

RESEARCH ON PATH OPTIMIZATION FOR MULTIMODAL TRANSPORTATION OF HAZARDOUS MATERIALS UNDER UNCERTAIN DEMAND

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Abstract:

In the process of long-distance and large-volume transportation of hazardous materials (HAZMAT), multimodal transportation plays a crucial role with its unique advantages. In order to effectively reduce the transportation risk and improve the reliability of transportation, it is particularly important to choose a suitable transportation plan for multimodal transport of HAZMAT. In this paper, we study the transportation of HAZMAT in multimodal transport networks. Considering the fluctuation in demand for HAZMAT during the actual transportation process, it is difficult for decision makers to obtain the accurate demand for HAZMAT orders in advance, leading to uncertainty in the final transportation plan. Therefore, in this paper, the uncertain demand of HAZMAT is set as a triangular fuzzy random number, and a multi-objective mixed integer linear programming model is established with the objective of minimizing the total risk exposure population and the total cost in the transportation process of HAZMAT. In order to facilitate the solution of the model, we combined the fuzzy random expected value method with the fuzzy random chance constraint method based on credibility measures to reconstruct the uncertain model clearly and equivalently, and designed a non-dominated sorting genetic algorithm (NSGA-II) to obtain the Pareto boundary of the multi-objective optimization problem. Finally, we conducted a numerical example experiment to verify the rationality of the model proposed in this paper. The experimental results indicate that uncertain demand can affect the path decision-making of multimodal transportation of HAZMAT. In addition, the confidence level of fuzzy random opportunity constraints will have an impact on the risk and economic objectives of optimizing the multimodal transportation path of HAZMAT. When the confidence level is higher than 0.7, it will lead to a significant increase in transportation risks and costs. Through sensitivity analysis, it can provide useful decision-making references for relevant departments to formulate HAZMAT transportation plans.

Keywords: materials transportation, multimodal transport, routing optimization, fuzzy random numbers, NSGA-II

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1. Introduction

With the accelerated industrialization of the world and the rapid rise of chemical enterprises, the demand for hazardous materials (HAZMAT) is growing. According to statistics, 95% of HAZMAT in China need to be transported over long distances every year, and the main body of HAZMAT transportation is still road transportation, accounting for up to 70%. Compared with other accidents, the probability of occurrence of HAZMAT accidents is low, but the consequences of accidents are devastating, so they are categorized with low-probability-high-consequence events (Mohri et al. 2022). However, with the gradual strengthening of supervision by government departments, the probability of HAZMAT road transport accidents has decreased, but the hazards of accidents have been increasing, causing serious casualties and economic losses (Zhu et al. 2022). Compared with single road transportation, multimodal transportation has broad development prospects as it can reduce transportation risks and improve transportation efficiency in long-distance transportation.

The current research on the optimization of HAZMAT transportation routes is mainly focused on the vehicle route problem (VRP) or the site-route optimization (LRP). Based on the VRP problem, mostly focusing on a single road transportation mode. Multimodal transport is a mode of transport that uses two or more modes of transport to complete orders together, which has been widely used in VRP problems in recent years (Chen et al. 2022; Du et al. 2022; Hu et al. 2022; Leleñ and Wasiak 2019). In the field of HAZMAT transportation, Bubbico et al. (2006) were the first to use a risk analysis tool for case studies to demonstrate that multimodal transport can significantly reduce the risk of transporting HAZMAT. Xie et al. (2012) proposed a multi-objective multimodal optimization model, which can optimize the transportation path and transshipment yard of HAZMAT simultaneously considering the cost and risk of intermodal transportation; Huang and Shuai (2014) divided the multimodal transportation of HAZMAT into two processes, transportation and transshipment, and constructed a bi-objective linear optimization model for cost and risk minimization, which proved that multimodal transportation of HAZMAT can reduce both risk and cost objectives. On this basis, Assadipour et al. (2016) proposed a tolling policy, developed a two-layer bi-objective

mixed integer programming model considering total cost and total risk and solved it, and the results showed that the government can make carriers choose a less risky transportation option by levying access fees at different transshipment points; Verma and Verter (2010) formed unit trains containing both HAZMAT and general cargo and developed a solution based on taboo search, demonstrating that operating mixed unit trains can effectively reduce multimodal transport risks. In order to further study the influence of transfer station on route optimization, Assadipour et al. (2015) considered the capacity limitation and congestion phenomenon of hub-and-spoke multimodal transport network transfer station, incorporated the queuing risk of HAZMAT into the total risk, established a dual-objective optimization model, and solved the congestion problem by giving HAZMAT a higher queuing priority; Ghaderi and Burdett (2019) established a two-stage stochastic programming model considering the interruption of transfer station, and proposed three heuristic algorithms to solve the problem. All the above studies are based on traditional risk models, and the risk value is characterized by accident probability and accident consequence. In order to study the influence of decision makers' risk aversion degree on route selection, Toumazis and Kwon (2013) established a road optimization model of public-rail intermodal transport with the minimum conditional value-at-risk (CVaR) as the goal, proving that the risk aversion degree of decision makers will have a significant impact on the route selection of HAZMAT multimodal transport. Xin et al. (2016a) studied the LRP problem of multimodal transport of HAZMAT, introduced the objective weight factor and established a single objective optimization model of "Cost-Risk", and finally improved Dijkstra algorithm and O-D matrix search algorithm to solve it.

