Transport path optimization algorithm based on fuzzy integrated weights*

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Natural disasters cause significant damage to roads, making route selection a complicated logistical problem. To overcome this complexity, we present a method of using a trapezoidal fuzzy number to select the optimal transport path. Using the given trapezoidal fuzzy edge coefficients, we calculate a fuzzy integrated matrix, and incorporate the fuzzy multi-weights into fuzzy integrated weights. The optimal path is determined by taking two sets of vertices and transforming undiscovered vertices into discoverable ones. Our experimental results show that the model is highly accurate, and requires only a few measurement data to confirm the optimal path. The model provides an effective, feasible, and convenient method to obtain weights for different road sections, and can be applied to road planning in intelligent transportation systems.

Keywords: fuzzy integrated weights, optimization, vertices

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1. Introduction

George and Kerstin[1] first discussed the logistics of vehicle routing in 1957. Since then, path optimization has been the focus of attention in computer science, operations research, transportation engineering, and geographic information science. Optimal path selection plays an important role in distribution activities, especially when spontaneous combustion and natural disasters occur. Damage to roadways can be classified as "serious damage", "medium damage", etc. These categorizations result in a vague characterization of network side length. The selected path is generally influenced by distance, time, traffic, and other factors, which constitute a fuzzy quantity network that is characterized by dynamic, random, and indefinite expressions. Therefore, the edge weights should be represented according to fuzzy set theory.

Transportation problems have been studied within a fuzzy environment. Chanas *et al.*[2] extended the classic transportation problem[3] to the fuzzy environment, and discussed a fuzzy integer transportation problem with fuzzy production using a minimal operator. Ishii and Tada[4] proposed fuzzy transportation and fuzzy integer transportation problems. Liu and Kao[5] used an extension principle to solve a fuzzy transportation problem. Liu[6] studied a fuzzy-dimensional transportation problem. With regard to fuzzy supply, demand, and unit product freight, Chakraborty and Chakraborty[7] used fuzzy parametric programming to minimize both transportation time and freight volume. Kaur and Kumar[8] presented a new fuzzy transportation problem in which the given freight and demand are fuzzy numbers. Keshavarz and Khorram[9] considered a transportation problem in which both the total shipping time and total benefit are fuzzy intervals, and then proposed an efficient algorithm based on parametric linear programming. Fuzzy theory has been studied in many systems, such as the sawtooth problem,[10] gene systems,[11] software development,[12] Internet systems,[13] precipitation,[14] airline networks,[15] online collaborative writing,[16] and discrete problems.[17] The methods discussed above are applied to one or two transport path optimization targets. For more integrated aims, the special correlation between different factors should be considered. This requires the edge weights to be considered in terms of fuzzy set theory. When analyzed and applied practically, this method is an efficient means of examining new transport path optimization algorithms.

2. Path optimization algorithm for fuzzy integrated weights

Within a transport network, the weighting of edge parameters may be subjected to a particular fuzzy distribution function (i.e., triangular or trapezoidal distribution). However, sometimes the edge can only be expressed as a possibility.[18–20] Representing edge coefficients with trapezoidal distribution functions may simplify the problem, particularly in determining the membership function. Therefore, we first determine the trapezoidal fuzzy numbers using bounding path optimization algorithms.

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2.1. Arithmetic algorithm for trapezoidal fuzzy numbers

Definition 1 Let $\underset{\sim}{A} \in X$, then the membership function of the fuzzy number $\underset{\sim}{A}$ will be expressed as

$$\mu_{\underset{\sim}{A}}(x) = \begin{cases} \dfrac{x-a}{b-a}, & a \le x \le b, \\ 1, & b \le x \le c, \\ \dfrac{x-d}{c-d}, & c \le x \le d, \\ 0, & \text{otherwise}, \end{cases} \tag{1}$$

where $a \le b \le c \le d$; a and d are the upper and lower bounds of $\underset{\sim}{A}$, respectively; the closed interval $[b,c]$ is the mid-weight of $\underset{\sim}{A}$. The coordinates are shown in Fig. 1.

