The Research of Emergency Logistics Path Optimization Based on Dual Objective Optimization Model

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by

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Abstract

For emergency logistics, effectiveness and efficiency are even more important than economy. However, due to the uncertainty of the transportation network reliability and travel time, there are some difficulties, like deterioration of the transportation system. After the Great Hanshin Earthquake in 1995 and the Great East Japan Earthquake in 2011, there are various issues such as relief supplies unable to be delivered on time or being stuck because of road disruption, and poor civil cooperation. Although there are a large number of researches on time minimization and road reliability, most of them are single-target optimization problems of transport system. In order to solve the aforementioned problems, in this paper, with the relief supplies quickly delivered to victims after a disaster, assuming that demand is sufficient, we focused on the dual objective optimization problem that are the reliability of the transportation network and minimization of transportation time, and developed a method that can select optimized path more efficiently. Based on that method we build a dual objective optimization model.

Keyword: Emergency logistics, Optimized path, Dual objective optimization model

1. Introduction

1.1. Background

After a disaster, the delivery of relief supplies, such as water, food and daily necessities, to a large number of affected people evacuated to shelters is one of the most important problems. For emergency logistics, effectiveness and efficiency are even more important than economy. However, due to the uncertainty of the transportation network reliability and transition time, there are some difficulties, like deterioration of the transportation system. After the Great Hanshin Earthquake in 1995 and the Great East Japan Earthquake in 2011, there are various issues such as relief supplies unable to deliver on time or being stuck because of road disruption, and poor civil cooperation. Similar relief supplies delivery problems have also occurred at the time of Sichuan Earthquake in 2008 and Qinghai Earthquake in 2010 in China. Although there are a large number of researches on time minimization and road reliability, most of them are single-target optimization problems of transport system.

1.2. Review of Existing Literature

Research on relief supplies delivery problem has important social significance and applied values. The existence of constraints (multipurpose, multiple means of transportation, multiple kinds of supplies

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and etc..) makes the construction and solution of relief supplies delivery model very complicated.

Several studies have been investigated regarding procurement of relief supplies and delivery path in recent years. Rathi, Church and Solanki [1)] studied the linear programming model of emergency supplies problem. In this model, the optimal solution of the number of transportation trucks on each route is obtained by setting the amount of material transportation of each route and the path between ODs. If the optimum number of tracks is not an integer, then increased the number of tracks to this real minimum integer. Fiedrich and Gehbauer [2)] studied the optimum model to distribute and relief supplies to multiple evacuation areas immediately after the disaster, with the aim of the minimum evacuation number, time, quantity of supplies and types restricted. Barbarsoglu and Arda [3)] built a model of two stages and multiple means of transportation and various kinds of supplies, and planned transportation of relief supplies. Assuming conditions that detailed information on the disaster situation cannot be obtained, they solved the balance problem between supply and demand.

In this research, we aim to construct a decision support model for useful preliminary planning from the standpoint of disaster prevention and reduction. Since it is difficult to grasp the actual damage situation accurately and apply it to the model in a complex situation in a disaster, various situations are set and analyzed at normal times. In order to solve the aforementioned problems, in this paper, with the relief supplies quickly delivered to affected people after a disaster, assuming that demand is sufficient, we focus on the dual objective optimization problem of the reliability of the transportation network and transition time and develop a method that can select optimized path more efficiently. Based on that method we build a dual objective optimization model. Finally, the analysis result is expressed directly by coordinate system drawing in order to help the dispatched people of emergency supplies choose the optimization route of emergency supplies highway transportation based on the specific conditions and requests.

2. Method and Structure

Since it is difficult to accurately grasp the circumstances and to apply them to the model after disasters, we assume various situations and analyse some data gathered in usual days. In conjunction with rapid delivery of relief supplies, we assume that supply is adequate for demand. Focusing on dual objective optimization problem of road reliability and time, we develop a method which can select the optimal path more efficiently.

The structure of this paper is as follows. Section 3 presents a single-target optimization model on time minimization. Section 4 presents the dual objective optimization model of the reliability of both transportation network and transition time. We study applications and provide experiment results for the example of Sichuan Ya'an Earthquake in 2013 in Section 5. Section 6 concludes our method and discusses future work.

