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 $\Gamma$ 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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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. $Q_i$ is the freight volume for the $i$ flow direction, and $f = n+1, \ldots, n+m$ . $P'$ is the gather of the selectable transportation route. $p'_i$ is the $l$ selectable transportation route in $P'$ , and $p'_i \in P'$ . $\psi^k_{yi} = 1$ or $\varepsilon$ 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. $K^a_{yi}$ is the social risk in section $(i, j)$ with $k$ transport mode. $c_{yi}^k$ is the transportation cost in section $(i, j)$ with $k$ transport mode. $t_{yi}^k$ is the transit time in section $(i, j)$ with $k$ transport mode. $t_{yi}^k$ is the time consumed after altering the transport mode at node $i$. $\theta_{yi}^k$ is the maximum carrying capacity of section $(i, j)$ with $k$ transport mode. $[T_i, T_j]$ is the time window restraint for delivering the hazardous chemical substance, $T_i$ is the earliest delivery time, and $T_j$ is the latest delivery time. $\delta$, $\gamma$ and $\eta$ are dimension conversion coefficients. $x^a_{yi}$ 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 $t$. $s_{yi}^k$ is a variable (ranging from 0 to 1) that indicates whether the hazardous chemical substance altered the transport mode at node $i$. $s_{yi}^k$ 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:

$$Z_1 = \sum_{j=1}^{F} \sum_{k \in K} \sum_{i \in P} \sum_{i \in f} Q_f^k x_{ij}^k R_i^k / \psi_{ij}^k .$$

(1)

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

$$Z_2 = \sum_{j=1}^{F} \sum_{k \in K} \sum_{i \in P} \sum_{i \in f} Q_f^k x_{ij}^k c_{ij}^k + \sum_{j=1}^{F} \sum_{k \in K} \sum_{i \in P} \sum_{i \in f} Q_f^k x_{ij}^k c_{ij}^k .$$

(2)

3.3.2 Constraint condition

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

$$\sum_{i \in P} x_{ij}^k - \sum_{i \in P} x_{ij}^k = \begin{cases} 1, & l \in \alpha(f) \\ 1, & i \in d(f), f \in F, p_i \in P' , \\ 0, & \text{else} \end{cases}$$

(3)

$$\sum_{k \in K} x_{ij}^k \leq 1, f \in F .$$

(4)

$$Q_i \leq \min \{ \theta_i \} ,$$

(5)

$$T_i \leq x_{ij}^k + \sum_{i \in P} \sum_{i \in f} x_{ij}^k + \sum_{i \in P} \sum_{i \in f} x_{ij}^k \leq T_z .$$

(6)

$$x_{ij}^k \in \{0, 1\} .$$

(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:

$$M1 = \min \{Z_1, Z_2 \} .$$

(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:

$$\eta_j = \frac{1}{[R^k_\alpha \oplus (c_{ij}^k + c_{ij}^k)]} .$$

(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:

$$P_{ij}^k = \left\{ \begin{array}{ll} \frac{[\tau_{ij}]^\alpha \times [\eta_j]^\beta}{\sum_{j \in N^k(i)} [\tau_{ij}]^\alpha \times [\eta_j]^\beta}, & \text{if } j \in N^k(i) \\ 0, & \text{other} \end{array} \right.$$

(10)

where $N^k(i)=U/\text{Tabu}_k$ is the selectable gather for ant $k$, $\tau_{ij}$ is the amount of pheromones deposited for transition from state $i$ to state $j$, $\alpha, \beta(\alpha > 0), \beta(\beta > 0), 0 \leq \alpha$ is a parameter to control the influence of $\tau_{ij}$, $\eta_j$ is the desirability of state transition $ij$, and $\beta \geq 1$ is a parameter to control the influence of $\eta_j$; $\tau_{ij}$ and $\eta_j$ 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:

$$\tau_{ij}^{(t+1)} = (1 - \rho) \tau_{ij}^{(t)} + \Delta \tau_{ij}^{(t)} ,$$

(11)

where $\rho$ is the pheromones evaporation rate ($0 \leq \rho < 1$). The pheromones deposit is calculated by

$$\Delta \tau_{ij}^{(t)} = \rho^\beta \sum_{k=1}^{K} \Delta \tau_{ij}^{(t+1)} .$$

(12)
where $r_{ij}$ is the amount of pheromones deposited for state transition $ij$, $\rho$ is the pheromone evaporation coefficient, and $\Delta r_{ij}^k$ 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 $[\tau_{\text{min}}, \tau_{\text{max}}]$. We ordered $\tau_{\text{max}}$ when the concentration exceeded $\tau_{\text{max}}$; otherwise, we ordered $\tau_{\text{min}}$ when the concentration exceeded $\tau_{\text{min}}$.

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

1) The values of each parameter $(\alpha, \beta, \rho, Q)$ are set. The number of ants is $m$, the maximum iteration number is $N_{\text{max}}$, the present iteration number is $n$, ant $n$, the amount of pheromones deposited for state transition $ij$, 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 iteration number is $n$. The iterations are updated as $n \leftarrow n + 1$.

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 $n = N_{\text{max}}$ 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.

![Hazardous chemical substance transport network](image)

**FIGURE 3** Hazardous chemical substance transport network

$V_1 = 1$ represents the output node of the hazardous chemical substance, and $V_2 = [2, 3, 4, 5, 6, 7, 8]$ represents the transfer node in the transport network of the hazardous 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. $k_i$ represents the railway, and $k_j$ 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>
<thead>
<tr>
<th>TABLE 1 Reference value in each road segment</th>
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<tbody>
<tr>
<td><strong>Type</strong></td>
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<tr>
<td><strong>Feasible Index</strong></td>
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<tr>
<td>Railway</td>
</tr>
<tr>
<td>Road</td>
</tr>
<tr>
<td><strong>Ability</strong></td>
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<td>Road</td>
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<tr>
<td><strong>Cost</strong></td>
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<tr>
<td>Road</td>
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<tr>
<td><strong>Time</strong></td>
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<tr>
<td>Railway</td>
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<tr>
<td>Road</td>
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</tbody>
</table>
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.

References

### Authors

<table>
<thead>
<tr>
<th>Name</th>
<th>Date of Birth</th>
<th>Place of Birth</th>
<th>Position and Grades</th>
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<th>Scientific Interest</th>
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<th>Experience</th>
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