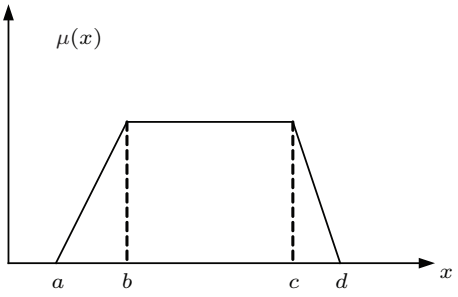


Fig. 1. Trapezoidal membership function of a fuzzy number.

According to the above definition, $\underset{\sim}{A}$ can be determined by the real quaternion (a,b,c,d). When $b=c$, $\underset{\sim}{A}$ becomes a triangular fuzzy number; when $a=b=c=d$, $\underset{\sim}{A}$ is an ordinary real number. Thus, a trapezoidal fuzzy number that is approximately equal to 5 is expressed as (4, 5, 5, 6), whereas the non-fuzzy number 5 can be expressed as (5, 5, 5, 5). This concept provides a unified representation of fuzzy and non-fuzzy numbers, and facilitates the calculation of qualitative and quantitative indicators.

According to Zadeh's extension principle, the addition, multiplication, and division of trapezoidal fuzzy numbers can be defined as follows. Let $\underset{\sim}{X} = (a_1,b_1,c_1,d_1)$ and $\underset{\sim}{Y} = (a_2,b_2,c_2,d_2)$, then the algebraic operations on $\underset{\sim}{X}$ and $\underset{\sim}{Y}$ will be expressed as

$$\begin{aligned} \underset{\sim}{X} \oplus \underset{\sim}{Y} &= (a_1,b_1,c_1,d_1) \oplus (a_2,b_2,c_2,d_2) \\ &= (a_1+a_2, b_1+b_2, c_1+c_2, d_1+d_2), \qquad (2) \\ \underset{\sim}{X} \otimes \underset{\sim}{Y} &= (a_1,b_1,c_1,d_1) \otimes (a_2,b_2,c_2,d_2) \\ &\approx (a_1 \times a_2, b_1 \times b_2, c_1 \times c_2, d_1 \times d_2), \qquad (3) \\ \underset{\sim}{X}(\div)\underset{\sim}{Y} &= (a_1,b_1,c_1,d_1)(\div)(a_2,b_2,c_2,d_2) \\ &\approx (a_1/d_2, b_1/c_2, c_1/b_2, d_1/a_2). \qquad (4) \end{aligned}$$

These computations extend ordinary algebraic algorithms to the fuzzy field, thereby facilitating the calculation and assessment of fuzzy numbers.

2.2. Ranking fuzzy numbers

As there is no direct linear order for fuzzy numbers, ranking them remains a difficult issue in fuzzy mathematics. However, practical significance of fuzzy equations indicates that fuzzy numbers can be ranked in practical applications. This dilemma has been extensively studied, and a variety of ordering methods have been proposed.

In general, the calculations required to rank fuzzy numbers are extremely complicated. The simplification proposed in this article is to transform fuzzy numbers into definitive non-fuzzy weights. The specific process is described as follows. Given the trapezoidal fuzzy number $\underset{\sim}{A} = (a,b,c,d)$ and its non-fuzzy number weight $h = D(\underset{\sim}{A})$, we solve

$$\begin{aligned} &\frac{1}{2} \times (b-a) \times 1.0 + 1.0 \times (h-b) \\ &= \frac{1}{2} \times (d-c) \times 1.0 + (c-h) \times 1.0, \end{aligned} \tag{5}$$

and obtain $h = D(\underset{\sim}{A}) = (a+b+c+d)/4$.

2.3. Synthesis of fuzzy matrix relationships

We define the domains $X = \{x_1, x_2, ..., x_m\}$ and $Y = \{y_1, y_2, ..., y_n\}$. The fuzzy relationship from X to Y can be written as $\underset{\sim}{R} = (r_{ij})_{m \times n}$, where $r_{ij} = \mu_{\underset{\sim}{R}}(x_i, y_j)$.

Definition 2 Let $\underset{\sim}{R} = (r_{ij})_{n \times m}$ and $Q = (q_{ij})_{m \times l}$. Thus, $\underset{\sim}{R} \circ \underset{\sim}{Q}$ is a fuzzy matrix $\underset{\sim}{S}$ with n rows and one column, and its elements are $s_{ik} = \bigvee_{j=1}^{m} (r_{ij} \wedge q_{jk})$ $(1 \le i \le n, 1 \le k \le l)$.