However, in the actual decision making, there are often complex and uncertain environments, and the actual intermodal transport situation cannot be accurately described using existing models. To address the dynamic uncertainties in the HAZMAT transportation route optimization problem, Esfandeh et al. (2018) consider the situation that some transportation roads are closed with time changes under the influence of policies, and achieve the effect of reducing transportation risk by changing the transporta-

tion route selection, based on the fuzzy nature of accident probability, Chai et al. (2018) considered the difference of risk distribution of HAZMAT transportation between different routes and put forward a new risk distribution equity model. Ke et al. (2020) establish a two-tier tolling based on the consideration of the total risk of transportation network and the risk fairness of the route strategy, which can greatly reduce the transportation risk in the network; Jabbarzadeh et al. (2020) propose a bi-objective two-stage stochastic program to study the impact of line disruptions on HAZMAT rail transportation schemes and demonstrate that deploying contingency disruption plans can significantly reduce HAZMAT transportation risks; Chiou (2017) proposed a risk-averse signaling strategy using budget of uncertainty (BOU), which considered the uncertainty of HAZMAT demand and developed a min-max two-level planning model to determine the optimal transportation route. In response to the research on the path optimization problem of multimodal transportation of HAZMAT in uncertain environments, Xin et al. (2016b) refined the transportation process into three steps, considering the time-varying characteristics of costs and risks during the transportation of HAZMAT, and established a model for selecting the shortest path for multimodal transportation of HAZMAT under time-varying conditions. Sun et al. (2019; 2020) comprehensively considered the uncertainty of time, cost and risk value in the process of intermodal transportation, used trapezoidal fuzzy numbers to describe the uncertain variables to establish a multi-objective fuzzy mixed integer linear programming model, and introduced the fuzzy expected value method and Jimenez fuzzy ranking method to clarify the uncertain variables. Mohammadi et al. (2017) considered the possibility of external interference at some transfer points during the multimodal transportation of HAZMAT in uncertain environments, and combined chance constrained programming with a possibility programming framework to handle uncertain fuzzy random variables, and designed heuristic algorithms to solve the problem.

Existing research has achieved certain results in optimizing the multimodal transportation path of HAZMAT in certain environments, but little consideration has been given to the impact of uncertain environments on the optimization of multimodal transportation paths of HAZMAT. As a result, decision-

makers cannot directly obtain accurate numerical values when formulating transportation plans, resulting in significant deviations from expectations in some results in actual transportation. In addition, existing literature mostly uses fuzzy numbers to express uncertain variables, ignoring the randomness existing in the environment, making the constructed models unable to accurately describe the actual intermodal transportation environment. Based on the above shortcomings, this article takes the uncertain demand for HAZMAT as a variable to study the optimization problem of multimodal transportation paths for HAZMAT. Taking into account the fuzziness and randomness of the demand for HAZMAT, the uncertain demand is expressed using fuzzy random numbers in uncertainty theory, and a multi-objective integer linear optimization model is established with the goal of minimizing the total cost and total risk of multimodal transportation, The expected value method and opportunity constraint method of fuzzy random numbers are used to clarify the uncertain objectives and constraints, respectively. Finally, non-dominated sorting genetic algorithm is used to solve the problem and obtain different optimal transportation plans.

2. Uncertain demand

In practical problems, it is often difficult to obtain the exact demands, so decision makers need to set the demand quantity as an uncertain variable. For uncertain problems usually two methods are used to quantify uncertain variables, fuzzy planning and stochastic planning. However, in practice, the actual demand for HAZMAT may be both fuzzy and stochastic, i.e., scholars can only fuzzy describe the demand as a most probable interval and a most probable value according to their own experience, but due to different experiences, the most probable value given by different scholars also varies, and the value can be estimated as a random variable obeying a certain distribution. For such a variable that embodies neither randomness nor fuzziness, Liu and Liu (2002) defines a plausibility measure. Assume that Γ is an abstract space consisting of elements γ , An ample field \mathcal{G} is a set class consisting of subsets of Γ , and any intersection, union, and complement of sets in Γ is closed. Let Pos be the likelihood measure defined on \mathcal{G} . Then the plausibility measure for the occurrence of event T is :

$$\text{Cr}(\mathbf{T}) = \frac{1}{2}(1 + \text{Pos}(\mathbf{T}^c)) \quad \mathbf{T} \in \mathcal{J} \quad (1)$$

where \mathbf{T}^c is the complement of the set \mathbf{T} . And the triplet $(\Gamma, \mathcal{J}, \text{Cr})$ is called the plausibility space. Therefore, the fuzzy random variable has the following theorems:

Theorem 2.(Liu and Liu 2002) Let $\xi(\omega, \gamma)$ is a fuzzy random variable, then the equilibrium opportunity measure \mathbf{Ch} of an event $\{\xi(\omega, \gamma) \in \mathbf{B}\}$ is defined as:

$$\text{Ch}\{\xi(\omega, \gamma) \in \mathbf{B}\} = [\alpha \cap \text{Pr}\{\omega \in \Omega | \text{Cr}\{\gamma \in \Gamma | \xi(\omega, \gamma) \in \mathbf{B}\} \geq \alpha\}] \quad (2)$$

Theorem 3.(Liu and Liu 2002) Let $\xi(\omega, \gamma)$ be a fuzzy random variable, then the expected value $E[\xi(\omega, \gamma)]$ of $\xi(\omega, \gamma)$ is:

$$E[\xi(\omega, \gamma)] = \int_0^{+\infty} \text{Ch}\{\xi(\omega, \gamma) \geq r\} dr - \int_{-\infty}^0 \text{Ch}\{\xi(\omega, \gamma) \leq r\} dr \quad (3)$$

In practical problems, the estimated demand for HAZMAT is usually given by experts based on their own experience. Since an accurate value cannot be obtained, the demand for HAZMAT $\tilde{e}(\omega, \gamma)$ can be expressed as a triangular fuzzy random number as shown in Fig. 1. Let the intermediate value $e(\omega)$ be a random variable subject to normal distribution, i.e., $e(\omega) \sim N(\mu, \delta^2)$, a and b are the left and right widths of the fuzzy variable $e(\omega)$. The values of $e(\omega)$, a , and b are estimated by scholars' experience, where $e(\omega) - a$ represents the minimum possible number of uncertain demands, $e(\omega) + b$ represents the maximum possible number of uncertain demands, and $e(\omega)$ represents the most likely value of uncertain demands. Therefore, the triangular fuzzy number of uncertain demand for HAZMAT can be expressed as $\tilde{e}(\omega, \gamma) = [e(\omega) - a, e(\omega), e(\omega) + b]$, where $e(\omega) \sim N(\mu, \delta^2)$.

