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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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 \( M_0 \) 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](image)

B. Symbol Representation

Suppose that, in the rescue network \( G = (M, A) \), \( M = \{M_0, M_1, M_2, \ldots, M_{D-2}, M_D\} \) is the nodes set, and \( A = \{A_1, A_2, \ldots, A_m\} \) is the alternative paths set between the rescue center \( M_0 \) and the disaster area \( M_D \), where \( A_i \in A \) is any one of the paths, which is composed of several road sections \( M_iM_j \). \( M_i \in M \) and \( M_j \in M \) are the two adjacent nodes on \( A_i \). The probability of secondary disasters in road section \( M_iM_j \) is \( \eta_{ij} \). The set of relevant factors that the decision maker should consider when making the rescue path selection decision is \( C = \{C_1, C_2, \ldots, C_n\} \), in which \( C_1, C_j \in C \) 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, \( C^a \), with the value of a clear number; a factor subset, \( C^c \), with the value of an interval number; a factor subset, \( C^f \), with the value of a fuzzy number; and \( C^a \cup C^c \cup C^f = C \).

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 \( C^c \cap C^b = \emptyset \).
\[ \rho = [\rho_1, \rho_2, \ldots, \rho_n] \] corresponds to the decision weight vector of the decision maker for each factor, where \( \rho_j \geq 0 \) and \( \sum_{j=1}^{n} \rho_j = 1 \). \( Q=[q_1, q_2, \ldots, q_n] \) 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 \( C_j \). \( B=[b_{ij}]_{n \times n} \) 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 \( S = \{ s_r | r = 0,1, \ldots, \frac{X}{2}, \frac{X}{2}, \frac{X}{2} + 1, \ldots, X \} \), where \( s_j \) represents the \( r + 1 \)th 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**

![Image of membership function](image)

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 \( s_j \) into the corresponding triangular fuzzy number \( \hat{s} \) [29]:

\[
\hat{s} = (s^1, s^2, s^3) = (\max\{(r-1)/X, 0\}, r/X, \min\{(r+1)/X, 1\}).
\]

**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 \( C_i \) is any factor in subset \( C \), it’s hard for decision makers to evaluate its corresponding expectation \( q_i \) at this time accurately. Thus, an interval number form \( q_i = [q_i^{low}, q_i^{high}] \) is often used, where \( q_i^{low} \geq q_i^{high} \).

**b. Expectations of Factors in Subset \( C^a \)**

The expectation of the factors in subset \( C^a \) 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 \( C_i \) and \( C_j \) are any two factors in subset \( C^a \), representing the delivery time of relief supplies and the remaining capacity of the path, respectively. The selection process of expectations \( q_i \) and \( q_j \) for \( C_i \) and \( C_j \),
is shown below:

**b.1. The Selection Process of \( q_i \)**

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

\[
l_i^{\text{min}} = \min\{t_i^{\text{up}} | \varphi(t_i) \geq \rho\}. \quad (2)
\]

\[
q_i = \min\{t_i^{\text{min}}\}. \quad (3)
\]

where \( t_i^{\text{min}} \) is the transportation time of goods on path \( A_i \) and \( \varphi(t_i) \) 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:

\[
l_i^{\text{min}} = \min\{\phi^{-1}(\rho) \cdot \sigma_i + \mu_i\}. \quad (4)
\]

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

**b.2. The Selection Process of \( q_i \)**

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 \( N(\nu_i, \xi_i) \). 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 \( q_i \) of the path is as follows:

\[
f_i^{\text{max}} = \max\{f_{ij} \cdot (1 - \psi_i(f_{ij})) \geq \rho'\}. \quad (5)
\]

\[
q_i = \min\{f_i^{\text{max}}\}. \quad (6)
\]

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

**c. The Expectations of Factors in Subset \( C_i' \)**

Assuming that \( C_i \) is any factor in subset \( C_i' \), for the selection of expectation \( q_i \) 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 \( q_i \in S \). In this paper, the case of \( X = 6 \) is considered, that is, \( S = \{s_0, s_1, ..., s_6\} = \{\text{very low, low, relatively low, medium, relatively high, high, and very high}\} \).

