Time-varying decision-making for hazardous chemical transportation in a complex transportation network

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Abstract

The transit and storage of hazardous chemicals are harmful. A distributed decision model for hazardous chemicals is developed in this study, with the time window established, to improve the efficiency of transportation and storage. The route, mode, time, and volume of each demand can be determined by this model. The model minimizes the total transportation risk and cost. The model is divided into two parts, and the corresponding ant colony algorithm is designed and achieved. The feasibility and efficiency of the model are illustrated through a numerical example with eight transfer nodes, six origin–destination (OD) demands, and multiple transportation mode alternatives. The developed model provides an effective approach for hazardous chemical substance transportation.

Keywords: hazardous chemicals, transportation decision, nonlinear mixed integer programming model, complex transportation network, ant colony algorithm

1 Introduction

A hazardous chemical substance, regardless of its physical or biochemical feature, contains materials that are harmful to humans. Such substance poses high danger during transport. Industries that use hazardous chemical substances have elicited much attention in recent years because of the high risk, diversity, and high perniciousness of these substances. Route selection is generally considered to achieve efficiency and low cost during the transport of these substances. Meanwhile, most scholars consider the transport process a low-risk event.

Many studies on the transport of hazardous chemical substances have been conducted in recent years. Current studies generally adopt double-route planning to reduce the risk and cost of the carriage [3–7]. Ren Chang-xing selected a rational transit line by adjusting the weight of the side boundary [8]. Zhang Jin proposed a nonlinear network transport model based on integrative storage [9]. Ma Chang-xi built a road transportation route multi-objective decision model for hazardous chemical substances after considering the transportation risk, service time, and population [10, 11]. We Hang constructed a route preference model based on a time-varying network condition [12]. Zou Zong-feng established a transportation route for a hazardous chemical substance based on the condition of the mixing time window. Fank considered shipment distance, transit time, human risk, accident probability, and accident consequence in the route selection index [13]. Huang employed a geographical information system (GIS) and a genetic algorithm (GA) to evaluate path risk [14]. Liang Qi-chao established an index that includes carriage risk, cost, and time and considered carriage cost the general objective [15]. Wu Feng considered accident risk, disaster, and remedy as key factors that influence security evaluations [16].

The results of most previous studies on the transportation problem can be mainly regarded from two aspects: risk and cost. However, these studies were merely under the condition of a sole mode of transportation or an established environmental implication. Only a few studies have considered transportation decision making under the conditions of multiple transportation modes.

In this study, a dynamic hazardous chemical transportation decision-making model was established in consideration of the complexity and time-varying feature of transport networks. This model optimizes control methods at low transportation risk and costs. The model not only considers the changed population conditions but also confirms the transportation route, shipping type, transit time, and cost.

2 Description of a hazardous chemical substance

The hazardous chemical substance transport network is the basis of the transport decision. In the transport network $G=(V,E,\Omega,\Gamma)$, V is the peak gather, E is the directed arc gather, and Γ is the arc cost gather. The urban and connected nodes of the transport network represent the network peak and directed arc, respectively. The hazardous chemical substance transport network is shown in Figure 1.

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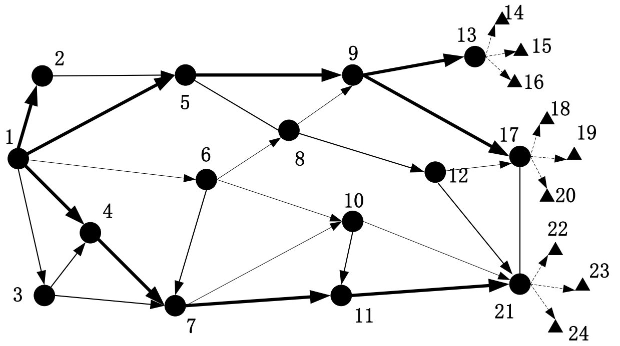

FIGURE 1 Modern logistics distribution network

Vertex set V includes the origin–destination, transfer, and goal nodes. The vertex of the total network can be divided into two stages. The first stage $V_1 = \{1, 2, ..., n\}$ represents the origin–destination and transfer nodes in the transport network. The second stage $V_2 = \{n+1, n+2, ..., n+m\}$ represents the goal node.