3. Mathematical model

3.1. Formulation of problem

A batch of HAZMAT is transported from the starting point O to the ending point D, and there are n intermediate nodes in the transportation. There are three modes of transportation between every two nodes: road, railway and waterway. The carrier can choose the original mode to continue transportation

or transfer to another mode at the nodes. The transportation distance, risk exposure population and HAZMAT capacity limit of different modes of transportation on each road section are different, and the risk exposure population and HAZMAT capacity limit of each transfer node are also different. According to the above questions, the following assumptions can be made:

1. Only one mode of transportation can be selected for each arc.
2. Each node can only carry out transshipment once at most.
3. During the transportation and transfer of HAZMAT, the maximum volume cannot exceed the capacity limit of each arc or transfer point.

3.2. Symbol and variable description

The main parameters and decision variables involved in the model are shown in Table 1 and Table 2.

3.3. Fuzzy random multi-objective mixed integer linear programming model

Objective function: Considering the safety and economy of multimodal transportation of HAZMAT, the following objective function is constructed:

$$\min Z_1 = \tilde{e}(\omega, \gamma) \cdot \left(\sum_{(i,j) \in A} \sum_{m \in M} x_{ij}^m \cdot \rho_{ij}^m + \sum_{k \in N} \sum_{m \in M} \sum_{n \in M} y_k^{mn} \cdot \rho_k \right) \quad (4)$$

$$\min Z_2 = \tilde{e}(\omega, \gamma) \cdot \left(\sum_{(i,j) \in A} \sum_{m \in M} x_{ij}^m \cdot (C^m \cdot D_{ij}^m + FC^m) + \sum_{k \in N} \sum_{m \in M} \sum_{n \in M} y_k^{mn} \cdot B^{mn} \right) \quad (5)$$

The objective function (4) represents the risk of the intermodal transportation process, which minimizes the sum of the exposed population tonnage of all arcs and the exposed population tonnage of all transfer points. The objective function (5) represents the economy of the intermodal transportation process, which minimizes the sum of transport cost, fixed cost and transfer cost at transfer points.

Constraint condition: According to the above description, the following constraints are established:

$$\sum_{(i,j) \in A} \sum_{m \in M} x_{ij}^m - \sum_{(j,i) \in A} \sum_{m \in M} x_{ji}^m = \begin{cases} 1 & \forall i = O \\ -1 & \forall i = D \\ 0 & \text{otherwise} \end{cases} \quad (6)$$

$$\frac{\sum_{(i,j) \in A} \sum_{m \in M} x_{ij}^m - \sum_{(j,i) \in A} \sum_{m \in M} x_{ji}^m}{\sum_{m \in M} x_{ij}^m} \leq 1, \quad \forall (i,j) \in A \quad (7)$$

$$\sum_{m \in M} \sum_{n \in M} y_k^{mn} \leq 1, \quad m \neq n, \quad \forall k \in N \quad (8)$$

$$\sum_{m \in M} \tilde{e}(\omega, \gamma) \cdot x_{ij}^m \leq Q_{ij}^m, \quad \forall (i,j) \in A \quad (9)$$

$$\sum_{m \in M} \sum_{n \in M} \tilde{e}(\omega, \gamma) \cdot y_k^{mn} \leq Q_k, \quad m \neq n, \quad \forall k \in N \quad (10)$$

$$x_{ij}^m \in \{0,1\}, \quad \forall (i,j) \in A, m \in M \quad (11)$$

$$y_k^{mn} \in \{0,1\}, \quad \forall k \in N, m \in M, n \in M, m \neq n \quad (12)$$

Equation (6) represents the conservation constraint on the transportation flow of HAZMAT at each node; Equation (7) indicates that HAZMAT between two nodes can only be transported through one transportation method; Equation (8) indicates that HAZMAT can only be transported once at most at the same node; Equations (9) and (10) respectively represent the capacity constraints for HAZMAT transportation sections and transfer nodes; Equations (11) and (12) are non-negative integer of variable constraint.

3.4. Equivalence treatment of uncertain variables

Because the model contains fuzzy random numbers, it is difficult to directly solve the multimodal transport route optimization model of HAZMAT established above. In order to get a clear and feasible solution, it is necessary to transform the uncertain variables in the model into an equivalent clear form.

3.4.1. Equivalence treatment of objective function

The demand for HAZMAT in objective functions (4) and (5) is a fuzzy random number, and the expected value of this fuzzy random number can be obtained through Theorem 3 as follows:

$$E[\tilde{e}(\omega, \gamma)] = \int_0^{+\infty} Cr\{\tilde{e}(\omega, \gamma) \geq r\} dr - \int_{-\infty}^0 Cr\{\tilde{e}(\omega, \gamma) \leq r\} dr = \left(\mu - \frac{1}{4}a + \frac{1}{4}b\right) \quad (13)$$

Objective functions (4) and (5) can be rewritten using the expected value method (Liu and Liu 2002; Yang et al. 2016) as follows:

$$\min \left(\mu - \frac{1}{4}a + \frac{1}{4}b \right) \cdot \left(\sum_{i \in N} \sum_{j \in N} \sum_{m \in M} x_{ij}^m \cdot \rho_{ij}^m \cdot D_{ij}^m + \sum_{k \in N} \sum_{m \in M} \sum_{n \in M} y_k^{mn} \cdot \rho_k \right), \quad m \neq n \quad (14)$$

$$\min \left(\mu - \frac{1}{4}a + \frac{1}{4}b \right) \cdot \left(\sum_{i \in N} \sum_{j \in N} \sum_{m \in M} x_{ij}^m \cdot (C^m \cdot D_{ij}^m + FC^m) + \sum_{k \in N} \sum_{m \in M} \sum_{n \in M} y_k^{mn} \cdot B_k^{mn} \right), \quad m \neq n \quad (15)$$

3.4.2. Equivalence treatment of constraints

For the uncertain variables in constraints (9) and (10), fuzzy random chance constraint based on balanced chance measure is adopted to deal with fuzzy random demand. According to Theorem 2, the corresponding fuzzy random chance constraints of constraints (9) and (10) can be rewritten as shown in equations (16) and (17), where the confidence level is acceptable to decision makers.

