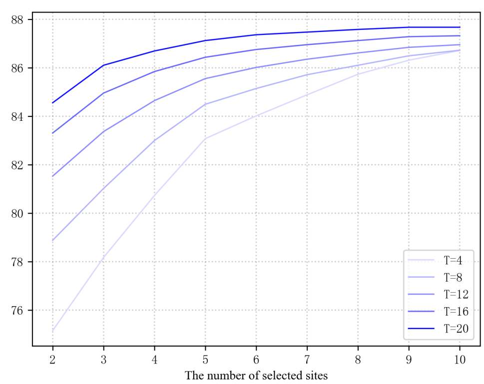

Figure 6: The figure of the per capita score.

$T \setminus Z_s$	2		3		4		5		6		7		8		9		10	
	d	f'_d	d	f'_d	d	f'_d	d	f'_d	d	f'_d	d	f'_d	d	f'_d	d	f'_d	d	f'_d
1	62.42	22.77	51.45	22.62	45.96	18.65	39.88	13.62	36.89	11.86	35.13	11.83	32.42	7.51	31.77	7.39	31.16	7.53
2	62.51	22.76	51.50	22.61	46.01	18.65	40.47	14.10	37.48	12.54	35.17	11.85	32.45	7.53	31.80	7.41	31.19	7.55
3	62.65	22.74	51.57	22.60	46.09	18.66	40.56	14.16	38.21	14.03	35.49	11.35	32.49	7.54	31.84	7.43	31.22	7.57
4	62.80	22.73	52.27	22.33	46.80	18.56	40.66	14.23	38.27	14.07	35.54	11.38	32.54	7.57	31.89	7.46	31.27	7.59
5	62.96	22.71	52.39	22.35	46.93	18.61	40.77	14.29	38.33	14.11	36.37	12.12	33.36	8.90	31.94	7.48	31.31	7.61
6	63.11	22.70	53.74	21.76	48.29	18.31	42.11	14.43	40.22	15.02	38.27	13.44	36.04	11.75	34.60	11.05	33.96	11.29
7	63.24	22.69	57.80	21.91	48.42	18.36	42.22	14.50	40.31	15.08	38.35	13.51	36.14	11.87	34.70	11.17	34.05	11.41
8	63.37	22.68	57.94	21.93	48.54	18.41	42.32	14.56	40.38	15.14	38.43	13.57	36.99	13.21	34.78	11.28	34.12	11.52
9	63.48	22.67	58.06	21.95	48.65	18.45	42.41	14.62	40.45	15.19	38.51	13.63	37.05	13.26	36.26	11.30	35.60	11.62
10	63.58	22.67	58.16	21.97	48.75	18.49	42.50	14.67	40.51	15.23	38.57	13.68	37.11	13.31	36.33	11.38	35.66	11.70
11	63.67	22.66	58.26	21.98	48.84	18.53	42.57	14.72	40.56	15.27	38.63	13.72	37.16	13.35	36.40	11.45	35.72	11.77
12	63.75	22.66	58.34	22.00	50.93	18.10	44.65	15.04	42.62	15.84	40.69	14.62	39.22	14.48	38.47	12.89	37.79	13.28
13	63.82	22.65	58.42	22.01	51.02	18.13	45.93	16.97	43.89	17.82	42.06	16.82	40.58	16.81	39.84	15.54	39.15	15.93
14	63.88	22.65	58.49	22.02	51.10	18.16	46.01	17.02	43.95	17.87	42.12	16.88	41.39	15.69	39.91	15.61	39.22	16.00
15	63.94	22.65	58.55	22.04	51.17	18.19	48.32	16.78	46.25	17.90	44.43	17.16	43.70	16.10	42.22	16.23	41.53	16.70
16	63.99	22.65	58.60	22.05	51.24	18.21	48.40	16.82	46.31	17.95	44.49	17.21	43.78	16.16	42.29	16.30	41.60	16.77
17	64.04	22.64	61.75	24.74	51.72	18.96	48.89	17.71	46.80	18.84	44.98	18.18	43.85	16.21	42.36	16.35	41.66	16.83
18	64.09	22.64	61.80	24.74	51.78	18.98	48.95	17.74	46.85	18.87	45.72	17.12	43.91	16.26	42.42	16.41	41.71	16.88
19	64.13	22.64	61.84	24.74	51.82	18.99	49.01	17.77	46.90	18.90	45.78	17.16	43.96	16.31	42.47	16.45	42.47	16.45
20	64.16	22.64	61.88	24.74	51.87	19.01	49.06	17.80	46.94	18.93	45.83	17.20	44.23	16.27	42.74	16.43	42.74	16.43

Table 7: The per capita transfer distance and the standard deviation of the transfer distances of the residents.