**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 \( G = \{g_i\}_{1 \leq i \leq n} \) and non-dimensionalize the decision matrix \( B = \{b_{ij}\}_{1 \leq i \leq n} \) as matrix \( E = \{e_{ij}\}_{1 \leq i \leq n} \). The specific dimensionless calculation formula is expressed as follows [31]:

**a. Non-Dimensionallization of Interval Value Factors**

It is assumed that the expectation and evaluation value of decision makers in terms of factor \( C_i \) in subset \( C_i' \) are \( q_i = [q_i^{\text{low}}, q_i^{\text{up}}] \) and \( b_i = [b_i^{\text{low}}, b_i^{\text{up}}] \), respectively. After non-dimensionalization, the corresponding values are still interval numbers:

\[
[g_i^{\text{low}}, g_i^{\text{up}}] = \left\{ \frac{q_i^{\text{low}} - b_i^{\text{low}}}{b_i^{\text{up}} - b_i^{\text{low}}}, \frac{q_i^{\text{up}} - b_i^{\text{up}}}{b_i^{\text{up}} - b_i^{\text{low}}} \right\}, C_i \in C_i' \cap C^{\text{b}}. \quad (7)
\]

\[
[e_i^{\text{low}}, e_i^{\text{up}}] = \left\{ \frac{b_i^{\text{low}} - b_i^{\text{low}}}{b_i^{\text{up}} - b_i^{\text{low}}}, \frac{b_i^{\text{up}} - b_i^{\text{up}}}{b_i^{\text{up}} - b_i^{\text{low}}} \right\}, A_i \in A, C_i \in C' \cap C^{\text{b}}. \quad (8)
\]

Among them:

\[
b_i^{\text{up}} = \max\{\max(\{b_{ij}\}_{1 \leq i \leq m}, q_i^{\text{up}})\}, C_i \in C'. \quad (9)
\]

**b. Non-Dimensionallization of Clear Number Value Factors**

Assuming that any two factors, \( C_i \) and \( C_j \) in subset \( C_i' \) are cost-type factors and benefit-type factors, respectively, that is, \( C_i \in C^v \) and \( C_j \in C^b \), the corresponding dimensionless rules are as follows:

\[
g_i = \frac{b_i^{*} - b_i^{*}}{b_i^{*} - b_i^{*}}, \quad e_i = \frac{b_i^{*} - b_i^{*}}{b_i^{*} - b_i^{*}}, i = 1, 2, ..., m. \quad (10)
\]

Among them:

\[
b_i^{*} = \max\{\max(\{b_{ij}\}_{1 \leq i \leq m}, q_i^{*})\}, C_i \in C'. \quad (11)
\]

\[
g_i = \frac{q_i^{*} - b_i^{*}}{b_i^{*} - b_i^{*}}, \quad e_i = \frac{b_i^{*} - b_i^{*}}{b_i^{*} - b_i^{*}}, i = 1, 2, ..., m. \quad (12)
\]

Among them:
\[ b_i^* = \max_{i \in C} (b_i, g_i) \]
\[ b_i^* = \min_{i \in C} (b_i, g_i) \]  \hspace{1cm} (13)

c. Non-Dimensionlessization of Language Phrase Value Factors

For any factor, \( C_n \) in subset \( C' \), the corresponding dimensionless rule is as follows:

\[ g_n = \begin{cases} 
q_n, & C_n \in C' \cap C^e \\
-\min(q_n), & C_n \in C' \cap C^c 
\end{cases} \]  \hspace{1cm} (14)

\[ e_n = \begin{cases} 
b_n, & A_n \in A, C_n \in C' \cap C^e \\
-\min(b_n), & A_n \in A, C_n \in C' \cap C^c 
\end{cases} \]  \hspace{1cm} (15)

The language phrases \( g_n \) and \( e_n \) obtained by formulas (10) and (11) are converted into corresponding triangular fuzzy numbers \((g_n, g_n^+, g_n^-)\) and \((e_n, e_n^+, e_n^-)\) using formula (1).