3. Single-target Optimization Model on Time Minimization

Evacuation center information (number, position, kind and quantity of relief supplies required) and data of the road damage situation are necessary for constructing model assumptions of the disaster situation. However, it is difficult to obtain such information quickly and accurately in actual afflicted areas, so it is not realistic to formulate an accurate delivery plan immediately after the disaster. This model is not a plan reflecting the detailed disaster situation, but considered as a preliminary delivery plan aiming for disaster reduction.

Assumptions of this model are as follows:

1. There is only one rescue emergency supply distribution center and its position is known.
2. The number of vehicles and their load capacities are known.
3. There are multiple demand nodes whose positions and demands of supplies are known.

The conceptual diagram of the delivery route of truck is shown in Fig.1

Table 1 Notations

Symbol	Description
T	The total time of all routes
K	set of vehicles, {1,...,k}
S	the quantity of routes
i, j	demand shelters, {0,...,N},0 is distribution center
d_{ij}(km)	distance of i and j
t_{ij}(min)	time required to vehicle from i to j
m_{pi}	amount of demands of supply p at node i
Q(ton)	amount of vehicle's load capacity
t_i(min)	the arrival time of vehicle at node i
l_i(min)	the latest arrival time of vehicle at node i
v	the average speed of vehicles
x_{ijk}	1, vehicle k transports from i to j 0, others
y_{ki}	1, supplies for i are transported by k 0, others

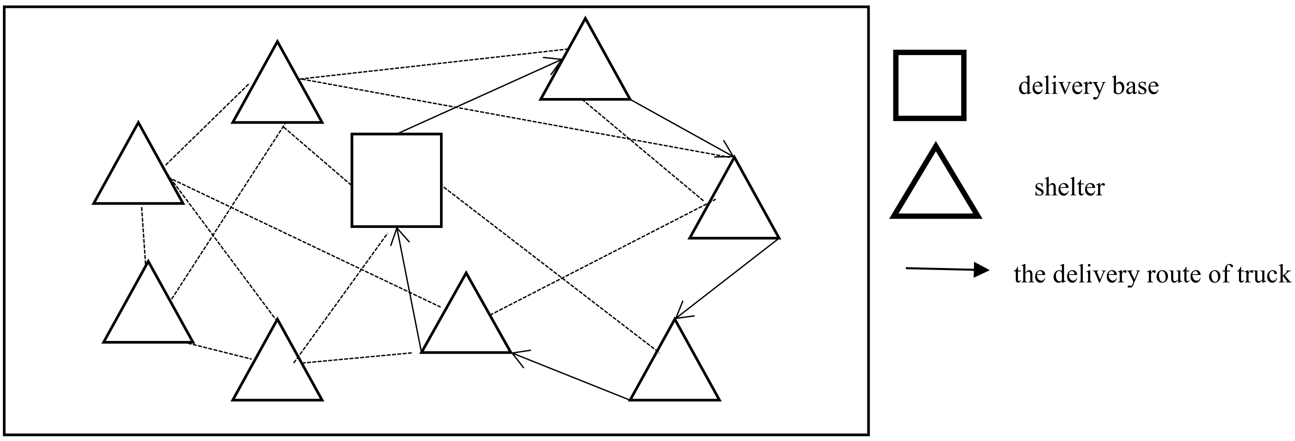

Fig.1 The conceptual diagram of the delivery route of truck

Based on the notations on table 1, we present the single-target optimization model on time minimization:

Model S

$$\min T = \sum_{k=1}^{K}\sum_{j=0}^{N}\sum_{i=0,i\neq j}^{N} x_{ijk}\, t_{ij} \tag{1}$$

s,t.

$$\sum_{k=1}^{S}\sum_{j=1}^{N} x_{ijk} \le K, i = 0 \tag{2}$$

$$\sum_{k=1}^{S}\sum_{i=1}^{N} x_{i0k} = \sum_{k=1}^{S}\sum_{j=1}^{N} x_{0jk} \tag{3}$$

$$\sum_{k=1}^{K} y_{ki} = 1, \forall i \in \{1,2...N\} \tag{4}$$

$$\sum_{i=0}^{N} x_{ijk} = y_{kj}, \forall j = \{1,2...N\}, K \in \{1,2...K\} \tag{5}$$

$$\sum_{j=0}^{N} x_{ijk} = y_{ki}, \forall i = \{1,2...N\}, K \in \{1,2...K\} \tag{6}$$

$$\sum_{i=1}^{N}\sum_{p=1}^{P} y_{ki} m_{pi} \le Q, k \in \{1,2...N\}, p \in \{1,2...P\} \tag{7}$$

