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Multi-objective optimization model and algorithm for hazardous materials transportation network under terrorist attack

Ruiqi XIONG[1,a], Changxi MA[2,b]

[1,2]School of Traffic and Transportation, Lanzhou Jiaotong Univ., P.O. Box 730070, Lanzhou City, Gansu Province.

[a]xrq12580@163.com, [b]machangxi@mail.lzjtu.cn

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Abstract. In order to reduce the risk of hazardous materials transportation under the background of terrorist attacks,a method based on genetic algorithm is proposed.Firstly,a hazardous materials transportation route optimization model is designed with objective function of minimizing transportation risks and minimizing transportation costs.Secondly, an improved multi-objective genetic algorithm with node priority encoding method is adopted to solve the model.In addition,roulette selection operation,crossover operation based on a priority index,single-bit neighbour exchange variation method are used during genetic manipulation.Finally, liquefied natural gas (LNG) transportation is chosen as an empirical research example.The results show that hazardous materials transportation routes with low transportation risks and costs can be quickly obtained through using the optimization model and algorithm,which are proposed under the background of the terrorist attacks in this paper.

Introduction

With the progress of China's economy and industrialization, the demand for hazardous materials rise sharply, such as chemical raw materials and so on. Those vehicles which transportation hazardous materials with high flammable and toxic will put a serious safety threats to the residents and environment around the accident road attachments.In recent years on a global scale, the number of terrorist attack incidents are going up year on year.It is very important for hazardous materials to keep a high safety transportation.But it is relatively weak and difficult for decisions makers to do a better protection, and it is easier for hazardous materials vehicles to be the target of terrorist attacks.So,in the context of terrorist attacks, many countries, governments and enterprises have put top priority on the safety problem of hazardous materials transportation routes.

At present, the studies on the routes optimization of hazardous materials transportation under the background of terrorist attacks are much less, some relevant literature's focus and key point are the analysis of the risk of terrorist attacks or the routes optimization strategy for hazardous materials transportation. Levine et al.[1] proposed a method to assess the potential risk of terrorist attacks based on the game theory; Bila M. Ayyub and Mark Kaminskiy et al.[2] proposed an all-security quantitative terrorist attack analysis method; Milazzo et al.[3] studied the transport of hazardous materials on urban roads in the context of terrorist attacks.In China,under the background of the terrorist attacks,Wu Wen and Shuai Bin[4]proposed a transport network risk analysis and calculation method based on the TNO model and the game theory under the background of the terrorist attacks; Zhang Zheng, Wu Zongzhi, Liu Mao[5] proposed a terrorist attack damage destructive function based on the defensive situation $R_a=f(V,S)$ based on defensive situation after the research of attraction;Ma Changxi et al.[6] constructed a hazardous materials

multi-objective decision-making model for road transportation under developed road network environment.In summary, the study on the transportation of hazardous materials in the background of terrorist attacks is still in its infancy, and its related research is lacking.In this paper, a hazardous materials transportation route optimization model with minimizing transportation risks and minimizing transportation costs is designed under the background of the terrorist attacks, and an improved multi-objective genetic algorithm was proposed to solve the practical examples.

Model Formulation

Due to the uncertainty and the strong man-made subjectivity of the terrorist attacks, a quantitative analysis method is used in this paper.Considering the possibility of the basic hazard of the routes (Such as: road conditions, population density) and the possible damage to the casualty environment caused by the terrorist attacks, the model is established to minimize the transportation risk and minimize the transportation cost.

Model assumptions. The model is based on the following assumptions:

(1) Terrorist attacks are single-point attacks to the road and there is no second attack;
(2) The hazardous materials vehicle's travel path is non-repeatable;
(3) The manner of terrorist attacks is detonateding the hazardous materials vehicles,regardless of other attacks;
(4) The hazardous materials vehicles meet road network load-bearing, limited high-traffic requirements.

Establishment of Index System. (1) Risk cost Z_1. The calculation of risk in the context of a terrorist attack is as follows [7]:

$R = P$ (attack occurs)× P (attack damage|attack occurs)× E (damage|attack occur and cause damage)

$$=TVC \tag{1}$$

In the formula (1),T is Threat;V is Vulnerability;C is Consequence.