The directed arc includes gather E_1 and gather E_2, where gather E_1 includes the various modes of transportation in the two nodes.

The arc parameters include the transportation capability (Ω) and generalized transport costs (Γ). Generalized transport costs mainly include the transportation risk (Γ_1), transportation cost (Γ_2), and transit time (Γ_3), where the transportation cost is a constant value. However, the value of transportation risk may differ in different periods. The initial networks are changed when multiple transportation modes exist between the two nodes in a transport network. If the two nodes have two transportation modes, the line should link the two nodes that correspond to different transportation modes. If a transit shipment task is involved in the transport network, the node must be spitted. The converted transport network is shown in Figure 2.

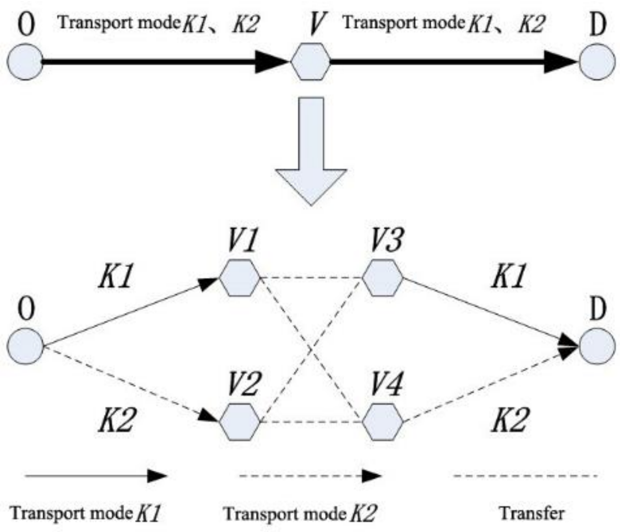

FIGURE 2 Transformation of a transport network

3 Model building

3.1 MODEL ASSUMPTION

Diverse flow directions exist in the hazardous chemical substance network; multiple transportation modes also exist among different ODs. We propose several assumptions to simplify the model:
1) We assume that the system considers only road traffic capacity during the hazardous chemical substance transportation process.
2) We assume that the transported hazardous chemical substances are of the same type; hazardous substances with the same flow direction cannot be segmented in the transportation process.
3) The random factor (e.g., operate miss, climate, natural environment) is disregarded.

3.2 PARAMETER SPECIFICATION

F is defined as the gather of the transport demand (OD), f is the variable of OD, and $f \in F$. $o(f)$ and $d(f)$ are the origin–destination and end point, respectively. Q_f is the freight volume for the f flow direction, and $f = n+1, ..., n+m$. P^f is the gather of the selectable transportation route. p_l^f is the l selectable transportation route in P^f, and $p_l^f \in P^f$. $\psi_{ij}^k = 1$ or ε is a feasible coefficient. K is the gather of the different transport modes for the hazardous chemical substance. T is the gather of the time frame of the hazardous chemical substance. R_{ij}^{tk} is the social risk in section (i, j) with k transport mode. c_{ij}^k is the transportation cost in section (i, j) with k transport mode. t_{ij}^k is the transit time in section (i, j) with k transport mode. c_i^k is the switching cost after altering the transport mode at node i. t_i^k is the time consumed after altering the transport mode at node i. θ_{ij}^k is the maximum carrying capacity of section (i, j) with k transport mode. $[T_1, T_2]$ is the time window restraint for delivering the hazardous chemical substance, T_1 is the earliest delivery time, and T_2 is the latest delivery time. δ, γ and η are dimension conversion coefficients. x_{ij}^{tk} is a variable (ranging from 0 to 1) that indicates whether the hazardous chemical substance passed section (i, j) with k transport mode during period t. x_i^k is a variable (ranging from 0 to 1) that indicates whether the hazardous chemical substance altered the transport mode at node i. s_o^f is the departure time in the f flow direction.

