Prospect Selection Decisions for Emergency Logistics Paths in Fuzzy Environments

Wenjun Sun, Changfeng Zhu, and Kangru Liu

Abstract—**In decision making and path selection in emergency logistics, the bounded rationality of decision makers and subsequent secondary disasters have a great impact on the final plan. However, some investigation factors are difficult to express in definite quantities. In this paper, we consider the occurrence of secondary disasters and the bounded rationality of decision makers, combined with triangular fuzzy theory and prospect theory. We construct a prospect decision-making model for an emergency logistics path in a fuzzy environment and verify the rationality of the model through numerical example analysis. The research results indicate that the model adopted in this paper can obtain the priority selection order of the path according to the factors investigated and provide a reference for decision makers to make emergency logistics path selection decisions.**

Index Terms—**bounded rationality, triangular fuzzy number, secondary disasters, path selection**

I. Introduction

When major natural disasters, such as earthquakes and typhoons, occur, large amounts of materials have to be transported from rescue centers to the disaster areas as part of relief efforts aimed at saving lives and reducing post-disaster losses. Many investigators, both nationally and internationally, have conducted extensive research on the problem of path selection in emergency logistics, as path selection is key to saving lives, reducing losses, and speeding up post-disaster reconstruction.

In a previous path selection study, some scholars have completed path selection by constructing a single-objective programming model: An adaptive path size logit model was constructed, and compared with several other models, which proves that its performance is relatively better [1]. A dynamic integrated evacuation planning method was proposed to minimize the maximum network clearing time when planning emergency paths [2]. With the aim of minimizing the total evacuation time, a transmission model, including a bidirectional multilane conflict elimination unit, has been used to obtain the optimal vehicle trajectory [3]. The proposed problem was transformed into a vehicle routing problem with multiple depots and took the minimum total transportation cost as the objective function [4]. Taking the minimum sum of the waiting times of personnel and the total travel time of vehicles as the objectives, an optimal strategy to reduce disaster losses was sought [5]. In other studies, to make the problem representation more perfect, the problem was divided into two stages or two levels, and a single-objective model was established at each stage or level [6,7].

Some scholars have completed path selection by constructing multi-objective programming models: A dual-objective mathematical model has been developed for path evaluation [8]. Based on an emergency rescue problem involving a fire in a mine, investigators established a bi-objective programming model of road hazard degree and rescue time to determine the risk level of the rescue path set [9]. In another study, using the number of paths, travel time, and path length as performance indicators of network vulnerability, a three-objective emergency traffic network design model was constructed [10]. A dynamic multi-objective emergency path planning model has been proposed to provide emergency path planning services for personnel in different accident scenarios [11]. In order to solve a vehicle routing problem in emergency food distribution scenarios, Q. Zhang, and S.W. Xiong constructed a multi-objective programming model for optimizing the path of emergency grain distribution [12]. A multi-objective route optimization model was constructed for the distribution of cold chain logistics enterprises, and in order to solve it, a heuristic algorithm was designed [13]. A three-objective emergency rescue path selection model for rescuing the wounded has also been constructed, in which the absolute deprivation cost and relative deprivation cost were used to describe the psychological trauma of those wounded at a disaster site [14]. Some research has described the impact of the path selection problem on vehicle arrival times by adding time window constraints to the model and developing meta-heuristic algorithms to work out the path selection problem with time windows, verifying the feasibility by examples [15–20].

Some scholars use modern data analysis and processing technology to analyze and process the information data in models. A prediction model was established for route selection, which provides a new solution and method for solving the vehicle routing problem [21, 22]. A. Jotshi et al.

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Wenjun Sun is a doctor degree candidate at School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China, and works at Rizhao Polytechnic, Rizhao 276826, China. (e-mail: sunwunjun@126.com).

Changfeng Zhu is a Professor at School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China. (Corresponding author, phone: +86 17726957836, e-mail: changfengzhu@163.com).

Kangru Liu is a postgraduate student at School of Traffic and Transportation, Lanzhou Jiaotong University, Lanzhou 730070, China. (e-mail: LiuSN1323@163.com).

used data fusion techniques to estimate information from various sources to develop a scheduling and routing simulation model [23].

Path selection by decision makers is not always rational [24], with various factors, including personality, risk preference, psychological state, and traffic environment, influencing decision making [25]. Particularly in emergency environments, disasters produce chaos, congestion, and panic, which affect decision makers' abilities to make decisions [26]. Therefore, it is crucial to consider bounded rationality in the decision-making process of path selection. Bounded rationality can more accurately describe path selection behavior in an uncertain environment [27]. None of the aforementioned models considers the decision makers' bounded rationality in path selection during the rescue process. Moreover, the processing of data information is based on the determined information data, giving an accurate form of data information or interval number form. Due to uncertainties in emergency logistics, in the process of path selection, there is considerable uncertain data information when expressing the relevant factors that affect decision making. In view of this, the prospect theory is introduced to describe the decision makers' bounded rationality when selecting emergency logistics paths in this paper. When using fuzzy theory to deal with uncertain data information, first, information is recorded in the form of language-level phrases, and then it is further transformed into triangular fuzzy numbers. Based on existing research, a prospect decision-making model in a fuzzy environment is constructed to select and sort an emergency logistics path. The significant contributions of this paper are as follows:

1) While using prospect theory to consider the decision makers' bounded rationality in path selection, it also further reveals the mechanism of "reflection effect" and "certainty effect" behind the negative and positive prospect values of alternative paths.
2) The occurrence of secondary disasters is included in the model analysis framework, and the model used can comprehensively investigate the relevant factors affecting the path selection decision.

The paper is arranged as follows: Section II presents the problems studied in this paper and the main mathematical symbols used. In Section III, a prospect decision-making model in a fuzzy environment is established, and the solution flow is designed. In Section IV, the rationality of the model established in Section III is verified through a numerical example, and the mechanism behind the solution results of the model is revealed through parameter disturbance analysis(DA). Section V presents the research conclusions of this paper and proposes follow-up research directions.

II. Problem Statement and symbol representation

A. Problem Statement

In this study, we considered a rescue path selection problem of decision makers with bounded rationality facing n alternative paths between a rescue center and a disaster area against the background of a major natural disaster, such as a typhoon or an earthquake, and secondary disasters. For descriptive purposes, a rescue network system G was built. Without loss of generality, we assume that multiple paths exist between the rescue center M_O and the disaster area M_D (Fig. 1). We then investigate path selection decisions made by the decision makers under the premise of considering relevant factors.