$$Ch\{\sum_{m \in M} \tilde{e}(\omega, \xi) \cdot x_{ij}^m \leq Q_{ij}^m\} \geq \alpha, \quad \forall (i,j) \in A \quad (16)$$

$$Ch\{\sum_{m \in M} \sum_{n \in M} \tilde{e}(\omega, \gamma) \cdot y_k^{mn} \leq Q_k\} \geq \alpha, \quad \forall k \in N, m \neq n \quad (17)$$

According to the related contents of triangular fuzzy variables (Liu and Gao 2008; Yang et al. 2016), when $0 < \alpha \leq \frac{1}{2}$, the credibility constraint $Cr\{\tilde{e}(\omega, \gamma) \leq Q_{ij}^m\} \geq \alpha$ can be rewritten as:

$$e(\omega) - (1 - \alpha) \cdot a \leq Q_{ij}^m \quad (18)$$

Due to $e(\omega) \sim N(\mu, \delta^2)$, the opportunity constraint $Pr(e(\omega) - (1 - \alpha) \cdot a \leq Q_{ij}^m) \geq \alpha$ can be rewritten as:

$$\mu + \Phi^{-1}(\alpha) \cdot \delta - (1 - 2\alpha)a \leq Q_{ij}^m \quad (19)$$

Similarly, when $\frac{1}{2} < \alpha \leq 1$, we have:

$$\mu + \Phi^{-1}(\alpha) \cdot \delta - (2\alpha - 1)b \leq Q_{ij}^m \quad (20)$$

Therefore, constraints (16) and (17) can be rewritten as:

$$\begin{cases} \sum_{m \in M} (\mu + \Phi^{-1}(\alpha) \cdot \delta - (1 - 2\alpha)a) \cdot x_{ij}^m \leq Q_{ij}^m & 0 < \alpha \leq \frac{1}{2}, \forall (i, j) \in A \\ \sum_{m \in M} (\mu + \Phi^{-1}(\alpha) \cdot \delta + (2\alpha - 1)b) \cdot x_{ij}^m \leq Q_{ij}^m & \frac{1}{2} < \alpha \leq 1, \forall (i, j) \in A \end{cases} \quad (21)$$

$$\begin{cases} \sum_{m \in M} \sum_{n \in M} (\mu + \Phi^{-1}(\alpha) \cdot \delta - (1 - 2\alpha)a) \cdot y_k^{mn} \leq Q_k & 0 < \alpha \leq \frac{1}{2}, \forall k \in N, m \neq n \\ \sum_{m \in M} \sum_{n \in M} (\mu + \Phi^{-1}(\alpha) \cdot \delta + (2\alpha - 1)b) \cdot y_k^{mn} \leq Q_k & \frac{1}{2} < \alpha \leq 1, \forall k \in N, m \neq n \end{cases} \quad (22)$$

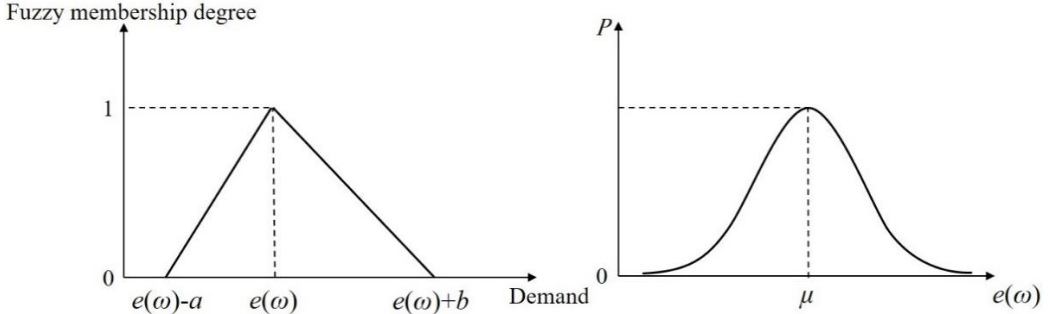


Fig. 1. Triangular fuzzy random demand

Table 1. Parameter description

Parameter	Representations	Units
N	The set of all nodes	
A	The set of all arcs	
M	The set modes of transportation	
D_{ij}^m	The distance transported by transportation mode m on arc (i, j)	km
C^m	Unit transportation cost of transportation mode m	CNY/(t·km)
FC^m	Fixed service costs of transportation mode m	CNY
B^{mn}	The cost of transfer from mode m to mode n at the node	CNY/t
Q_{ij}^m	The maximum capacity transported by mode m on arc (i, j)	t
Q_k	The maximum transfer capacity at node k	t
ρ_{ij}^m	The number of exposed population transported by mode m on arc (i, j)	one thousand people
ρ_k	The number of exposed population at node k	one thousand people

Table 2. Decision variables

Decision	Representations
x_{ij}^m	If the HAZMAT are transported on the arc (i, j) by the mode of transportation m , $x_{ij}^m = 1$; otherwise, $x_{ij}^m = 0$.
y_k^{mn}	If the HAZMAT is transferred from transportation mode m to mode n at node k , $y_k^{mn} = 1$; otherwise, $y_k^{mn} = 0$.

Through clarification, the established uncertain programming model can be transformed into an equivalent and clear multi-objective integer linear programming model, with the objective function of risk objective (14) and cost objective (15), constraint package (6)~(8), equation (11)~(12), and equation (21)~(22).

4. Algorithm solving

The model of multimodal transport route optimization of HAZMAT under uncertain demand constructed in this paper has a complicated structure, and it is difficult to obtain an accurate solution directly. Therefore, the Non-dominated Sorting Genetic Algorithm-II (NSGA-II) with elite strategy is

adopted to solve the model. Compared with the traditional genetic algorithm, NSGA-II can retain the excellent individuals of the parents and reduce the difficulty of solving the model (Deb et al. 2000; Verma et al. 2021).