B.1.3. Profit-and-Loss Editing

Finally, we calculate the “gain” or “loss” of the evaluation value \( e_n \) of each factor in each path relative to the reference point \( g_j \). When \( e_n > g_j \) or \( e_n < g_j \), it is regarded as gain; when \( g_j > e_n \) or \( g_j < e_n \), it is regarded as loss. \( d_n \) 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 \( d_n \) is different, as follows:

\[ d_n = \begin{cases} 
\sqrt{\frac{(e_n^m - g_j^m)^2 + (e_n^m - g_j^m)^2}{2}}, & C_n \in C' \\
\sqrt{\frac{(e_n^m - g_j^m)^2 + (e_n^m - g_j^m)^2 + (e_n^m - g_j^m)^2}{3}}, & C_n \in C' 
\end{cases} \]  \hspace{1cm} (16)

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

\[ F(e_n) = \begin{cases} 
d_n, & e_n \geq g_j, i = 1,2, \ldots, m \\
-d_n, & e_n < g_j, i = 1,2, \ldots, m 
\end{cases} \]  \hspace{1cm} (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, \( V = [v(e_n)]_{m \times n} \), is established, in which the value function \( v(e_n) \) 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 its calculation formula is:

\[ v(e_n) = \begin{cases} 
(F(e_n))^\alpha, & F(e_n) \geq 0 \\
-\lambda \cdot (F(e_n))^\beta, & F(e_n) < 0 
\end{cases} \]  \hspace{1cm} (18)

In the formula, the parameters \( \alpha, \beta (0 < \alpha, \beta \leq 1) \) represent the risk preference coefficient, where \( \beta \) is the loss sensitivity coefficient (SC), \( \alpha \) is the gain SC, and \( \lambda(\lambda \geq 1) \) 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 \( w(p_i) \) 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]:

\[ w(p_i) = \begin{cases} 
\frac{p_i^\gamma}{p_i + (1 - p_i)^\gamma}, & \text{(faced with gains)} \\
\frac{p_i^\delta}{p_i + (1 - p_i)^\delta}, & \text{(faced with losses)} 
\end{cases} \]  \hspace{1cm} (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, \( \delta = 0.69 \), \( \gamma = 0.61 \). \( p_i \) represents the probability of secondary disasters in alternative path \( A_i \). The calculation formula is as follows:

\[ p_i = \max_{d_i, b_i^*} \{ \eta_{i, j} \}. \]  \hspace{1cm} (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 \( W = [W(e_n)]_{m \times n} \) is established, where \( W(e_n) \) is the prospect value of decision factor \( C_j \) for alternative path \( A_i \). The formula is:

\[ W(e_n) = v(e_n) \cdot w(p_i), \quad j = 1,2, \ldots, n; i = 1,2, \ldots, m. \]  \hspace{1cm} (21)

Then, the prospect value \( U(A_i) \) of the \( ith \) alternative path \( A_i \) is:
\[ U(A) = \sum_{j=1}^{n} [\rho_j \cdot W(e_j)], i = 1,2,\ldots,m. \] (22)

Obviously, the larger \( U(A) \) of the alternative path, the better path \( A \) 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 \( b_0 \) and expectation \( q_j \) of each investigated factor \( C_j \) in related factor set \( C \) and conduct dimensionless processing, convert these into corresponding triangular fuzzy numbers \((e_{i1}^0, e_{i2}^0, e_{i3}^0)\) and \((e_{i1}^0, e_{i2}^0, e_{i3}^0)\) form in accordance with formula (1).

Step 2: If there is an evaluation value \( e_w \) and an expectation \( g_0 \) in the form of language phrases after dimensionless processing, convert these into corresponding triangular fuzzy numbers \((e_{i1}^0, e_{i2}^0, e_{i3}^0)\) and \((g_{i1}^0, g_{i2}^0, g_{i3}^0)\) 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 \( e_j \) 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 \( v(e_j) \) 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 \( W(e_j) \) of decision factor \( C_j \) on \( A_i \) and establish the prospect decision matrix \( W \).