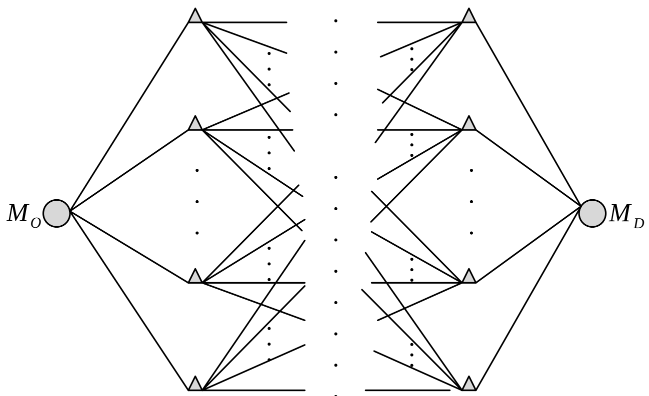

Fig. 1. Rescue network system G

B. Symbol Representation

Suppose that, in the rescue network $G=(M,A)$, $M=\{M_o,M_1,M_2,...,M_{z-2},M_D\}$ is the nodes set, and $A=\{A_1,A_2,...,A_m\}$ is the alternative paths set between the rescue center M_O and the disaster area M_D, where $A_i \in A$ is any one of the paths, which is composed of several road sections M_xM_y. $M_x \in M$ and $M_y \in M$ are the two adjacent nodes on A_i. The probability of secondary disasters in road section M_xM_y is η_{xy}. The set of relevant factors that the decision maker should consider when making the rescue path selection decision is $C=\{C_1,C_2,...,C_n\}$, in which $C_i,C_j \in C$ are any two different factors, and C_i and C_j are additively independent. In this paper, the factors in C are divided as follows:

1) According to the value of each factor in C, C is divided into a factor subset, C^n, with the value of a clear number; a factor subset, C^i, with the value of an interval number; a factor subset, C^f, with the value of a fuzzy number; and $C^n \cup C^i \cup C^f = C$.
2) According to the influence of each factor on the profit and loss of decision making, the factors in C can be divided into benefit type and cost type. The set of cost-type factors is denoted as C^c, and the smaller the value of the factor in C^c, the better; the set of benefit-type factors is C^b, and the larger the value of the factor in C^b, the better. There are $C^c \cup C^b = C$, and $C^c \cap C^b = \varnothing$.

$\rho = [\rho_1, \rho_2, ..., \rho_n]$ corresponds to the decision weight vector of the decision maker for each factor, where $\rho_j \geq 0$ and $\sum_{j=1}^{n} \rho_j = 1$. $Q = [q_1, q_2, ..., q_n]$ is the expectation vector for each influencing factor given by the decision maker according to existing information and future predictions, where q_j is the decision maker's expectation of factor C_j. $B = [b_{ij}]_{m \times n}$ is the decision matrix, where b_{ij} is the evaluation value of alternative path A_i against factor C_j when secondary disasters occur. Most of the time, the values of q_j and b_{ij} etc., cannot be given a definite number or interval and can be described only by language phrases, such as high, relatively high, low, or relatively low, that indicate the degree, and the expectation q_j and evaluation value b_{ij} of the same factor C_j are in the same form of expression. In this paper, the set of language phrases is denoted as $S = \{s_r \mid r = 0, 1, ..., \frac{X}{2} - 1, \frac{X}{2}, \frac{X}{2} + 1, ..., X\}$, where s_r represents the *r+1th* language phrase in *S*, and *X* is an even number. The language phrase set *S* has the following three basic properties [28]:

1) Orderliness: when $j > k$, s_j is always better than s_k, which is denoted as $s_j \succ s_k$;
2) An inverse operator *neg*: when *k* = *X-j*, there is always $neg(s_j) = s_k$;
3) Minimization and maximization operations: when $s_j \succ s_k$, $min\{s_j, s_k\} = s_k$ and $max\{s_j, s_k\} = s_j$.

III. Prospect Decision Model in A Fuzzy Environment

A. Triangular Fuzzy Numbers

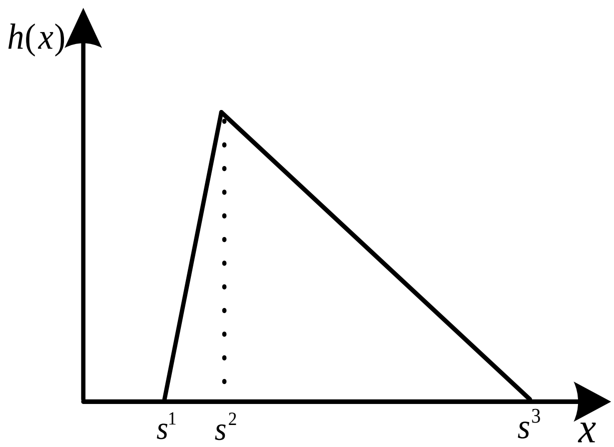

Fig. 2. Image of membership function

A fuzzy number, $\hat{s} = (s^1, s^2, s^3)$, with membership function $h(x)$, as shown in Fig. 2, is a triangular fuzzy number, where s^1, s^2, s^3 are real numbers, $0 \leq s^1 \leq s^2 \leq s^3$, s^2 is the principal value of triangular fuzzy number $\hat{s}$, and s^1 and s^3 are lower and upper bounds of $\hat{s}$, respectively [28].

For information processing and calculation, language phrases need to be digitized. In this paper, the conversion rules of formula (1) were adopted to convert the language phrase s_r into the corresponding triangular fuzzy number $\hat{s}$ [29]:

$$\begin{aligned} \hat{s} &= (s^1, s^2, s^3) \\ &= (max\{(r-1)/X, 0\}, r/X, min\{(r+1)/X, 1\}). \end{aligned} \quad (1)$$

B. Prospect Decision Model

Prospect theory, a bounded rational decision-making theory, was first put forward by A. Tversky and D. Kahneman, in 1979 [30]. The main components of prospect theory are reference point dependence, risk preference reversal, and loss aversion, etc.

The application of prospect theory to evaluate alternative paths involves two main sequential stages: an editing stage and an evaluation stage. The measurement information needs to be edited as a "loss" or "gain" relative to a reference point in the first stage. The "loss" or "gain" is subjectively evaluated according to value and weight functions in the second stage.