The risk influence factors for hazardous materials transportation are diverse, the main factors include the types of hazardous materials, transportation vehicles, related personnel, roads and the environment, emergency rescue and other six aspects.This paper mainly considers the impact factors in the context of terrorist attacks, so the objective factors are selected as risk analysis.The threat is indicated by the inherent characteristics of the link: the population density h_1, the surrounding rescue situation h_2, and the traffic condition h_3.Refering to the relevant hazardous materials transportation evaluation literature[8], the relevant factors are divided into scoring in Table 1, the classification of the weight value in Table 2.

Table 1 Comparison scores of three threaten factors

Threat factors	Population density	Rescue situation	Road traffic conditions
Population density	1	7	5
Rescue situation	1/7	1	1/2
Road traffic conditions	1/5	2	1

Table 2 Assessment and comparison scores of the threaten factors

Scoring	Population density(h_1)	Rescue situation(h_2)	Road traffic conditions(h_3)
1	0~0.4	2 or more fire stations and can arrive in 3 minutes	Highway or Grade 1 Road and the roads are unimpeded
2	0.4~0.8	2 or more fire stations and can arrive in 5 minutes	Grade 2 or Grade 3 Road, and the roads are mostly straight and flat roads
3	0.8~1.2	Only 1 fire station can arrive in 5 minutes	Grade 2 or Grade 3 Road,and the roads are mostly undulating
4	1.2~1.8	The nearest fire station can be reached within 10 minutes	Grade 4 Road, and the roads' conditions are basically good
5	1.8 or more	Nearby fire station can not arrive in time	Grade 4 Road,and the roads' conditions are worse

According to the Table 1, a comparison matrix U can be obtained,

$$U=\begin{bmatrix}1 & 7 & 5\\ 1/7 & 1 & 1/2\\ 1/5 & 2 & 1\end{bmatrix}.$$

And by using the Analytic Hierarchy Process, the maximum eigenvalue is obtained: $l_{\max}=3.013$,feature vectoris obtained: $W^T=(0.738,0.094,0.168)$.

The following is consistency check:

$$C_R=\frac{C_I}{R_I}=\frac{l-n}{(n-1)R_I}=\frac{3.013-3}{(3-1)0.58}\approx 0.0065<0.1$$

Because the consistency tests are reasonable, so the value for three factor's weight,which influencing threat, are the followings:(c_1,c_2,c_3)=(0.738,0.094,0.168).

The threat expression can be obtained through Table 1 and Table 2 :

$$T=h_1c_1+h_2c_2+h_3c_3 \tag{2}$$

In this paper, the vulnerability assessment method in paper[9].Vulnerability is defined as the probability of a successful terrorist attack. In the process of defending a terrorist attack, there will be three processes:the defender identifies the terrorist attack, launches the defense system,and successfully defends the terrorist attack.Vulnerability of the expression:

$$V=(1-E_s)P_k \tag{3}$$

In formula (3),E_s is the probability that the defender intervenes and succeeds; P_k is he probability of the success of a terrorist attack after a defensive failure.

Hazardous materials vehicles accidents will cause serious casualties and property damages, and it is most serious for vehicles to cause casualties and bad effects,so the consequences of C

considers the impact of terrorist attacks within the scope of casualties.Due to the way of attacking is to detonate hazardous materials transportation vehicles explosion, and the main cause of casualties is the overpressure caused by the explosion. Therefore, the accident consequences is obtained through calculating the energy generated from different hazardous materials explosions with TNT equivalent model and then the number of casualties is obtained.The expression is as follows [10] :

$$W = \frac{hME_C}{E_{TNT}} \tag{4}$$

And then the standardized distance will be obtained through the energy oexplosion:

$$\overline{R} = \frac{R}{(W / P_0)^{1/3}} \tag{5}$$

In formula (5), $\overline{R}$ is the normalized distance; P_0 is the atmospheric pressure, the unit is kpa; R is the actual distance, the unit is km.

According to the standard distance obtained by the table and probit model derived from the probability of death at different distances [11], as shown in Table 3.

