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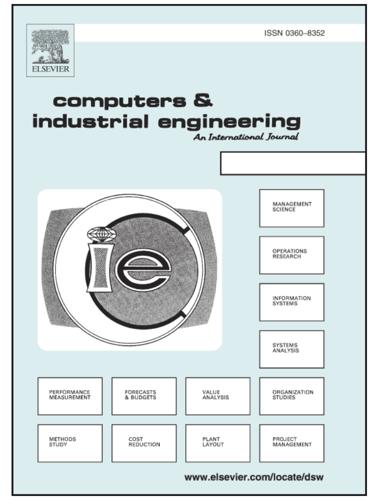

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Multi-objective Location-Routing Model for Hazardous Material Logistics with Traffic Restriction Constraint in Inter-city Roads

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Abstract

Effective solutions to the hazardous material location and routing problem are of practical significance, for both logistics companies and government departments. However, most existing hazardous material location and routing studies lack certain practicabilities in dealing with real-life problems. In this paper, we present a novel multi-objective optimization method for finding the optimal routes in hazardous material logistics under the constraint of traffic restrictions in inter-city roads. In addition, to move the solution method closer to practical application, we propose to consider multiple paths between every possible origin-destination pair. The resulting multi-objective location-routing model is able to jointly address the important aspects of risk, cost, and customer satisfaction in hazardous material logistics management. A single genetic algorithm and an adaptive weight genetic algorithm are proposed to solve the proposed model respectively, whose chromosomes contain two types of genes, representing warehouses and transportation routes respectively. A real-world case study is provided to illustrate the efficacy of the proposed model and its associated solution method.

Keywords: Hazardous material logistics, Location-routing model, Traffic restriction constraint, Adaptive weight genetic algorithms

1. Introduction

Logistics management of hazardous materials (hydrocarbons, explosives, chemicals, etc.) has become a problem of major concern for countries throughout the world. Large quantities of hazardous materials are frequently transported routinely. In China, it is estimated that approximately 200 million tons of hazardous chemicals are being transported annually, and those carried out through road transportation account for 80%. The main difference bet en hazardous material logistics and logistics for other types of material or goods is the high risk associated with an incident during any improper operation, storage, transportation and disposal, which may seriously imperil people, property and the environment. To understand the magnitude of the problem, we note that between 2011 and 2015, 1058 hazardous chemicals incidents with 1375 deaths have been reported in China by the State Administration of Work Safety. In particular, 35.4% of the aforementioned incidents occurred on road and 11.2% happened in warehouse storage.

As indicated above, transportation and storage operations have a high accident rate in hazardous material logistics. Clearly, arranging transportation routes and selecting warehouse locations properly can significantly reduce the risk of such incidents and their potential adverse impact upon environmental and social aspects. Furthermore, warehouse

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locations directly influence the routing options available whilst any particular routes may in turn, affect the determination of the locations of potential warehouse. Thus, correctly modelling the location-routing problem (LRP) can be an effective means to mitigate the transportation risk and warehouse site risk simultaneously.

Hazardous material logistics problem is a special type of freight logistics problem. In order to reduce risk associated with hazardous material logistics, national and provincial governments generally forbid vehicles carrying hazardous materials to pass certain road segments in inter-city roads. For example, according to the traffic restriction scheme imposed by the Shandong Provincial Department of Transportation (of China), the hazardous material vehicles are banned crossing the expressways from 19:00 p.m to 6:00 a.m. The governments also typically set temporary traffic restrictions on certain roads for hazardous material vehicles during a festival, a conference, an extreme weather or road construction. Traffic restriction for hazardous materials vehicles will generally increase the logistics cost of hazardous materials enterprises and reduce their logistics efficiency. In response to such unfavorable situations, hazardous material companies have increasingly placed their attention on the scheduling of transportation routes. To aid in dealing with this important issue, in an effort to obtain reliable solutions for real life applications to the problem of hazardous material logistics management, we focus this study on the consideration of traffic restriction constraint in inter-city roads.

The LRPs are generally treated via the representation of the road network as a weighted complete graph. Each arc of the graph represents the path for a possible origin-destination pair. Traditional logistics studies typically assume that there is one and only one path from each origin to each destination, which contradicts with the reality on road network, since for each pair of origin-destination, there are generally multiple links. Akgün et al. (2000) proposed that it was usually necessary to consider alternative paths and evaluate them under given criteria as a multi-objective programming. When addressing alternative paths with respect to different criteria, a carrier can switch among the paths according to different objectives. For example, the carrier may prefer a cheaper itinerary in case where transportation time is non-critical, even though there is a minimal-time path between the two nodes expressing the origin and the destination. In this paper, we propose to consider alternative paths between every possible origin-destination pair, where paths are chosen subject to three different criteria characterizing the alternatives in the road network: transportation risk, transportation cost and transportation time. In addition, inspired by the work of Wei et al. (2015a), these three criteria are considered as time-dependent variables instead of being assumed to be constant, whose values are dependent upon the departure time. Of course, different start times of transporting usually imply the choice of different “optimal” routes for a hazardous material vehicle. This is dealt with in this work also.

