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A Credibilistic Mixed Integer Programming Model for Time-Dependent Hazardous Materials Vehicle Routing Problem

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Abstract

Hazardous materials are harmful to environment and human health due to their toxic ingredients. It is very important to intensify efforts in the safety management of hazardous materials, and fundamentally prevent and reduce accidents. In this study, we consider a time-dependent hazardous materials vehicle routing problem in a two-echelon supply chain system. The goal is to determine the departure time and the optimal route with a minimum risk value for hazardous materials transportation. Considering that time has a significant influence on the transportation risk, we formulate a time-dependent transportation risk model and propose a credibilistic mixed integer programming model to minimize the expected risk. An improved genetic algorithm whose chromosomes contain two types of genes is designed to handle the proposed model. Numerical experiment is given to illustrate the efficiency of the proposed model and algorithm. Compared with the traditional transportation risk model, the time-dependent transportation risk model can significantly reduce the risk around 42%.

Keywords: hazardous materials, vehicle routing problem, credibilistic mixed integer programming, genetic algorithm

1 Introduction

With the development of economy, the demand for hazardous materials is continuously increasing in recent years. In China, a significant majority of hazardous materials shipments are moved via the highway networks, of which 95% are long distance transportation. Hazardous materials play an important role to the improvement of peoples living standards. However, there have also been some accidents at the same time, which result in significant impact to the population and damage to the environment. As an indispensable part of the chemical industry, hazardous materials transportation managements have attracted much attention due to the risk factor involved. Therefore, it requires an optimization for the vehicle routing problem of hazardous materials in a risk reduction perspective.

In this following, we review the literature on vehicle routing problem and risk assessment methods on hazardous materials transportation.

1.1 Vehicle Routing Problem

Vehicle routing problem (VRP) was first proposed by Dantzig and Ramser [3], which is always described as a integer programming problem seeking to service a number of customers with a fleet of vehicles. Erera Alan Laurence [10] proposed a continuum approximation model to deal with two basic VRP. Panda and Das [14]

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considered a cost varying multi-objective interval transportation problem, and presented a solution procedure of cost varying interval transportation problem under two vehicles. Liu et al. [13] established a kind of stochastic programming model for VRP with time-constrained and proposed an improved genetic algorithm for the model of two-paired vehicles. Lin [11] studied a VRP with pickup and delivery time windows by minimizing the sum of vehicle fixed costs and travelling costs. Wei et al. [21] considered a chance-constrained programming model on hazardous materials transportation that the transportation costs and the number of affected people are fuzzy variables. Du et al. [5] presented a fuzzy multi-objective programming model which minimized the hazardous materials transportation risk to life, travel time and fuel consumption. Du et al. [4] proposed a fuzzy bi-level programming model to minimize the total transportation risk, and designed four fuzzy simulation-based heuristic algorithms to search the best strategies allocating customers to depots and determining the optimal routing solutions with respect to each group of depots and customers. In these studies, the time required to cross route was assumed as constant over time. However, in reality, it is not acceptable when the results are needed more exact.

In time-dependent problems, the original work was done by Gupta and Gupta [7], in which time dependency was presented in scheduling problems. Since then, problems with time-dependent processing times have received increasing attention. Park [15] constructed a mixed integer linear programming formulation to deal with the bi-criteria vehicle scheduling problem with time and area-dependent travel speeds. Haghani and Jung [8] proposed a formulation for the dynamic VRP with time-dependent travel times and presented a genetic algorithm to solve the model. Woensel et al. [22] considered a VRP with dynamic travel times due to potential traffic congestion. Soler et al. [18] dealt with the VRP with time windows that considered time-dependent travel times and costs. Wei et al. [20] focused on the depot location and vehicle scheduling, and discussed the influence of fuzzy-randomness in hazardous materials transportation. Although the above studies had considered a series of time-dependent vehicle routing problem (TDVRP), the path risk is usually set to a fixed value without considering the impact of time in a traveling salesman problem.

This work considers a time-dependent hazardous materials VRP, of which the transportation risk is expressed as different fuzzy variables at different times, and uses credibilistic mixed integer programming to obtain the minimum risk.

1.2 Risk Measures for Hazardous Materials Inventory and Transportation

Hazardous materials inventory accidents can result in significant impact to the population and damage to the environment, which have the characteristics of low probability and high consequence. Until recently, the most popular measure of transportation risk for hazardous materials was based on the accident probability and consequence.

Batta and Chiu [2] considered the population exposure model of hazardous materials to measure the transportation risk. Erkut and Ingolfsson [6] proposed three risk measurement models based on big disaster circumvention, including the maximum number of exposed population, the minimum expected loss variance and the minimum expected effect on transport routes. Verma and Verter [19] used the Gaussian plume model to calculate the exposed zone, and then estimated population exposure. Pradhanangad et al. [16, 17] considered the hazardous materials VRP and used the loading and the size of population exposure on the route to measure the risk. Apostolos et al. [1] proposed the definition of robust risk measure as the worst possible when each probability measure is likely to occur. Yuan et al. [23] first considered the variation of vehicle loading in hazardous material VRP and proposed a dynamic transportation risk model. Although the above studies have considered the influence of loading on transportation risk, the transportation risk is generally treated as constant or fuzzy variable without considering the time-dependent in the process of analysis and evaluation. However, in the real-life transportation process, the time-dependent situation is more exact.

The main innovations of our study are to propose a time-dependent transportation risk model for hazardous materials traveling salesman problem, and present a credibilistic mixed integer programming model to handle the fuzziness on transportation risk. The goal is to determine the optimal route for TDVRP, which has a minimum risk value. The rest of this study is constructed as follows. Section 2 defines a time-dependent transportation risk, and then formulate a credibilistic mixed integer programming model. Section 3 designs a genetic algorithm in which the chromosome includes both departure time gene and service order gene. Section 4 presents illustrative examples to show the efficiency of the proposed model and algorithm.

