Study on multimodal network expansion for hazardous materials based on disruption

Lutong Yu, Liying Song*

School of Traffic and Transportation, Beijing Jiaotong University, Beijing, 100044, China

*Corresponding author’s e-mail: lysong@bjtu.edu.cn

Abstract: This paper studies the multimodal network expansion problem for hazardous materials. In this study, the transportation characteristics of hazardous materials and disruption are considered, the mixed integer probability robust model is established with risk and cost as the objective. A numerical case is solved by CPLEX, and the decision of network expansion and flow distribution is obtained. Through the comparison between the robust model and the traditional model, it is proved that the robust model can complete the transport of hazardous materials in the network with lower cost-risk. The paper also provides advice to decision-makers with different risk preferences through the Pareto frontier.

1. Introduction
In recent years, China has issued some policies to promote the development of multimodal transport, hazardous materials as the main raw materials of modern industry, they are in great demand for transportation. According to China National Logistics and Purchasing Federation’s Dangerous Chemicals Logistics Branch, the volume of hazardous material transported in China has exceeded 1.8 billion tons in 2018, but only 200 million tons of hazardous materials in multimodal transportation. Most of the existing multimodal transportation networks transport ordinary goods, and the terminal of hazardous materials is insufficient. Therefore, it is of great significance to study the expansion of the multimodal transportation network of hazardous materials.

At present, the researches of domestic and foreign scholars on the optimization of multimodal transport network mainly focus on general goods [1-4], but the researches on hazardous materials are few. The existing research on the multimodal transportation network of hazardous materials is mainly aimed at the terminal locating, so we review the most relevant literature. Hai [5] established the evaluation index system of hazardous materials terminal configuration, and established the comprehensive evaluation method of railway terminal opening through expert consultation and analytic hierarchy process, which can provide the decision basis in the decision making of expansion, reconstruction and cancellation of railway terminal with hazardous materials. Xiao [6] analyzed the factors affecting the locating of hazardous materials terminals, established a multi-objective 0-1 mixed integer linear programming model for the locating of hazardous materials terminal, and taken Chengdu as an example to solve the problem. Wang [7] considered the master-subordinate hierarchical decision-making relationship between railway decision-making departments and hazardous materials transportation customers, established a two-layer programming model with the maximization of simultaneous volume with minimum environmental risk as the upper target and the minimization of customer transportation cost as the lower target, and designed a heuristic algorithm to solve it. Xie [8] studied the location problem of multimodal transport facilities for hazardous materials, established a...
two-objective nonlinear programming model, and transformed it into a linear programming model through simplification, and then solved it through the objective weighting method. Jiang [9] simplified the model based on Xie and solved the problem by using Lingo directly. Xin [10] considered the node time, established the multimodal transport location-route model, and solved it by using Dijkstra improved algorithm and O-D matrix search algorithm. Huang [11] considered a variety of hazardous materials and established a multi-commodity flow model based on point-arc network with the goal of minimum system cost and minimum systemic risk. Three multi-objective solving methods were respectively used to solve the problem, proving that the augmented e constraint algorithm was more suitable for the solution of this problem. Zhao [12] considered that hazardous materials would influence each other and thus led to the change of transfer time, proposed a prioritized queuing rule to calculate queuing time, and established 0-1 integer programming, and used CPLEX to solve the problem. Li [13] took the total cost and risk cost as the target to establish the multi-period robustness probability model, and used simulated annealing algorithm to solve the problem. He also compared the multi-period planning method with the single-period planning method, and proved that the multi-period network planning method is superior to the single-period planning.

The above literature has the following problems: 1) it fails to consider the restriction that only the same terminals can transport hazardous materials to each other; 2) it lacks research on disruption risk; and 3) it fails to consider capacity changes of existing terminals.