$$t_j = \sum_{i=0, j \ne i}^{N} x_{ijk}\left(t_i + t_{ij}\right), \forall j \in \{1,2...N\} \tag{8}$$

$$t_{ij} = \frac{d_{ij}}{v} \tag{9}$$

$$t_i \le l_i, \forall i \in \{1,2...N\} \tag{10}$$

Formula (1) is the objective function. Formula (2), (3) show that the quantity of the routes starting from the delivery site is equal to the quantity of the routes arriving to the delivery site. Formula (4) means that the relief supplies of each evacuation shelter are shipped by a unique track. Formula (5), (6) represents that at some point of the evacuation centres, the relief supplies are shipped by track k which enters this point from the previous point, then leaves and delivers supplies to the next point. Formula (7) represents the sum of the tasks of each track does not exceed the capacity limit of the vehicle. Formula (8) means that the arrival time of point j is equal to the arrival time of point i plus the travel time of track. Formula (9) represents that the travel time of the track between point i and j is equal to the distance between two points divided by speed. Formula (10) represents that each track needs to reach each evacuation centre before the predetermined latest time.

We apply to the virtual problem and explain the solution of the model. The condition setting of the virtual problem is expressed as follows:

Delivery base: 1; Shelter: 8; relief supplies type: 2; The average speed of trucks: 60km/h; The number of trucks: 5; Load capacity: 10t. The location of each shelter, amount of demand for goods, and arrival time limit are known.

Demand amount of supplies and arrival time limit were set as shown in Table 2.

Table 2 Demand amount of supplies and arrival time limit

Shelter	1	2	3	4	5	6	7	8
Demand amount of supplies; P1 (t)	5	2	3	1	4	1	0	3
Demand amount of supplies; P2(t)	4	2	0	3	2	3	2	1
Latest end time (min)	30	35	24	15	50	62	80	100

The distances of each evacuation center and the distance between shelters from delivery bases were set as shown in Table 3

Table 3 The distances

dij(km)	0	1	2	3	4	5	6	7	8
0	0	16	6	14	7	18	19	7	8
1		0	18	13	20	13	15	14	19
2			0	12	5	10	14	12	12
3				0	14	14	9	16	18
4					0	8	18	8	11
5						0	14	10	12
6							0	13	15
7								0	8
8									0

We can directly solve the model by software named LINGO. LINGO is an optimization software for linear, nonlinear, and integer programming. When we get the specific data and use them in the calculation, we can just input the objective function, the constraints and numerical condition of this model, and output the optimal delivery route. Then we can get the optimal solution as shown in Fig.2.

Fig.2 Calculation results by using LINGO

When calculating with LINGO, set delivery base to 1. The number of evacuation shelters shall be between 2 and 9.

The results are,

1) Optimal solution: Transport time is 132 minutes
2) Route of truck1: delivery base-4-2- delivery base;
3) Route of truck2: delivery base-1- delivery base;
4) Route of truck4: delivery base-8-5- delivery base;
5) Route of truck5: delivery base-3-6- 7-delivery base;

The loading condition (unit: t) of each truck is shown in Table 4.

Table 4 The loading condition (unit: t)

Truck / P	1	2	4	5
P1	3	5	7	4
P2	5	4	3	5
Total loading capacity	8	9	10	9

4. Dual Objective Optimization Model of the Reliability of the Transportation Network and Transition Time

4.1. Model

Based on model S and hypothetical road reliability, we present the dual objective optimization model of the reliability of both transportation network and transportation time as:

$$\begin{cases} \min T(x) = \sum_{(i,j)\in L} t_{ij}(x) & (11) \\ \max R(x) = \prod_{(i,j)\in L} r_{ij}(x) & (12) \end{cases}$$

{Li} is set of routes between i and j，0＜λ＜1.

s.t. x is a route L between i and j. $x=L_1, L_2, \dots L_m$

$T(x)$: transportation time of route L; $R(x)$: Reliability of route L.

$$\begin{cases} \overline{T}(x) = \frac{T^*(x)}{T(x)} = \frac{T_{\min}(x)}{T(x)} & (13) \\ \overline{R}(x) = \frac{R(x)}{R^*(x)} = \frac{R(x)}{R_{\max}(x)} & (14) \end{cases}$$

We suppose that λ is the weighting coefficient, $U(x)$ is the utility function:

$$\max U(x) = \max\left[\lambda \overline{T}(x) + (1-\lambda)\overline{R}(x)\right] \quad (15)$$

4.2. Analysis

We suppose that s is a delivery site, t is an evacuation centre, node 1~5 are nodes of road network, and the delivery time(h) and reliability of each route as shown in Fig. 3.