$T \setminus Z_s$	2		3		4		5		6		7		8		9		10	
	b_1	f'_p	b_1	f'_p	b_1	f'_p	b_1	f'_p	b_1	f'_p	b_1	f'_p	b_1	f'_p	b_1	f'_p	b_1	f'_p
1	240	1483	420	2392	514	1872	644	977	849	1173	1139	1296	1254	1313	1419	1438	1704	1471
2	240	1455	420	2395	514	1877	644	1332	849	1434	1139	1297	1254	1314	1419	1440	1704	1472
3	240	1416	420	2399	514	1883	644	1342	934	1434	1049	1384	1254	1317	1419	1442	1704	1474
4	240	1371	370	2133	464	1752	644	1353	934	1436	1049	1383	1254	1319	1419	1445	1704	1476
5	240	1326	370	2136	464	1761	644	1364	934	1438	1049	1523	1254	1385	1419	1448	1704	1478
6	240	1283	370	1756	464	1715	644	1300	934	1645	1049	1636	1254	1383	1419	1397	1704	1432
7	240	1244	334	3031	464	1729	644	1313	934	1651	1049	1640	1254	1388	1419	1400	1704	1434
8	240	1208	334	3037	464	1743	644	1324	934	1657	1049	1644	1214	1646	1419	1403	1704	1436
9	240	1176	334	3042	464	1755	644	1334	934	1662	1049	1647	1214	1647	1419	1658	1704	1662
10	240	1147	334	3047	464	1766	644	1343	934	1666	1049	1650	1214	1649	1419	1661	1704	1664
11	240	1122	334	3051	464	1775	644	1352	934	1670	1049	1653	1214	1651	1419	1663	1704	1666
12	240	1099	334	3056	464	2204	644	1738	934	1944	1049	1839	1214	1781	1419	1800	1704	1789
13	240	1078	334	3060	464	2216	644	1955	934	2110	1049	2041	1214	1940	1419	1941	1704	1923
14	240	1060	334	3064	464	2227	644	1964	934	2117	1049	2046	1254	2087	1419	1946	1704	1927
15	240	1044	334	3067	464	2237	644	2395	934	2460	1049	2328	1254	2331	1419	2156	1704	2118
16	240	1029	334	3070	464	2246	644	2403	934	2467	1049	2334	1254	2337	1419	2160	1704	2122
17	240	1015	334	2427	464	2389	644	2507	934	2534	1049	2394	1254	2342	1419	2164	1704	2126
18	240	1003	334	2431	464	2396	644	2514	934	2539	1139	2536	1254	2347	1419	2168	1704	2130
19	240	992	334	2435	464	2402	644	2520	934	2543	1139	2540	1254	2351	1419	2172	1704	2174
20	240	981	334	2439	464	2408	644	2526	934	2547	1139	2545	1254	2379	1419	2198	1704	2197

Table 8: The total cost and the standard deviation of the numbers of residents that transfer to each selected shelter.

$T \setminus Z_s$	2	3	4	5	6	7	8	9	10
1	OT	JOT	JOTV	JLOTV	JLOQTV	HJLOQTV	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
2	OT	JOT	JOTV	JLOTV	JLOQTV	HJLOQTV	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
3	OT	JOT	JOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
4	OT	LOT	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
5	OT	LOT	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
6	OT	LOT	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
7	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
8	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOSTVX	HJLOQSTVX	HJLOQSTVWX
9	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOSTVX	HJLOQSTVX	HJLOQSTVWX
10	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOSTVX	HJLOQSTVX	HJLOQSTVWX
11	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOSTVX	HJLOQSTVX	HJLOQSTVWX
12	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOSTVX	HJLOQSTVX	HJLOQSTVWX
13	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOSTVX	HJLOQSTVX	HJLOQSTVWX
14	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
15	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
16	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
17	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
18	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOQTV	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
19	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOQTV	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
20	OT	OTV	LOTV	JLOTV	HJLOTV	HJLOQTV	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX

Table 9: The combination of the selected sites.

From Table 6, we have $\overline{y(4)}^2 = 75.15$, $\overline{y(4)}^3 = 78.17$, $\overline{y(4)}^6 = 84.02$, $\overline{y(4)}^9 = 86.32$. So

$$\begin{aligned}\beta^3(4) &= (78.17 - 75.15)/(370 - 240) = 0.023231,\\ \beta^6(4) &= (84.02 - 75.15)/(934 - 240) = 0.012781,\\ \beta^9(4) &= (86.32 - 75.15)/(1419 - 240) = 0.009474.\end{aligned}$$

The value of $\beta^{Z_s}(T)$ is shown in Table 10. We draw the figure of $\beta^{Z_s}(T)$ under $T = 4, 8, 12, 16, 20$, as shown in Fig 7. From Table 10 and Fig 7, we could see that the value of $\beta^{Z_s}(T)$ is relatively large when Z_s is small; and the value of $\beta^{Z_s}(T)$ is relatively small when Z_s is large. This indicates that, the increment of b has relatively large influence on $\overline{y(T)}^{Z_s}$ when Z_s is small. However, the increment of b has relatively small influence on $\overline{y(T)}^{Z_s}$ when Z_s is large. So, we could see that, the effect of b on $\overline{y(T)}^{Z_s}$ is obvious when Z_s is small, and the effect of b on $\overline{y(T)}^{Z_s}$ is not obvious when Z_s is large.