2 Problem Description and Mathematical Models

2.1 Problem Description and Notations

Consider a two-echelon supply chain system composed of a single manufacturer and multiple retailers. The vehicle starts and returns at the manufacturer after serving all the retailers, and the transportation process takes the serial routing mode. The objective is to determine the departure time at manufacturer and transportation route by minimizing the total transportation risk from manufacturer to customers. Some necessary assumptions are as follows:

- The vehicle should start and end at the manufacturer within a fixed time window;
- The demands of retailers are known.

2.2 Notations

Notations from manufacturer to retailers

n	number of retailers
i, j	denote the indices of locations in which index 0 indicates manufacturer's location, $i, j = 0, 1, 2, \ldots, n$
r_i	retailer whose service order is i in the transportation route. Set $r_0 = 0$ and $r_{n+1} = 0$, which means vehicle starts from the manufacturer and also returns to it
s_{ij}	the distance between node i and node j
$v(t)$	the speed of the vehicle at time t
Δt_i	unloading time at retailer i
$\widetilde{\mu}_{ij}(t)$	the unit mass and the unit distance transportation risk at time t on arc (i, j), which is a fuzzy variable
q_i	the quantity of hazardous materials transported from the manufacturer to retailer i
q_{ij}	the transportation quantity of hazardous materials on arc (i, j)
t_i	the departure time at manufacturer or retailers
t_{ij}	the travel time on arc (i, j)
t_{ij}^u	the travel time on arc (i, j) if the departure time t_i in time interval u
t_w^*	the demarcation point for congestion time interval and free-flow time interval
$d^*(u)$	the maximum travel distance in time interval u
Δd_{ij}	the distance between departure time t_i and time t_u^* on arc (i, j) if $t_i \in [t_{u-1}^*, t_u^*]$
R_{ij}	the transportation risk on arc (i, j)
R_{ij}^u	the transportation risk on arc (i, j) if the departure time t_i in time interval u.

Decision Variables

t_0	the departure time at manufacturer
x_{ij}	if arc from i to j is active with $i, j = 0, 1, \ldots, n$, it takes value 1; otherwise, it takes value 0.

2.3 Mathematical Formulation

In reality, the population density of the areas exposed to transportation risk may vary during different parts of the day due to the daily mobility of the residents. Moreover, the number of vehicles potentially affected by a hazardous materials accident depends of the traffic intensity of the corresponding arc. The impact area of a hazardous material accident depends on: (1) the load of the truck, and (2) dynamic characteristics of the prevailing meteorological conditions, especially in the case where the accident consequences relate to the dispersion of pollutants.

The transportation risk is usually measured as the total number of exposed people in the accident (Batta and Chiu [2]). Moreover, the more quantity of hazardous materials a vehicle loads, the more number of exposed people in the accident. Therefore, we should establish the relationship between transportation risk and cargo quantity of hazardous materials. When the vehicle arrives at each retailer, part of the hazardous materials will be unloaded, and the rest of the hazardous materials determine the risk at the next trip. As a result, transportation risk should consider the change of the loading, which means the transportation risk is essentially dynamic. Thus, we need to calculate the transportation loading on each arc. Determine the retailer whose service order is i in the transportation route, which can be expressed as

$$r_i = \arg\max_{1\le j\le n}(x_{r_{i-1}j}), \quad i = 1, 2, \ldots, n. \tag{1}$$

Thus, the loading on arc $(i, i+1)$ is $\sum_{k=i+1}^{n} q_{r_k}$.

In the previous literatures, the path risk is usually set to a fixed value without considering the impact of time. In practice, however, the population density around the path is different at different times. Taking into account the impact of traffic congestion on the population density, the cargo transport time is divided into five time intervals, such as 7:00-9:00 (the first time interval), 9:00-11:00 (the second time interval), 11:00-13:00 (the third time interval), 13:00-16:00 (the fourth time interval), and 16:00-19:00 (the fifth time interval). Since different congestion situation brings different population density, we set a five-level risk function corresponding the peak and off-peak during the working hours of each day. Considering that the quantity of hazardous materials a vehicle loads affects number of exposed people in the accident, the unit mass and unit distance risk at time t can be expressed as

$$\widetilde{\mu}_{ij}(t) = \begin{cases} \widetilde{\mu}_{ij}^1, & \text{if } t_0^* \le t \le t_1^* \\ \widetilde{\mu}_{ij}^2, & \text{if } t_1^* < t \le t_2^* \\ \widetilde{\mu}_{ij}^3, & \text{if } t_2^* < t \le t_3^* \\ \widetilde{\mu}_{ij}^4, & \text{if } t_3^* < t \le t_4^* \\ \widetilde{\mu}_{ij}^5, & \text{if } t_4^* < t \le t_5^*. \end{cases} \tag{2}$$

As in [9], traffic congestion in the TDVRP is modeled through a two-level speed function including congestion speed and free speed. To make it more realistic, we consider a five-level speed function corresponding the peak and off-peak during the working hours of each day, which can be expressed as

$$v(t) = \begin{cases} v_1, & \text{if } t_0^* \le t \le t_1^* \\ v_2, & \text{if } t_1^* < t \le t_2^* \\ v_3, & \text{if } t_2^* < t \le t_3^* \\ v_4, & \text{if } t_3^* < t \le t_4^* \\ v_5, & \text{if } t_4^* < t \le t_5^*. \end{cases} \tag{3}$$

And the maximum travel distance in these time intervals can be expressed as

$$d^*(u) = \begin{cases} v_1(t_1^* - t_0^*), & \text{if } u = 1 \\ v_2(t_2^* - t_1^*), & \text{if } u = 2 \\ v_3(t_3^* - t_2^*), & \text{if } u = 3 \\ v_4(t_4^* - t_3^*), & \text{if } u = 4 \\ v_5(t_5^* - t_4^*), & \text{if } u = 5. \end{cases} \tag{4}$$

The travel time on arc (i, j) depends on the departure time t_i, the distance s_{ij} and time difference Δd_{ij} .

$$\Delta d_{ij} = \sum_{u=1}^{5} v_u(t_u^* - t_i)sgn[(t_u^* - t_i)(t_i - t_{u-1}^*)] \tag{5}$$

where $sgn(x)$ is a symbolic function. When $x > 0$ it takes value 1; otherwise, it takes value 0.

