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Route Optimization of Hazardous Chemical Logistics Transportation Based on Improved Ant Colony Algorithm

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The construction of safe and efficient logistics transportation routes for hazardous chemicals can effectively ensure the safety of personnel and property. In this paper, the transportation distance and transportation risk in the distribution process of hazardous chemicals are taken as the optimization objectives. Besides, considering the risk impact of the hazardous chemicals' weight change on the distribution route planning, a bi-objective optimization model that minimizes the distribution distance and transportation risk was constructed. Then, the traditional ant colony algorithm was improved by selecting the non-dominated solutions from the single solution results of the ant colony algorithm, and the transportation risk and transportation distance objective of the selected optimal non-dominated solution were extracted, to calculate the weights of the two and integrate them into the update process of overall calculation information. Finally, the simulation test method was used to compare and analyse the difference in route planning between the traditional risk measurement model and the improved one of hazardous chemicals transportation. The experimental results show that the improved risk measurement model can better distinguish the route with less risk. It also has stronger algorithmic optimization abilities and sensitivity to population exposures, so as to provide a variety of planning routes for personnel and meet the diverse needs of transport distances and transportation risks.

1. Introduction

According to statistics, in 2017, the world's transportation volume of hazardous chemicals exceeded 4 billion tons, and most of them were transported by road. During the transportation course, hazardous chemicals are easily exposed to serious conditions such as high loading capacity of vehicles and complex transportation environment etc. Due to their inflammable and explosive characteristics, it can cause serious social harm in case of any accident in the transportation process (Zou and Zhang, 2011; Leonelli et al., 2000). In recent years, there has been an increasing demand for the use of hazardous chemicals. It is of great practical significance to study the rational transportation of hazardous chemicals and construct safe and efficient logistics routes for hazardous chemicals (Conca et al., 2016).

The vehicle distribution path problem for the transportation of hazardous chemicals can be seen as a special type of vehicle routing problem (VRP) (Wei et al., 2015; Boyer et al., 2013). Researchers have also conducted a number of studies on the transport problem of hazardous chemicals. Kara and Trev proposed the concept of "population exposure" to study the influence range of hazardous chemical leakage on the surrounding people (Kara and Verter, 2004; Trev et al., 2007); Verma proposed a "Gaussian plume model" and applied it to the calculation of the radiation range for the leakage of hazardous chemicals (Verma and Verter, 2007; Verma et al., 2011). In the studies above, it's all assumed that the quality of hazardous chemicals remains constant during vehicle transportation. However, under actual conditions, the weight of on-board chemicals is constantly changing when the vehicle performs distribution operations at multiple distribution points. At present, some literatures consider the weight change of hazardous chemicals on the same distribution route, but ignoring the difference in weight changes of vehicles on different distribution routes. This deficiency shall seriously affect the route optimization ability of the constructed model (Pradhananga et al., 2010; Pradhananga et al., 2014).

For the bi-objective or multi-objective optimization problems of vehicle distribution route (e.g., the bi-objective of transportation cost and transportation risk, or that of transportation distance and transportation risk etc.)

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(Samanlioglu, 2013; Xie et al., 2012), the existing research mostly adopts the weighted approach of the two optimization objectives according to their respective weight ratios, but this approach is in lack of exact theoretical basis due to the application of the empirical method (Yu and Yang, 2011; Ding et al., 2012). In recent years, non-dominated solution algorithms have been applied to the VRP problems of multi-objective optimization, such as genetic algorithms, particle swarm optimization, and ant colony algorithms etc. (Aziza and Krichen, 2018; Bian et al., 2012).
In this paper, the transportation distance and transportation risk in the distribution process of hazardous chemicals are taken as the optimization objectives. Besides, considering the risk impact of the hazardous chemicals' weight change on the distribution route planning, a bi-objective optimization model that minimizes the distribution distance and transportation risk was constructed. Then, the traditional ant colony algorithm was improved by selecting the non-dominated solutions for the single solution results of the ant colony algorithm, and the transportation risk and transportation distance objective of the selected optimal non-dominated solution were extracted, to calculate the weights of the two and integrate them into the update process of overall calculation information. The research conclusions can provide a theoretical reference for the safe transportation of hazardous chemicals.

2. Risk measurement for logistics route planning of hazardous chemicals

Traditionally, the transportation risk R_l of the transport vehicle on any route l can be expressed as:

$$R_l = p_l \cdot \varphi_l \tag{1}$$

In formula 1, p_l and φ_l are respectively the occurrence probability of an accident on the vehicle transportation route and the number of persons affected. In case of leakage accident for hazardous chemicals, supposing that the range of the accident point radius λ is the risk area, then the risk measurement model of personnel can be expressed (Figure 1).