We also notice that, when T is constant, the reduction of d is fast first and then slow with the increase of Z_s, on the whole. Similar to the previous analysis about $\overline{y(T)}^{Z_s}$, let $d^{Z_s}(T)$ be the per capita transfer distance, $\gamma^{Z_s}(T)$ be the reduction of d generated by the unit increment of the cost when the biggest total refuge time is T and the number of selected sites is Z_s. Then $\gamma^{Z_s}(T) = (d^2(T) - d^{Z_s}(T))/(b_1^{Z_s}(T) - b_1^2(T))$, in which, $Z_s = 3, 4, \ldots, 10$.

For example, when $T = 4$, from Table 8, we have $b_1^2(4) = 240$, $b_1^3(4) = 370$, $b_1^6(4) = 934$, $b_1^9(4) = 1419$. From Table 7, we have $d^2(4) = 62.8$, $d^3(4) = 52.27$, $d^6(4) = 38.27$, $d^9(4) = 31.89$. Then

$$\begin{aligned}\gamma^3(4) &= (62.8 - 52.27)/(370 - 240) = 0.081,\\ \gamma^6(4) &= (62.8 - 38.27)/(934 - 240) = 0.035346,\\ \gamma^9(4) &= (62.8 - 31.89)/(1419 - 240) = 0.026217.\end{aligned}$$

The value of $\gamma^{Z_s}(T)$ is shown in Table 11. We draw the figure of $\gamma^{Z_s}(T)$ under $T = 4, 8, 12, 16, 20$, as shown in Fig 8. From Table 11 and Fig 8, we could see that, on the whole, the smaller the Z_s, the larger the $\gamma^{Z_s}(T)$, and the larger the Z_s, the smaller the $\gamma^{Z_s}(T)$. Then, we draw the conclusion that the increment of b has relatively large influence on d when Z_s is small. While the increment of b has relatively small influence on d when Z_s is large. Therefore, the effect of b on d is obvious when Z_s is small, and the effect of b on d is not obvious when Z_s is large.

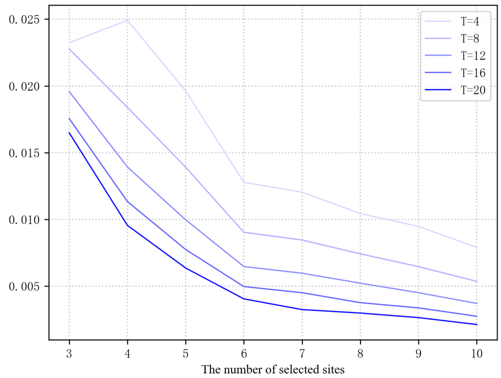

Figure 7: The graph of $\beta^{Z_s}(T)$.

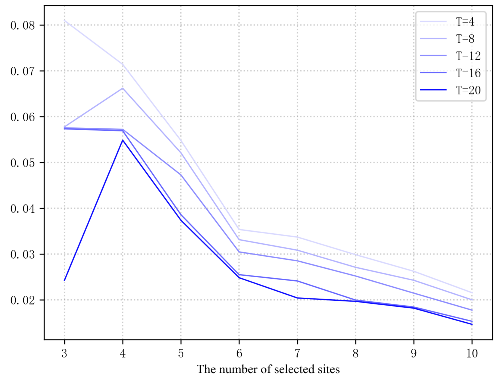

Figure 8: The graph of $\gamma^{Z_s}(T)$.