In reality, apart from traffic restrictions and alternative paths for each origin to each destination, time windows should be considered as an important constraining factor in hazardous material logistics, which is highly relevant to customer experience and satisfaction. The prevailing studies involve the use of two types of time window, hard or soft. When a hard time window is used, a vehicle that arrives too early at a customer must wait until the customer is ready for service. This is because hard time windows refer to a strict time interval that a servicing vehicle can not violate when visiting a customer. While in the case of using a soft time window, every time window may be violated barring a penalty cost. For hazardous material transportation, long-haul transportation accounts for more than 95%. Therefore, modelling the customer satisfaction issues is a natural idea. In this paper, the customer satisfaction level is associated with the arrival time at each customer, and the approach of enabling soft time windows is adopted.

The key contributions of this paper are: i) it presents a novel approach to considering the influence of traffic restrictions on the hazardous chemical logistics, focusing on the presence of traffic conditions on real road networks, including traffic restrictions in inter-city roads; ii) it formulates a multi-objective model with soft time windows for hazardous material logistics while considering alternative paths between every possible origin-destination pair. The remainder of this paper is organized as follows. Section 2 provides an overview of the relevant literature on hazardous material logistics. The problem tackled is formulated in Section 3. The proposed techniques to solve the formulated problem are discussed in Section 4. A case study of our approach is summarized in Section 5. Finally, Section 6 provides concluding remarks and briefly discusses further work.

2. Related work

Existing studies about hazardous material logistics management can generally be classified into the following groups: risk assessment (Patel et al., 1994; Erkut and Ingolfsson, 2005; Cordeiro et al., 2016), network design (Kara and Verter, 2004; Verter and Kara, 2008; Bianco et al., 2009; Chiou, 2017), routing (Sherali et al., 1997; Akgün et al., 2000; Dadkar et al., 2008; Du et al., 2016; Garrido and Bronfman, 2016; Du et al., 2017; Hu et al., 2017a), routing and scheduling (Nozick et al., 1997; Chang et al., 2005; Androutsopoulos and Zografos, 2010; Wei et al., 2015a; Fang et al., 2017), location and routing (Helander and Melachrinoudis, 1997; Cappanera et al., 2003; Alumur and Kara, 2007; Wei et al., 2015b), inventory and routing (Hu et al., 2017b). In the following, only the most relevant streams of LRP studies about hazardous material logistics management are reviewed.

One earliest representative LRP about hazardous material logistics management was conducted by Revelle (1991). The model simultaneously located the warehouses and selected routes for the spent nuclear fuel shipments, minimizing the total cost and total risk of transportation using a weighting method of multi-objective programming. List and Mirchandani (1991) proposed a hazardous material location-routing model that simultaneously considered total zone risk (transportation and treatment risk), total transportation cost, and risk equity, where the risk equity was measured as the maximum zone risk per unit population. Cappanera et al. (2003) developed a discrete LRP model that jointly minimized the transportation cost and facility establishment cost, with an aim to obtain the optimal number of facilities. In that work, an effective Branch and Bound algorithm was presented to deal with the Obnoxious Facility Location and Routing problem.

Recently, Alumur and Kara (2007) presented a multi-objective model for hazardous waste LRP, attempting to minimize the total cost and transportation risk, by employing a linear composite objective function to solve such a multi-objective model. The model was implemented in the Central Anatolian region of Turkey by the use of the software CPLEX. This work helped determination of technologies and locations of treatment centers, locations of disposal centers, routing of different types of waste to treatment centers (with compatible technologies), and routing of waste residues to disposal centers. Following which, Samanlioglu (2013) further studied the hazardous waste management problem. In addition to treatment centers and disposal centers, recycling centers were also incorporated in this continued study. In the mathematical model underlying this further development, three criteria were considered, respectively minimizing: the total cost, the total transportation risk and the total site risk. In particular, a lexicographic weighted Tchebycheff formulation was developed to find representative efficient solutions with the assistance of CPLEX.