Table3 the relations between death probability and overpressure

Overpressure peak(kpa)	Probability of death(q)
16.548	1%
90.325	50%
299.933	95%

In order to simplify the model, the explosion model is set up as a point circle model. The influence range of the explosion is circular, the influence range is S (km^2), and the diffusion decreases with increasing distance,so the influence range can be divided into four areas according to the difference from death probability (it is <1%, 1% - 50%, 50% - 95%,> 95% respectively). Also, the probability of death can be seen as a interval average value in a certain distance range, then the number of deaths in the section can be obtained through multiplying the population distribution number and the death probability:

$$Q = Spq \tag{6}$$

In formula (6), p is unit population density,the unit is person/km^2; q is the probability of death; S is the area of the affected area, the unit is km^2.

The weights of threats, vulnerabilities and consequences are obtained by the above solution method, and then the risk weight of each road section can be obtained:

$$\begin{aligned} R &= TVC \\ &= (h_1c_1 + h_2c_2 + h_3c_3)(1 - E_s)P_kSpq \end{aligned} \tag{7}$$

(2)Economic cost Z_2. Compared with general cargo transportation, the optimization of transportation of hazardous materials focuses on the minimization of transportation risks.In this paper, the economic cost considerations are relatively simplified, taking into account only the fuel

costs incurred by the length of the path.

$$W_{ij} = d_{ij} f \tag{8}$$

In equation (8), d_{ij} is the distance from i to j, the unit is km; f is the average fuel cost per kilometer, the unit is km / yuan.

Objective function. The urban road network has physical properties such as road routes, intersections, and other various logical attributes such as route length, passage time, traffic conditions, and safety[12].In this paper, a weighted directed graph $G = (V, E)$ is used to abstract the road network.V represents the intersection and each town in the road, and is the node in the road network represenst the node set of the vehicle in the next direction of travel in the network; E represents the set of edges between the nodes.In the model, weights are assigned to each path,and the magnitude of the weights is given by the terrorist attack risk assessment.Based on the above discussion, the objective functions are as follows:

$$Min\ Z_1 = Min\sum_{i=1}^{n}\sum_{j=1}^{n} R_{ij}S_{ij} \tag{9}$$

$$Min\ Z_2 = Min\sum_{i=1}^{n}\sum_{j=1}^{n} W_{ij}S_{ij} \tag{10}$$

$$S_{ij} = \begin{cases} 1 & 0<i, j \le n, \text{the vehicle passes through this road} \\ 0 & \text{the vehicle does not pass through this road} \end{cases} \tag{11}$$

$$s.t \begin{cases} \sum_{j=1}^{n} X_{1j} - \sum_{k=1}^{n} X_{k1} = 1 & (12) \\ \sum_{j=1}^{n} X_{ij} - \sum_{k=1}^{n} X_{ki} = 0 \quad i=2,3...n-1 & (13) \\ \sum_{j=1}^{n} X_{nj} - \sum_{k=1}^{n} X_{kn} = -1 & (14) \end{cases}$$

Where constraint (12) is the starting point constraint, constraint (13) is the intermediate node constraint, and constraint (14) is the end point constraint condition.

Solution Algorithm

There are two objective functions in the above model, which belong to the NP-hard problem, and the traditional multi-objective genetic algorithm can not solve. In this paper, genetic algorithm with Elite Retention Strategy (NSPA2) is adopted to solve the transportation routes optimization model for hazardous materials in the background of terrorist attacks.Algorithm flow chart shown in Fig. 1.

Encoding and decoding. Due to the uncertainty of selecting the path nodes, the node set is range with the length of the path, so the priority coding method is chosen to code. In this paper, the gene location is used to represent the chromosomal gene to mark nodes, and the priority of the different nodes in the path is distinguished through the difference of gene nodes. The priority of the starting node is denoted by the number 1, and the terminating node is expressed in terms of the total number of nodes, so that the priority of each node is different[13].If there are *n* nodes in the network, a node of length *n* is constructed by the priority of *n* nodes, where the first node is 1 and the last node is *n*.Such chromosomes are decoded to form a path from the starting point to the end point.The basic method of decoding is to select the node with highest priority among the current nodes, and put this node into the decoding sequence. If the selected current node is the termination node, a node sequence can be obtained as decoding sequence.