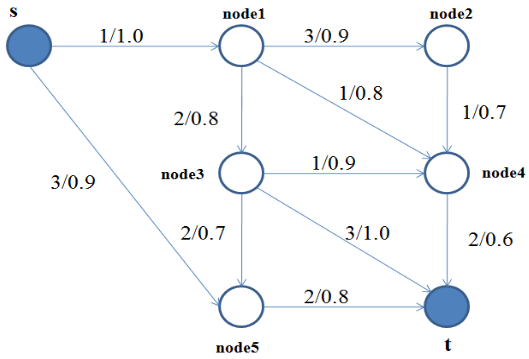

Fig.3 example of road network (time/reliability)

Among many conceivable routes, we select 3 feasible delivery routes as follows:

Route 1：s→5→t T_1=5, R_1=0.72

Route 2：s→1→4→t T_2=4, R_2=0.48

Route 3：s→1→3→t T_3=6, R_3=0.8

Therefore, we use formula (13), (14) to change time and reliability to dimensionless quantities.

Since T_{min}=4, R_{max}=0.8, we get dimensionless quantities shown as Table 5.

Table 5

Route	Dimensionless quantity of time	Dimensionless quantity of reliability	Utility value	Utility value range
1	0.8	0.9	0.9-0.1λ	(0.8,0.9)
2	1	0.6	0.6+0.4λ	(0.6,1)
3	0.67	1	1-0.33λ	(0.67,1)

Then it is possible to calculate the utility metrics of each route by formula (15).

The utility function of each routes are shown as Fig.4.

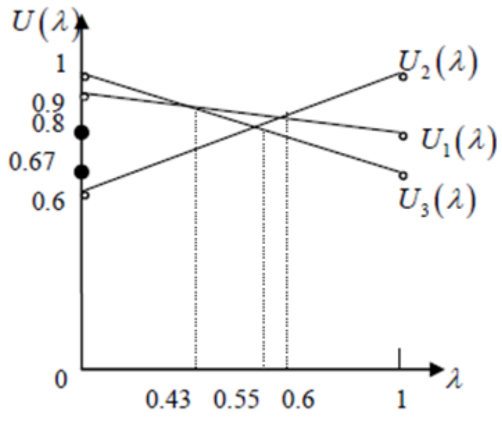

Fig.4 The utility function

Result analysis:

When $\lambda \in$ (0, 0.43), $U_3(x)$ is a maximum, route 3 is the optimal solution.

When $\lambda \in$ (0.43, 0.6), $U_1(x)$ is a maximum, route 1 is the optimal solution.

When $\lambda \in$ (0.6, 1), $U_2(x)$ is a maximum, route 2 is the optimal solution.

When λ=0.43, $U_1(x) = U_3(x)$, route 1 and 3 are the optimal solution.

When λ=0.6, $U_1(x) = U_2(x)$, route 1 and 2 are the optimal solution.

By using such charts, the countermeasure decision makers can compare the general utility value of each route intuitively. And it is possible to select the appropriate route and make an appropriate delivery plan by practical situation efficiently.

5. Application of the model

For 2013 Sichuan Ya'an earthquake disaster, we set up a total of 12 evacuation shelters in Ya'an City and surrounding areas damaged. With Chengdu as a delivery base center for relief goods, we applied it to a single target time minimization model for emergency transport within 12 hours immediately after a disaster. A map of the target area is shown as shown in Fig. 5

Fig.5 Map of the target area

Table 6 shows the distances between the delivery base and the 12 evacuation shelters. In addition, the population of each evacuation shelter, the demand amount of goods, and the transportation time limit are shown in Table 7.