3.3 MODEL BUILDING

3.3.1 Objective function

The transportation route, mode, and time are generally considered in the decision making process for hazardous chemical substance transport. The optimization objectives are (1) minimize the social risk and (2) minimize the transportation expenses, which include the reloading fee.

The social risks involved in the transport of a hazardous chemical substance can be calculated as:

$$Z_1 = \sum_{f\in F}\sum_{k\in K}\sum_{(i,j)\in p_l^f}\sum_{t\in T} Q_f x_{ij}^{tk} R_{ij}^{tk} / \psi_{ij}^{k} . \tag{1}$$

The expense generated from hazardous chemical substance transport can be calculated as

$$Z_2 = \sum_{f\in F}\sum_{k\in K}\sum_{(i,j)\in p_l^f} Q_f x_{ij}^{tk} c_{ij}^{k} + \sum_{f\in F}\sum_{k\in K}\sum_{j\notin o(f)} Q_f x_i^{tk} c_i^{k} . \tag{2}$$

3.3.2 Constraint condition

The constraint condition mainly includes the node flow, traffic capacity, and delivery time.

$$\sum_{(i,j)\in p_l^f} x_{ij}^{fk} - \sum_{(i,j)\in p_l^f} x_{ji}^{fk} = \begin{cases} 1, i\in o(f) \\ -1, i\in d(f), f\in F, p_l^f \in P^f \\ 0, else \end{cases} , \tag{3}$$

$$\sum_{k\in K} x_{ij}^{fk} \le 1, f\in F , \tag{4}$$

$$Q_{ij} \le \min_{(i,j)\in p^f} (\theta_{ij}) , \tag{5}$$

$$T_1 \le s_o^f + \sum_{k\in K}\sum_{(i,j)\in p_l^f} x_{ij}^{fk} t_{ij}^{Tk} + \sum_{i\notin o(f)}\sum_{k_1\in K}\sum_{k_2\in K} x_{ij}^{fk} t_{k_1k_2}^{i} \le T_2 , \tag{6}$$

$$x_{ij}^{fk} \in \{0,1\} . \tag{7}$$

The constraint condition in Equation (3) is utilized to guarantee directivity and flow balance during transportation. The constraint condition in Equation (4) represents only one mode or path of transportation. The constraint condition in Equation (5) indicates that traffic cannot exceed the capacity of the road segment. The constraint condition in Equation (7) shows that the value range of the decision variable is from 0 to 1. The multi-objective optimization model, M1, can be briefly expressed as:

$$\mathrm{M1} = \min\{Z_1, Z_2\} . \tag{8}$$

Subject to Equations (1) – (7).

4 Ant colony algorithm design

In computer science and operations research, the ant colony optimization algorithm is a probabilistic technology for solving computational problems that can be reduced to finding good paths through graphs.

This algorithm is a member of the ant colony algorithms family in swarm intelligence methods and constitutes some meta-heuristic optimizations. The algorithm searches for an optimal path in a graph based on the behaviour of ants seeking a path between their colony and a food source. The original idea has since been diversified to solve a wider class of numerical problems. As a result, several problems that draw on the various aspects of the behaviour of ants have emerged.

4.1 HEURISTIC INFORMATION

Multiple selections for transport can be considered in deciding the pathway for a hazardous chemical substance. Under this circumstance, the original transport network should be converted through Figure 2. The decision making for hazardous chemical substance transport not only affects the population and transportation cost but also involves the mode of transport. Therefore, the heuristic information can be described as follows:

$$\eta_{ij} = \frac{1}{[R_{ij}^{tk} \oplus (c_{ij}^k + c_i^k)]} . \tag{9}$$

4.2 STATE TRANSITION

The trail level represents a posteriori indication of the desirability of a particular move. Trails are usually updated when all ants have completed their solutions. The level of trails that correspond to moves that are part of "good" or "bad" solutions is increased or decreased, respectively.