$T \setminus Z_s$	3	4	5	6	7	8	9	10
1	0.021056	0.024161	0.023342	0.017406	0.013059	0.012673	0.011467	0.009570
2	0.020000	0.023212	0.022426	0.016667	0.012514	0.012130	0.010984	0.009160
3	0.018444	0.021861	0.021114	0.013761	0.013016	0.011341	0.010280	0.008572
4	0.023231	0.024911	0.019629	0.012781	0.012040	0.010444	0.009474	0.007903
5	0.020923	0.023036	0.018020	0.011729	0.011038	0.009497	0.008634	0.007193
6	0.018769	0.021295	0.016535	0.010749	0.010087	0.008629	0.007837	0.006523
7	0.023830	0.019777	0.015173	0.009856	0.009246	0.007850	0.007125	0.005922
8	0.022766	0.018393	0.013911	0.009035	0.008455	0.007423	0.006463	0.005362
9	0.021809	0.017054	0.012772	0.008285	0.007726	0.006786	0.005852	0.004850
10	0.021064	0.015893	0.011733	0.007608	0.007083	0.006211	0.005360	0.004426
11	0.020319	0.014866	0.010817	0.007003	0.006502	0.005688	0.004911	0.004051
12	0.019574	0.013929	0.009975	0.006470	0.005970	0.005226	0.004512	0.003709
13	0.019043	0.013214	0.009282	0.006009	0.005538	0.004825	0.004173	0.003422
14	0.018511	0.012545	0.008713	0.005620	0.005155	0.004300	0.003876	0.003169
15	0.017979	0.011875	0.008144	0.005259	0.004796	0.004004	0.003596	0.002930
16	0.017553	0.011339	0.007748	0.004971	0.004512	0.003767	0.003376	0.002746
17	0.017234	0.010848	0.007351	0.004712	0.004265	0.003550	0.003172	0.002568
18	0.016915	0.010357	0.006980	0.004467	0.003604	0.003343	0.002977	0.002398
19	0.016809	0.009955	0.006683	0.004251	0.003426	0.003166	0.002816	0.002268
20	0.016489	0.009554	0.006361	0.004049	0.003248	0.002988	0.002646	0.002131

Table 10: The increment of per capita score generated by the unit increment of cost.

$T \setminus Z_s$	3	4	5	6	7	8	9	10
1	0.060944	0.060073	0.055792	0.041921	0.030356	0.029586	0.025997	0.021352
2	0.061167	0.060219	0.054554	0.041100	0.030412	0.029645	0.026047	0.021393
3	0.061556	0.060438	0.054678	0.035216	0.033572	0.029744	0.026132	0.021469
4	0.081000	0.071429	0.054802	0.035346	0.033696	0.029842	0.026217	0.021537
5	0.081308	0.071563	0.054926	0.035490	0.032868	0.029191	0.026310	0.021619
6	0.072077	0.066161	0.051980	0.032983	0.030705	0.026696	0.024182	0.019911
7	0.057872	0.066161	0.052030	0.033040	0.030766	0.026726	0.024207	0.019939
8	0.057766	0.066205	0.052104	0.033127	0.030828	0.027084	0.024249	0.019980
9	0.057660	0.066205	0.052153	0.033184	0.030865	0.027136	0.023087	0.019044
10	0.057660	0.066205	0.052178	0.033242	0.030915	0.027177	0.023113	0.019071
11	0.057553	0.066205	0.052228	0.033300	0.030952	0.027218	0.023130	0.019092
12	0.057553	0.057232	0.047277	0.030447	0.028504	0.025185	0.021442	0.017732
13	0.057447	0.057143	0.044282	0.028718	0.026897	0.023860	0.020339	0.016851
14	0.057340	0.057054	0.044233	0.028718	0.026897	0.022179	0.020331	0.016844
15	0.057340	0.057009	0.038663	0.025490	0.024116	0.019961	0.018422	0.015307
16	0.057340	0.056920	0.038589	0.025476	0.024104	0.019931	0.018405	0.015294
17	0.024362	0.055000	0.037500	0.024841	0.023560	0.019911	0.018388	0.015287
18	0.024362	0.054955	0.037475	0.024841	0.020434	0.019901	0.018380	0.015287
19	0.024362	0.054955	0.037426	0.024827	0.020412	0.019892	0.018372	0.014795
20	0.024255	0.054866	0.037376	0.024813	0.020389	0.019655	0.018168	0.014631

Table 11: The reduction of per capita distance generated by the unit increment of cost.

4.2.2 Comparison

We have set $\overline{y(T)}^{Z_s}$ prior to d and solved the model above. Next, we set the priority of the objectives in the order of d, f'_d, $\overline{y(T)}^{Z_s}$, f'_y, b and f'_p (which is noted as the second order) to solve the model, i.e., d has priority over $\overline{y(T)}^{Z_s}$. The combinations of the selected sites under the second order are shown in Table 12. We could derive the differences of $\overline{y(T)}^{Z_s}$ (noted as Δy) and the differences of d (noted as Δd) respectively under the two orders for each T and each Z_s. The results are shown in Table 13. We could see from Table 13 that, the solutions of $\overline{y(T)}^{Z_s}$ and d under the first order are both not lower than that under the second order, for the same T and Z_s. From Table 9 and Table 12, we know that the combinations of the selected sites are the same under the two orders, when the difference is 0 in Table 13. Otherwise, the combinations of the selected sites are not the same under the two orders, when the difference is not 0 in Table 13.