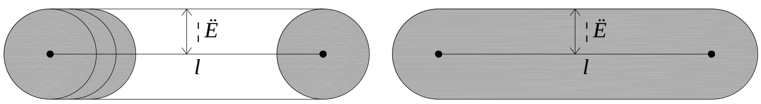


Figure 1: Traditional risk measurement model of personnel

The existing literatures haven't considered the risk changes caused by changes in the weight of hazardous chemicals and changes in the radius of the accident point, which shall lead to the following problems:
(1) The weight of hazardous chemicals in the vehicle is reduced accordingly for each order delivered. When the last order is delivered, there has been no hazardous chemical in the vehicle, i.e., the transportation risk is zero. However, it has been thought in the existing literature that the transportation risk of hazardous chemicals in the whole process of transportation remains unchanged, which shall result in the final calculated value being high;
(2) When the distribution point is unchanged and the distribution planning route changes, the overall transportation risk of hazardous chemicals also varies, but the traditional risk measurement model does not consider such factors.
Therefore, in view of the above defects, this paper improves the personnel risk measurement model of hazardous chemicals shown in Figure 1. Figure 2 depicts the improved model.

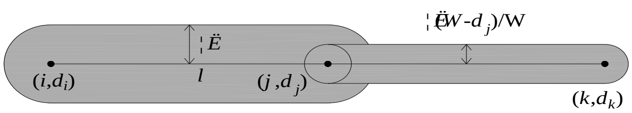


Figure 2: Improved risk measurement model of personnel

A practical example was used to explain the improved personnel risk measurement model, as shown in Figure 3, where A is the storage warehouse, and B, C, and D are distribution points of goods, and the probability and risk during transportation are represented on each side. When λ is constant, it can be calculated that the optimal distribution route is A-D-C-B-A or A-B-C-D-A (Figure 3(a)); when λ decreases with the change of cargo weight, the optimal delivery route at this time is A-B-C-B-A, A-D-C-D-A. This is because the risk on the A-D route is greatly increased, and the model eliminates it from the optimal route by automatic identification. Therefore, the measurement method with λ variable can ensure more reasonable vehicle route planning.

3. Model establishment and algorithm design

Supposing that the model's decision variables are x_{ij}^{lk} and y_i^{lk}, when the transport vehicle moves from the distribution point i to the delivery point j, and (i, j) is the kth side of the lth planned route, then x_{ij}^{lk}=1, otherwise x_{ij}^{lk}=0; when the i-th distribution point is on the lth planned route and also the kth to-be-distributed point on the route, y_i^{lk}=1, otherwise y_i^{lk}=0.
The total demand for hazardous chemicals on the l-th planned route is expressed as:

$$\sum_{m\in N}\sum_{k} d_m y_m^{lk} \tag{2}$$

d_m is the demand for hazardous chemicals at the m-th point to be delivered. The transport volume of chemicals on the kth side is given as:

$$\sum_{n\geq k}\sum_{m\in N} d_m y_m^{ln} \tag{3}$$

When (i, j) is the kth side of the lth planned route, the transport volume of hazardous chemicals is given as:

$$\sum_{m\in N}\sum_{n\geq k} d_m y_m^{ln} x_{ij}^{lk} \tag{4}$$

When (i, j) is on the lth planned route, the transport volume of hazardous chemicals at this time is given as:

$$\sum_{k}\sum_{m\in N}\sum_{n\geq k} d_m y_m^{ln} x_{ij}^{lk} \tag{5}$$

Based on formula 2-5, the volume of hazardous chemicals transported on (i, j) is expressed as:

$$\sum_{l\in L}\sum_{k}\sum_{m\in N}\sum_{n\geq k} d_m y_m^{ln} x_{ij}^{lk} \tag{6}$$

The corresponding transportation risk is given as:

$$r_{ij} = \sum_{l\in L}\sum_{k}\sum_{m\in N}\sum_{n\geq k} d_m y_m^{ln} x_{ij}^{lk} p_{ij}\varphi_{ij} / W \tag{7}$$

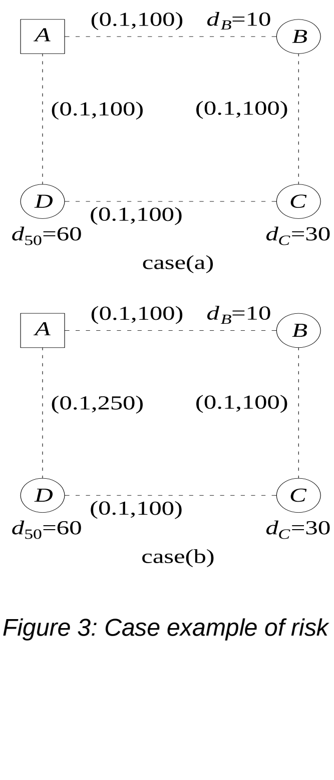


Figure 3: Case example of risk measurement model

Based on the distribution route and transportation risk of hazardous chemicals, the relevant optimization model is established.