B.1. Editing Stage

B.1.1. Expected Editing

As the goal of the decision maker in this study is to optimize the emergency logistics path selection, in the selection of reference points, the decision maker's expectation q_j for factor C_j is selected as the reference point.

a. Expectations of Factors in Subset C^i

Assuming that C_l is any factor in subset C^i, it's hard for decision makers to evaluate its corresponding expectation q_l at this time accurately. Thus, an interval number form $q_l = [q_l^{low}, q_l^{up}]$ is often used, where $q_l^{up} \geq q_l^{low}$.

b. Expectations of Factors in Subset C^n

The expectation of the factors in subset C^n can be represented by a definite value. In the path selection of emergency logistics, the delivery time of relief supplies and the remaining capacity of the path are the two most important factors to be investigated. Without loss of generality, it is advisable to assume that C_t and C_r are any two factors in subset C^n, representing the delivery time of relief supplies and the remaining capacity of the path, respectively. The selection process of expectations q_t and q_r for C_t and C_r

is shown below:

b.1. The Selection Process of q_t

To consider the time uncertainty factor in emergency logistics caused by disasters when transporting relief supplies through path A_i, reliability ρ should be considered in the selection of time expectation q_t, as follows:

$$t_i^{min} = min\{t_i \mid \varphi_i(t_i) \geq \rho\}. \quad (2)$$

$$q_t = min\{t_i^{min}\}. \quad (3)$$

where t_i^{min} is the transportation time of goods on path A_i and $\varphi_i(t_i)$ is the probability of transportation time.

If the path in the road network is composed of multiple road sections, combined with the separation effect of the road sections and the central limit theorem, the transportation time of the path can be expected to follow a normal distribution $N(\mu_i, \sigma_i^2)$. Formula (2) can then be then expressed as:

$$t_i^{min} = min\{\phi^{-1}(\rho) \cdot \sigma_i + \mu_i\}. \quad (4)$$

where $\phi^{-1}(\cdot)$ is the inverse function of standard distribution, σ_i is the standard deviation, and μ_i is the mean value of transportation time on A_i.

b.2. The Selection Process of q_r

During a disaster, the traffic capacity of a path can be expected to be damaged to some extent, assuming that, after the disaster, the remaining capacity of path A_i approximately follows the normal distribution of $N(v_i, \xi_i)$. To avoid poor reconfigurability due to various factors, such as road congestion caused by excessive traffic volumes during the emergency transportation process, the selection rule of the expected remaining capacity q_r of the path is as follows:

$$f_i^{max} = max\{f_i \mid (1 - \psi_i(f_i)) \geq \rho'\}. \quad (5)$$

$$q_r = min\{f_i^{max}\}. \quad (6)$$

where f_i^{max} is the maximum value of the transported material quantity on path A_i; $\psi_i(\cdot)$ is a probability function, and ρ' is the reliability.

c. The Expectations of Factors in Subset C^f

Assuming that C_u is any factor in subset C^f, for the selection of expectation q_u of this factor, it is necessary to collect and sort information through the Delphi method and focus interview method on the basis of a preliminary evaluation of the existing path, and obtain the expectation value of the decision maker for the influencing factors, and its value is $q_u \in S$. In this paper, the case of *X = 6* is considered, that is, $S = \{s_0, s_1, ..., s_6\}$ = {very low, low, relatively low, medium, relatively high, high, and very high}.

B.1.2. Dimensionless Editing of Information

To eliminate the impact of different physical dimensions on the deviation of the subsequent evaluation, it is necessary to non-dimensionalize the expected (reference point) vector $Q = (q_1, q_2, ..., q_n)$ obtained above as $G = (g_1, g_2, ..., g_n)$ and non-dimensionalize the decision matrix $B = \{b_{ij}\}_{m\times n}$ as matrix $E = \{e_{ij}\}_{m\times n}$. The specific dimensionless calculation formula is expressed as follows [31]:

a. Non-Dimensionlessization of Interval Value Factors

It is assumed that the expectation and evaluation value of decision makers in terms of factor C_l in subset C^i are $q_l = [q_l^{low}, q_l^{up}]$ and $b_{il} = [b_{il}^{low}, b_{il}^{up}]$, respectively. After non-dimensionalization, the corresponding values are still interval numbers:

$$[g_l^{low}, g_l^{up}] = \begin{cases} [\dfrac{q_l^{low} - b_l^{low}}{b_l^{up} - b_l^{low}}, \dfrac{q_l^{up} - b_l^{low}}{b_l^{up} - b_l^{low}}], C_l \in C^i \cap C^b \\ [\dfrac{b_l^{up} - q_l^{up}}{b_l^{up} - b_l^{low}}, \dfrac{b_l^{up} - q_l^{low}}{b_l^{up} - b_l^{low}}], C_l \in C^i \cap C^c \end{cases}. \quad (7)$$

$$[e_{il}^{low}, e_{il}^{up}] = \begin{cases} [\dfrac{b_{il}^{low} - b_l^{low}}{b_l^{up} - b_l^{low}}, \dfrac{b_{il}^{up} - b_l^{low}}{b_l^{up} - b_l^{low}}], A_i \in A, C_l \in C^i \cap C^b \\ [\dfrac{b_l^{up} - b_{il}^{up}}{b_l^{up} - b_l^{low}}, \dfrac{b_l^{up} - b_{il}^{low}}{b_l^{up} - b_l^{low}}], A_i \in A, C_l \in C^i \cap C^c \end{cases}. \quad (8)$$

Among them:

$$\left.\begin{aligned} b_l^{up} &= max(\max_{1\leq i\leq m}(b_{il}^{up}), q_l^{up}) \\ b_l^{low} &= min(\min_{1\leq i\leq m}(b_{il}^{low}), q_l^{low}) \end{aligned}\right\}, C_l \in C^i. \quad (9)$$

b. Non-Dimensionlessization of Clear Number Value Factors

Assuming that any two factors, C_t and C_r in subset C^n, are cost-type factors and benefit-type factors, respectively, that is, $C_t \in C^c$ and $C_r \in C^b$, the corresponding dimensionless rules are as follows:

$$g_t = \frac{b_t^+ - q_t}{b_t^+ - b_t^-}, e_{it} = \frac{b_t^+ - b_{it}}{b_t^+ - b_t^-}, i = 1, 2, ..., m. \quad (10)$$

Among them:

$$\begin{cases} b_t^+ = max(\max_{1\leq i\leq m}(b_{it}), q_t) \\ b_t^- = min(\min_{1\leq i\leq m}(b_{it}), q_t) \end{cases}. \quad (11)$$

$$g_r = \frac{q_r - b_r^-}{b_r^+ - b_r^-}, e_{ir} = \frac{b_{ir} - b_r^-}{b_r^+ - b_r^-}, i = 1, 2, ..., m. \quad (12)$$