4.2.3 Discussions

In this case, we set the different orders of priority for the six objectives to solve the model. In the first order, we take the $\overline{y(T)}^{Z_s}$ as the highest priority, from the solutions, we know that, when T remains constant, the $\overline{y(T)}^{Z_s}$ and the d shows upward and downward trend respectively with the increase of Z_s. It could be seen that the satisfaction of the residents and the transfer efficiency are both constantly rising with the increase of Z_s. So, in order to improve the satisfaction of the residents and the transfer efficiency, we could consider selecting more emergency shelters. Meanwhile, we could see that, on the whole, f'_y and f'_d both show downward trend with the increase of Z_s when T remains constant. This reveals that more emergency sites mean greater fairness. So, in order to improve the fairness in location decision making, we could consider selecting more emergency sites.

From the previous analysis, we also notice that, when T remains constant, the same increase of fund could produce larger increment of $\beta^{Z_s}(T)$ and larger reduction of $\gamma^{Z_s}(T)$ when Z_s is relatively small, then the efficiency of funds is obvious. Otherwise, the efficiency of funds is not obvious when Z_s is relatively big. So, in order to make full use of funds, we should avoid selecting excessive emergency shelters.

In addition, from the analysis in 4.2.2, we know that, if we take $\overline{y(T)}^{Z_s}$ as the highest priority of the objectives in the model, the satisfaction of the residents for the emergency sites will be improved. Thus,

$T \setminus Z_s$	2	3	4	5	6	7	8	9	10
1	OW	LOS	JLOV	JLOVX	JLOQVX	JLOQTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
2	OW	LOS	LOSV	JLOVX	JLOQVX	HJLOQVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
3	OW	LOS	LOSV	JLOVX	JLOQTV	JLOQTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
4	OW	LOS	LOSV	JLOVX	JLOQTV	JLOQTVX	HJLOQTVX	HJLOQSTVX	HJLOQSTVWX
5	OW	LOS	LOSV	JLOVX	JLOQTV	HJLOQTV	HJLOQSTV	HJLOQSTVX	HJLOQSTVWX
6	OW	LOS	LOSV	JLOVX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
7	OW	LOS	LOSV	JLOVX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
8	OW	LOS	LOSV	JLOVX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
9	OW	LOS	LOSV	JLOVX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
10	OW	LOS	LOSV	JLOVX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
11	OW	LOS	LOSX	JLOSX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
12	OW	LOS	LOSX	JLOSX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
13	OW	LOS	LOSX	JLOSX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
14	OW	LOS	LOSX	JLOSX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
15	OW	LOS	LOSX	JLOSX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
16	OW	LOS	LOSX	JLOSX	JLOQVX	HJLOQVX	HJLOQSVX	HJLOQSVWX	HJLOQSTVWX
17	OW	LOS	LOSX	JLOSX	HJLOSX	HJLOQSX	HJLOQSWX	HJLOQSVWX	HJLOQSTVWX
18	OW	LOS	LOSX	JLOSX	HJLOSX	HJLOQSX	HJLOQSWX	HJLOQSVWX	HJLOQSTVWX
19	OW	LOS	LOSX	JLOSX	HJLOSX	HJLOQSX	HJLOQSWX	HJLOQSTVX	HJLOQSTVWX
20	OW	LOS	LOSX	JLOSX	HJLOSX	HJLOQSX	HJLOQSWX	HJLOQSTVX	HJLOQSTVWX

Table 12: The combinations of the selected sites under the second order.