$$\min Z_1 = \sum_{i \in N} \sum_{j \in N} \sum_{l \in L} \sum_{k} c_{ij} x_{ij}^{lk} \tag{8}$$

$$\min Z_2 = \sum_{i \in N} \sum_{j \in N} \sum_{l \in L} \sum_{k} \sum_{m \in N} \sum_{n \geq k} d_m y_m^{ln} x_{ij}^{lk} p_{ij} \varphi_{ij} \big/ W \tag{9}$$

$$\sum_{i \neq 0, i \in N} \sum_{k} d_i y_i^{lk} \leq W, \quad l \in L \tag{10}$$

$$\sum_{k} \sum_{i \neq 0, i \in N} x_{0i}^{lk} = 1, \quad l \in L \tag{11}$$

$$\sum_{k} \sum_{i \neq 0, i \in N} x_{i0}^{lk} = 1, \quad l \in L \tag{12}$$

$$\sum_{i \in N} x_{ij}^{lk} - \sum_{p \in N} x_{jp}^{lk} = 0, \quad j \neq i, j \in N \tag{13}$$

$$\sum_{l \in L} \sum_{k} y_i^{lk} = 1, \quad i \neq 0, i \in N \tag{14}$$

$$\sum_{j \in N} x_{ij}^{lk} = y_i^{lk}, \quad i \neq 0, i \in N \tag{15}$$

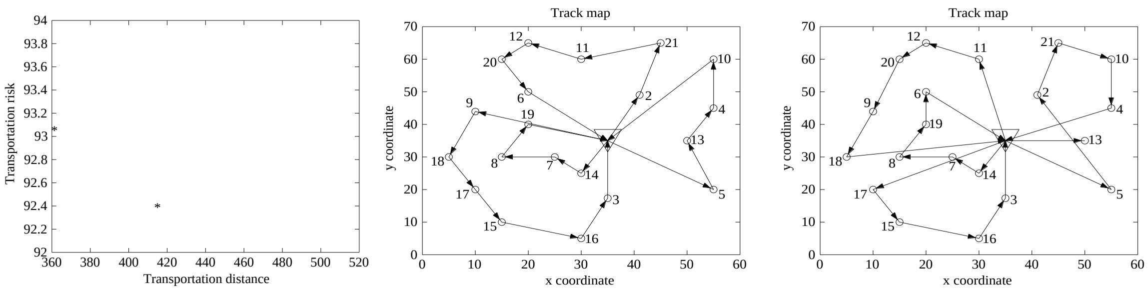
Formulas 10-15 are the constraints for optimization objectives, where formula 10 is the maximum cargo capacity for single shipment; formulas 11 and 12 are the constraints for the delivery vehicle to be distributed according to the planned route; formulas 13 and 14 indicate the one-to-one correspondence relationship between to-be-delivered distribution point and delivery vehicles.

According to the above formula and description, the calculation steps of the improved ant colony algorithm proposed in this paper are as follows:

(a) Set the number of ant colonies, and the maximum number of iterations; then, initialize the non-dominated solution set and tabu table of the ant colony;

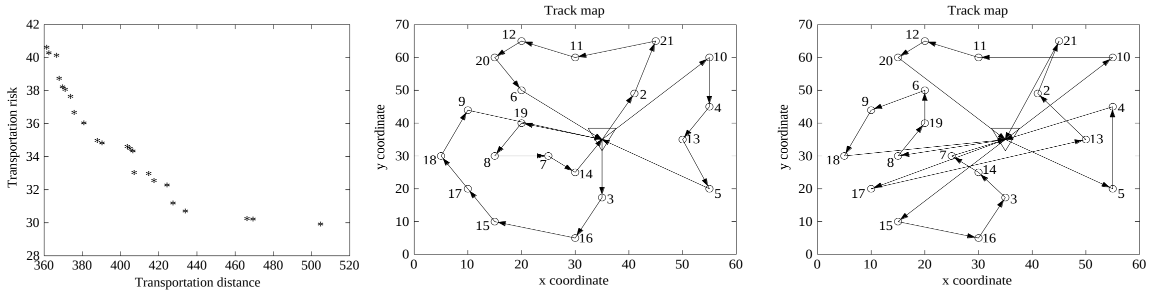
(b) Given that v=$depot_1$, and the ant starts from the ith distribution point, the next distribution point j is selected according to formula 17; when the demand of the distribution point j meets the capacity requirement of delivery vehicle, then i=j, and the system records the delivery route from i to j; otherwise, the ant continues to search for the next distribution point;

(c) When all the distribution points do not meet the vehicle capacity requirements, the ants return to the warehouse and record the route from point i to the warehouse. At this time, the single route planning is completed. Then, the route planning is re-performed for M times, and the non-dominated solution is deleted from the obtained solution sets. Finally, the pheromone is updated using formula 18 until the optimal distribution route is selected.