Generally, the k^{th} ant moves from state *i* to state *j* with probability:

$$p_{ij}^k = \begin{cases} \dfrac{[\tau_{ij}]^\alpha \times [\eta_{ij}]^\beta}{\sum_{j\in N^k(i)} [\tau_{ij}]^\alpha \times [\eta_{ij}]^\beta}, & \text{if } j\in N^k(i) \\ 0, & \text{other} \end{cases} , \tag{10}$$

where $N^k(i) = U/Tabu^k$ is the selectable gather for ant k, τ_{ij} is the amount of pheromones deposited for transition from state i to state *j*, $\alpha(\alpha>0)$, $\beta(\beta>0)$, $0\le\alpha$ is a parameter to control the influence of τ_{ij}, η_{ij} is the desirability of state transition *ij*, and $\beta \ge 1$ is a parameter to control the influence of η_{ij}. τ_{ij} and η_{ij} represent the attractiveness and trail level for the other possible state transitions.

4.3 PHEROMONE UPDATE

When all the ants have completed a solution, the trails are updated by:

$$\tau_{ij} \leftarrow \rho \cdot \tau_{ij} + \sum \Delta\tau_{ij}^{k}, \Delta\tau_{ij}^{k} = Q / f^{k}. \tag{11}$$

where τ_{ij} is the amount of pheromones deposited for state transition *ij*, ρ is the pheromone evaporation coefficient, and $\Delta\tau_{ij}^{k}$ is the amount of pheromones deposited by the k^{th} ant.

4.4 PHEROMONE MAINTENANCE

To avoid arithmetic stagnation, the pheromone concentration section was set to $[\tau_{\min}, \tau_{\max}]$. We ordered $\tau_{\max}$ when the concentration exceeded $\tau_{\max}$; otherwise, we ordered $\tau_{\min}$ when the concentration exceeded $\tau_{\min}$.

The implementation of the dynamic route optimization selection process is summarized below:

1) The values of each parameter (α, β, ρ, Q) are set. The number of ants is *m*, the maximum iteration number is $N_{\max}$, the present iteration number is $n \leftarrow 1$, pheromone $\tau_{ij} \leftarrow 1$, and the departure of the hazardous chemical substance is *t*.
2) *m* ants are placed in the origin–destination of each direction. The ants select the next node according to Equation (8) and repeat the transition rule until the capacity restraint is met.
3) The pheromone is updated globally.
4) The departure time of the hazardous chemical substance is updated as $t \leftarrow t + \Delta t$. Return to step 2 until the departure time quantum has traversed. The iterations are updated as $n \leftarrow n+1$.
5) End the process when $n = N_{\max}$ and the optimal solution has produced an output. Otherwise, return to step 2.

5 Applications

The hazardous chemical substance transport network is shown in Figure 3.

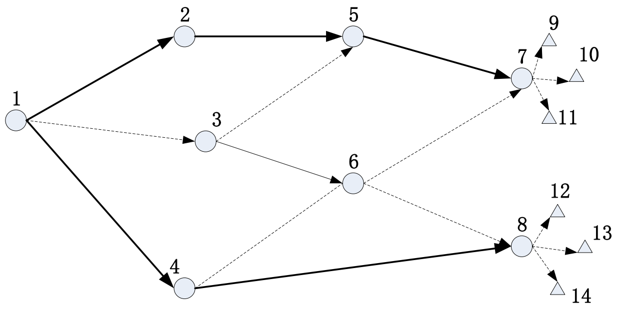

FIGURE 3 Hazardous chemical substance transport network

$V_1 = 1$ represents the output node of the hazardous chemical substance, and $V_1 = \{2,3,4,5,6,7,8\}$ represents the transfer node in the transport network of the azardous chemical substance. $V_2 = \{9,10,11,12,13,14\}$ represents the goal node of the hazardous chemical substance. We divided one day into T sections $T = [3,6,...,21]$. Two transportation modes exist in the hazardous chemical substance transport network. k_1 represents the railway, and k_2 represents the road. The thick line in the figure represents the transportation mode between the railway and the road. The filament and imaginary line represent the existing road transportation only.

The restraint of the time window is $[6,18]$, and the quantity demanded is $R = [23,16,11,25,13,32]$. The line parameters are described in Table 1.