$T \setminus Z_s$	2		3		4		5		6		7		8		9		10	
	Δy	Δd	Δy	Δd	Δy	Δd	Δy	Δd	Δy	Δd	Δy	Δd	Δy	Δd	Δy	Δd	Δy	Δd
1	0.19	6.00	1.23	2.62	0.55	2.42	1.76	0.51	1.48	0.58	0.03	0.95	0.00	0.00	0.00	0.00	0.00	0.00
2	0.35	6.02	1.28	2.60	1.07	2.20	1.78	0.51	1.50	0.58	1.51	0.58	0.00	0.00	0.00	0.00	0.00	0.00
3	0.59	6.06	1.35	2.58	1.15	2.22	1.82	0.51	0.04	0.64	0.05	0.65	0.00	0.00	0.00	0.00	0.00	0.00
4	0.85	6.09	1.45	3.17	1.24	2.86	1.86	0.50	0.10	0.60	0.09	0.60	0.00	0.00	0.00	0.00	0.00	0.00
5	1.14	6.13	1.57	3.19	1.35	2.92	1.89	0.50	0.15	0.56	0.08	1.05	0.14	0.38	0.00	0.00	0.00	0.00
6	1.42	6.17	1.70	4.43	1.47	4.06	1.94	1.73	1.75	2.14	1.67	2.07	1.34	1.20	1.52	0.40	0.00	0.00
7	1.68	6.19	1.87	8.40	1.60	4.12	2.00	1.74	1.83	2.13	1.76	2.08	1.38	1.24	1.55	0.45	0.00	0.00
8	1.92	6.22	2.12	8.45	1.73	4.18	2.05	1.75	1.91	2.11	1.83	2.10	1.41	2.03	1.57	0.48	0.00	0.00
9	2.15	6.25	2.35	8.49	1.83	4.24	2.11	1.76	1.98	2.10	1.89	2.12	1.49	2.04	1.58	1.92	0.00	0.00
10	2.35	6.27	2.56	8.52	1.92	4.29	2.15	1.78	2.04	2.08	1.95	2.13	1.56	2.06	1.66	1.95	0.00	0.00
11	2.53	6.29	2.75	8.56	3.36	3.49	3.43	0.70	2.10	2.06	2.00	2.14	1.61	2.06	1.72	1.98	0.00	0.00
12	2.7	6.31	2.91	8.58	3.45	5.53	3.47	2.72	2.17	4.07	2.05	4.16	1.68	4.09	1.79	4.02	0.00	0.00
13	2.84	6.33	3.07	8.61	3.55	5.57	3.53	3.94	2.24	5.28	2.13	5.50	1.75	5.41	1.88	5.36	0.00	0.00
14	2.98	6.34	3.21	8.64	3.63	5.61	3.60	3.97	2.32	5.29	2.21	5.52	1.82	6.19	1.96	5.40	0.00	0.00
15	3.11	6.35	3.34	8.66	3.70	5.64	3.66	6.23	2.41	7.55	2.28	7.80	1.91	8.48	2.04	7.69	0.00	0.00
16	3.22	6.36	3.45	8.67	3.77	5.68	3.75	6.27	2.50	7.57	2.37	7.83	2.01	8.53	2.14	7.74	0.00	0.00
17	3.32	6.38	3.57	11.79	3.84	6.13	3.82	6.72	3.82	6.73	3.69	6.77	3.71	6.21	2.22	0.98	0.00	0.00
18	3.42	6.39	3.67	11.81	3.90	6.16	3.89	6.54	3.89	6.54	3.75	7.28	3.78	6.03	2.26	0.99	0.00	0.00
19	3.50	6.40	3.78	11.82	3.96	6.17	3.96	6.57	3.95	6.57	3.83	7.31	3.85	6.06	0.00	0.00	0.00	0.00
20	3.59	6.41	3.87	11.83	4.01	6.20	4.01	6.20	4.02	6.20	3.90	6.95	3.91	5.92	0.00	0.00	0.00	0.00

Table 13: The Δy and the Δd under the two orders.

the behavior of residents will better follow the planning of the government in emergency planning.

In the case, we only take f'_p as the lowest priority among the six objectives of the model. If we upgrade the priority level of f'_p, the numbers of the residents among all emergency shelters will be more balanced. Thus, the residents will not be excessively concentrated in some emergency shelters. Therefore, emergency planner should consider the priority order of the six objectives, according to the actual situation.

5 Conclusion

This paper study the emergency planning problem considering the subjective preference. We select six attributes to analyze the subjective preference of the residents. According to different evaluation methods, the six attributes are divided into three categories, then initial subjective score of every demand point for every candidate emergency site is obtained. Base on this, we assume that the subjective preferences of the residents for the attributes of the emergency shelters change with the total refuge time, i.e., the preference weights of the residents for the attributes of the emergency shelters are dynamic. Therefore, the subjective scores of the residents for the emergency shelters also change with the total refuge time. In the emergency planning, it is impossible for us to make a location decision for each total refuge time. Under the condition that the probability of each total refuge time is the same, we take the average value of the scores at all total refuge times as the primary basis for location decision making. For improving the transfer efficiency, we minimize the per capita transfer distance. Considering fairness, we minimize respectively the standard deviations of the scores and the distances of the residents at all demand points. Considering safety, the standard deviation of the numbers of the residents among the selected shelters is taken as a factor in emergency planning, so as to avoid the excessive gathering of the residents. In addition, we propose the objective of minimizing the total cost.

The model is applied to a case, we find that, the more the emergency shelters, the higher the satisfaction degree of the residents, and the shorter the per capita distance, the more fairness is satisfied. However, the utilization effect of funds decreases with the increase of the number of the emergency shelters. Therefore, in order to improve residents' satisfaction and transfer efficiency, and avoid the inefficient utilization of funds, we should consider selecting an appropriate number of emergency shelters.