If $t_i \in [t_0^*, t_1^*]$, the travel time t_{ij} can be expressed as

$$t_{ij}^1(t_i, d_{ij}) = \begin{cases} \dfrac{d_{ij}}{v_1}, & \text{if } d_{ij} \le \Delta d_{ij} \\ \dfrac{d_{ij} - \Delta d_{ij}}{v_2} + (t_1^* - t_i), & \text{if } \Delta d_{ij} \le d_{ij} \le d^*(2) + \Delta d_{ij} \\ \dfrac{d_{ij} - d^*(2) - \Delta d_{ij}}{v_3} + (t_2^* - t_i), & \\ \qquad \text{if } d^*(2) + \Delta d_{ij} \le d_{ij} \le \sum_{u=2}^{3} d^*(u) + \Delta d_{ij} & \\ \dfrac{d_{ij} - d^*(2) - d^*(3) - \Delta d_{ij}}{v_4} + (t_3^* - t_i), & \\ \qquad \text{if } \sum_{u=2}^{3} d^*(u) + \Delta d_{ij} \le d_{ij} \le \sum_{u=2}^{4} d^*(u) + \Delta d_{ij} & \\ \dfrac{d_{ij} - d^*(2) - d^*(3) - d^*(4) - \Delta d_{ij}}{v_5} + (t_4^* - t_i), & \\ \qquad \text{if } \sum_{u=2}^{4} d^*(u) + \Delta d_{ij} \le d_{ij} \le \sum_{u=2}^{5} d^*(u) + \Delta d_{ij} & \end{cases} \tag{6}$$

which is equivalent to

$$\begin{aligned} t_{ij}^1(t_i, d_{ij}) = {} & \frac{d_{ij}}{v_1} sgn(\Delta d_{ij} - d_{ij}) + \left(\frac{d_{ij} - \Delta d_{ij}}{v_2} + t_1^* - t_i\right) sgn[(d^*(2) + \Delta d_{ij} - d_{ij})(d_{ij} - \Delta d_{ij})] \\ & + \sum_{w=3}^{5} \left(\frac{d_{ij} - \sum_{u=2}^{w-1} d^*(u) - \Delta d_{ij}}{v_w} + t_{w-1}^* - t_i\right) \\ & sgn\left[\left(\sum_{u=2}^{w} d^*(u) + \Delta d_{ij} - d_{ij}\right)\left(d_{ij} - \sum_{u=2}^{w-1} d^*(u) - \Delta d_{ij}\right)\right]. \end{aligned} \tag{7}$$

Similarly, we have

$$\begin{aligned} t_{ij}^2(t_i, d_{ij}) = {} & \frac{d_{ij}}{v_2} sgn(\Delta d_{ij} - d_{ij}) + \left(\frac{d_{ij} - \Delta d_{ij}}{v_3} + t_2^* - t_i\right) sgn[(d^*(3) + \Delta d_{ij} - d_{ij})(d_{ij} - \Delta d_{ij})] \\ & + \sum_{w=4}^{5} \left(\frac{d_{ij} - \sum_{u=3}^{w-1} d^*(u) - \Delta d_{ij}}{v_w} + t_{w-1}^* - t_i\right) \\ & sgn\left[\left(\sum_{u=3}^{w} d^*(u) + \Delta d_{ij} - d_{ij}\right)\left(d_{ij} - \sum_{u=3}^{w-1} d^*(u) - \Delta d_{ij}\right)\right] \end{aligned} \tag{8}$$

$$\begin{aligned} t_{ij}^3(t_i, d_{ij}) = {} & \frac{d_{ij}}{v_3} sgn(\Delta d_{ij} - d_{ij}) + \left(\frac{d_{ij} - \Delta d_{ij}}{v_4} + t_3^* - t_i\right) sgn[(d^*(4) + \Delta d_{ij} - d_{ij})(d_{ij} - \Delta d_{ij})] \\ & + \left(\frac{d_{ij} - d^*(4) - \Delta d_{ij}}{v_5} + t_4^* - t_i\right) sgn\left[\left(\sum_{u=4}^{5} d^*(u) + \Delta d_{ij} - d_{ij}\right)(d_{ij} - d^*(4) - \Delta d_{ij})\right] \end{aligned} \tag{9}$$

$$t_{ij}^4(t_i, d_{ij}) = \frac{d_{ij}}{v_4} sgn(\Delta d_{ij} - d_{ij}) + \left(\frac{d_{ij} - \Delta d_{ij}}{v_5} + t_4^* - t_i\right) sgn[(d^*(5) + \Delta d_{ij} - d_{ij})(d_{ij} - \Delta d_{ij})] \tag{10}$$

$$t_{ij}^5(t_i, d_{ij}) = \frac{d_{ij}}{v_5} sgn(\Delta d_{ij} - d_{ij}). \tag{11}$$

Therefore, the travel time on arc (i,j) is

$$t_{ij}(t_i,d_{ij})=\sum_{u=1}^{5}t_{ij}^{u}(t_i,d_{ij})sgn[(t_u^*-t_i)(t_i-t_{u-1}^*)] \tag{12}$$

and the departure time t_j can be expressed as

$$t_j=t_i+t_{ij}(t_i,d_{ij})+\Delta t_{i+1}. \tag{13}$$

The transportation risk on arc (i,j) depends on the departure time t_i. If $t_i\in[t_0^*,t_1^*]$, transportation risk on arc (i,j) can be expressed as