Table 6

Distance	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13
H1	0	139	172	214	178	129	175	81.5	58.2	333	279	105	84.4
H2	139	0	34.7	76.8	40.5	12.5	40.1	67	90.4	136	142	24.2	60.6
H3	172	34.7	0	42.2	39.3	45.9	60.9	83.7	124	134	140	118	93.9
H4	214	76.8	42.2	0	81.3	87.9	103	124	166	237	182	160	136
H5	178	40.5	39.3	81.3	0	51.6	48.4	106	129	156	102	123	99.7
H6	129	12.5	45.9	87.9	51.6	0	49.5	57.4	80.9	206	152	74.6	51.1
H7	175	40.1	60.9	103	48.4	49.5	0	104	128	222	168	122	98.1
H8	81.5	67	83.7	124	106	57.4	104	0	25.3	261	207	55.3	30.3
H9	58.2	90.4	124	166	129	80.9	128	25.3	0	284	230	80.8	55.9
H10	333	136	134	237	156	206	222	261	284	0	54.8	278	255
H11	279	142	140	182	102	152	168	207	230	54.8	0		255
H12	105	24.2	118	160	123	74.6	122	55.3	80.8	278	224	0	25.1
H13	84.4	60.6	93.9	136	99.7	51.1	98.1	30.3	55.9	255	201	25.1	0

Table 7

Shelters	Population(thousands)	Demand(t)	Time limit(h)	Unloading time(h)
H2	350	3.50	8	0.5
H3	120	1.20	8	0.3
H4	60	0.6	8	0.2
H5	138	1.38	8	0.3
H6	259	2.59	8	0.4
H7	140	1.40	8	0.3
H8	650	6.50	8	0.6
H9	500	5.00	8	0.5
H10	97	0.97	8	0.1
H11	77	0.77	8	0.1
H12	165	1.65	8	0.3
H13	260	2.60	8	0.4

Assuming that the population in the relevant area is all about the population affected by the disaster, and assuming that the demand amount of goods is in a linear relationship with the population, the loading and unloading time of the baggage becomes linearly related to the demand amount of supplies. For the application of this model, the required time limit was set to 8h. The running speed of the truck was set at 80km/h. By substituting the above conditions and data into the model of Chapter 3 and calculating using LINGO, an optimal solution is obtained.