Definition 3 Consider a directed network $G = (V,A,W)$, with vertices $V = \{v_s, v_1, v_2, \ldots, v_t\}$, arcs $A = \{i,j | i,j \in V\}$, and fuzzy edge weights $W = \{W_{i,j}(i,j) \in A\}$, where $W_{ij}(a,b,c,d)$ is a trapezoidal fuzzy number. If P is a path from s to t, then P can be represented by the string $v_s e_{si} v_i \cdots v_j e_{jt} v_t$.

Definition 4 If $W(p) = \sum F(W_{i,j}) | W_{i,j:} e_{i,j} \in p$, then $W(p)$ is the fuzzy integral sum of path p. P_{st} denotes the collection of all paths from s to t in G. If $P^* \in P_{st}$ and, for any $P \in P_{st} : W(P^*) \le W(P)$,

$$W(p^*) \le W(p), \tag{6}$$

then P^* is the shortest fuzzy path from s to t within G.

The path optimization algorithm for fuzzy integrated weights proceeds as follows.

(i) Let $\underset{\sim}{d}_{ij}$ denote all of the trapezoidal fuzzy edge weights ($\underset{\sim}{d}_{ij}$ may represent the transit time, transport distance, capacity, transportation costs, etc.). The membership function is

expressed as

$$\mu_{\tilde{d}_{ij}}(x)=\begin{cases}\dfrac{x-a_{ij}}{m_{ij}^1-a_{ij}}, & a_{ij}\le x\le m_{ij}^1,\\ 1, & m_{ij}^1<x\le m_{ij}^2,\\ \dfrac{x-b_{ij}}{m_{ij}^2-b_{ij}}, & m_{ij}^2<x\le b_{ij},\\ 0, & \text{otherwise.}\end{cases}\tag{7}$$

(ii) Calculate the transport network fuzzy integrated weights. The matrix of fuzzy integrated weights for each edge in the transport network is obtained using the method given in Section 3. The previous fuzzy multi-weights are then converted into fuzzy integrated weights. The fuzzy integrated weight of each edge is the trapezoidal fuzzy number $\underset{\sim}{I}_{ij}$.

(iii) Let $\lambda\in[0,1]$. Calculate $L_{ij}^*(\lambda)=\underset{\sim}{I}_{ij}^{\mathrm{L}}+(\underset{\sim}{I}_{ij}^{m}-\underset{\sim}{I}_{ij}^{\mathrm{L}})\lambda$ and $R_{ij}^*(\lambda)=\underset{\sim}{I}_{ij}^{\mathrm{R}}-(\underset{\sim}{I}_{ij}^{\mathrm{R}}-\underset{\sim}{I}_{ij}^{m})\lambda$.

(iv) Let $L_{ij}^*(\lambda)$ and $R_{ij}^*(\lambda)$ be the respective edge weights of the transport network. Determine the optimal route within the transport network.

(v) Let $L_{ij}^*(\lambda)$ be the edge weight of the transport network, and determine the optimal path within the transport network node $v_{\mathrm{s}}-v_{\mathrm{t}}$. Two sets of vertices S and $\bar{S}$ are given; S consists of vertices along the optimal path, whereas $\bar{S}$ consists of vertices that cannot find the optimal path. The initial set of S contains only the starting vertex v_{s}. The starting vertex is marked as 0, and the other vertices are temporarily marked as ∞.

(vi) The shortest path length from vertex v_{s} to vertex v_j is selected continuously from set $\bar{S}$ and added to set S by placing a permanent label on vertex v_j. There are two possible ways of reaching v_{s} from the newly added vertex. One is to directly connect with v_{s}, and the other is to connect to a known vertex of the optimal path in collection S, giving a new optimal path $l_k(v_j)=\min\{l_{k-1}(v_j),l_{k-1}(v_i)+L_{ij}^*(\lambda)\}$, where v_i is the vertex of set S, and v_j is a tentative node and an arbitrary element of set $\bar{S}$.

(vii) Repeat Step (vi) until the target vertex v_{t} is added to set S.

(viii) Repeat Steps (v)–(vii), and calculate the optimal path against fuzzy edge weight $R_{ij}^*(\lambda)$.