Among them:

$$\begin{cases} b_r^+ = max(\max_{1\le i\le m}(b_{ir}), q_r) \\ b_r^- = min(\min_{1\le i\le m}(b_{ir}), q_r) \end{cases}. \tag{13}$$

c. Non-Dimensionlessization of Language Phrase Value Factors

For any factor, C_u, in subset C^f, the corresponding dimensionless rule is as follows:

$$g_u = \begin{cases} q_u, C_u \in C^f \cap C^b \\ neg(q_u), C_u \in C^f \cap C^c \end{cases}. \tag{14}$$

$$e_{iu} = \begin{cases} b_{iu}, A_i \in A, C_u \in C^f \cap C^b \\ neg(b_{iu}), A_i \in A, C_u \in C^f \cap C^c \end{cases}. \tag{15}$$

The language phrases g_u and e_{iu} obtained by formulas (10) and (11) are converted into corresponding triangular fuzzy numbers (g_u^1, g_u^2, g_u^3) and $(e_{iu}^1, e_{iu}^2, e_{iu}^3)$ using formula (1).

B.1.3. Profit-and-Loss Editing

Finally, we calculate the "gain" or "loss" of the evaluation value e_{ij} of each factor in each path relative to the reference point g_j. When $e_{ij} > g_j$ or $e_{ij} \succ g_j$, it is regarded as gain; when $g_j > e_{ij}$ or $g_j \succ e_{ij}$, it is regarded as loss. d_{ij} is the distance between the two, that is, the size of the gain or loss value. For different types of factors, the expression form of d_{ij} is different, as follows:

$$d_{ij} = \begin{cases} \sqrt{\dfrac{[(e_{ij}^{low} - g_j^{low})^2 + (e_{ij}^{up} - g_j^{up})^2]}{2}}, C_j \in C^i \\ \sqrt{(e_{ij} - g_j)^2}, C_j \in C^n \\ \sqrt{\dfrac{[(e_{ij}^1 - g_j^1)^2 + (e_{ij}^2 - g_j^2)^2 + (e_{ij}^3 - g_j^3)^2}{3}}, C_j \in C^f \end{cases}. \tag{16}$$

To represent "gain" and "loss" intuitively, a profit-and-loss decision matrix (PALDM) $F = [F(e_{ij})]_{m\times n}$ is established, where $F(e_{ij})$ is the profit-and-loss value of every factor evaluation value e_{ij} relative to the reference point g_j. The calculation formula can be expressed as follows:

$$F(e_{ij}) = \begin{cases} d_{ij}, e_{ij} \ge g_j, i = 1,2,...,m \\ -d_{ij}, e_{ij} < g_j, i = 1,2,...,m \end{cases}. \tag{17}$$

B.2. Evaluation Stage

B.2.1. Value Function

To measure the influence of "loss" or "gain" on the subjective satisfaction of the decision makers' path selection, a value function matrix, $V = [v(e_{ij})]_{m\times n}$, is established, in which the value function $v(e_{ij})$ is called the subjective utility function, which reflects the value that the actual utility of each factor examined in the path deviates from the reference point, and it's calculation formula is:

$$v(e_{ij}) = \begin{cases} (F(e_{ij}))^\alpha, F(e_{ij}) \ge 0 \\ -\lambda \cdot (-F(e_{ij}))^\beta, F(e_{ij}) < 0 \end{cases}. \tag{18}$$

In the formula, the parameters $\alpha, \beta (0 < \alpha, \beta \le 1)$ represent the risk preference coefficient, where β is the loss sensitivity coefficient (SC), α is the gain SC, and $\lambda (\lambda \ge 1)$ is the loss avoidance coefficient. According to the calibration parameters of Tversky et al. [32–34], usually, $\alpha = \beta = 0.88$, and $\lambda = 2.25$.

B.2.2. Weight Function

This function $\omega(p_i)$ is used to describe the psychological effects on human beings. In general, people usually obsess with small probability events and neglect medium and large ones. When facing with gains, decision makers hold a risk-averse attitude, whereas in the face of losses, they hold a risk-preferred attitude. Its form is as follows [30]:

$$\omega(p_i) = \begin{cases} \dfrac{p_i^\gamma}{[p_i^\gamma + (1-p_i)^\gamma]^{1/\gamma}}, (faced\ with\ gains) \\ \dfrac{p_i^\delta}{[p_i^\delta + (1-p_i)^\delta]^{1/\delta}}, (faced\ with\ losses) \end{cases}. \tag{19}$$

where $\gamma (0 < \gamma < 1)$ is the acquired perception probability coefficient (PPC), and $\delta (0 < \delta < 1)$ is the loss PPC. According to the calibration parameters of Tversky et al. [32, 35], usually, δ=0.69, γ=0.61. p_i represents the probability of secondary disasters in alternative path A_i. The calculation formula is as follows:

$$p_i = \max_{M_x M_y \in A_i} \{\eta_{xy}\}. \tag{20}$$

B.2.3. The Prospect Value of Alternative Paths

The prospect values of decision factors for each alternative path is computed, and the prospect decision matrix $W = [W(e_{ij})]_{m\times n}$ is established, where $W(e_{ij})$ is the prospect value of decision factor C_j for alternative path A_i. The formula is:

$$W(e_{ij}) = v(e_{ij}) \cdot \omega^T(p_i), j = 1,2,...,n; i = 1,2,...,m. \tag{21}$$

Then, the prospect value $U(A_i)$ of the *ith* alternative path A_i is:

$$U(A_i)=\sum_{j}^{n}[\rho_j \cdot W(e_{ij})], i=1,2,...,m. \qquad (22)$$

Obviously, the larger $U(A_i)$ of the alternative path, the better path A_i can be expected to be. When optimizing an emergency logistics path, the paths should be sorted by the prospect value to obtain the priority order of path selection.

C. Model Solving

The solution steps of the prospect decision model in a fuzzy environment are described as follows:

Step 1: Determine the evaluation value b_{ij} and expectation q_j of each investigated factor C_j in related factor set C and conduct dimensionless processing according to formulas (7)–(15).

Step 2: If there is an evaluation value e_{iu} and an expectation g_u in the form of language phrases after dimensionless processing, convert these into corresponding triangular fuzzy numbers $(e_{iu}^1, e_{iu}^2, e_{iu}^3)$ and (g_u^1, g_u^2, g_u^3) form in accordance with formula (1).

Step 3: In accordance with formula (16), calculate the gain or loss value (d_{ij}) of the evaluation value (e_{ij}) of each factor C_j in path A_i relative to g_j. Then, in accordance with formula (17), a PALDM F is established to intuitively represent “gain” and “loss.”

