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Path Optimization of Hazardous Chemicals Transportation Based on Improved NSGA-II Algorithm

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Different stakeholders have different concerns about the transportation of hazardous chemicals. Multi-objective optimization comprehensively considering transportation risks and transportation interests is the primary demand for the transportation of hazardous chemicals. For this, this paper studies the multi-objective combinatorial optimization problem of multiple hazardous chemicals in the same distribution range of transportation network. Firstly, according to the transportation characteristics of hazardous chemicals, the calculation methods of distribution paths in terms of physical dissimilarity and spatial dissimilarity were proposed. Then, a multi-objective optimization model of hazardous chemicals transportation was established with transportation risk, cost and time as optimization objectives, and the model was solved by the improved NSGA-II algorithm. Finally, the feasibility of the optimization method was verified in practical examples. The research results show that the proper increase of transportation risk value can greatly reduce the transportation cost and transportation time. When the calculation results only emphasize the optimal risk, there exist a large number of shared road sections in different transportation planning paths, so that the transportation risks are concentrated; however, after setting the threshold and increasing the constraint conditions, the phenomenon of the shared road section is significantly reduced, and the distribution of the hazardous chemicals transportation risks is relatively dispersed, to further control the potential hazards. This shall provide a theoretical reference for the risk regulation of hazardous chemicals transportation and the cost control of carriers.

1. Introduction

With the rapid development of modern industry, a large number of hazardous chemicals have been applied more widely, and the transportation volume has also increased significantly (Zou and Zhang, 2011). Hazardous chemicals may cause serious accidents such as leakage, explosion, burning and chemical pollution during transportation, and such accidents have the characteristics of low probability of occurrence and high risk of accidents (Zhao, 2007; Han et al., 2014; Jiang and Ying, 2014). Different stakeholders have different concerns about the transportation of hazardous chemicals. For chemical manufacturers and carriers, more consideration is given to the optimal path and minimum cost during the transportation of hazardous chemicals. For supervision departments, their main concerns are the transport risk and risk distribution of hazardous chemicals (Kang, 2011; Marcotte et al., 2009; Zhang et al., 2014). Thus, it’s necessary to construct a multi-objective optimization model that considers both transportation risk and transportation benefits to meet regulatory needs and cost control, which is the primary goal of future hazardous chemicals transportation (Zhou et al., 2013; Samanlioglu, 2013).

In the early transportation planning of dangerous goods, single-variable optimization is often considered, that is, only considering one single condition of optimal path, optimal risk, or optimal cost etc., but the single-variable optimization criterion can no longer meet the needs of all decision makers (Han et al., 2014; Gao, 2011). Based on single optimization criterion, the researchers have proposed a multi-criteria optimization method for hazardous chemicals (Xie, 2018). Lim et al., by taking the transportation cost and transportation risk as optimization objectives, established a path planning model to solve the problem through the Markov model (Lim and Desai, 2010); Fan et al. proposed to ban the transportation of hazardous chemicals in the prosperous areas of the city, and to carry out the path planning of hazardous goods under these conditions

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(Fan et al., 2015); Androutsopoulos et al., (2010) took the shortest transport distance and minimum risk as the optimization objectives for transportation scheduling of hazardous chemicals; Das et al., (2012) and Pradhananga et al., (2014) used the heuristic algorithm to solve the transportation path of hazardous chemicals, and the established model innovatively considered the constraints with time window; Pamucar et al., (2016) proposed an adaptive neural network model for optimal design of dangerous goods transport in urban environments. Most of the above studies only consider the distribution of transportation risks between different regions. However, when there are many transportation tasks, the same road section may also be the shared one of multiple planning paths. The dissimilarity of the same road section on different planning paths provides a new research idea for decentralization of transportation risks and optimization of the transportation path. But now there has been no related studies yet (Chang et al., 2005).
In view of the insufficient research above, based on the risk distribution of hazardous chemicals in the transportation process, this paper proposes a multi-objective optimization model that comprehensively considers the transportation risks, transportation costs and transportation time of hazardous chemicals, and uses the improved NSGA-II algorithm to solve the model. Finally, the feasibility of the optimization method was verified by practical examples. This shall provide a theoretical reference for the risk regulation of hazardous chemicals transportation and the cost control of carriers.