(ix) Analyze the results according to the nature of the problem. By taking a different weight λ in [0, 1], we obtain the series P_{st}, as well as the optimal path p_{st}^*, and the corresponding optimal weight λ^*. The results from these calculations are then combined to create the fuzzy optimal path set. The edge weights of this set are vague, resulting in a vague optimal path. However, this set contains more information, and provides a wider variety of options for decision makers.

3. Calculation of fuzzy integrated weights

The following parameters are used to give the edge weights for path optimization: i) fuzzy running time between points i and j; ii) running distance; iii) running costs; and iv) capacity. They are denoted by $\underset{\sim}{T}_{ij}$, $\underset{\sim}{S}_{ij}$, $\underset{\sim}{C}_{ij}$, and $\underset{\sim}{Q}_{ij}$, respectively. Each of these weights is a fuzzy number.

The matrix of a fuzzy edge weight within a transport network can be expressed as

$$\underset{\sim}{M}=\begin{bmatrix}\underset{\sim}{T}_{12} & \underset{\sim}{S}_{12} & \underset{\sim}{C}_{12} & \underset{\sim}{Q}_{12}\\ \underset{\sim}{T}_{23} & \underset{\sim}{S}_{23} & \underset{\sim}{C}_{23} & \underset{\sim}{Q}_{23}\\ \cdots & \cdots & \cdots & \cdots\\ \underset{\sim}{T}_{ij} & \underset{\sim}{S}_{ij} & \underset{\sim}{C}_{ij} & \underset{\sim}{Q}_{ij}\end{bmatrix}.\tag{8}$$

To normalize the fuzzy matrix, we let $\underset{\sim}{T}=\max\{\underset{\sim}{T}_{ij}\}$, $\underset{\sim}{S}=\max\{\underset{\sim}{S}_{ij}\}$, $\underset{\sim}{C}=\max\{\underset{\sim}{C}_{ij}\}$, and $\underset{\sim}{Q}=\max\{\underset{\sim}{Q}_{ij}\}$, and obtain the following standardized fuzzy matrix $\underset{\sim}{\bar{M}}$:

$$\underset{\sim}{\bar{M}}=\begin{bmatrix}\underset{\sim}{T}_{12}/\underset{\sim}{T} & \underset{\sim}{S}_{12}/\underset{\sim}{S} & \underset{\sim}{C}_{12}/\underset{\sim}{C} & \underset{\sim}{Q}_{12}/\underset{\sim}{Q}\\ \underset{\sim}{T}_{23}/\underset{\sim}{T} & \underset{\sim}{S}_{23}/\underset{\sim}{S} & \underset{\sim}{C}_{23}/\underset{\sim}{C} & \underset{\sim}{Q}_{23}/\underset{\sim}{Q}\\ \cdots & \cdots & \cdots & \cdots\\ \underset{\sim}{T}_{ij}/\underset{\sim}{T} & \underset{\sim}{S}_{ij}/\underset{\sim}{S} & \underset{\sim}{C}_{ij}/\underset{\sim}{C} & \underset{\sim}{Q}_{ij}/\underset{\sim}{Q}\end{bmatrix}.\tag{9}$$

In consideration of the subjective intent of decision makers, the coefficient matrix is determined as $\underset{\sim}{W}=\{W_{\underset{\sim}{T}},W_{\underset{\sim}{S}},W_{\underset{\sim}{C}},W_{\underset{\sim}{Q}}\}$, which represents the importance placed on running time, running distance, transportation costs, and capacity in path optimization decisions. The coefficient matrix and the standardized matrix $\underset{\sim}{\bar{M}}$ are subsequently combined together, resulting in the following fuzzy integrated matrix for each line of the transport network:

$$\begin{aligned}\underset{\sim}{I}&=(W_{\underset{\sim}{T}},W_{\underset{\sim}{S}},W_{\underset{\sim}{C}},W_{\underset{\sim}{Q}})\begin{bmatrix}\underset{\sim}{T}_{12}/\underset{\sim}{T} & \underset{\sim}{S}_{12}/\underset{\sim}{S} & \underset{\sim}{C}_{12}/\underset{\sim}{C} & \underset{\sim}{Q}_{12}/\underset{\sim}{Q}\\ \underset{\sim}{T}_{23}/\underset{\sim}{T} & \underset{\sim}{S}_{23}/\underset{\sim}{S} & \underset{\sim}{C}_{23}/\underset{\sim}{C} & \underset{\sim}{Q}_{23}/\underset{\sim}{Q}\\ \cdots & \cdots & \cdots & \cdots\\ \underset{\sim}{T}_{ij}/\underset{\sim}{T} & \underset{\sim}{S}_{ij}/\underset{\sim}{S} & \underset{\sim}{C}_{ij}/\underset{\sim}{C} & \underset{\sim}{Q}_{ij}/\underset{\sim}{Q}\end{bmatrix}\\ &=(\underset{\sim}{I}_{12},\underset{\sim}{I}_{23},\ldots,\underset{\sim}{I}_{ij}).\end{aligned}\tag{10}$$

By this point, the previous fuzzy multi-weights can be converted into fuzzy integrated weights. However, the fuzzy integrated weight of each edge is still a trapezoidal fuzzy number.

4. Numerical examples and discussion

We consider the example of the Nanjing Branch of the Jiangsu Postal Express and Logistics Company. In this branch, we optimize the mail delivery routes for nine surrounding cities. Figure 2 shows the cargo transportation capacity and number of trucks. Spots 1–9 represent Yangzhou, Zhenjiang, Changzhou, Wuxi, Suzhou, Shanghai, Jurong, Maanshan, and Chuzhou, respectively. The numbers in brackets near the city

codes refer to the volume of cargo (bags), and the figures on the connection lines refer to the distance between cities (in km). These distances are assumed to be reversible.

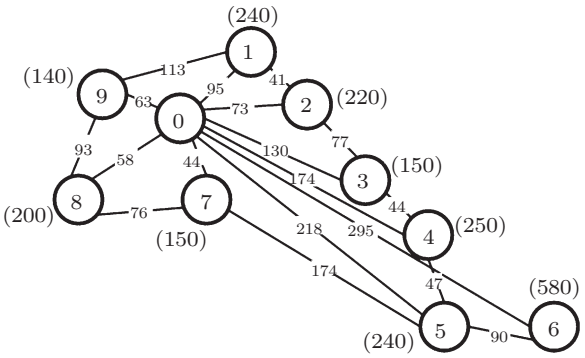


Fig. 2. Transportation capacity (bags) and mileage (km) to nine surrounding cities.

Currently, the Nanjing Branch adopts a single-point round-trip distribution for its postal centers across the nine cities. These centers have shuttles that depart at 21:00 every night and return at 16:00 the next day. There are two types of long-distance transport vehicle, 8 ton and 12 ton. The company stipulates that the daily transportation distance of each truck should not exceed 600 km. To ensure driving safety, two drivers are deployed when the transportation distance is over 350 km.

For mail distribution across these nine cities, the Nanjing Branch needs to employ eight 8-ton trucks, one 12-ton truck, and 11 drivers. The total delivery distance is 2297 km, and the total delivery cost is 5719 yuan.

The trapezoidal fuzzy numbers given by the optimization algorithm for the edge weights are shown in Table 3.

Table 1. Distances between cities (in km).

City	Nanjing	Yangzhou	Zhenjiang	Changzhou	Wuxi	Suzhou	Shanghai	Jurong	Maanshan	Chuzhou
Nanjing	0	95	73	130	174	218	295	44	58	63
Yangzhou		0	41	138	120	200	264	62	141	113
Zhenjiang			0	77	121	136	240	43	120	122
Changzhou				0	44	87	171	86	151	186
Wuxi					0	47	131	131	192	229
Suzhou						0	90	174	235	274
Shanghai							0	260	316	253
Jurong								0	76	102
Maanshan									0	93
Chuzhou										0

Table 2. Single-point round-trip distribution.

Right link	Transportation distance/km	Transportation capacity/bag	Truck type	Drivers needed
0–1–0	190	240	8t	1
0–2–0	145	220	8t	1
0–3–0	259	150	8t	1
0–4–0	349	250	8t	1
0–5–0	436	240	8t	2
0–6–0	591	580	12t	2
0–7–0	87	150	8t	1
0–8–0	116	200	8t	1
0–9–0	125	140	8t	1

Table 3. Edge weights expressed as trapezoidal fuzzy numbers.