Step 4: According to formula (18), calculate the value $v(e_{ij})$ that the actual utility value of each investigated factor C_j in path A_i deviates from the reference point and establish a value function matrix V.

Step 5: Use formula (20) to obtain the probability p_i of secondary disasters occurring on path A_i and convert it into the subjective weight $\omega(p_i)$ of the decision makers through formula (19).

Step 6: Use formula (21) to calculate the prospect value $W(e_{ij})$ of decision factor C_j on A_i and establish the prospect decision matrix W.

Step 7: According to formula (22), the prospect value $U(A_i)$ of each alternative path A_i is obtained and sorted according to the size of $U(A_i)$ to determine the preferred path.

IV. Example Analysis

A. Example Description and Parameter Setting

See Fig. *3* for the composition of an emergency logistics network system. There are nine nodes in total, M_O for the rescue center, M_D for the disaster area. There are six alternative paths from M_O to M_D containing different road sections: path A_1 (sections *1, 2, 5,* and *10*), path A_2 (sections *1*, *4*, *7*, and 10), path A_3 (sections *1*, *4*, *9*, and *12*), path A_4 (sections *3*, *6*, *7*, and *10*0, path A_5 (sections *3*, *6*, *9*, and *12*), and path A_6 (sections *3*, *8*, *11*, and *12*). The probability of secondary disasters in each road section predicted by meteorological and geological departments is shown in Table I. In decision making on path selection during the emergency rescue, the four main factors considered are as follows [36, 37]: the passage time of the path (C_1), the remaining capacity of the path (C_2), the bumpiness degree of the path (C_3), and the completeness of path service facilities (C_4). Assuming that the decision weighting vector of the decision maker for the influencing factors of each path is $\rho=[0.4, 0.4, 0.15, 0.05]$, to transport materials to a demand point in time at an early stage of rescue, people usually show a preference for risk in the path selection of emergency logistics. Here, we discuss the decision-making problem of a risk-preference type decision maker. When this kind of decision maker selects the reference point, the reliability of the delivery time is equal or greater than 0.3, and the reliability of remaining capacity is not less than 0.2. Assuming that the transport time for goods and the remaining capacities of the six paths are approximately subject to a normal distribution, the mean value and standard deviation corresponding to each path when the disaster occurs are shown in Table II.

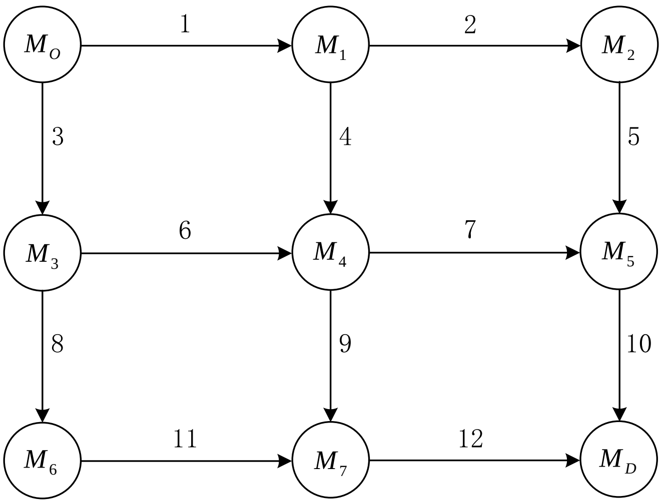

Fig. 3. Emergency logistics network

TABLE I
PROBABILITY OF SECONDARY DISASTERS IN EACH ROAD SECTION

Probability	Road Section											
	M_OM_1	M_1M_2	M_OM_3	M_1M_4	M_2M_5	M_3M_4	M_4M_5	M_3M_6	M_4M_7	M_5M_D	M_6M_7	M_7M_D
η_{xy}	0.1%	0.5%	0.1%	0.5%	0.8%	0.5%	0.8%	0.5%	0.8%	1.2%	0.8%	3%

TABLE II
RELATED PARAMETERS OF ALTERNATIVE PATHS

Parameters		Paths					
		A_1	A_2	A_3	A_4	A_5	A_6
C_1	u_i	210	220	260	280	290	300
(min)	σ_i	30	50	60	12	30	20
C_2	u_i	700	720	680	630	660	650
(pcu)	σ_i	60	100	80	60	80	40

B. Example solution

B.1. Editing Stage

According to formulas (2)–(6), it is calculated that $q_1 = min$ {194.26, 193.78, 228.54, 273.71, 274.27, 289.51}=193.78, and $q_2 = min$ {750.52, 804.2, 747.36, 680.52, 727.36, 683.68}=680.52. Using the Delphi method and the focus interview method, we obtained $Q = [193.78$, 680.52, relatively high, medium]. The decision matrix when secondary disasters occur is shown in Table III.

TABLE III
ALTERNATIVE PATH DECISION MATRIX

Paths	Factors			
	C_1	C_2	C_3	C_4
A_1	210	700	medium	medium
A_2	220	720	medium	medium
A_3	260	680	high	low
A_4	280	630	very high	relatively low
A_5	290	660	very high	low
A_6	300	650	high	relatively low

According to formula (1), all language phrases in S are converted into homologous triangular fuzzy numbers:

s_0 : very low = (0.00, 0.00, 0.17)
s_1 : low = (0.00, 0.17, 0.33)
s_2 : relatively low = (0.17, 0.33, 0.50)
s_3 : medium = (0.33, 0.50, 0.67)
s_4 : relatively high = (0.50, 0.67, 0.83)
s_5 : high = (0.67, 0.83, 1.00)
s_6 : very high = (0.83, 1.00, 1.00)

Among the four factors influencing the path selection decision, C_1 and C_3 belong to the cost type, while C_2 and C_4 belong to the benefit type. Through formulas (7)–(15), the expected vector Q and the decision matrix shown in Table III are non-dimensionalized:

Q = [1.00,0.56, (0.17,0.33,0.50), (0.33,0.50,0.67)].