Under the condition of different transportation periods on the railway and road, the populations referred to in each section are described in Table 2.

The calculated transportation route, mode, and volume in each flow direction are shown in Table 3.

TABLE 1 Reference value in each road segment

	Type	**Directed edge**										
		(1,2)	*(1,3)*	*(1,4)*	*(2,5)*	*(3,5)*	*(3,6)*	*(4,6)*	*(4,8)*	*(5,7)*	*(6,7)*	*(6,8)*
Feasible Index	Railway	1	ε	1	1	ε	ε	ε	1	1	ε	ε
	Road	1	1	1	ε	1	1	1	1	ε	ε	1
Ability	Railway	30	—	45	35	—	—	—	35	20	—	—
	Road	20	15	25	25	20	20	25	15	20	25	25
Cost	Railway	10	—	9	12	—	—	—	9	10	—	—
	Road	12	11	8	14	10	10	10	11	12	11	9
Time	Railway	1.7	—	1.6	2.0	—	—	—	1.8	2.1	—	—
	Road	1.8	1.6	1.7	1.8	2.1	2.0	2.1	2.1	2.0	1.9	1.8

TABLE 2 Population referred to in each section (railway/road)

Directed Edge	Time interval (h)							
	[0,3)	*[4,6)*	*[7,9)*	*[10,12)*	*[13,15)*	*[16,18)*	*[19,21)*	*[22,24)*
(1,2)	40/60	40/60	60/60	80/60	50/60	60/60	80/60	40/60
(1,3)	60/—	60/—	140/—	160/—	140/—	150/—	170/—	90/—
(1,4)	50/70	50/70	80/70	100/70	70/70	80/70	100/70	50/70
(2,5)	20/40	20/40	60/40	80/40	50/40	60/40	80/40	20/40
(3,5)	30/—	30/—	50/—	70/—	50/—	60/—	70/—	40/—
(3,6)	60/—	60/—	80/—	100/—	80/—	90/—	110/—	70/—
(4,6)	50/—	60/—	50/—	70/—	60/—	60/—	80/—	50/—
(4,8)	100/80	100/80	120/80	150/80	130/80	130/80	150/80	100/80
(5,7)	70/90	70/90	90/90	120/90	100/90	100/90	120/90	80/90
(6,7)	85/—	80/—	90/—	120/—	100/—	110/—	125/—	90/—
(6,8)	90/—	90/—	120/—	140/—	120/—	120/—	150/—	90/—

TABLE 3 Path choice in each flow direction

Flow direction	Pathway and shipping type	Departure time	Population	Cost
1→9	1→（Railway）→2→（Railway）→5→（Road）→7	[8,9)	210	782
1→10	1→（Road）→2→（Railway）→5→（Railway）→7	[5,6)	170	544
1→11	1→（Road）→3→（Road）→5→（Road）→7	[4,5)	160	363
1→12	1→（Road）→4→（Road）→6→（Road）→8	[2,3)	190	675
1→13	1→（Road）→3→（Road）→6→（Road）→8	[5,6)	210	390
1→14	1→（Railway）→4→（Railway）→8	[7,8)	150	576

Table 3 shows the following: the transportation route of the hazardous chemical substance is 1→2→5→7→9, the departure time is [8,9), transportation route 1→2→5 is for railway transportation, and transportation route 5→7 is for road transportation. The transportation route of the (1→11) direction is 1→3→5→7→11, and the departure time is [7, 8). The transport mode is road transportation. The transportation route of the (1→13) direction is 1→3→6→8→13; the departure time is [7, 8). The transportation route of the (1→14) direction is 1→4→8→14; the departure time is [8, 9), and the transport mode is road transportation. The overall populations influenced by the hazardous chemical substance are 109 million tons, and the cost is 3300 million dollars.

6 Conclusions

A transportation decision-making optimization model was established in this study. The complexity of the transport network and the transportation route, mode, and time were defined in the model. The decision-making optimization model was created based on the ant colony algorithm. The results indicate that the model is feasible and provides an effective approach for hazardous chemical substance transportation.

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