2. Description of hazardous chemicals transportation problems

It’s assumed that hazardous chemicals are transported within the planned road network G=(V, E), where V is the set of distribution points, i, j, k represent individual distribution points within V, E is a set of non-directional road sections; A is a set of directional road segment; b indicates the transportation marking number.
Firstly, the traditional risk measurement model was used to evaluate the transportation of hazardous chemicals. Let the probability of accident be p_{ij}, the radius of accident impact be λ_{ij}; the population density within the radius of accident impact be q_{ij}, then the risk value of hazardous chemicals transportation on the path (i, j) can be expressed as:

$$r_{ij}^{k} = \pi\left(\lambda_k\right)^2 q_{ij} p_{ij} \tag{1}$$

Cumulative transportation risk is given as:

$$R = \sum_{b=1}^{B} \sum_{k \in K} \sum_{(i,j) \in A} r_{ij}^{k} x_{ij}^{b} y_{k}^{b} \tag{2}$$

Hazardous chemicals transport vehicles should select different routes from the previous transport during each transport, so as to disperse the risks to the greatest extent, and the common road sections of different routes should be as few as possible. To define the concept of “path dissimilarity”, given that the vehicle transports k_1 type of hazardous chemicals for the b_1-th time, and transport path is p_{b1}; the vehicle transports k_2 type of hazardous chemicals for the b_2-th time, and transport path is p_{b2}, then the dissimilarity function D_1between the two is given as:

$$D_1\left(p_{b_1}, p_{b_2}\right) = 1 - \frac{1}{2}\left[\frac{\Upsilon\left(p_{b_1} \cap p_{b_2}, k_1\right)}{\Upsilon\left(p_{b_1}, k_1\right)} + \frac{\Upsilon\left(p_{b_1} \cap p_{b_2}, k_2\right)}{\Upsilon\left(p_{b_2}, k_2\right)}\right] \tag{3}$$

At $p_{b1}= p_{b2}$, D1 = 0; when there is no shared section between p_{b1} and pb2, D1 = 1. According to formula 3, the closer the D1 value is to 1, the better the dissimilarity of the two transport paths.
“space dissimilarity” D2 was defined. D2 indicates the dispersion degree of hazardous chemicals transport risks, and it’s expressed as:

$$D_2\left(p_{b_1}, p_{b_2}\right) = \frac{1}{2}\left\{\frac{\sum_{(i_{b_1}, j_{b_1}) \in p_{b_1}} d\left[\left(i_{b_1}, j_{b_1}\right), p_{b_2}\right]}{\left|p_{b_1}\right|} + \frac{\sum_{(i_{b_2}, j_{b_2}) \in p_{b_2}} d\left[\left(i_{b_2}, j_{b_2}\right), p_{b_1}\right]}{\left|p_{b_2}\right|}\right\} \tag{4}$$

d is the spatial distance function, which is expressed as:

$$d\left[\left(i_{b_1}, j_{b_1}\right), p_{b_2}\right] = \min\left\{\Pi\left[\left(i_{b_1}, j_{b_1}\right), \left(i_{b_2}, j_{b_2}\right)\right] \middle| \forall\left(i_{b_2}, j_{b_2}\right) \in p_{b_2}\right\} \tag{5}$$

3. Model solving algorithm design

The classical NSGA-II algorithm in the meta-heuristic algorithm has been proved by many researches to be one of the most effective methods for multi-objective optimization algorithms. This paper improves the traditional NSGA-II algorithm and applies it to the solution of the model.

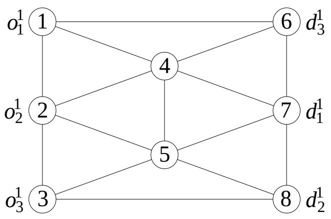


Figure 1: Transport network

The improved NSGA-II algorithm was explained by taking the transport network in Fig.1 as an example. The chromosome in the algorithm is coded by the weight matrix method based on node priority, the coding length is n, and the weight matrix is B×n structure. It's assumed that three transportation operations are performed for the same hazardous chemical in the whole transportation road network, and different distribution points are represented by o_b^k and d_b^k. Fig.2 shows the chromosome coding structure of each distribution point, in which the numbers indicate the priority value.