2. Problem description and Model

2.1 Problem description
In this paper, the multi-modal transport network is composed of cities, multi-modal terminals, highways and railways. Different multi-modal transport terminals can transfer different types of hazardous materials. It is worth mentioning that multi-modal transport terminals and path are at risk of disruption due to natural disasters or man-made accidents. In this network, different kinds of hazardous materials are transported between different OD pairs. When railway transportation is adopted, both the starting and ending stations of the railway must be capable of transporting such goods. Government agencies typically invest in intermodal networks, creating new terminals and expand existing terminals to address disruption risks and increase the multimodal transportation of hazardous materials, but these investments may be limited. In this paper, the following assumptions are made: terminal and link after the disruption, completely lost capacity; the probability of disruption of the terminal is known.

2.2 Mathematical model

2.2.1 Symbol description
a) Set
- $N$: Set of node, $N_2$: Set of existing terminals, $N_3$: Set of candidate terminals, $A$: Set of arcs, $A_1$: Set of roads, $A_2$: Set of rails, $K$: Set of kinds of goods, $W$: Set of OD pairs, $S$: Set of disruption scenarios, $O$: Set of origins, $D$: Set of destinations,

b) Parameter
- $d_{ij}$: Distance from $i$ to $j$, $(i, j) \in A$, $C_j$: Cost of building candidate terminal, $c_{ij}$: Unit capacity expansion cost, $c_r$: Unit transportation cost of road, $c_r$: Unit transportation cost of rail, $c_{ij}$: Unit fixed cost of rail, $c_r$: Unit transfer cost, $C_y$: Transportation cost, $C_t$: transfer cost, $r$: Risk radius in transportation, $r_1$: Risk radius in transfer, $P_s$: Probability of $s \in S$ scenario, $P$: Accident probability, $P_{ij}$: Accident probability of arc $(i, j) \in A$, $P_i$: Accident probability of node $i \in N$, $\rho$: Population density, $\rho_i$: Population density of node $i \in N$, $g$: (1, if node $i$ is disruption; 0, otherwise), $\alpha^k$: Risk coefficient of type $k \in K$ goods, $b^k$: Cost coefficient of type $k \in K$ goods, $V_{ij}^{b,k}$:
Initial capacity of type $k \in K$ goods in terminal $i \in N$, $V^0_{ij}$: Initial capacity of type $k \in K$ goods in terminal $(i,j) \in A$, $V^d_{ij}$: Current capacity of arc $(i,j) \in A$, $V^i_{ik}$: Current capacity of type $k \in K$ goods in terminal $i \in N$, $d^i_k$: The type $k$ demand of OD pair $w \in W$.

c) Decision variables

$F^i_k$: 1, if terminal $i$ is opened to transfer type $k$ goods; 0, otherwise.

$E^i_k$: Amount of type $k \in K$ goods is expanded in terminal $i \in N$

$X^w_{ij}$: Amount of type $k \in K$ goods of freight flow for OD pair $w \in W$ on arc $(i,j) \in A$ under scenario $s \in S$.

2.2.2 Model

The cost in this question is divided into two parts: 1) The cost of network expansion: the cost of new terminals and the cost of expansion of existing terminals; 2) Cost of flow allocating: transportation cost and transfer cost. The risks in the network include transportation risk and transfer risk. The costs and risks involved are formulated as follows.

$$
\begin{align*}
C_y &= \begin{cases} 
X^w_{ij} [d^i_k] & \forall ij \in A, \quad \forall w \in W, k \in K \\
X^w_{ij} [d^i_k + c_{ij}] & \forall ij \in A 
\end{cases} \quad (1) \\
C_i &= \sum_{k \in K} X^w_{ih} [c_{ih}] \quad \forall i \in N_s, s \in S, k \in K, w \in W \quad (2) \\
R_y &= X^w_{ij} [P_y] [d^i_k] [r_y] \quad \forall s \in S, w \in W, k \in K \quad (3) \\
R_e &= \sum_{k \in K} X^w_{ih} [P_y] [r_i] \quad \forall s \in S, k \in K, w \in W \quad (4)
\end{align*}
$$

Equations (1) - (4) respectively represent the transportation cost, transfer cost, transportation risk and transfer risk.