In this paper, we assume the emergency shelter has no capacity constraint. In the future, we will consider making the location decision under the condition of capacity constraint, and taking more attributes of emergency shelters as the research object. Furthermore, we could conduct more specific research on the emergency planning in the actual disaster area.

Declaration of interests

No potential conflict of interest was reported by the authors.

References

[1] Ipong, L. G., Ongy, E. E., Bales, M. C. Impact of Magnitude 6.5 Earthquake on the Lives and Livelihoods of Affected Communities: The Case of Barangay Lake Danao, Ormoc city, Leyte, Philippines. International Journal of Disaster Risk Reduction, 2020, 46: 101520.

[2] Ao, Y. B., Huang, K., Wang, Y., Wang, Q. M., Martek, L. Influence of Built Environment and Risk Perception on Seismic Evacuation Behavior: Evidence from Rural Areas Affected by Wenchuan Earthquake. International Journal of Disaster Risk Reduction, 2020, 46: 101504.

[3] Zhang, H. J., Wang, F., Tang, H. L., Dong, Y. C. An Optimization-Based Approach to Social Network Group Decision Making with an Application to Earthquake Shelter-Site Selection. International Journal of Environmental Research and Public Health, 2019, 16(15): 2740.

[4] Li, J., Liu, W. Lifeline Engineering Systems-Network Reliability Analysis and Aseismic Design. Shanghai scientific and technical publisher: Shanghai, China, 2021.

[5] Weber, A. Theory of the Location of Industries. The University of Chicago Press: Chicago, USA, 1929.

[6] Hakimi, S. L. Optimum Locations of Switching Centers and the Absolute Centers and Medians of a Graph. Operations Research, 1964, 12(3): 450-459.

[7] Hakimi, S. L. Optimum Distribution of Switching Centers in a Communication Network and Some Related Graph Theoretic Problems. Operations Research. 1965, 13(3): 462-475.

[8] Toregas, C., Swain, R., ReVelle, C., Bergman, L. The Location of Emergency Service Facilities. Operations Research, 1971, 19(6): 1363–1373.

[9] Church, R., ReVelle, C. The Maximal Covering Location Problem. Papers of the Regional Science Association. 1974, 32(1): 101–118.

[10] Xu, W., Ma, Y. J., Zhao, X. J., Li, Y., Qin, L. J., Du, J. A Comparison of Scenario-based Hybrid Bilevel and Multi-objective Location-allocation Models for Earthquake Emergency Shelters: A Case Study in the Central Area of Beijing, China. International Journal of Geographical Information Science, 2018, 32(2): 236-256.

[11] Hu, F. Y., Yang, S. N., Xu, W. A Non-dominated Sorting Genetic Algorithm for the Location and Districting Planning of Earthquake Shelters. International Journal of Geographical Information Science, 2014, 28(7): 1482-1501.

[12] Coutinho-Rodrigues, J., Tralhão, L., Alçada-Almeida, L. Solving a Location-routing Problem with a Multiobjective Approach: The Design of Urban Evacuation Plans. Journal of Transport Geography, 2012, 22(2), 206–218.

[13] Wang, J., Situ, C. Q., Yu, M. Z. The Post-disaster Emergency Planning Problem with Facility Location and People/Resource Assignment. Kybernetes, 2020, 49(10): 2385-2418.

[14] Wang, Y. Y., Xu, Z. S., Filip, F. G. Multi-Objective Model to Improve Network Reliability Level under Limited Budget by Considering Selection of Facilities and Total Service Distance in Rescue Operations. International Journal of Computers, Communications & Control, 2022, 17(1): 1-18.

[15] Saadatseresht, M., Mansourian, A., Taleai, M. Evacuation Planning Using Multiobjective Evolutionary Optimization Approach. European Journal of Operational Research, 2009, 198(1): 305-314.

[16] Kulshrestha, A., Wu, D., Lou, Y. Y., Yin, Y. F. Robust Shelter Locations for Evacuation Planning with Demand Uncertainty. Journal of Transportation Safety & Security, 2011, 3(4): 272-288.

[17] Xu, Z. S. Approaches to Multiple Attribute Decision Making with Intuitionistic Fuzzy Preference Information. Systems Engineering - Theory & Practice, 2007, 27(11): 62-71.

[18] Gong, C. Investment Decision Analysis and Optimization: Based on Prospect Theory. Electronic industry press: Beijing, China, 2019.

[19] Trivedi, A., Singh, A. A Hybrid Multi-objective Decision Model for Emergency Shelter Location-relocation Projects Using Fuzzy Analytic Hierarchy Process and Goal Programming Approach. International Journal of Project Management, 2017, 35(5): 827-840.