Node coding	1	2	3	4	5	6	7	8
b=1	1	4	6	5	8	2	7	3
b=2	6	2	4	7	8	5	1	3
b=3	3	8	6	4	7	1	5	2

Figure 2: Chromosome coding structure

Node coding	1	2	3	4	5	6	7	8
b=1	1	4	6	5	8	2	7	3
b=2	6	2	4	7	8	5	1	3
b=3	3	8	6	4	7	1	5	2

Father 1

Node coding	1	2	3	4	5	6	7	8
b=1	7	3	2	5	3	1	4	8
b=2	5	7	1	6	7	2	4	3
b=3	2	1	8	3	6	5	4	7

Father 2

After cross operation

Node coding	1	2	3	4	5	6	7	8
b=1	1	4	6	5	8	2	7	3
b=2	5	7	1	6	7	2	4	3
b=3	3	8	6	4	7	1	5	2

Child 1

Node coding	1	2	3	4	5	6	7	8
b=1	7	3	2	5	3	1	4	8
b=2	6	2	4	7	8	5	1	3
b=3	2	1	8	3	6	5	4	7

Child 2

Figure 3: Gene exchange

The initial population was constructed and initialized. Then, the non-dominated method was used to separate the different isolations within the population, and calculate the crowded distance $c(z_s)$ of individuals in each hierarchy.

Cross-operation and mutation operations were sequentially performed on the parent chromosome. In this paper, two cross operations of gene exchange and gene recombination were designed. In gene exchange process, two chromosomes were randomly selected from the progeny population to generate γ different transport serial numbers, and then these corresponding γ serial numbers were exchanged (Fig.3). The specific process of genetic recombination is shown in Fig.4.

$$c(z_s) = \frac{1}{H}\sum_{h=1}^{H}\left|\varphi_{s+1}^{h} - \varphi_{s-1}^{h}\right| \tag{6}$$

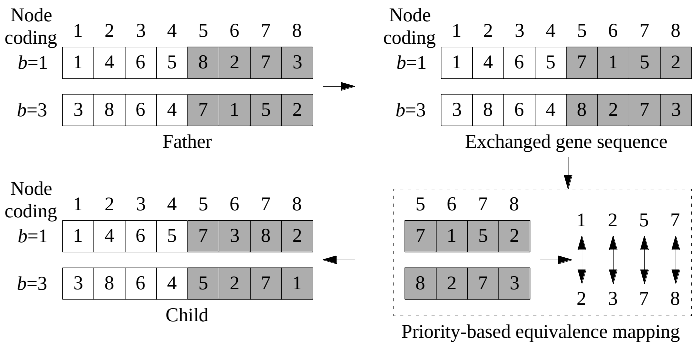
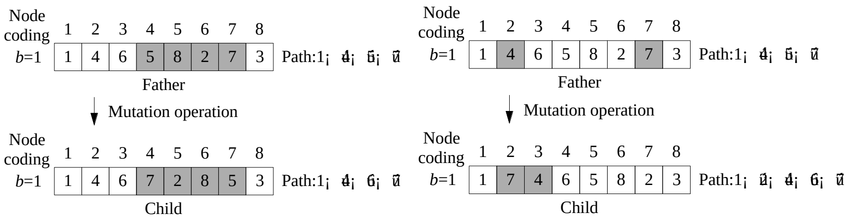


Figure 4: Gene recombination



(a) Local inversion (b) Random insertion

Figure 5: Gene mutation

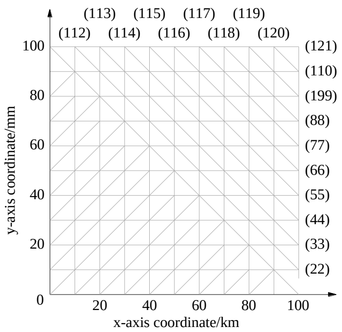


Figure 6: Schematic diagram of constructed network structure

Fig.5 shows the process of gene mutation. In this paper, local inversion and random insertion were adopted to perform genetic mutation.