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

IV. EXAMPLE ANALYSIS

A. Example Description and Parameter Setting

<table>
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<th>Probability</th>
<th>( M_0 )</th>
<th>( M_1 )</th>
<th>( M_3 )</th>
<th>( M_4 )</th>
<th>( M_6 )</th>
<th>( M_7 )</th>
<th>( M_8 )</th>
<th>( M_9 )</th>
<th>( M_{10} )</th>
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<td>( \eta_{ij} )</td>
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<td>0.5%</td>
<td>0.1%</td>
<td>0.5%</td>
<td>0.8%</td>
<td>0.5%</td>
<td>0.8%</td>
<td>0.8%</td>
<td>1.2%</td>
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</tbody>
</table>

See Fig. 3 for the composition of an emergency logistics network system. There are nine nodes in total, \( M_0 \) for the rescue center, \( M_0 \) for the disaster area. There are six alternative paths from \( M_0 \) to \( M_0 \) 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 100), 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 1. 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

<table>
<thead>
<tr>
<th>Probability</th>
<th>( M_0 )</th>
<th>( M_1 )</th>
<th>( M_2 )</th>
<th>( M_3 )</th>
<th>( M_4 )</th>
<th>( M_5 )</th>
<th>( M_6 )</th>
<th>( M_7 )</th>
<th>( M_8 )</th>
<th>( M_9 )</th>
<th>( M_{10} )</th>
<th>( M_{12} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta_{ij} )</td>
<td>0.1%</td>
<td>0.5%</td>
<td>0.1%</td>
<td>0.5%</td>
<td>0.8%</td>
<td>0.5%</td>
<td>0.8%</td>
<td>0.8%</td>
<td>1.2%</td>
<td>0.8%</td>
<td>3%</td>
<td></td>
</tr>
</tbody>
</table>
B. Example solution

B.1. Editing Stage

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

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Paths</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_1 )</td>
<td>( A_1 )</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>( \mu_i )</td>
</tr>
<tr>
<td>( \sigma_i )</td>
<td>30</td>
</tr>
<tr>
<td>( C_2 )</td>
<td>( \mu_i )</td>
</tr>
<tr>
<td>( \sigma_i )</td>
<td>60</td>
</tr>
</tbody>
</table>

TABLE III

ALTERNATIVE PATH DECISION MATRIX

<table>
<thead>
<tr>
<th>Paths</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_1 )</td>
<td>( C_1 )</td>
</tr>
<tr>
<td>( A_2 )</td>
<td>210</td>
</tr>
<tr>
<td>( A_3 )</td>
<td>220</td>
</tr>
<tr>
<td>( A_4 )</td>
<td>260</td>
</tr>
<tr>
<td>( A_5 )</td>
<td>280</td>
</tr>
<tr>
<td>( A_6 )</td>
<td>290</td>
</tr>
<tr>
<td>( A_7 )</td>
<td>300</td>
</tr>
</tbody>
</table>

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

\[ s_6 : \text{very low} = (0.00, 0.00, 0.17) \]
\[ s_7 : \text{low} = (0.00, 0.17, 0.33) \]
\[ s_8 : \text{relatively low} = (0.17, 0.33, 0.50) \]
\[ s_9 : \text{medium} = (0.33, 0.50, 0.67) \]
\[ s_{10} : \text{relatively high} = (0.50, 0.67, 0.83) \]
\[ s_{11} : \text{high} = (0.67, 0.83, 1.00) \]
\[ s_{12} : \text{very high} = (0.83, 1.00, 1.00) \]

Among the four factors influencing the path selection decision, \( C_1 \) and \( C_2 \) belong to the cost type, while \( C_3 \) 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:

\[ F = [F(e_{ij})]_{4 \times 4} = \begin{bmatrix} -0.15 & 0.22 & 0.17 & 0.00 \\ -0.25 & 0.44 & 0.17 & 0.00 \\ -0.62 & 0.00 & -0.17 & -0.33 \\ -0.81 & -0.56 & -0.29 & -0.17 \\ -0.91 & -0.23 & -0.29 & -0.33 \\ -1.00 & -0.34 & -0.17 & -0.17 \end{bmatrix} \]