4.1. Chromosome coding and initialization population

Assuming that the transportation network of the multimodal transport path optimization problem for HAZMAT has \bar{N} nodes and \bar{A} arcs, so a two-segment encoding structure can be adopted. The first segment is a 0-1 code of length \bar{N} , where 1 represents the HAZMAT transportation passing through this node, and otherwise 0 represents not passing through this node. Since the starting and ending points must be selected, so the first and last bits of the first encoding are assigned a value of 1, and the middle segment randomly generates 0-1 random numbers. The second segment is a transportation mode code with a length of \bar{A} , which numbers all arcs in the network with numbers 1 to a . The a -th gene represents which transportation method is used to transport HAZMAT on the arc with number a . A real numbers 1, 2, or 3 are randomly generated to represent road, railway, and waterway transportation, respectively. Combining two coding segments into one segment \bar{X} , then chromosome \bar{X} can be represented as:

$$\bar{X} = [\{x_1, x_2, \dots, x_{\bar{N}}\} \{y_1, y_2, \dots, y_{\bar{A}}\}] \quad (23)$$

The first segment of chromosome with a value of 1 is the selected node of the transportation plan. If these nodes can satisfy constraint (3) then it means that a connected O-D path can be generated. Otherwise, it will return and re-generate a chromosome. The arc between two selected adjacent nodes is the selected arc, and the second chromosome segment corresponding to the arc is the selected transportation mode for the arc. If the transportation plan generates a loop, then delete the selected arc between two nodes with farther node numbers apart. As shown in Fig. 2, the resulting chromosome can be represented as a multimodal transportation scheme. Generate an initial chromosome using the coding rules mentioned above. If the generated chromosome does not meet the constraint conditions, it is returned for regeneration. Cycle this produces chromosomes until the population size is reached.

4.2. Non-dominated sorting

NSGA-II proposes a fast non-dominated sorting method for comparing all individuals in a population. Suppose that there are two parameters U_i and W_i in each chromosome i of population P , where U_i is the number of individuals dominating individual i in P , and W_i is the set of individuals dominated by individual i in P . Save all the individuals with $W_i = 0$ in the population in the set Z_1 , then traverse the dominant individual set $W_{i'}$ of all individuals i' in Z_1 , and perform $U_j - 1$ on all the individuals j in $W_{i'}$. If the result is 0, save individual j as in the set Z_2 and repeat the above hierarchical operation for Z_2 until all individuals in P are stratified.

4.3. Genetic strategy

4.3.1. Select operator

In order to prevent local stacking, after non-dominated sorting of all individuals, those with greater crowding in the same hierarchy are selected first. The crowding degree i_d is calculated as follows:

$$i_d = \begin{cases} \sum_{j=1}^n \frac{f_j^{i+1} - f_j^{i-1}}{f_j^{\max} - f_j^{\min}} & 2 \leq i \leq U_i - 1 \\ \infty & i = 1, U_i \end{cases} \quad (24)$$

where n is the number of objective functions, U_i is the number of individuals at the non-dominance level of individual i , f_j^{\max} and f_j^{\min} are the maximum and minimum values of the objective value j at the non-dominance level of individual i , and f_j^{i+1} and f_j^{i-1} are the left and right neighboring values of individual i at the objective function value j . The elite strategy of NSGA-II guarantees the convergence of the algorithm by performing a binary tournament operation on the non-dominated rank Z_i and crowding degree i_d of individual i in the population, so as to keep the excellent individuals in the parent in the offspring and ensure the convergence of the algorithm.

4.3.2. Crossover operator

Crossover operator is the most important operation to change population diversity, and the commonly used crossover methods include partially-matched crossover (PMX), two-point crossover and order

crossover (OX). In this paper, according to the crossover probability P_c , the chromosomes that perform crossover operation are selected. As shown in Fig. 3, two points are randomly selected in the first segment of the selected chromosome except the first and second points, and the segments between the two points are crossover operated. Similarly, two points are randomly selected from all the segments encoded in the second segment, and the segments between the two points are crossed, thus ensuring the diversity of the population.

4.3.3 Mutation operator

The mutation operator is used to generate new chromosomes by changing some of the genes in the parent chromosome, thus maintaining the diversity of the chromosome set. In this paper, the chromosome that performs mutation operation is selected according to the crossover probability P_m . As shown in fig. 4, the middle genes encoded by the first segment of chromosome randomly selects the mutation positions of two different elements and exchanges their elements to realize reciprocity; the same mutation operation is executed for all gene of the second segment encoding.

4.4 Termination conditions

By setting the maximum number of iterations, the optimal solution is updated after each iteration by an elite retention strategy. The algorithm is stopped when the number of iterations reaches the maximum number of iterations and the resulting optimal solution is output.

5. Computational experiment

In this paper, we design a HAZMAT multimodal transportation network with 13 nodes and 34 arcs as shown in Fig. 5, and applies algorithms to optimize its solution. The parameters of unit cost, exposed population and maximum capacity of HAZMAT for each arc and transfer node under different transportation modes in the intermodal network are set as shown in Tables 3~6. The confidence level of fuzzy random chance constraint α is set to 0.8, and the corresponding $\Phi^{-1}(\alpha)$ is taken as 0.842 against the standard normal distribution table. The demand for HAZMAT is an uncertain variable, and its most likely value follows the normal distribution of $(1000, 2^2)$ tons. The left and right widths of fuzzy random variables are 100t and 150 t respectively.