According to formulas (16) and (17), the PALDM can be obtained as follows:

$$F = [F(e_{ij})]_{6\times4} = \begin{bmatrix} -0.15 & 0.22 & 0.17 & 0.00 \\ -0.25 & 0.44 & 0.17 & 0.00 \\ -0.62 & 0.00 & -0.17 & -0.33 \\ -0.81 & -0.56 & -0.29 & -0.17 \\ -0.91 & -0.23 & -0.29 & -0.33 \\ -1.00 & -0.34 & -0.17 & -0.17 \end{bmatrix}.$$

TABLE IV
DECISION MATRIX AFTER NON-DIMENSIONALIZATION

Paths	Factors			
	C_1	C_2	C_3	C_4
A_1	0.85	0.78	(0.33,0.50,0.67)	(0.33,0.50,0.67)
A_2	0.75	1.00	(0.33,0.50,0.67)	(0.33,0.50,0.67)
A_3	0.38	0.56	(0.00,0.17,0.33)	(0.00,0.17,0.33)
A_4	0.19	0.00	(0.00,0.00,0.17)	(0.17,0.33,0.50)
A_5	0.09	0.33	(0.00,0.00,0.17)	(0.00,0.17,0.33)
A_6	0.00	0.22	(0.00,0.17,0.33)	(0.17,0.33,0.50)

B.2. Evaluation stage

The value matrix is obtained from formula (18):

$$V = [v(e_{ij})]_{6\times4} = \begin{bmatrix} -0.42 & 0.26 & 0.21 & 0.00 \\ -0.66 & 0.49 & 0.21 & 0.00 \\ -1.48 & 0.00 & -0.47 & -0.85 \\ -1.87 & -1.35 & -0.76 & -0.47 \\ -2.07 & -0.62 & -0.76 & -0.85 \\ -2.25 & -0.87 & -0.47 & -0.47 \end{bmatrix}.$$

The prospect decision matrix is obtained from formulas (19)–(21):

$$W = [W(e_{ij})]_{6\times4} = \begin{bmatrix} -0.019 & 0.016 & 0.013 & 0.000 \\ -0.030 & 0.030 & 0.013 & 0.000 \\ -0.120 & 0.000 & -0.038 & -0.069 \\ -0.084 & -0.060 & -0.034 & -0.021 \\ -0.167 & -0.050 & -0.061 & -0.069 \\ -0.182 & -0.070 & -0.038 & -0.038 \end{bmatrix}.$$

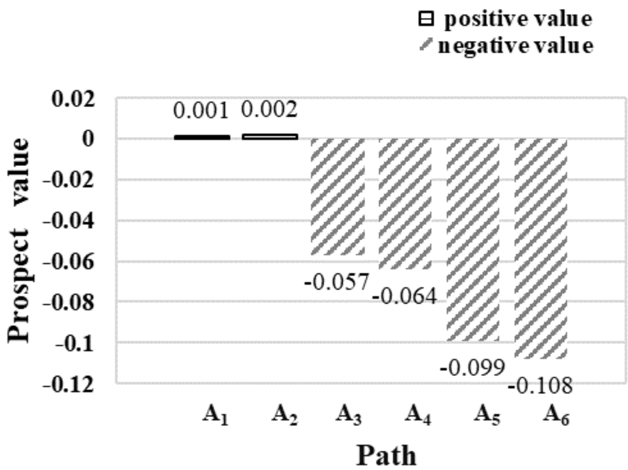

Fig. 4. The prospect results of alternative paths

The prospect result of each path calculated according to formula (22) is shown in Fig. 4. Obviously, $U(A_2) > U(A_1) > U(A_3) > U(A_4) > U(A_5) > U(A_6)$. Therefore, when choosing the emergency rescue path, path A_2 should be given priority.

C. Parametric DA

C.1. DA of Risk Preference Coefficients β and α

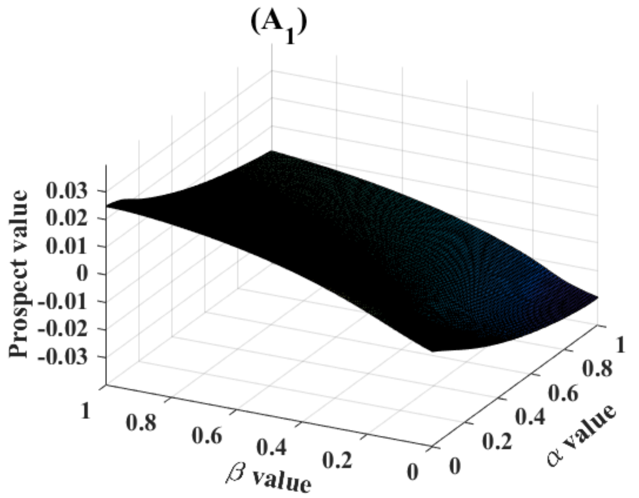

Fig. 5. DA of β and α on PT of A_1

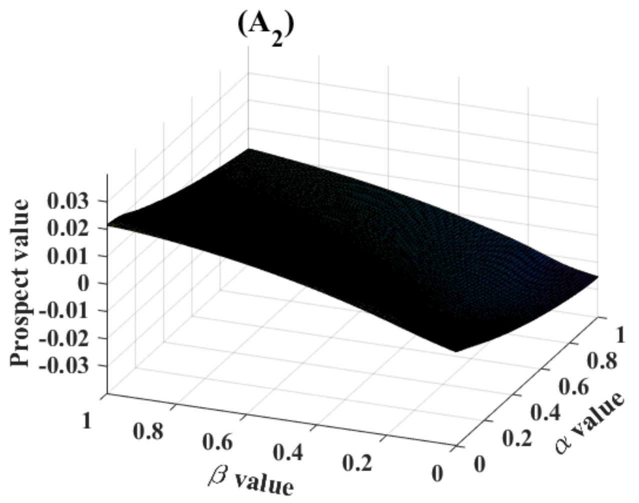

Fig. 6. DA of β and α on PT of A_2

We can see from Fig. 5–Fig. 10 that the prospect values in alternative paths A_1 and A_2 are positive, whereas those in paths A_3, A_4, A_5, and A_6 are all negative. Among these paths, the prospect values of $A_3 - A_6$ are not affected by the value of α but increase greatly with an increase in the value of β. The prospect values of A_1 and A_2 are affected by α value and decrease with an increase in the value of α. At the same time, the prospect values of A_1 and A_2 increase with an increase in β value, but the increase in these values is smaller than the increase under $A_3 - A_6$.