[20] Ma, Y. J., Xu, W., Qin, L. J., Zhao, X. J. Site Selection Models in Natural Disaster Shelters: A Review. Sustainability, 2019, 11(2): 399.

[21] Sabouhi, F., Tavakoli, Z. S., Bozorgi-Amiri, A., Sheu, J. B. A Robust Possibilistic Programming Multi-Objective Model for Locating Transfer Points and Shelters in Disaster Relief. Transportmetrica A: Transport Science, 2019, 15(2): 326-353.

[22] Ng, M. W., Park, J., Waller, S. T. A Hybrid Bilevel Model for the Optimal Shelter Assignment in Emergency Evacuations. Computer-Aided Civil and Infrastructure Engineering, 2010, 25(8): 547-556.

[23] Tsai, C. H., Yeh, Y. L. The Study of Integrating Geographic Information with Multi-Objective Decision Making on Allocating the Appropriate Refuge Shelters: Using Kengting National Park as an Example. Natural Hazards, 2016, 82: 2133–2147.

[24] Şenik, B., Uzun, O. An Assessment on Size and Site Selection of Emergency Assembly Points and Temporary Shelter Areas in Düzce. Natural Hazards, 2021, 105: 1587-1602.

[25] Nappi, M. M. L., Souza, J. C. Disaster Management: Hierarchical Structuring Criteria for Selection and Location of Temporary Shelters. Natural Hazards, 2015, 75: 2421-2436.

[26] Aman, D. D., Aytac, G. Multi-Criteria Decision Making for City-scale Infrastructure of Post-earthquake Assembly Areas: Case Study of Istanbul. International Journal of Disaster Risk Reduction, 2022, 67: 102668.

[27] Wu, H. Y, Ren, P. J., Xu, Z. S. Addressing Site Selection for Earthquake Shelters with Hesitant Multiplicative Linguistic Preference Relation. Information Sciences, 2020, 516: 370-387.

[28] Song, S. Y., Zhou, H., Song, W. Y. Sustainable Shelter-site Selection Under Uncertainty: A Rough QUALIFLEX Method. Computers & Industrial Engineering, 2019, 128: 371-386.

[29] China Earthquake Administration. Site and Supporting Facilities for Earthquake Emergency Shelter (GB21734). China Standard Press: Beijing, China, 2008.

[30] Wang, Y. Y., Zhou, B., Xu, Z. S. An Empirical Study on the Evaluation of Rural Human Settlement with Normal Distribution-Based Weighting Method and AHP. Mathematics in Practice and Theory, 2017, 47(16): 100-107.

[31] Yager, R. R. On Ordered Weighted Averaging Aggregation Operators in Multicriteria Decision Making. IEEE Transactions on Systems, Man, and Cybernetics, 1988, 18(1): 183-190.

[32] Xu, Z. S. An Overview of Methods for Determining OWA Weights. International Journal of Intelligent Systems, 2005, 20(8): 843-865.

[33] Saaty, T. L. A Scaling Method for Priorities in Hierarchical Structures. Journal of Mathematical Psychology, 1977, 15(3): 234-281.

[34] Filip, F. G., Zamfirescu, C. B., Ciurea, C. Computer-supported collaborative decision-making. Springer, 2017.

[35] Xiao, T. J. Behavioral Decision Theory: Modeling and Analysis. Science Press, Beijing, China, 2020.

[36] Yang, B. A., Zhang, K. J. Research on Theory, Method and Application of Multi-objective Decision Analysis. Donghua university press: Shanghai, 2008.

[37] Yu, W. Y. Reachability Guarantee Based Model for Pre-positioning of Emergency Facilities under Uncertain Disaster Damages. International Journal of Disaster Risk Reduction, 2020, 42: 101335.

[38] Poorzahedy, H., Rouhani, O. M. Hybrid Meta-heuristic Algorithms for Solving Network Design Problem. European Journal of Operational Research, 2007, 182(2): 578-596.

[39] Leon, E., Kelman, I., Kennedy, J., Ashmore, J. Capacity Building Lessons from a Decade of Transitional Settlement and Shelter. International Journal of Strategic Property Management, 2009, 13(3): 247–265.

C O P E
Member since 2012
JM08090

This journal is a member of, and subscribes to the principles of,
the Committee on Publication Ethics (COPE).
https://publicationethics.org/members/international-journal-computers-communications-and-control

Cite this paper as:

Yiying Wang, Zeshui Xu; (2022). A Multi-objective Location Decision Making Model for Emergency Shelters Giving Priority to Subjective Evaluation of Residents, *International Journal of Computers Communications & Control*, 17(4), 4749, 2022.
https://doi.org/10.15837/ijccc.2022.4.4749