Right link	Said edge	Trapezoidal fuzzy number	Right link	Said edge	Trapezoidal fuzzy number
0–1	trucks	2,6,11,12	0–6	trucks	1,2,5,9
	distance	5,8,16,18		distance	4,11,13,18
	drivers	4,8,11,15		Drivers	2,7,13,20
	capacity	5,8,12,16		capacity	7,8,10,15
0–2	trucks	1,4,8,11	0–7	trucks	6,7,10,12
	distance	6,15,21,22		distance	7,14,18,22
	drivers	8,11,12,15		Drivers	8,12,14,16
	capacity	3,7,10,15		capacity	10,14,20,22
0–3	trucks	1,3,9,11	0–8	trucks	2,4,9,10
	distance	2,8,12,15		distance	2,8,12,13
	drivers	1,5,10,13		Drivers	4,9,13,15
	capacity	3,8,12,15		capacity	2,8,10,12
0–4	trucks	4,6,9,10	0–9	trucks	2,8,11,14
	distance	5,11,18,20		distance	3,8,15,18
	drivers	3,8,10,15		Drivers	1,5,10,12
	capacity	9,15,20,23		capacity	9,15,24,28
0–5	trucks	2,5,9,12			
	distance	3,6,12,15			
	drivers	1,6,9,13			
	capacity	11,18,20,25			

The fuzzy integrated weights and the fuzzy integrated weight matrix are calculated as follows:

$$\underset{\sim}{M} = \begin{bmatrix} (2,6,11,12) & (5,8,16,18) & (4,8,11,15) & (5,8,12,16) \\ (1,4,8,11) & (6,15,21,22) & (8,11,12,15) & (3,7,10,15) \\ (1,3,9,11) & (2,8,12,15) & (1,5,10,13) & (3,8,12,15) \\ (4,6,9,10) & (5,11,18,20) & (3,8,10,15) & (9,15,20,23) \\ (2,5,9,12) & (3,6,12,15) & (1,6,9,13) & (11,18,20,25) \\ (1,2,5,9) & (4,11,13,18) & (2,7,13,20) & (7,8,10,15) \\ (6,7,10,12) & (7,14,18,22) & (8,12,14,16) & (10,14,20,22) \\ (2,4,9,10) & (2,8,12,13) & (4,9,13,15) & (2,8,10,12) \\ (2,8,11,14) & (3,8,15,18) & (1,5,10,12) & (9,15,24,28) \end{bmatrix}.$$

Similarly, $L_{ij}^{*}(\lambda)$ and $R_{ij}^{*}(\lambda)$ are calculated for λ in the range [0, 1], as well as in the optimal path. The calculated results are shown in Fig. 3.

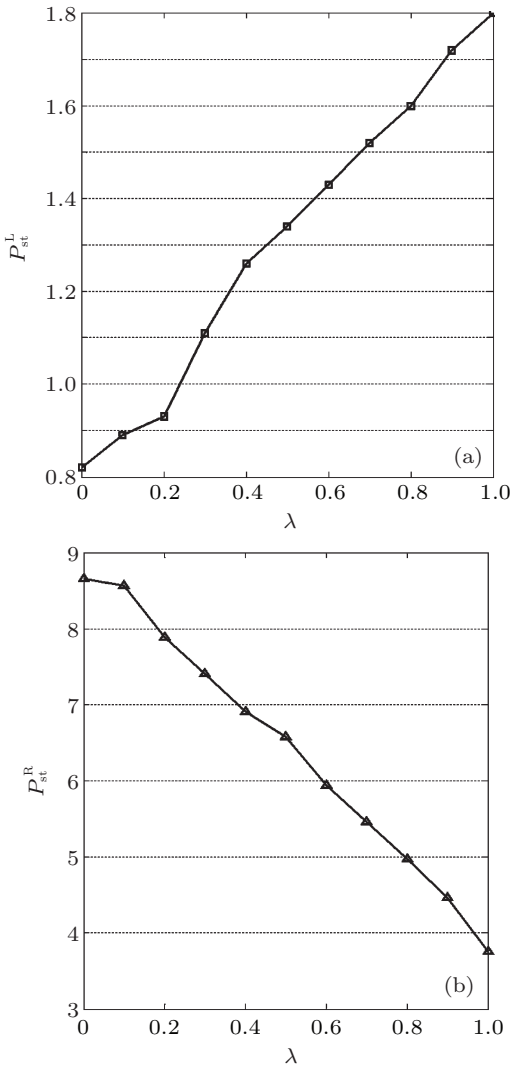


Fig. 3. Calculation results. (a) Weights of P_{st}^{L} as λ increases from 0 to 1. (b) Weights of P_{st}^{R} as λ increases from 0 to 1.