$$R_{ij}^1(t_i,d_{ij})=\begin{cases} q_{ij}d_{ij}\widetilde{\mu}_{ij}^1, & \text{if } d_{ij}\le \Delta d_{ij}\\ q_{ij}[\Delta d_{ij}\widetilde{\mu}_{ij}^1+(d_{ij}-\Delta d_{ij})\widetilde{\mu}_{ij}^2], & \text{if } \Delta d_{ij}\le d_{ij}\le d^*(2)+\Delta d_{ij}\\ q_{ij}[\Delta d_{ij}\widetilde{\mu}_{ij}^1+d^*(2)\widetilde{\mu}_{ij}^2+(d_{ij}-d^*(2)-\Delta d_{ij})\widetilde{\mu}_{ij}^3], & \\ \qquad \text{if } d^*(2)+\Delta d_{ij}\le d_{ij}\le \sum_{u=2}^{3}d^*(u)+\Delta d_{ij} & \\ q_{ij}\left[\Delta d_{ij}\widetilde{\mu}_{ij}^1+\sum_{u=2}^{3}d^*(u)\widetilde{\mu}_{ij}^u+\left(d_{ij}-\sum_{u=2}^{3}d^*(u)-\Delta d_{ij}\right)\widetilde{\mu}_{ij}^4\right], & \\ \qquad \text{if } \sum_{u=2}^{3}d^*(u)+\Delta d_{ij}\le d_{ij}\le \sum_{u=2}^{4}d^*(u)+\Delta d_{ij} & \\ q_{ij}\left[\Delta d_{ij}\widetilde{\mu}_{ij}^1+\sum_{u=2}^{4}d^*(u)\widetilde{\mu}_{ij}^u+\left(d_{ij}-\sum_{u=2}^{4}d^*(u)-\Delta d_{ij}\right)\widetilde{\mu}_{ij}^5\right], & \\ \qquad \text{if } \sum_{u=2}^{4}d^*(u)+\Delta d_{ij}\le d_{ij}\le \sum_{u=2}^{5}d^*(u)+\Delta d_{ij} & \end{cases} \tag{14}$$

which is equivalent to

$$\begin{aligned} R_{ij}^1(t_i,d_{ij}) &= q_{ij}d_{ij}\widetilde{\mu}_{ij}^1 sgn(\Delta d_{ij}-d_{ij})\\ &+q_{ij}[\Delta d_{ij}\widetilde{\mu}_{ij}^1+(d_{ij}-\Delta d_{ij})\widetilde{\mu}_{ij}^2]sgn[(d^*(2)+\Delta d_{ij}-d_{ij})(d_{ij}-\Delta d_{ij})]\\ &+\sum_{w=3}^{5}q_{ij}\left[\Delta d_{ij}\widetilde{\mu}_{ij}^1+\sum_{u=2}^{w-1}d_u^*\widetilde{\mu}_{ij}^u+\left(d_{ij}-\sum_{u=2}^{w-1}d^*(u)-\Delta d_{ij}\right)\widetilde{\mu}_{ij}^w\right]\\ &\quad sgn\left[\left(\sum_{u=2}^{w}d^*(u)+\Delta d_{ij}-d_{ij}\right)\left(d_{ij}-\sum_{u=2}^{w-1}d^*(u)-\Delta d_{ij}\right)\right]. \end{aligned} \tag{15}$$

Similarly, we have

$$\begin{aligned} R_{ij}^2(t_i,d_{ij}) &= q_{ij}d_{ij}\widetilde{\mu}_{ij}^2 sgn(\Delta d_{ij}-d_{ij})\\ &+q_{ij}[\Delta d_{ij}\widetilde{\mu}_{ij}^2+(d_{ij}-\Delta d_{ij})\widetilde{\mu}_{ij}^3]sgn[(d^*(3)+\Delta d_{ij}-d_{ij})(d_{ij}-\Delta d_{ij})]\\ &+\sum_{w=4}^{5}q_{ij}\left[\Delta d_{ij}\widetilde{\mu}_{ij}^1+\sum_{u=3}^{w-1}d^*(u)\widetilde{\mu}_{ij}^u+\left(d_{ij}-\sum_{u=3}^{w-1}d^*(u)-\Delta d_{ij}\right)\widetilde{\mu}_{ij}^w\right]\\ &\quad sgn\left[\left(\sum_{u=3}^{w}d^*(u)+\Delta d_{ij}-d_{ij}\right)\left(d_{ij}-\sum_{u=3}^{w-1}d^*(u)-\Delta d_{ij}\right)\right] \end{aligned} \tag{16}$$

$$\begin{aligned} R_{ij}^3(t_i,d_{ij}) &= q_{ij}d_{ij}\widetilde{\mu}_{ij}^3 sgn(\Delta d_{ij}-d_{ij})\\ &+q_{ij}[\Delta d_{ij}\widetilde{\mu}_{ij}^3+(d_{ij}-\Delta d_{ij})\widetilde{\mu}_{ij}^4]sgn[(d^*(4)+\Delta d_{ij}-d_{ij})(d_{ij}-\Delta d_{ij})]\\ &+q_{ij}[\Delta d_{ij}\widetilde{\mu}_{ij}^1+d^*(4)\widetilde{\mu}_{ij}^4+(d_{ij}-d^*(4)-\Delta d_{ij})\widetilde{\mu}_{ij}^5]\\ &\quad sgn\left[\left(\sum_{u=4}^{5}d^*(u)+\Delta d_{ij}-d_{ij}\right)(d_{ij}-d^*(4)-\Delta d_{ij})\right] \end{aligned} \tag{17}$$

$$R^4_{ij}(t_i, d_{ij}) = q_{ij}d_{ij}\widetilde{\mu}^4_{ij}sgn(\Delta d_{ij} - d_{ij}) \\ +q_{ij}[\Delta d_{ij}\widetilde{\mu}^4_{ij} + (d_{ij} - \Delta d_{ij})\widetilde{\mu}^5_{ij}]sgn[(d^*(5) + \Delta d_{ij} - d_{ij})(d_{ij} - \Delta d_{ij})] \tag{18}$$

$$R^5_{ij}(t_i, d_{ij}) = q_{ij}d_{ij}\widetilde{\mu}^5_{ij}sgn(\Delta d_{ij} - d_{ij}). \tag{19}$$