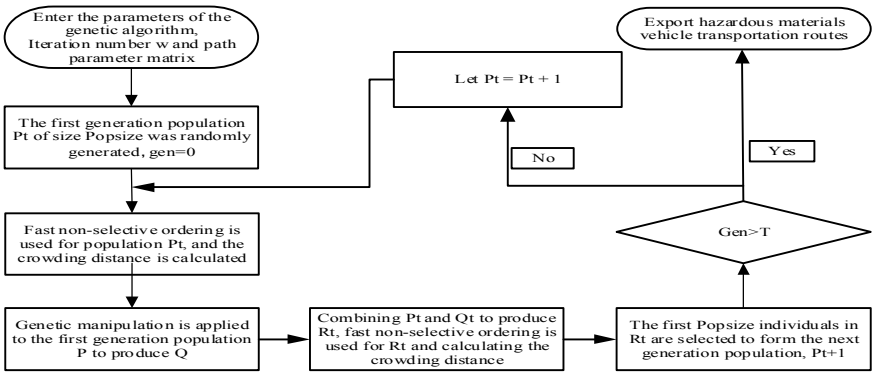

Fig.1 Algorithm flow chart

Fitness function. Due to the value of the objective function in the model is always positive,so the individual fitness function can be set as follows.

$$S(x)=\begin{cases} M-T(x), & if \quad T(x)<M \\ 0, & if \quad T(x)\geq M \end{cases}, \tag{15}$$

Design of Genetic Operators. (1)Select operator. The roulette selection strategy is used as a selection operation.Firstly, the chromosomes were sorted according to the size of chromosome target value, then the discs were partitioned according to the size of the population, and the corresponding fitness scores were given.Finally, a number between 0 and 1 is generated randomly, and the different individuals can be selected through the random number, which correspond to the probability of different roulette regions. After the selection operation, the Elite Rule Retention Policy is adopted to select the best individuals, which will be put into the next generation to continue operation, through the above operations, it is sure that the best individuals of the next generation must inferior to the previous generation in each evolutionary process.

(2) Crossover operator. In this section,the priority index crossover operator is used to guarantee the succession of the children to the parents and the superiority of the offspring to the parents.The crossover method randomly selects two genes on the chromosome which have been coded according to the priority level, which are not the initial node and the end node, and then the alleles corresponding to the chromosomal fragments including the two selected genes are prioritized Level to produce a new sequence of gene combinations in order to expect beneficial genes to bind to each other.

(3) Mutation operator. In this section,the single-parent ortho-substitution method was used to carry out the mutation.First, two genes were selected randomly, which did not contain the initial node and the termination node, and the gene fragments which would be ortho-exchanged were determined by the two selected gene positions.Then, if the ortho-interchangeable gene sequence contains an even number of genes, the even-numbered genes in the gene fragment are interchanged with the odd-numbered genes adjacent to the left-adjacent gene. If the sequence of the ortho-interchangeable gene contains an odd number of genes, the last gene in the gene fragment remains unchanged, and the odd-numbered genes in the remainder of the gene fragment are interchanged with the even-numbered genes in its right neighbor.

Empirical Research

Suppose a 15-ton LNG vehicle is shipped from LanZhou to FuXian. The driving route shown in Fig. 2.

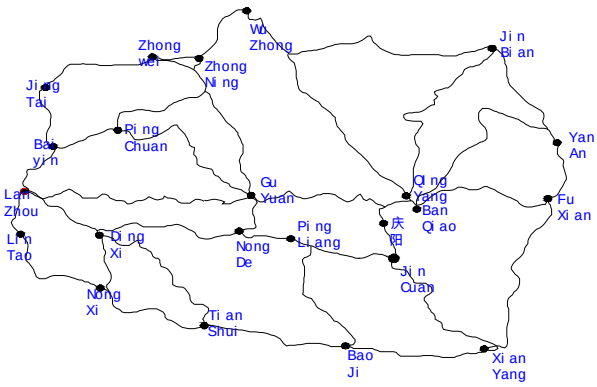

Fig.2 The route of Hazardous Materials

By analyzing the roads network, 23 nodes of the road network map is obtained.Hazardous materials transportation vehicles from the 1st point of departure to reach the destination 23 points. The line segments between nodes are the distance (km) of the links, as shown in Fig.3.