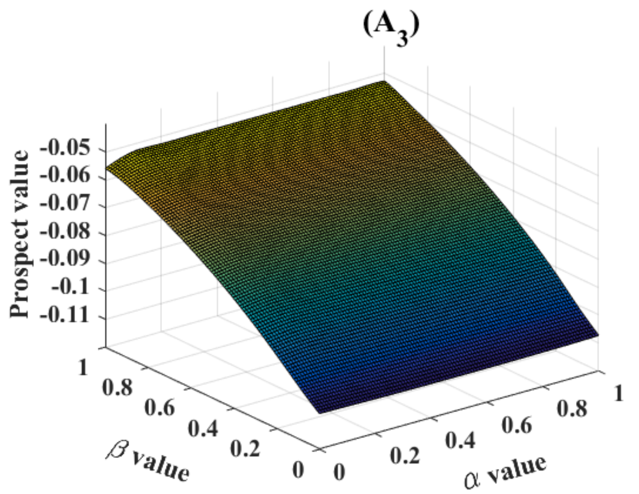

Fig. 7. DA of β and α on PT of A_3

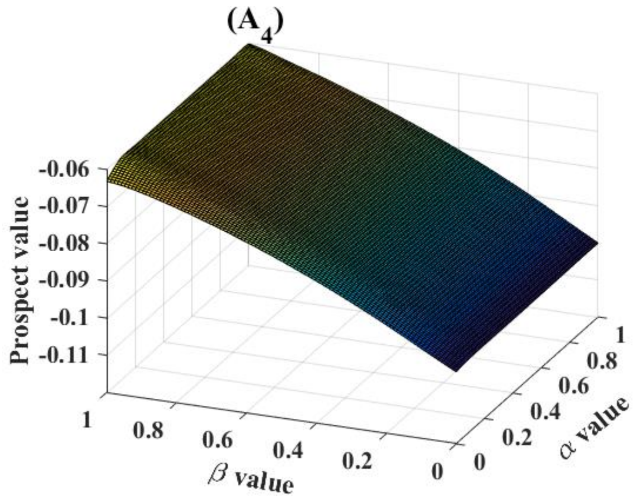

Fig. 8. DA of β and α on PT of A_4

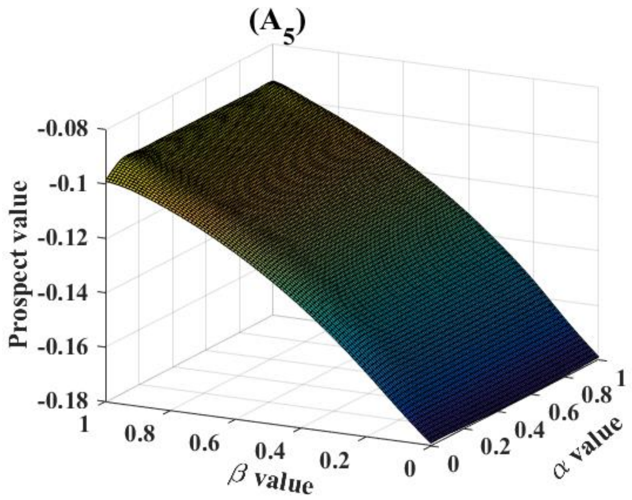

Fig. 9. DA of β and α on PT of A_5

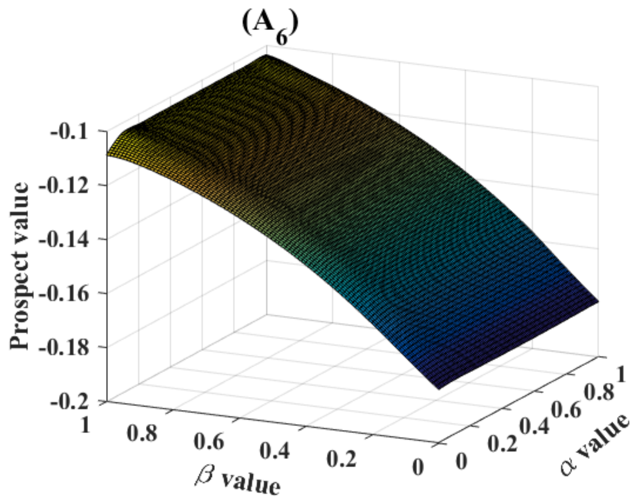

Fig. 10. DA of β and α on PT of A_6

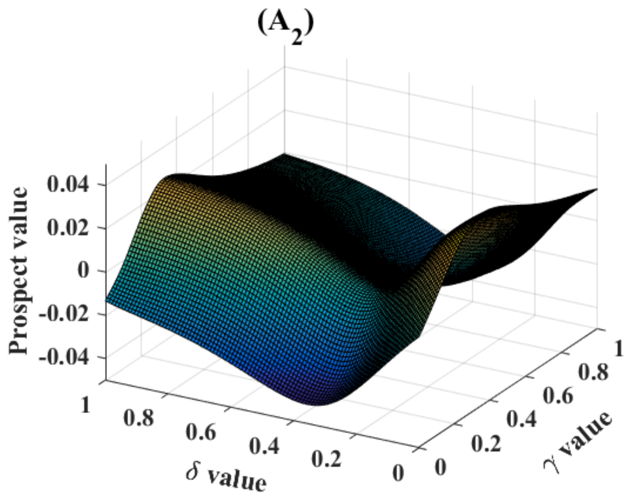

Fig. 12. DA of γ and δ on PT of A_2

To sum up, for the alternative path with negative prospect value, its prospect value is independent of α value and only increases with the increases of β value. The perception of path prospect value to β value is stronger than that of α value, which indicates that decision makers are risk preference at this time, want to seek greater risks to try to get rid of the "loss" pursue "gain," that reflects a strong "reflex effect." And for the path with positive prospect value, the change in the prospect value is also affected by the value of α, which reflects that the decision makers have a certain risk aversion awareness under such circumstances, initially showing a "certainty effect." [39].