Therefore, the transportation risk on arc (i, j) is

$$R_{ij}(t_i, d_{ij}) = \sum_{u=1}^{5} R^u_{ij}(t_i, d_{ij})sgn[(t^*_u - t_i)(t_i - t^*_{u-1})] \tag{20}$$

and the time-dependent transportation risk can be expressed as

$$R = \sum_{0\le i\le n-1} R_{r_ir_{i+1}}(t_{r_i}, d_{r_ir_{i+1}}). \tag{21}$$

Since $\widetilde{\mu}_{ij}(t)$ is a fuzzy variable, R is also a fuzzy variable. Therefore, we adopt the expected value criterion of fuzzy variable defined by Liu and Liu [12] to measure the transportation risk. Based on the aforementioned descriptions of assumptions, notations, and risk measure, we formulate a credibilistic mixed integer programming model for hazardous materials transportation as follows

$$\min \quad R = E\left[\sum_{0\le i\le n-1} R_{r_ir_{i+1}}(t_{r_i}, d_{r_ir_{i+1}})\right] \tag{22}$$

$$\text{s.t.} \quad q_{r_ir_{i+1}} = \sum_{k=i+1}^{n} q_{r_k}, \quad 0 \le i \le n \tag{23}$$

$$t_i \ge t^*_0, \quad 0 \le i \le n \tag{24}$$

$$t_{r_n} + t_{r_n0} \le t^*_5 \tag{25}$$

$$\sum_{i\ne j} x_{ij} = \sum_{i\ne j} x_{ij} = 1, \quad 0 \le i, j \le n \tag{26}$$

$$\sum_{0\le i,j\le n} x_{ij} \le \alpha - 1, \ 2 \le \alpha \le n \tag{27}$$

$$x_{ij} \in \{0, 1\}, \ 0 \le i, j \le n \tag{28}$$

$$\text{Constraints} \quad (1) - (5), (7) - (13), (15) - (21).$$

Constraint (23) is the vehicle loading constraint on each arc. Constraints (24) and (25) are the vehicle working time constraints. Constraint (26) ensures that each customer must be visited exactly once. Constraint (27) is subtour elimination constraint. Constraint (28) specifies 0-1 decision variable.

3 Algorithm

TDVRP is a NP-hard problem, which is difficult for us to obtain the exact solution by the traditional algorithm, and heuristic algorithms are generally used to solve the problem. Therefore, we design a genetic algorithm to solve the proposed model.

3.1 Representation Structure

The solution of the model consists of the departure time at manufacturer and routing variables. In this problem, we design each chromosome structure as $V = (t_0, r_1, r_2, \ldots, r_n)$, which contains the departure time at manufacturer and service orders which can replace the routing variables x_{ij} (see Fig. 1).

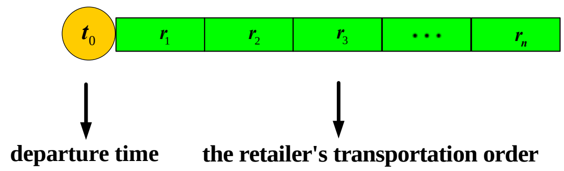

Figure 1: Chromosome structure

3.2 Initialization Process

Define an inter number *pop_size* as the size of population. Randomly generate a vector V_1. If V_1 satisfies constraints of the TDVRP, we get a chromosome. Otherwise, repeat this process until the constraints are satisfied. Then a feasible chromosome is initialized. Repeat the above process *pop_size* times. Denote the generated chromosomes as $V_1, V_2, ..., V_{pop\_size}$.

3.3 Evaluation Function

Let V_i be a feasible chromosome. It is easy to calculate the risk variable R_i. Then, we get the objective values of the *pop_size* chromosomes. Define the evaluation function as follows:

$$eval(V_i) = a(1-a)^{i-1}, \quad i = 1, 2, ..., pop\_size.$$

3.4 Selection Process

We utilize the method of spinning the roulette wheel to select particles. For any $i = 1, 2, \ldots, pop\_size$, we calculate

$$q_i = \sum_{j=1}^{i} Eval(V_j).$$

Generate a random number $r \in (0, q_{pop\_size}]$. Select the ith chromosome V_i if $q_i < r \leq q_{i+1}$. Repeat the above process *pop_size* times to get *pop_size* chromosomes.

3.5 Crossover Process

Denote P_c as the crossover probability, and divide chromosomes into pairs. We will introduce the crossover operation on the pair of chromosomes V and V'(suppose there are 8 retailers). Firstly, select the departure time t_0 and t'_0 on the chromosome V and V' respectively, and take a weigthed compromise method to generate two new departure time. Secondly, randomly select a gene segment from the service order on the chromosome V (which is 4,1,8), and select a gene segment at the same place on V' (which is 2,3,5). Remove the genes 2,3,5 from V, and combine the rest part of V and gene segment 2,3,5 from V'. Remove the genes 4,1,8 from V', and combine the rest part of V' and gene segment 4,1,8 from V (see Fig. 2). Select two chromosomes from the parent and children with small objective values to replace the parent.

3.6 Mutation Process

Denote P_m as the mutation probability. In mutation operation, we repeat the following process *pop_size* times. Randomly generate a number r_i from [0,1]. If $r_i < P_m$, select the ith chromosome V_i as the parent of mutation(suppose there are 8 retailers). Randomly select two gene locations from the service order on the chromosome V_i, and change them to get a child (see Fig. 3). If the new chromosome is better than V_i, we use the new chromosome to replace V_i.

A new generation of population is generated after the evaluation, selection, crossover and mutation operations. Repeat this cycle G times and we obtain a satisfactory solution.