TABLE IV

DECISION MATRIX AFTER NON-DIMENSIONALIZATION

<table>
<thead>
<tr>
<th>Paths</th>
<th>Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_1 )</td>
<td>( C_1 )</td>
</tr>
<tr>
<td>( A_2 )</td>
<td>0.85</td>
</tr>
<tr>
<td>( A_3 )</td>
<td>0.75</td>
</tr>
<tr>
<td>( A_4 )</td>
<td>0.38</td>
</tr>
<tr>
<td>( A_5 )</td>
<td>0.19</td>
</tr>
<tr>
<td>( A_6 )</td>
<td>0.09</td>
</tr>
<tr>
<td>( A_7 )</td>
<td>0.00</td>
</tr>
</tbody>
</table>

B.2. Evaluation stage

The value matrix is obtained from formula (18):

\[ V = [v(e_{ij})]_{4 \times 4} = \begin{bmatrix} -0.42 & 0.26 & 0.21 & 0.00 \\ -0.66 & 0.49 & 0.21 & 0.00 \\ -1.48 & 0.00 & -0.47 & -0.85 \\ -1.87 & -1.35 & -0.76 & -0.47 \\ -2.07 & -0.62 & -0.76 & -0.85 \\ -2.25 & -0.87 & -0.47 & -0.47 \end{bmatrix} \]

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

\[ W = [W(e_{ij})]_{4 \times 4} = \begin{bmatrix} -0.019 & 0.016 & 0.013 & 0.000 \\ -0.030 & 0.030 & 0.013 & 0.000 \\ -0.120 & 0.000 & -0.038 & -0.069 \\ -0.084 & -0.060 & -0.034 & -0.021 \\ -0.167 & -0.050 & -0.061 & -0.069 \\ -0.182 & -0.070 & -0.038 & -0.038 \end{bmatrix} \]

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

C. Parametric DA

C.1. DA of Risk Preference Coefficients \( \beta \) and \( \alpha \)

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 \( \alpha \) but increase greatly with an increase in the value of \( \beta \). The prospect values of \( A_1 \) and \( A_2 \) are affected by \( \alpha \) value and decrease with an increase in the value of \( \alpha \). At the same time, the prospect values of \( A_1 \) and \( A_2 \) increase with an increase in \( \beta \) value, but the increase in these values is smaller than the increase under \( A_3 - A_6 \).
To sum up, for the alternative path with negative prospect value, its prospect value is independent of $\alpha$ value and only increases with the increases of $\beta$ value. The perception of path prospect value to $\beta$ value is stronger than that of $\alpha$ 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 $\alpha$, 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 $\gamma$ and $\delta$

![Fig. 10. DA of $\beta$ and $\alpha$ on PT of $A_6$](image10.png)

![Fig. 12. DA of $\gamma'$ and $\delta$ on PT of $A_2$](image12.png)

![Fig. 13. DA of $\gamma$ and $\delta$ on PT of $A_4$](image13.png)

![Fig. 11. DA of $\gamma'$ and $\delta$ on PT of $A_1$](image11.png)

![Fig. 14. DA of $\gamma$ and $\delta$ on PT of $A_3$](image14.png)
From Fig. 11–Fig. 16, it can be seen that alternative paths $A_1$ and $A_4$ have positive prospect values. At the beginning, their prospect values increase with an increase in the $\gamma$ value and decrease in accordance with an increase in the $\delta$ value. When the value of $\gamma$ increases to about 0.3, their prospect values gradually tend to become stable, and no significant changes occur. When the value of $\delta$ is around 0.4, as the value of $\delta$ continues to increase, the prospect value of the alternative path also increases, with a large increase. For alternative paths $A_1 - A_4$ with negative prospect values, their prospect values are not affected by $\gamma$ value but change only in accordance with a change in the value of $\delta$.

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

V. Conclusions

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.

REFERENCES


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