The results are calculated for multiple optimal paths, so that decision makers can select the optimal path according to the circumstances. The optimized results are listed in Tables 4 and 5, and are illustrated in Figs. 4 and 5.

For the first optimized result, the Nanjing branch needs to employ three 12-ton trucks, and six drivers. The total delivery distance is 1438 km, and the total delivery cost is 3834 yuan.

Table 4. Optimized result (1).

Right link	Transportation Mileage/km	Transportation Capacity/bag	Trucks needed	Drivers needed
0–2–6–0	608	799	12t	2
0–1–8–9–0	392	581	12t	2
0–3–4–5–7–0	438	791	12t	2

Table 5. Optimized result (2).

Right link	Transportation Mileage/km	Transportation Capacity/bag	Trucks needed	Drivers needed
0–6–0	590	582	12t	2
0–1–2–0	209	461	8t	1
0–3–4–5–0	438	639	12t	2
0–7–8–9–0	274	491	8t	1

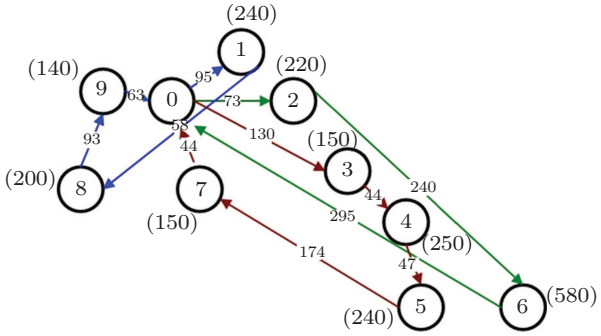


Fig. 4. (color online) Optimized result (1).

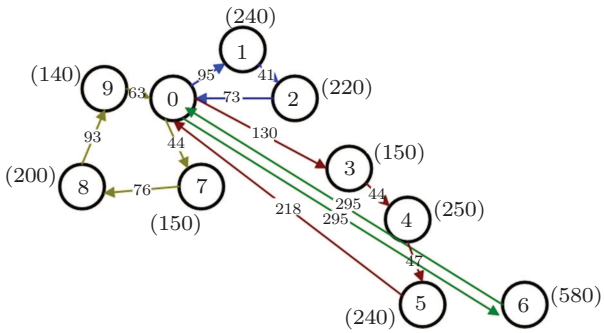


Fig. 5. (color online) Optimized result (2).

For the second optimized result, the Nanjing branch needs to employ two 8-ton trucks, two 12-ton trucks, and six drivers.

The total delivery mileage is 1511 km, and the total delivery cost is 3810 yuan.

As shown in the calculation above, the original delivery program cannot meet the cargo stowage requirements based on the deadweight capacity, resulting in a waste of manpower and material resources. Using the optimization algorithm produces reductions in manpower, cost, and transport requirements. The two optimized results provide different perspectives on these savings. In terms of reducing manpower, five fewer drivers will be needed, or the current personnel arrangement could be used to improve service levels. From the perspective of money saving, the daily delivery cost can be reduced by 1909 yuan using the optimization algorithm. From the perspective of material saving, the original eight 8-ton trucks and one 12-ton truck can be reduced to two 8-ton trucks and four 12-ton trucks.

5. Conclusion

The optimization algorithm presented in this paper can reduce total logistical costs and fuel costs, thus reducing waste and helping to prevent environmental pollution. However, our algorithm operates under conditions that are assumed to be ideal and stable. Moreover, we have not considered specific road conditions or highway and bridge tolls. With the rapid development of e-commerce, distribution volumes across cities are expected to change significantly. Thus, we should employ a rational approach to continuously optimize the distribution program based on changes in current conditions.

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