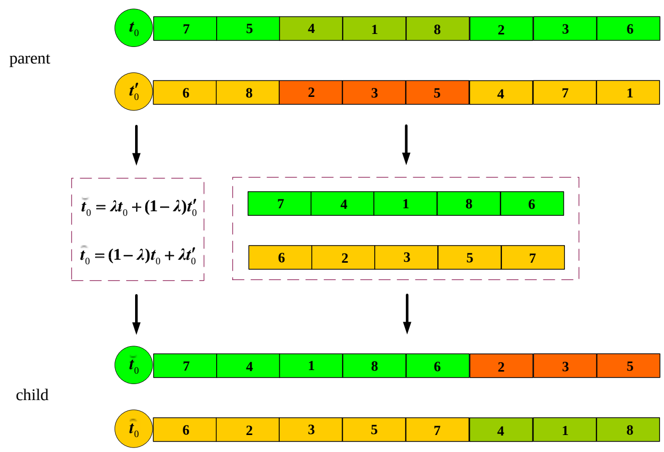

Figure 2: Crossover operation

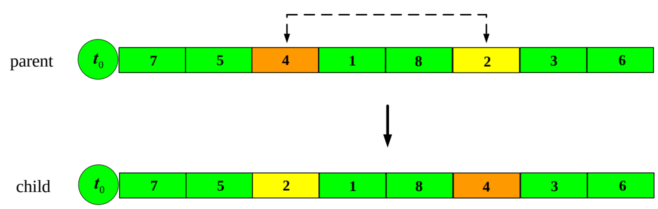

Figure 3: Mutation operation

4 Numerical Experiments

To illustrate the efficiency of the proposed model and algorithm, a numerical example is provided in this section, which considers a two-echelon supply chain problem with a manufacturer and eight retailers. Suppose the demarcation points for congestion time interval and free-flow time interval are 7:00, 9:00, 11:00, 13:00, 16:00, and 19:00, respectively. The unloading time is $\Delta t_i = 12$ minutes ($i = 1, 2, \ldots, 8$). The speeds at different time intervals are $v_1 = 30, v_2 = 70, v_3 = 40, v_4 = 60$ and $v_5 = 30$. The demands of retailers are given in Table 1. The distances among manufacturer and retailers are given in Table 2. The unit mass transportation risk at five different time intervals are presented in Tables 3-7.

Table 1: The supply quantity at retailers (ton)

R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
2.2	0.8	1.4	2.7	0.1	0.5	2	1.1

Table 2: The distances among manufacturer and retailers (km)

	M	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
M	0	50	17	34	19	22	30	38	11
R_1	50	0	32	24	20	29	18	21	30
R_2	17	32	0	15	22	39	26	23	31
R_3	34	24	15	0	20	42	31	24	29
R_4	19	20	22	20	0	17	26	32	22
R_5	22	29	39	42	17	0	22	31	31
R_6	30	18	26	31	26	22	0	28	60
R_7	38	21	23	24	32	31	28	0	26
R_8	11	30	31	29	22	31	60	26	0

The proposed genetic algorithm is employed on the numerical illustration using the MATLAB software.

Table 3: The unit mass transportation risks among manufacturer and retailers at the first time interval ($\times 10^{-7}$)

	M	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
M	(0,0,0)	(80,86,90)	(63,66,70)	(42,47,48)	(77,79,84)	(46,48,51)	(40,43,46)	(62,66,70)	(100,105,110)
R_1	(80,86,90)	(0,0,0)	(32,35,37)	(66,70,72)	(34,36,38)	(50,53,55)	(88,91,95)	(51,53,57)	(80,83,88)
R_2	(63,66,70)	(32,35,37)	(0,0,0)	(61,63,66)	(80,82,86)	(83,85,88)	(45,47,49)	(50,52,56)	(33,36,38)
R_3	(42,47,48)	(66,70,72)	(61,63,66)	(0,0,0)	(68,70,73)	(30,33,35)	(51,53,56)	(48,50,54)	(53,56,58)
R_4	(77,79,84)	(34,36,38)	(80,82,86)	(68,70,73)	(0,0,0)	(68,70,73)	(77,80,84)	(50,52,55)	(21,24,26)
R_5	(46,48,51)	(50,53,55)	(83,85,88)	(30,33,35)	(68,70,73)	(0,0,0)	(50,52,55)	(33,36,38)	(76,78,80)
R_6	(40,43,46)	(88,91,95)	(45,47,49)	(51,53,56)	(77,80,84)	(50,52,55)	(0,0,0)	(45,48,50)	(33,36,39)
R_7	(62,66,70)	(51,53,57)	(50,52,56)	(48,50,54)	(50,52,55)	(33,36,38)	(45,48,50)	(0,0,0)	(55,58,60)
R_8	(100,105,110)	(80,83,88)	(33,36,38)	(53,56,58)	(21,24,26)	(76,78,80)	(33,36,39)	(55,58,60)	(0,0,0)

Table 4: The unit mass transportation risks among manufacturer and retailers at the second time interval ($\times 10^{-7}$)

	M	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
M	(0,0,0)	(15,18,20)	(25,28,30)	(46,50,53)	(27,30,32)	(18,20,25)	(46,47,49)	(28,30,34)	(17,20,25)
R_1	(15,18,20)	(0,0,0)	(32,37,43)	(10,16,23)	(13,18,23)	(30,33,36)	(20,26,30)	(14,16,21)	(16,21,25)
R_2	(25,28,30)	(32,37,43)	(0,0,0)	(34,36,41)	(16,21,28)	(21,27,36)	(18,23,30)	(20,26,35)	(33,38,43)
R_3	(46,50,53)	(10,16,23)	(34,36,41)	(0,0,0)	(27,35,45)	(12,16,21)	(20,26,35)	(17,20,21)	(21,28,36)
R_4	(27,30,32)	(13,18,23)	(16,21,28)	(27,35,45)	(0,0,0)	(27,29,31)	(33,36,40)	(10,12,14)	(20,22,24)
R_5	(18,20,25)	(30,33,36)	(21,27,36)	(12,16,21)	(27,29,31)	(0,0,0)	(20,26,34)	(13,18,23)	(18,24,31)
R_6	(46,47,49)	(20,26,30)	(18,23,30)	(20,26,35)	(33,36,40)	(20,26,34)	(0,0,0)	(7,9,11)	(13,18,24)
R_7	(28,30,34)	(14,16,21)	(20,26,35)	(17,20,21)	(10,12,14)	(13,18,23)	(7,9,11)	(0,0,0)	(22,23,27)
R_8	(17,20,25)	(16,21,25)	(33,38,43)	(21,28,36)	(20,22,24)	(18,24,31)	(13,18,24)	(22,23,27)	(0,0,0)