4. Example verification and result analysis

A numerical example was established to verify the feasibility of the proposed model. Fig.6 shows the network structure of the example. It consists of 121 distribution points and 320 unoriented road sections. The coordinates of each distribution point can be observed in Fig.6. It's assumed that the initial population size is 350, the maximum number of iterations is 300, and the crossover probability and mutation probability are 0.8 and 0.5, respectively.
Table 1 lists the obtained optimal values of the three objective functions without any constraints, where $f_1^{**}(x)$, $f_2^*(x)$, and $f_3^*(x)$ corresponding to z* represent the optimal values of this objective function respectively, and $f_1(x)$, $f_2(x)$, and $f_3(x)$, represents the value obtained under the constraint of the optimal value.
It can be seen from Table 1 that without any constraints, the optimization results of the regulatory authorities and the carriers vary greatly. When minimizing the risk, the $f_2(x)$ value is increased by approximately 30% compared to $f_2^*(x)$, and the $f_3(x)$ value is increased by approximately 27% over $f_3^*(x)$; when minimizing the cost, the $f_1(x)$ value is increased by approximately 135% over $f_1^*(x)$; when minimizing the transport time, the

$f_1(x)$value is increased by approximately 140% over $f_1^*(x)$. Therefore, blind pursuit of the minimum risk will greatly increase the cost of the carriers, and the regulatory authorities need to set the risk threshold under the premise of risk control, to ensure the optimization results in equilibrium state.

Table 1: Optimal values of the three objective functions without any constraints

z^*	$f_1(x)$	$f_2(x)$	$f_3(x)$	D_1	D_2
$f_1^*(x)$	3.24	3 160.56	17.70	0.49	4.22
$f_2^*(x)$	7.45	2 438.13	14.41	0.76	6.88
$f_3^*(x)$	7.52	2 511.85	13.96	0.84	4.17

Table 2: Objective function value under optimal risk conditions

Solution	$f_1(x)$	$f_2(x)$	$f_3(x)$	D_1	D_2
F_1	3.70	2 881.00	16.43	0.89	5.62
F_2	3.68	2 863.18	16.34	0.98	5.62
F_3	3.59	2 850.25	16.33	0.98	5.62

Table 3: Objective function value under optimal cost conditions

Solution	$f_1(x)$	$f_2(x)$	$f_3(x)$	D_1	D_2
F_1	6.23	2 474.46	14.41	1.02	8.70
F_2	6.12	2 480.90	14.66	0.99	7.96
F_3	6.09	2 481.35	14.27	1.02	9.48

Table 4: Objective function value under optimal transport time conditions

Solution	$f_1(x)$	$f_2(x)$	$f_3(x)$	D_1	D_2
F_1	6.22	2 512.36	14.20	1.00	9.24
F_2	6.20	2 508.74	14.19	1.00	8.63
F_3	5.79	2 527.88	14.21	1.00	9.45

Table 2, 3, and 4 respectively list the optimal solution of the multi-objective function obtained by using the algorithm proposed in this paper under the optimal conditions of risk, cost and transportation time. F_1-F_3 in the table indicates the first three optimal solutions.

It can be seen from the table that as the optimal risk value f1(x) increases, the transportation cost and transportation time decrease. Therefore, appropriately increasing the transportation risk under the premise of risk control can significantly reduce the transportation cost and transportation time; When the calculation results only emphasize the risk optimal, there exist a large number of shared road sections in different transportation planning paths, so that the transportation risks are concentrated. After setting the risk threshold and increasing the constraint conditions, the phenomenon of shared road sections is significantly reduced, making the distribution of hazardous chemicals transportation risks is relatively dispersed and further controlling the potential hazards.

5. Conclusions

Taking both the transportation risks of hazardous chemicals and the transportation interests of carriers into consideration, this paper studies the multi-objective combinatorial optimization problem of multiple hazardous chemicals in the same distribution range of transportation network. Firstly, according to the transportation characteristics of hazardous chemicals, the calculation methods of distribution routes for physical dissimilarity and spatial dissimilarity were proposed. Then, multi-objective optimization model of hazardous chemicals transportation was established by taking transportation risk, transportation cost and transportation time as optimization objectives, and the model was solved by the improved NSGA-II algorithm. Finally, the feasibility of the optimization method was verified by practical examples. The research results show that the appropriate increase of transportation risk value can greatly reduce the transportation cost and transportation time. When the calculation results only emphasize the optimal risk, there exist a large number of shared road sections in different transportation planning paths, so that the transportation risks are concentrated. After setting the risk threshold and increasing the constraint conditions, the phenomenon of shared road sections is significantly reduced, making the distribution of hazardous chemicals transportation risks is relatively dispersed and further controlling the potential hazards.

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