Objective:

$$
\begin{align*}
\text{Min} C &= \sum_{w \in W} \sum_{k \in K} F^i_k [C_y] + \sum_{w \in W} \sum_{k \in K} E^i_k [C_i] + \sum_{w \in W} \sum_{k \in K} \sum_{v \in N_s} X^w_{ij} [C_v] [a^i] + \sum_{w \in W} \sum_{k \in K} \sum_{s \in S \cup N} X^w_{ij} [C_y] [a^i] \\
\text{Min} R &= \sum_{w \in W} \sum_{k \in K} \sum_{v \in N_s} X^w_{ij} [R_y] [a^i] + \sum_{w \in W} \sum_{k \in K} \sum_{s \in S \cup N} X^w_{ij} [R_e] [a^i] 
\end{align*}
$$

Subject to:

$$
\begin{align*}
\sum_{k \in K} X^w_{hi} - \sum_{j \in N} X^w_{ij} &= \begin{cases} 
-d^w_k & \forall \{i \in O_s \}
\end{cases} \quad \forall i \in N \setminus \{O_s, D_u \}, \forall w \in W, s \in S, k \in K \\
V^i_k &= g^i_j [V^0_{ik} + F^i_k [Q^i] + E^i_k] \quad \forall i \in N, k \in K \\
V^d_{ij} &= g^i_j [V^0_{ij}] \quad \forall ij \in A \\
\sum_{w \in W} \sum_{k \in K} X^w_{hi} &\leq V^i_k \quad \forall i \in N \cap (N_2 \cup N_3), s \in S, k \in K \\
\sum_{k \in K \cap w} X^w_{ij} &\leq V^d_{ij} \quad \forall ij \in A, s \in S, k \in K \\
\sum_{k \in K} F^i_k [C_y] + \sum_{k \in K} E^i_k [C_e] &\leq B \\
E^i_k &\geq 0 \quad \forall i \in N, k \in K \\
X^w_{ij} &\geq 0 \quad \forall ij \in A, k \in K, s \in S, w \in W \\
F^i_k &\in [0,1] \quad \forall i \in N, k \in K
\end{align*}
$$
Equation (5) is the cost objective function, equation (6) is the risk objective function; Equation (7) reflects the conservation of flow; Equation (8) represents the relationship between the current terminal capacity and the initial capacity, which is affected by the disruption state; Equation (9) represents the relationship between the current capacity and the initial capacity of the arc; Equation (10) ensures that the amount of goods passing through the terminal is less than the terminal capacity; Equation (11) ensures that the amount of goods passing through the arc is less than the capacity of the link. Equation (12) ensures that the network expansion cost is less than the investment budget; Equation (13)-(15) define the domains of the decision variables.

2.2.3. Method
We use the linear weighting method to convert the two targets into a single target. The dimensions of the two targets are different, so we need to conduct normalization. In order to avoid the fact that the target is too small for observation, the total target is multiplied by an amplification factor, and the total objective function is shown in (16).

\[
\text{Min} Z = \left( u \frac{C}{C_{\text{min}}} + (1-u) \frac{R}{R_{\text{min}}} \right) M
\]

(16)

\( u \) represents the weighting coefficient, \( C_{\text{min}} \) and \( R_{\text{min}} \) respectively represent the minimum cost and risk obtained by a single target, and \( M \) represents the amplification coefficient.