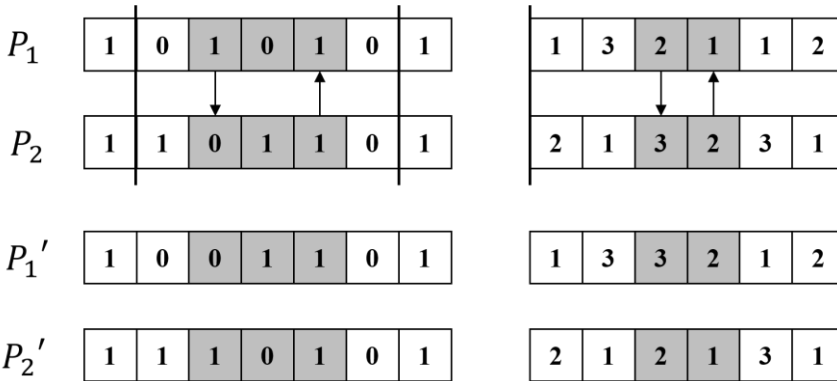


Fig. 3 Crossover operator

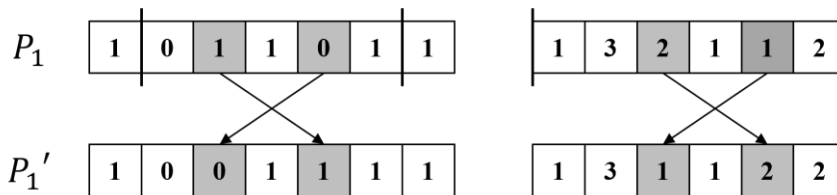


Fig. 4. Mutation operator

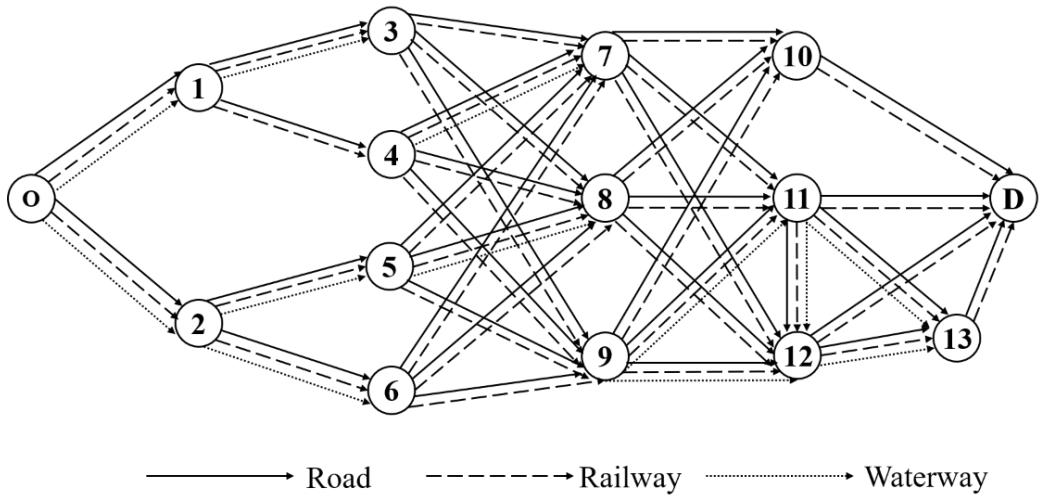


Fig. 5. Intermodal transportation of HAZMAT network

Table 3. Information of HAZMAT transportation arcs

Arc	Distances (km)	Risk (Thousand people)	Capacity limits (t)	Arc	Distances (km)	Risk (Thousand people)	Capacity limits (t)
O-1	(104,134,131)	(130,170,135)	(1 350,1 250,1 300)	6-9	(243,257, —)	(325,235, —)	(1 450,1 400, —)
O-2	(143,151,126)	(215,215,180)	(1 400,1 350,1 300)	7-10	(226,237, —)	(280,195, —)	(1 550,1 250, —)
1-3	(212,194,124)	(265,240,175)	(1 300,1 200,1 200)	7-11	(197,227, —)	(320,285, —)	(1 300,1 100, —)
1-4	(226,197, —)	(230,195, —)	(1 450,1 080, —)	7-12	(211,223, —)	(180,255, —)	(1 450,1 350, —)
2-5	(246,299,258)	(220,305,150)	(1 450,1 250,1 250)	8-10	(201,202, —)	(265,245, —)	(1 450,1 450, —)
2-6	(224,212,170)	(265,275,235)	(1 350,1 300,1 350)	8-11	(199,200, —)	(250,210, —)	(1 250,1 050, —)
3-7	(244,187, —)	(325,210, —)	(1 300,1 150, —)	8-12	(221,233, —)	(320,230, —)	(1 300,1 350, —)
3-8	(276,249, —)	(285,315, —)	(1 400,1 400, —)	9-10	(210,200, —)	(305,230, —)	(1 400,1 200, —)
3-9	(179,187, —)	(350,295, —)	(1 350,1 250, —)	9-11	(178,245,130)	(295,195,135)	(1 250,1 400,1 250)
4-7	(156,143,198)	(350,235,200)	(1 450,1 180,1 100)	9-12	(214,176,155)	(305,215, 95)	(1 350,1 150,1 150)
4-8	(206,197, —)	(290,160, —)	(1 400,1 100, —)	10-D	(212,272, —)	(235,295, —)	(1 450,1 300, —)
4-9	(204,221, —)	(275,220, —)	(1 350,1 350, —)	11-12	(158,195,170)	(165, 95 ,125)	(1 250,1 250,1 250)
5-7	(178,198, —)	(280,310, —)	(1 250,1 250, —)	11-13	(143,214,103)	(285,285,150)	(1 350,1 350,1 350)
5-8	(186,164,174)	(300,240,170)	(1 550,1 100,1 100)	11-D	(223,264, —)	(250,280, —)	(1 450,1 400, —)
5-9	(201,214, —)	(195,195, —)	(1 400,1 300, —)	12-13	(169,116,197)	(180,155, 95)	(1 300,1 300,1 300)
6-7	(256,179, —)	(305,290, —)	(1 350,1 080, —)	12-D	(275,179, —)	(330,260, —)	(1 350,1 150, —)
6-8	(246,267, —)	(295,200, —)	(1 150,1 150, —)	13-D	(118,154, —)	(105,135, —)	(1 450,1 400, —)

Table 4. Information of nodes

Node	Risk (Thousand people)	Capacity limits (t)	Node	Risk (Thousand people)	Capacity limits (t)	Node	Risk (Thousand people)	Capacity limits (t)
1	15	1 350	6	22	1 200	11	19	1 200
2	18	1 300	7	20	1 350	12	21	1 450
3	25	1 350	8	30	1 250	13	12	1 400
4	27	1 450	9	26	1 300			
5	24	1 350	10	28	1 350			

5.1. Computation result

The algorithm is programmed by

MATLAB(R2017a), and the processor is a notebook computer with Intel (R) Core (TM) i5-7300 HQ CPU @ 2.50 GHz. The relevant parameters of the algorithm are follows. The population size $Pop = 150$, the maximum number of iterations $Gen = 50$, $P_c = 0.8$ and $P_m = 0.1$.