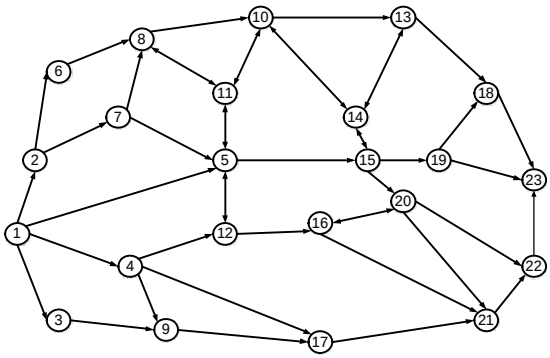

Fig.3 The simplified of road network map

Each path distance (unit: km) and the risk value (unit; person) are obtained by analyzing the data from the model,as shown in Table4.

Table4 The distance and risk value

Section	(Distance, Risk)	Section	(Distance, Risk)	Section	(Distance, Risk)	Section	(Distance, Risk)
1-2	(75,11)	5-7	(190,9)	10-13	(287,58)	17-21	(137,21)
1-3	(71,19)	5-11	(190,36)	10-14	(291,30)	18-19	(195,46)
1-4	(95,14)	5-12	(68,23)	12-16	(63,37)	18-23	(81,32)
1-5	(96,83)	5-15	(43,47)	13-14	(380,31)	19-23	(165,26)
2-6	(63,31)	6-8	(65,38)	13-18	(145,26)	20-21	(178,39)
2-7	(131,12)	7-8	(126,47)	14-15	(56,39)	20-22	(225,21)
3-9	(82,16)	8-10	(59,36)	15-19	(60,34)	21-22	(151,25)
4-9	(77,8)	8-11	(141,31)	15-20	(96,26)	22-23	(254,23)
4-12	(169,15)	9-17	(144,21)	16-20	(71,48)		
4-17	(203,17)	10-11	(93,33)	16-21	(205,23)		

The datas of road section are input to genetic algorithm and solved on VC ++ 6.0 platform.Finally, five pareto solutions (Fig. 4, Table 5) are obtained under the condition that the population size is 100 and the number of iterations is 200.The optimal risk cost is 112 and the economic cost is 364.

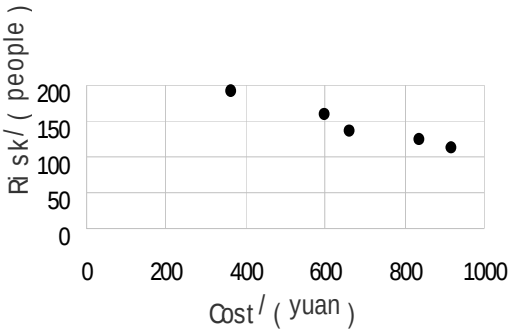

Fig.4 The pareto under population of 100 and iteration of 200

Table5 The pareto under population of 100 and iteration of 200

Travel paths	Risk cost/(people)	Economic cost/(yuan)
1-4-9-17-21-22-23	112	918
1-5-15-19-23	190	364
1-4-12-5-15-19-23	159	600
1-2-7-5-15-19-23	135	664
1-3-9-17-21-22-23	125	839

From Fig.4 and Table 5, the optimal risk cost is 112 when the travel route is 1-4-9-17-21-22-23,but the economic cost is the highest among the 5 solutions.The optimal economic cost is 364 when the travel route is 1-5-15-19-23,and the risk cost is the highest among the 5 solutions.On the whole, with the decrease of the risk cost, the economic cost shows a gradual upward trend.Therefore, the choose of the optimal transportation route for hazardous material and balance the cost of risk and economic cost is a practical problem,decision-makers need to make the choice according to the actual conditions, their preferences and so on.

Conclusions

Due to the great ambiguity and randomness of terrorist attacks, in this paper, A more reasonable routes evaluation model under the background of terrorist attacks is obtained through quantitative evaluation by combing threats, vulnerabilities and consequences, and economic cost factors are taken into account.In the model, the threat factors are obtained by the classification and evaluation method. The vulnerable factors are expressed as the possibility of being attacked by road sections, and the consequence factors are used to predict the casualty situation.Then, the model is solved by using the multi-objective genetic algorithm with LNG transportation as an example.Finally, a optimal solution of transportation routes for hazardous materials vehicles are obtained. The study results show that the model method and algorithm in this paper can provide some efficient and reasonable decision supports for decision-makers to choose a safety and economic transportation routes for hazardous materials vehicles.

Acknowledgements

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