Table 5: The unit mass transportation risks among manufacturer and retailers at the third time interval ($\times 10^{-7}$)

	M	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
M	(0,0,0)	(45,50,53)	(115,117,120)	(50,52,56)	(32,36,40)	(81,83,87)	(52,54,55)	(98,100,104)	(33,36,37)
R_1	(45,50,53)	(0,0,0)	(75,78,80)	(55,61,66)	(37,42,46)	(87,89,90)	(44,47,51)	(67,74,82)	(34,37,41)
R_2	(115,117,120)	(75,78,80)	(0,0,0)	(67,74,81)	(44,49,56)	(78,80,82)	(50,55,60)	(85,87,90)	(36,42,46)
R_3	(50,52,56)	(55,61,66)	(67,74,81)	(0,0,0)	(75,82,90)	(33,38,43)	(56,62,69)	(83,88,90)	(88,92,95)
R_4	(32,36,40)	(37,42,46)	(44,49,56)	(75,82,90)	(0,0,0)	(75,86,90)	(64,70,79)	(55,61,67)	(76,83,89)
R_5	(81,83,87)	(87,89,90)	(78,80,82)	(33,38,43)	(75,86,90)	(0,0,0)	(55,61,67)	(36,42,46)	(81,83,91)
R_6	(52,55,54)	(44,47,51)	(50,55,60)	(56,62,69)	(64,70,79)	(55,61,67)	(0,0,0)	(50,56,61)	(36,42,48)
R_7	(98,100,104)	(67,74,82)	(85,87,90)	(83,88,90)	(55,61,67)	(36,42,46)	(50,56,61)	(0,0,0)	(61,68,74)
R_8	(33,36,37)	(34,37,41)	(36,42,46)	(88,92,95)	(76,83,89)	(81,83,91)	(36,42,48)	(61,68,74)	(0,0,0)

Table 6: The unit mass transportation risks among manufacturer and retailers at the fourth time interval($\times 10^{-7}$)

	M	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
M	(0,0,0)	(63,75,79)	(24,28,32)	(27,35,39)	(48,55,66)	(19,23,26)	(18,22,26)	(54,61,65)	(21,26,29)
R_1	(63,75,79)	(0,0,0)	(15,24,31)	(49,58,62)	(16,26,32)	(61,68,71)	(49,57,61)	(31,45,57)	(20,29,41)
R_2	(24,28,32)	(15,24,31)	(0,0,0)	(31,45,57)	(39,45,48)	(27,39,49)	(22,33,41)	(25,36,48)	(16,26,32)
R_3	(27,35,39)	(49,58,62)	(31,45,57)	(0,0,0)	(34,49,62)	(15,23,29)	(38,45,48)	(24,35,46)	(27,40,49)
R_4	(48,55,66)	(16,26,32)	(39,45,48)	(34,49,62)	(0,0,0)	(34,39,41)	(54,59,62)	(25,36,46)	(26,39,48)
R_5	(19,23,26)	(61,68,71)	(27,39,49)	(15,23,29)	(34,39,41)	(0,0,0)	(25,36,46)	(16,26,32)	(24,33,42)
R_6	(18,22,26)	(49,57,61)	(22,33,41)	(38,45,48)	(54,59,62)	(25,36,46)	(0,0,0)	(22,33,42)	(16,26,33)
R_7	(54,61,65)	(31,45,57)	(25,36,48)	(24,35,46)	(25,36,46)	(16,26,32)	(22,33,42)	(0,0,0)	(27,41,52)
R_8	(21,26,29)	(20,29,41)	(16,26,32)	(27,40,49)	(26,39,48)	(24,33,42)	(16,26,33)	(27,41,52)	(0,0,0)

Set $\lambda = 0.2$, *pop_size*=200, P_c=0.8 and P_m=0.2. By running the proposed algorithm, we obtain the result as follows: the departure time at manufacturer is 9:00, and transportation route is $1 \to 9 \to 5 \to 2 \to 8 \to 6 \to 4 \to 3 \to 7 \to 1$. The minimum transportation risk is 221.4282. Fig.4 shows the convergence process. And we have also calculated the the departure time and departure cargo quantity at manufacturer or retailers, which are shown in Table 8. It is found that the transportation route goes through three time intervals including 9:00-11:00, 11:00-13:00 and 13:00-16:00, and most of the cargos are transported during off-peak time intervals, which leads to minimal risk. In reality, the departure time at manufacturer is usually arranged in a specified time window due to the actual situation, we can also calculate the corresponding results (see Table 9).

Table 7: The unit mass transportation risks among manufacturer and retailers at the fifth time interval ($\times 10^{-7}$)

	M	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
M	(0,0,0)	(50,52,55)	(58,60,62)	(150,152,155)	(53,55,58)	(93,96,98)	(52,55,57)	(93,96,98)	(43,45,48)
R_1	(50,52,55)	(0,0,0)	(79,81,86)	(45,67,82)	(30,46,57)	(45,68,83)	(65,67,86)	(75,82,102)	(36,55,73)
R_2	(58,60,62)	(79,81,86)	(0,0,0)	(55,82,101)	(36,54,70)	(83,81,88)	(41,61,75)	(89,87,90)	(30,46,57)
R_3	(150,152,155)	(45,67,82)	(55,82,101)	(0,0,0)	(62,91,112)	(27,42,53)	(126,128,136)	(44,64,82)	(110,112,118)
R_4	(53,55,58)	(30,46,57)	(36,54,70)	(62,91,112)	(0,0,0)	(62,91,112)	(53,77,98)	(85,87,89)	(46,70,86)
R_5	(93,96,98)	(45,68,83)	(83,81,88)	(27,42,53)	(62,91,112)	(0,0,0)	(45,67,83)	(60,66,77)	(82,82,86)
R_6	(52,55,57)	(65,67,86)	(41,61,75)	(126,128,136)	(53,77,98)	(45,67,83)	(0,0,0)	(61,62,76)	(60,66,70)
R_7	(93,96,98)	(75,82,102)	(89,87,90)	(44,64,82)	(85,87,89)	(60,66,77)	(61,62,76)	(0,0,0)	(50,75,92)
R_8	(43,45,48)	(36,55,73)	(30,46,57)	(110,112,118)	(46,70,86)	(82,82,86)	(60,66,70)	(50,75,92)	(0,0,0)