3. Results and Discussion

3.1 A numerical case
In the numerical case, the multimodal transport network consists of 17 cities, 4 multimodal transport terminals, 3 candidate multimodal transport terminals and two modes (road, rail) of transport. The network is shown in Fig. 1. In this case, three types hazardous materials are transported between four OD pairs (1-14,). Terminal 18 and 20 can transfer all kinds of hazardous materials, while terminal 19 and 21 can only transfer two kinds of hazardous materials. There are two disruption scenarios: terminal 18 and the path connected to it have a 20% probability of disruption; 80% of the network may not disrupt. Data for the network are shown in Table 1.
### 3.2 Results and discussion

#### 3.2.1. Result

By calculation, network expansion decision: terminal 18 transfer capacity of type 1 goods increased by 1000TEU, terminal 20 expanded the capacity of the type 1 goods by 4,000 TEU, terminal 21 expanded the capacity of the type 3 goods by 1,000 TEU, terminal 22 expanded the capacity of the type 3 goods by 4,000 TEU, terminal 21 increased the capacity for transshipment of the type 3 goods by 1,000 TEU. Terminal 22 was opened to transfer type 1 and 2 goods. Terminal 24 was opened to transfer type 2 and 3 goods.

The freight flow allocation strategy is shown in Table 2.

### Table 2 Solution of flow allocation

| OD   | Type of goods | Scenario 1  | Scenario 1  |
|------|---------------|-------------|-------------|
| 1-14 | 1             | 1-3-6-9-11-14 | 1-18-20-21-14 |
|      | 2             | 1-22-20-21-14 | 1-22-20-21-14 |
|      | 3             | 1-3-6-9-11-14 | 1-18-20-21-14 |
| 2-13 | 1             | 2-4-6-10-13   |             |
|      | 2             |              |             |
|      | 3             |              |             |
| 5-17 | 1             | 5-8-10-15-17  |             |
|      | 2             |              |             |
| 7-17 | 2             | 7-24-21-17    |             |
|      | 3             |              |             |

In table 2, the risk has the greatest effect in the flow path of 1-14. In Scenario 2, the freight flow of 1-14 is mainly transferred through terminal 18, however, in Scenario 1, the freight flow cannot pass because terminal 18 is disrupt, but the freight flow can be transported through new terminal 22. Therefore, it is necessary to consider the disruption risk in network planning. Due to the insufficient transfer capacity of terminal 22, the type 1 goods of OD (1-14) are transported by road (1-3-6-9-11-14), which reflects the advantage of separable flow. When the optimal path cannot meet all the freight volume, the freight flow can be divided for the optimal path selection.

#### 3.2.2. The influence of robustness model on network expansion decision

In order to ensure the security of the network, the traditional model usually makes the decision with the worst-case scenario that the disruption is bound to happen. The network expansion decision of the traditional model is as follows: terminal 21 opens the capacity of type 1 goods, the transfer capacity is 2000TEU, terminal 22 is opened for transferring type 1, 2 and 3 goods, and terminal 24 is opened for...
transferring type 2 and 3 goods. The total target is 2124.5, and the total cost is 278200279 Yuan. The overall goal of the robustness model is 2.1061e+03, which is superior to the traditional model. Its cost is 262220000, 5.7% lower than that of the traditional model. This is because the cost of expanding the existing terminal is lower than that of building a new terminal. In the traditional model, terminal 18 is considered as disruption, so expansion is not carried out. Instead, other terminals are chosen to be built. When the gap between capacity expansion and new construction cost is widened, the total cost will be reduced even more.

3.2.3. The influence of risk preference on decision making
Decision makers usually have different risk preferences, so the Pareto solution in Fig. 2 can be a suggestion for decision makers.

![Figure 2 Pareto frontier](image)

4. Conclusions
1) In this paper, the transport characteristics and risk characteristics of hazardous materials are considered, and the cost and risk of different hazardous materials are represented by cost coefficient and risk coefficient, and the mixed integer probability robust model is established.

2) Taking the numerical network as an example, the decision of network expansion and flow allocation is obtained, and the advantages of the robust model are proved. At the same time, the Pareto frontier is used to provide suggestions for decision makers with different risk preferences.

3) Considering the dynamic model of hazardous materials multimodal transport network and applying it to the actual network is the future research direction.

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