The Pareto optimal transportation plan for multimodal transportation of HAZMAT obtained by us is shown in Table 7 and Fig. 6. According to Table 7, it can be seen that the transportation plan with the lowest risk is $O \rightarrow \text{waterway} \rightarrow 2 \rightarrow \text{waterway} \rightarrow 5 \rightarrow \text{railroad} \rightarrow 9 \rightarrow \text{waterway} \rightarrow 11 \rightarrow \text{road} \rightarrow D$ when the fuzzy random demand is [900, (1 000,2²), 1 150] tons. At this time, the total transportation risk is in 991 743.75 thousand people exposure-ton, and the total cost is 254 157.75 CNY; In addition, we can also choose the least costly transportation plan as $O \rightarrow \text{waterway} \rightarrow 1 \rightarrow \text{waterway} \rightarrow 3 \rightarrow \text{railway} \rightarrow 9 \rightarrow \text{railway} \rightarrow 10 \rightarrow D$, which at this time increases the total risk of transportation by 17.92%, but reduces the total cost of transportation by 21.71%. As can be seen from Fig. 6, the risk and cost objectives of HAZMAT multimodal transportation route optimization are in a contradictory trend, and if the risk value of the scheme is reduced, it will lead

to an increase in the total transportation cost. Therefore, the risk and cost factors should be considered in the optimization of multimodal transportation route for HAZMAT, and the transportation scheme should be selected reasonably.

5.2. Result analysis

As can be seen from Table 5, the freight rate of traditional road transportation is lower than that of railway and waterway transportation in the environment of low volume and short distance, and with the increase of demand and transportation distance, the cost gap between road, railway and waterway transportation gradually increases. As shown in Table 7, transport by rail or water has a lower risk value and cost value, the carrier will be more willing to choose a long rail direct highway, waterway transportation and a short distance shuttle combination of combined transportation. So under the background of long distance bulk cargo transport, compared to a single way to transport, multimodal transport can save costs at the same time effectively reduce the risk of transportation, makes the carrier for higher transport efficiency.

Table 5. Information on different modes of HAZMAT transportation

	Unit cost (CNY/ km · t)	Fix cost (CNY/ t)
Road	0.35	5.0
Railway	0.12	18.6
Waterway	0.09	12.0

Table 6. Information on different modes of HAZMAT transportation

	Unit cost (CNY/ km · t)
Road - Railway	8.0
Road - Waterway	9.5
Railway -Waterway	12.0

Table 7. Pareto optimal transportation path sets

Order	Cost (CNY)	Risk (Thousand people·t)	Path selection	Transportation mode
1	198 991.69	1 169 437.50	O-1-3-9-10-D	Waterway-Waterway-Railway-Railway-Railway
2	201 204.00	1 123 875.00	O-1-3-7-11-D	Waterway-Waterway-Railway-Railway-Railway
3	201 416.63	1 083 375.00	O-2-5-8-10-D	Waterway-Waterway-Waterway-Railway-Railway
4	203 299.88	1 047 937.50	O-1-3-7-10-D	Waterway-Waterway-Railway-Railway-Railway
5	218 198.81	1 037 306.25	O-2-5-9-11-D	Waterway-Waterway-Railway-Railway-Railway
6	222 172.88	1 022 118.75	O-2-5-9-11-D	Waterway-Waterway-Railway-Waterway-Railway
7	241 086.38	1 015 537.50	O-1-3-7-10-D	Waterway-Waterway-Railway-Railway-Road
8	254 157.75	991 743.75	O-2-5-9-11-D	Waterway-Waterway-Railway-Waterway-Road

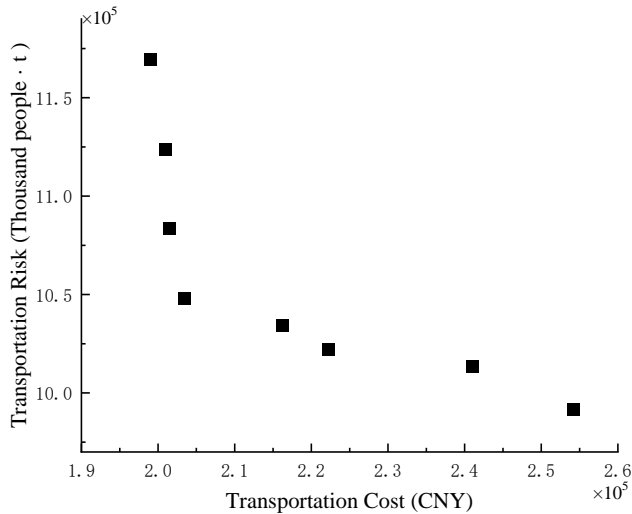


Fig. 6. Pareto optimal solution to the optimization problem of multimodal transport path for HAZMAT

In order to better analyze the impact of the growth of uncertain demand on the risk and cost of multimodal transportation of HAZMAT, three models with different HAZMAT demand are designed in this paper for comparison. Model I ($e=1\ 000\ t$) is the case of definite demand. Model II ($e(\omega)\sim(1\ 000,2^2)t$, $a=100$, $b=150$) and Model III ($e(\omega)\sim(1\ 000,2^2)t$, $a=200$, $b=300$) refers to the uncertain demand situation under two different widths.

As can be seen from Figure 7, compared with the case of deterministic demand, the Pareto frontier curve under uncertain demand shifts to the upper right, and the lowest transportation cost increases by 8.54%, while the lowest transportation risk increases by 20.62%, and we can see that the growth of uncertain demand has a more significant impact on the risk target, which proves that the consideration of uncertain demand in the multimodal transportation model of HAZMAT proposed in this paper. This proves the necessity of considering demand uncertainty in the multimodal transport model of HAZMAT proposed in this paper. In addition, with the increase of the left and right widths of fuzzy random demand, the Pareto frontier curve constantly moves to the upper right. When the most optimistic demand exceeds the limited capacity of some road sections and transfer points, the optimal transportation scheme changes, and the distribution law of Pareto frontier solution also changes. This phenomenon

may be caused by the influence of fuzzy random chance constraints under uncertain demand, and the confidence level α is too large, which leads to the relatively conservative solution. Therefore, this paper analyzes the sensitivity of confidence level α .