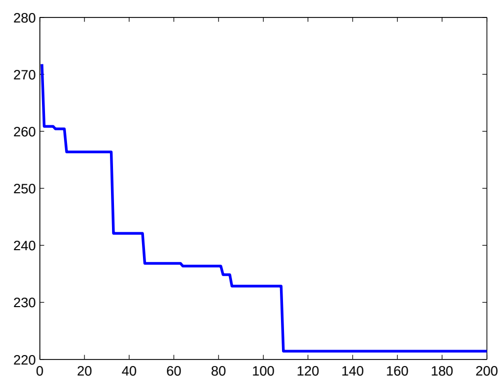

Figure 4: Convergence curve of GA

Table 8: The departure time and departure cargo quantity at manufacturer or retailers

transportation route	1	9	5	2	8	6	4	3	7
the departure time at manufacturer/retailers	9:00	9:21	9:52	10:21	10.51	11.44	12.59	13:26	14:04
departure cargo quantity at manufacturer/retailers	11.7	10.6	7.9	5.7	3.7	2.7	1.3	0.5	0

Table 9: The results of the departure time in specified departure time

specified departure time window	the departure time at manufacturer	transportation route	risk
7:00-9:00	9:00	$1 \to 9 \to 5 \to 2 \to 8 \to 6 \to 4 \to 3 \to 7 \to 1$	221.4282
9:00-11:00	9:19	$1 \to 9 \to 5 \to 2 \to 8 \to 6 \to 4 \to 3 \to 7 \to 1$	226.3290
11:00-13:00	13:00	$1 \to 9 \to 5 \to 2 \to 8 \to 3 \to 4 \to 6 \to 7 \to 1$	297.4423
13:00-16:00	14:58	$1 \to 9 \to 2 \to 5 \to 3 \to 6 \to 8 \to 7 \to 4 \to 1$	269.6925
16:00-19:00	-	-	-

However, if the risk on the arc is considered as a fixed value in one day, we usually take the average risk of the arc in one day as its risk. We can calculate the unit mass average transportation risk (see Tables 10). The result with time-fixed transportation risk is also shown in Table 11. Comparing with the result arising from time-dependent risk, it is found that the transportation route is different, and the time-dependent model could reduce risk around 42%. The example tells us that consideration on variable vehicle departure time could significantly reduce the risk. Therefore, we choose the time-dependent model to solve this hazardous materials VRP.

Table 10: The unit mass average transportation risks among manufacturer and retailers ($\times 10^{-7}$)

	M	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
M	(0,0,0)	(51,57,60)	(57,60,63)	(63,68,71)	(48,51,56)	(52,54,58)	(42,45,47)	(67,71,75)	(43,47,50)
R_1	(51,57,60)	(0,0,0)	(47,51,56)	(45,55,61)	(26,34,40)	(55,63,67)	(54,58,65)	(48,54,64)	(38,45,54)
R_1	(57,60,63)	(47,51,56)	(0,0,0)	(50,60,70)	(43,51,58)	(59,63,69)	(36,44,51)	(54,58,64)	(30,38,44)
R_1	(63,68,71)	(45,55,61)	(50,60,70)	(0,0,0)	(54,66,77)	(24,31,37)	(59,63,69)	(44,52,59)	(60,66,72)
R_1	(48,51,56)	(26,34,40)	(43,51,58)	(54,66,77)	(0,0,0)	(54,63,70)	(57,65,73)	(45,50,55)	(38,48,55)
R_1	(52,54,58)	(55,63,67)	(59,63,69)	(24,31,37)	(54,63,70)	(0,0,0)	(39,49,57)	(32,38,44)	(57,60,66)
R_1	(42,45,47)	(54,58,65)	(36,44,51)	(59,63,69)	(57,65,73)	(39,49,57)	(0,0,0)	(37,42,48)	(32,38,43)
R_1	(67,71,75)	(48,54,64)	(54,58,64)	(44,52,59)	(45,50,55)	(32,38,44)	(37,42,48)	(0,0,0)	(43,53,61)
R_1	(43,47,50)	(38,45,54)	(30,38,44)	(60,66,72)	(38,48,55)	(57,60,66)	(32,38,43)	(43,53,61)	(0,0,0)

Table 11: Comparisons between time-dependent model and time-fixed model

	the departure time at manufacturer	transportation route	risk
time-dependent model	9:00	$1 \to 9 \to 5 \to 2 \to 8 \to 6 \to 4 \to 3 \to 7 \to 1$	221.4282
time-fixed model	7:00-14:00	$1 \to 9 \to 5 \to 2 \to 8 \to 4 \to 3 \to 7 \to 6 \to 1$	383.5057

5 Conclusion

In this study, a time-dependent hazardous materials vehicle routing problem was studied under fuzzy transportation risk. The objective was to obtain the optimal route and the departure time for hazardous materials transportation. First, we formulated a time-dependent risk measure for hazardous materials transportation. Then, we proposed a credibilistic mixed integer programming model and designed an improved genetic algorithm whose chromosomes contain two types of genes to search a satisfactory solution.

Future research may be conducted in several directions. First, more real-life factors will be considered, such as multiple objects, multiple periods, time windows, and more flexible distribution modes. Furthermore, we will perfect the credibilistic mixed integer programming model for hazardous materials supply chain management via adding production risk and inventory risk.

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