C.2. DA of PPCs γ and δ

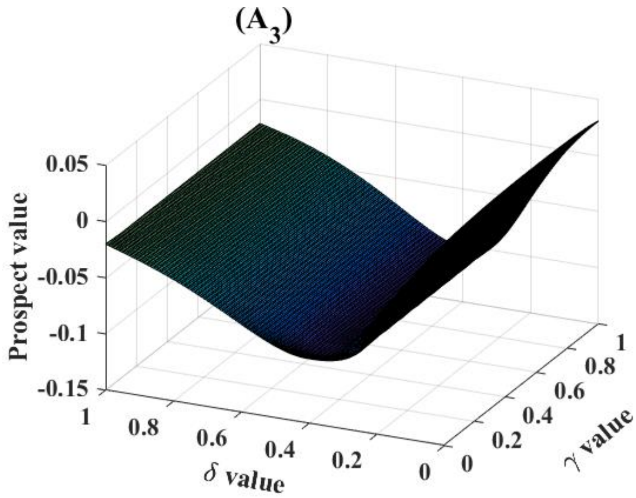

Fig. 13. DA of γ and δ on PT of A_3

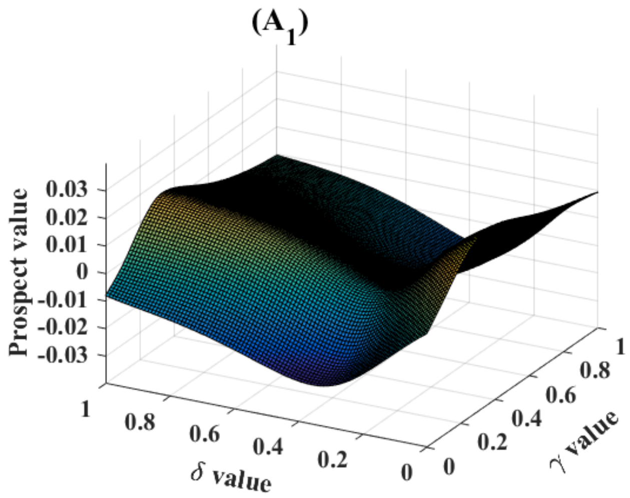

Fig. 11. DA of γ and δ on PT of A_1

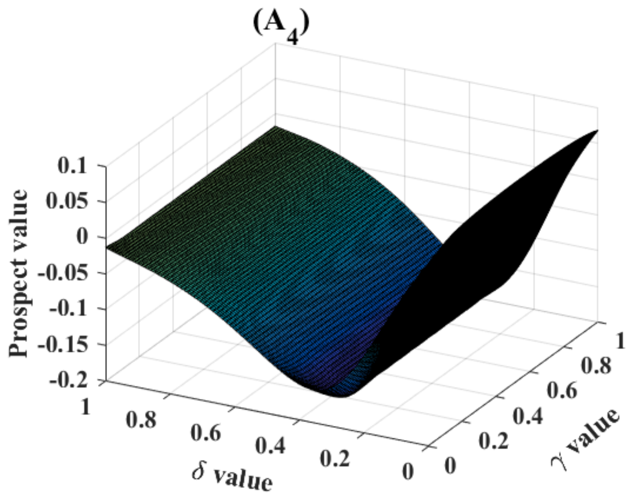

Fig. 14. DA of γ and δ on PT of A_4

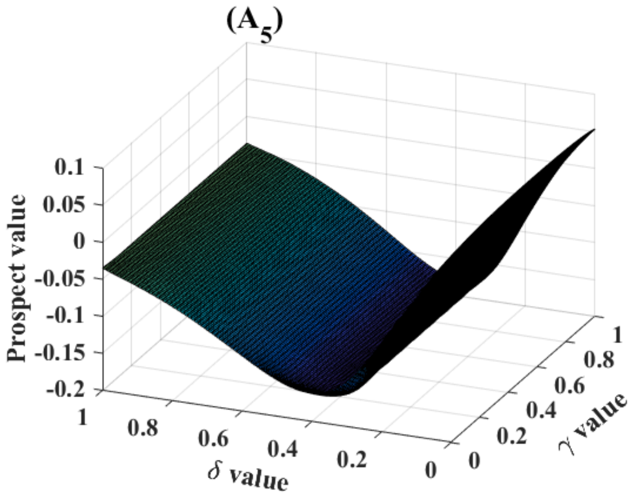

Fig. 15. DA of γ and δ on PT of A_5

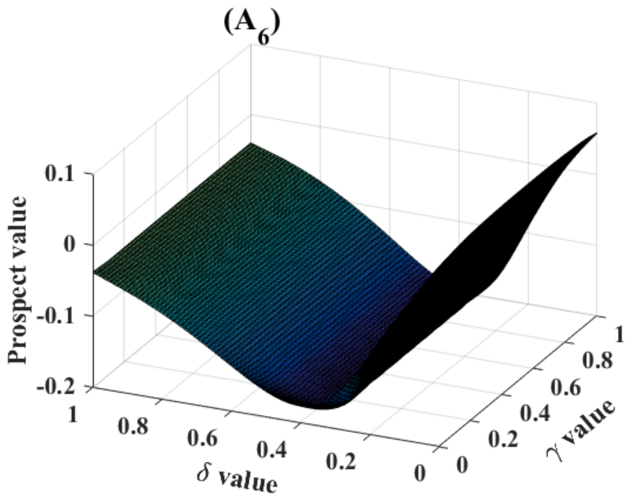

Fig. 16. DA of γ and δ on PT of A_6

From Fig. 11–Fig. 16, it can be seen that alternative paths A_1 and A_2 have positive prospect values. At the beginning, their prospect values increase with an increase in the γ value and decrease in accordance with an increase in the δ value. When the value of γ increases to about 0.3, their prospect values gradually tend to become stable, and no significant changes occur. When the value of δ is around 0.4, as the value of δ continues to increase, the prospect value of the alternative path also increases, with a large increase. For alternative paths $A_3 - A_6$ with negative prospect values, their prospect values are not affected by γ value but change only in accordance with a change in the value of δ.

To sum up, when alternative paths have positive prospect values, the acquisition PPC γ will affect their prospect values. When the prospect values of alternative paths are negative, their prospect values will perceive the loss PPC δ more strongly, which indicates that decision makers' perception to loss is stronger than that to gain [38, 39].

V. Conclusion

1) The prospect decision-making model of path selection in a fuzzy environment adopted in this paper comprehensively considers all factors to be examined in path selection and obtains the priority selection order of alternative paths. It provides a reference for decision makers to make emergency logistics path selection decisions.
2) In the process of emergency rescue, secondary disasters often occur, affecting the formulation of rescue decisions. In this model, the occurrence probability of subsequent secondary disasters of each alternative path is included in the calculation process of the path prospect value to examine the impact of secondary disasters when making emergency path selection decisions.
3) The DA of risk preference coefficients shows that when the prospect value of an alternative path has a positive value (i.e., facing gain), the decision maker initially has the characteristic of "certainty effect," reflecting a certain risk aversion awareness. Conversely, when the prospect value of an alternative path is negative (i.e., facing loss), the decision maker has the characteristic of a "reflection effect." The DA of PPC shows that a risk-preference type decision maker perceives loss more strongly than gain.
4) In this paper, the impact of the decision makers' bounded rationality and secondary disasters on the path prospect value is investigated in the selection decision-making process. However, how to depict the relationship between emergencies and secondary disasters in the model remains to be further studied, and it can be improved along this direction in the future.

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Wenjun Sun was born in Shandong, China, in 1980. He is a doctor at the School of Traffic and Transportation, Lanzhou Jiaotong University, China, majoring in logistics management. He has a strong interest in emergency logistics, game theory and management.