5.3. Sensitivity analysis of confidence level α

The uncertain demand of HAZMAT directly affects the choice of optimal path through the fuzzy random chance constraint of capacity, so the choice of confidence level α also affects the carrier's decision. Different confidence levels indicate the different acceptability of decision makers on the reliability of transportation scheme, and the higher the confidence level, the more reliable the transportation scheme planning is. In order to facilitate the sensitivity comparison analysis, this paper considers the optimal values of single-objective optimization under the cost objective and risk objective of the multimodal transportation path problem for HAZMAT separately, and Figure 8 gives the comparison of the optimal values of cost objective and risk objective under different confidence levels. From Fig. 8, it can be seen that in Model III, when the confidence level is less than 0.7, the change of confidence level has almost no effect on the selection of optimal values of cost and risk for multimodal transportation of HAZMAT; when the confidence level is greater than 0.7, the risk target and cost target of transportation

scheme increase significantly with the increase of confidence level, which indicates that increasing the reliability preference of transportation scheme will inevitably lead to the increase of total risk and total cost of transportation. Therefore, decision makers

need to choose the suitable confidence level according to their own situation and develop a multimodal transportation scheme for HAZMAT that meets the actual environment.

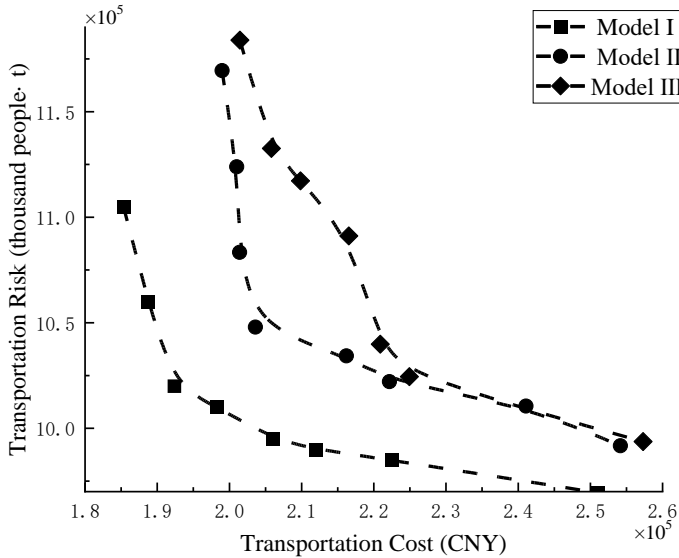


Fig. 7. Pareto optimal solution of multimodal transport paths for HAZMAT under different demands

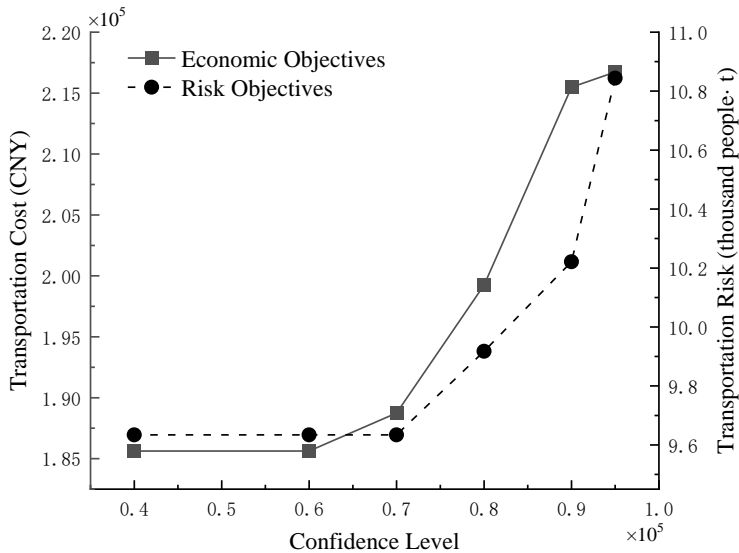


Fig. 8. The influence of different confidence levels on transportation risks and costs

6. Conclusions

In this study we consider the phenomenon of uncertain demand in the multimodal transportation of HAZMAT and use triangular fuzzy stochastic numbers to express the uncertain demand. Meanwhile, we design a fuzzy stochastic programming method considering transportation risk and cost to model this class of HAZMAT multimodal transportation path optimization problem and derive an equivalent crisp model for this problem. We also design a non-dominated ranking genetic algorithm to solve the model and obtain Pareto boundary values. Finally, a sensitivity analysis verify the impact of confidence levels on multimodal transportation schemes, risks, and cost objectives for HAZMAT. The calculation results and sensitivity analysis can prove the effectiveness of the proposed multimodal transportation path optimization model for HAZMAT under uncertain demand, and the following management insights can be obtained, which can provide decision-making reference for relevant departments to formulate HAZMAT transportation plans.

1. The risk objectives and cost objectives in multimodal transport of HAZMAT are changing, and improving one of them will inevitably lead to the deterioration of the other. At this point, Pareto boundary can provide different alternatives for decision makers.
2. Uncertainty in demand can have an impact on the risk and cost of multimodal transportation of HAZMAT. Therefore, decision makers need to reasonably assess the uncertain demand interval, too wide demand interval may lead to the increase of transportation risks and costs, and the optimal transportation solution changes.
3. Improving the confidence level will lead to the increase of transportation risks and costs, so decision makers need to choose reasonable reliability preferences according to their own conditions to formulate transportation plans.

However, this paper only considers the transportation demand between single O-D pairs, which has certain limitations. The multimodal transportation route optimization problem between multiple O-D pairs and multiple batches of HAZMAT will be considered in the subsequent study.

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