Route of Truck A ：H1→H9→H8→H3→H4

Route of Truck B ：H1→H12→H13→H6→H2→H7→H5→H11→H10

The main road network and delivery routes are shown in Fig.6

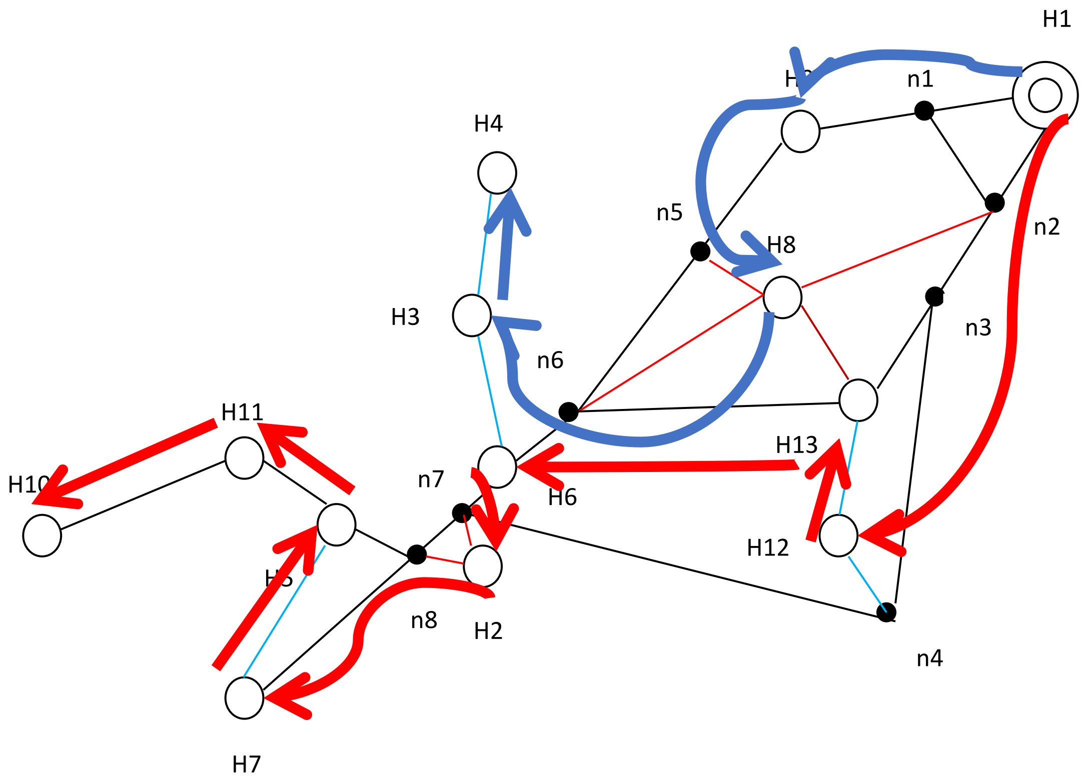

Fig.6 The main road network and delivery routes

Fix the evacuation centers and the delivery order delivered by truck A and truck B, and consider the reliability of the main road network and apply it to the dual-purpose optimization model. In order to apply the model, reliability is given to each link, network utility function from delivery base H1 to each evacuation shelter is established, time and reliability are confirmed, and then we can intuitively compare each delivery route plan. The distance between each node of the road network is known. Since the running speed of the truck was set at 80 km / h, the transportation time between each node was obtained. We also assume the reliability to each link is related to the construction level of the road, the road grade and the surrounding topography. The reliability of each link is set as shown in Table 8

Table 8 The reliability of each link

reliability	H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	n1	n2	n3	n4	n5	n6	n7	n8
H1														0.9	1						
H2																				0.7	0.8
H3				0.6		0.6															
H4			0.6																		
H5							0.5				0.7										0.9
H6			0.6																1	1	
H7					0.5																1
H8													0.7		0.8			0.8	0.6		
H9														1				1			
H10											0.8										
H11					0.7					0.8											
H12													0.8				0.7				
H13								0.7				0.8				1			0.9		
n1	0.9								1						1						
n2	1							0.8						1		1					
n3													1		1		1				
n4												0.7				1				1	
n5								0.8	1										1		
n6						1		0.6					0.9					1			
n7		0.7				1											1				1
n8		0.8			0.9		1													1	

Among many conceivable routes, 3 realizable routes of truck A can be set as follows:

Route A1 : H1→n1→H9→n5→H8→n6→H6→H3→H4

T_{A1}=4.0175, R_{A1}=0.1555

Route A2 : H1→n1→H9→n5→H8→n5→n6→H6→H3→H4

T_{A2}=4.6825, R_{A2}=0.2304

Route A3 : H1→n2→n1→H9→n5→H8→n6→H6→H3→H4

T_{A3}=4.555, RA_3=0.1728

Therefore, time and reliability are made dimensionless using Eqs. (13) and (14) in Chapter 4. Since Tmin = 4.0175 and Rmax = 0.2304, the dimensionless quantity in Table 9 can be obtained. Then the utility index of each route can be calculated by the equation (15).

Table 9 The utility index of each route (Truck A)

Route	Dimensionless quantity of time	Dimensionless quantity of reliability	Utility value	Utility value range
A1	1	0.67	0.67+0.33λ	(0.67,1)
A2	0.86	1	1-0.14λ	(0.86,1)
A3	0.83	0.75	0.75+0.08λ	(0.75,0.83)

The utility function of each route is shown in Fig.7

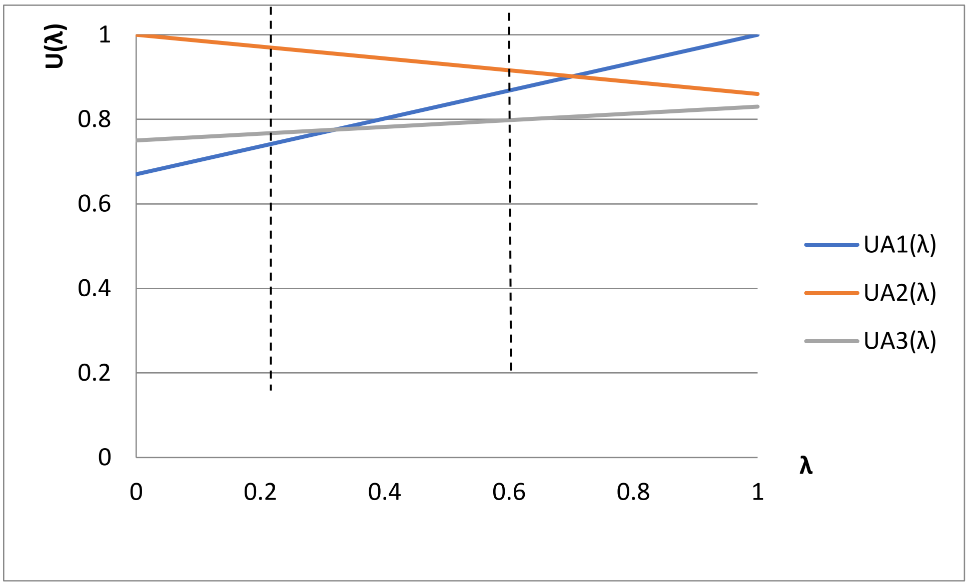

Fig.7 The utility function of each route

Among many conceivable routes, 3 realizable routes of truck B can be set as follows:

Route B1 : H1→n2→n3→H13→H12→H13→n6→H6→n7→H2→n8→H7 →H5→H11→H10, T_{B1}=7.8663, R_{B1}=0.0903

Route B2 : H1→n2→n3→n4→H12→H13→n6→H6→n7→H2→n8→H7→H5→H11→H10 T_{B2}=7.8163, R_{B2}=0.0790

Route B3 : H1→n2→n3→H13→H12→H13→n6→H6→n7→H2→n8→H7 →H5 →H11 →H10 T_{B3}=8.1538, R_{B3}=0.1625

Therefore, time and reliability are made dimensionless using Eqs. (13) and (14) in Chapter 4. T_{min}=7.8163 and R_{max}=0.1625 the dimensionless quantity in Table 10 can be obtained. Then the utility index of each route can be calculated by the equation (15).

Table 10 The utility index of each route (Truck B)

Route	Dimensionless quantity of time	Dimensionless quantity of reliability	Utility value	Utility value range
B1	0.99	0.56	0.56+0.43λ	(0.56,0.99)
B2	1	0.49	0.49+0.51λ	(0.49,1)
B3	0.95	1	1-0.05λ	(0.95,1)

The utility function of each route is shown in Fig.8

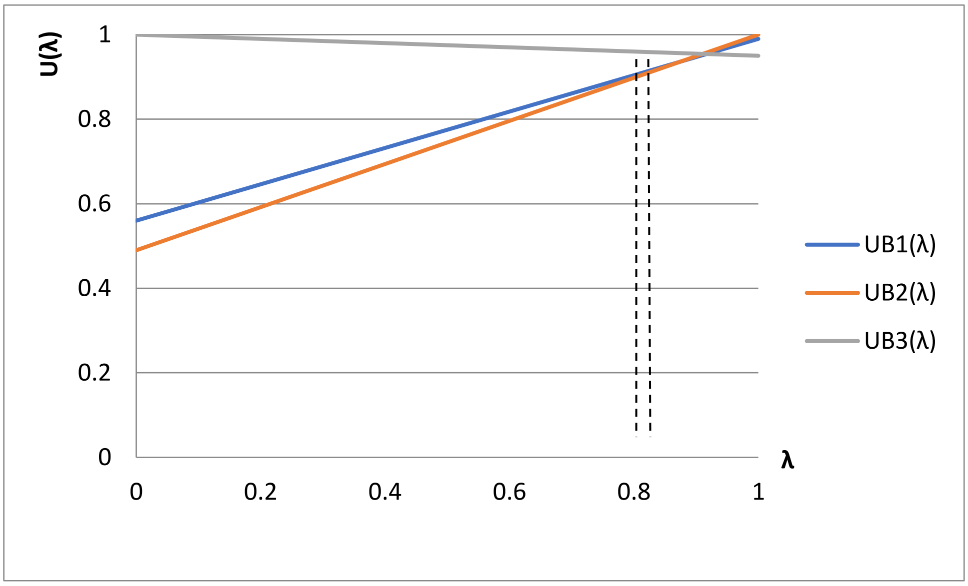

Fig.8 The utility function of each route

6. Conclusion

This research provides a method to find the optimal supply route, and the analysis result is expressed directly by coordinate system drawing, so as to help dispatchers of emergency supply choose the optimization route of emergency supplies highway transportation based on the specific conditions and requests.

Then the method is applied for Sichuan Ya'an and the surrounding area where earthquake had actually occurred. The feasibility of making relief supply delivery plan before disaster is also confirmed by single target objective optimization. Then we apply the results to the dual objective optimization model, considering the time and reliability, we can choose the optimal route, which is responsible for actual situations, from a number of feasible routes. This method's validity is confirmed. As a result, the usefulness of the model is verified and some issues are also identified to be improved in future.

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