(a) Non-dominated solution *(b) The shortest distance planning* *(c) Minimum risk planning*

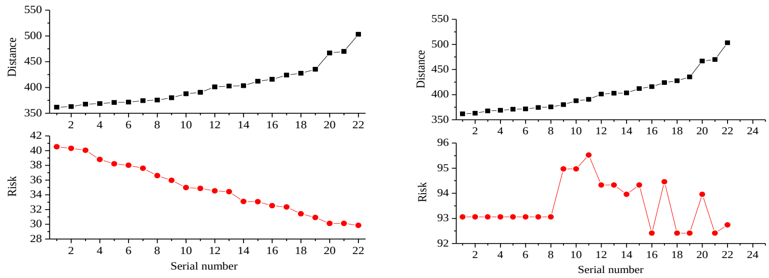
Figure 4: Non-dominated solution and route planning of traditional risk measurement model



(a) Non-dominated solution *(b) The shortest distance planning* *(c) Minimum risk planning*

Figure 5: Non-dominated solution and route planning of improved risk measurement model

4. Test results and analysis



(a) Traditional risk measurement model *(b) Improved risk measurement model*

Figure 6: The shortest distance and minimum risk obtained by traditional and improved risk measurement models

The simulation test was conducted to verify the feasibility of this model. In the test, 1 warehouse and 20 distribution points were set, the p_l and φ_l values were randomly generated, the number of ants was set to 50, the limit capacity of the vehicle was set to 70, and the maximum number of iterations was 12,000. The traditional risk measurement model and the improved measurement model proposed in this paper were used for route planning, respectively. Figure 4 and 5 show their non-dominated solutions and planning routes respectively.

Comparing Figure 4(a) with Figure 5(a), it can be seen that more non-dominated solutions can be obtained by using the improved risk measurement model, and the planning distribution routes by the improved model include the routes planned by the traditional model, which indicates that the improved risk measurement model can be used to compare and analyse the routes that have been planned and then make screening, so as to obtain a route more suitable for VRP problems finally.

By comparison of Figure 4(b) with Figure 5(b), the same shortest transportation route plan is obtained by using the traditional model and the improved model, but the order of the delivery vehicles to access the distribution points vary. According to the calculation results, when following the route planned in Figure 4(b), the overall retained personnel risk on the entire route is 440,000 person-times; following the route planned in Figure 5(b), the overall retained personnel risk on the entire route is 400,000 person-times, indicating that the improved model can better identify the less risky route and have stronger algorithm optimization ability. Comparing Figure 4(c) with Figure 5(c), the number of vehicles distributed under the minimum risk condition is 5; when there are more vehicles, the vehicle capacity constraint is also reduced, which can resist the transportation risk.

Figure 6 shows the shortest distance and minimum risk information obtained by the traditional and the improved measurement models. It can be seen from the figure that 20 routes in the traditional risk measurement model shall be eliminated, in which route 2-15 can be dominated by route 1, and route 17 and 18 can be dominated by route 16. The elimination of the non-dominated route indicates that the traditional risk measurement model is roughly planned in an unreasonable measuring method, while the improved model can effectively identify the potential risks on different routes and provide diversified planning routes for personnel selection, satisfying the diverse needs of the transportation distance and transportation risks.

5. Conclusions

In this paper, taking the transportation distance and transportation risk in the distribution process of hazardous chemicals as the optimization targets, a bi-objective optimization model that minimizes the distribution distance and transportation risk was constructed. The simulation test was used to compare and analyse the differences in route planning between the traditional and improved risk measurement models. The conclusions are as follows:

(1) The non-dominated solutions were selected from the single solution result of the ant colony algorithm. The transportation risk and transportation distance objectives of the optimal non-dominated solution were extracted, to calculate the weights of the two and include them in the update process of overall calculation information.

(2) The improved risk measurement model can better identify the less risky route. It has stronger algorithm optimization ability and sensitivity to the number of population exposures, so as to provide a variety of planning routes for personnel selection and meet the diverse needs of transportation distance and the transportation risks.

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