Most recently, Mahmoudabadi and Seyedhosseini (2013) developed a bi-level programming and proposed a trade-off between cost and risk to determine the safest paths for hazardous material transportation as well as the best locations of distribution centers. With the assumptions that the transportation cost and the number of potentially affected people were imprecisely described (using fuzzy variables), Wei et al. (2015b) proposed a chance-constrained programming model that produced an optimized balance between the transportation risk and cost. To solve such a multi-objective problem, they designed a fuzzy simulation-based genetic algorithm. Weckman (2015) proposed a bi-objective model to handle the uncertainty in describing the transportation, location, and allocation of hazardous materials, where the transportation cost was assumed to be a stochastic variable. In this work, the objective function was set to minimize the weighted sum of the total cost and risk of locating facilities and transportation. A novel genetic algorithm with its chromosomes being represented as a two-dimensional matrix was applied to solve the mathematical model. Hu et al. (2017a) considered a time-dependent hazardous material vehicle routing problem within a two-echelon supply chain system, and designed an improved genetic algorithm whose chromosomes may contain two types of gene. With the assumptions that the demands of retailers are uncertain, Hu et al. (2017b) reported a credibilistic programming model in order to minimize the positive deviations of expected risk and expected cost from the given risk level and cost level. Again, an improved genetic algorithm whose chromosomes involved two types of gene was created to implement the proposed model.

The aforementioned approaches have collectively made significant progress towards finding useful solutions to hazardous material LRPs. However, a common deficiency of the existing literature is that the models usually lack the practicability in complex real-life settings. For example, traffic restrictions in inter-city roads on vehicles carrying hazardous material are not taken into account. Whilst hazardous material logistics is a special type of freight logistics, accidents involving hazardous material generally cause terrible consequences, including serious traffic jams, which are difficult to take emergency rescue and accident disposal. Therefore, governments usually take traffic restriction measures to reduce the transportation risk by banning hazardous material vehicles on certain roads in specified times. For instance, in China, there are 13 provinces (including selected municipalities and autonomous regions) that impose restrictions on time and roads or completely ban on hazardous material vehicles. Further to the examples given previously regarding the restrictions introduced by Shandong province, prohibiting any hazardous material vehicles from passing through its expressway, Hebei, Jilin and Henan provinces among others, all implement a similar restriction scheme. Thus, considering the traffic restriction constraint cannot be ignored in order to perform a realistic optimization. Instead, such consideration will help obtain a more reliable solution. Inspired by this observation, this paper presents a novel approach for addressing the hazardous materials LRP, with a focus on traffic restriction constraint imposed in inter-city roads.

Another common limitation of the above outlined approaches is that they consider one and only one path, e.g., the shortest path for each possible origin-destination pair. This simplifies the computational process, but does not appropriately reflect real-life situations. Searching for a number of alternative paths is obviously useful in selecting routes for hazardous material transportation. For example, when the optimal route becomes infeasible in the case of adverse weather conditions or road construction, the carrier can choose a suboptimal route. Akgün et al. (2000) and Dell'Olmo et al. (2005) considered the problem of finding a set of alternative paths with different criteria between an origin and a destination. However, their work is extremely simplified by considering merely two nodes in a road network. Garaix et al. (2010) addressed a vehicle routing problem with alternative paths and applied the resultant technique to a real-world dial-a-ride problem in the French Doubs Central area. Yet, there is no work on LRP concerning the alternative paths between every possible origin-destination pair. In this paper, we consider such situations where there are alternative paths for each possible origin-destination pair, and three constraining attributes of transportation risk, transportation time and transportation cost have to be satisfied. Furthermore, all of these constraints are assumed to be time-dependent.

In the current literature, the minimization of cost and tthat of risk are the most commonly employed objectives to determine the best routes and optimized locations. However, other than cost and risk, customer satisfaction level also plays a significant role in making effective routing decisions and this should be maximized. This is because in hazardous material logistics vehicles are often routed according to a certain customer time window (due to their work time constraints for instance), especially regarding long-haul transportation (Rancourt et al., 2013), which is highly relevant to customer satisfaction level.

Generally speaking, service occurring within the customer desirable time window would generate a high satisfaction level as opposed to a degraded customer satisfaction level if service takes place earlier or most detrimentally later than expected (Barkaoui et al., 2015). Andreatta et al. (2016) discussed how the expected penalty cost might be evaluated and how this computation could be integrated in a branch-and-price procedure to obtain heuristic solutions in the vehicle routing problem with hard time windows. Yuichi et al. (2010) presented an effective algorithm for the vehicle routing problem involving time windows, with the introduction of a novel penalty function to eliminate any violation of the hard time window constraint. Iqbal et al. (2015) put forward a new model for a multi-objective vehicle routing problem where soft time windows are involved, by adding penalty terms to the solution cost whenever a vehicle serves a customer outside of a specified time window. Tang et al. (2009) applied fuzzy membership functions to characterize issues regarding customer penalty cost that may be due to time window violations, in a vehicle routing problem. As exampled by these existing works, LRPs with time windows are frequently dealt with. Unfortunately, customer satisfaction levels are not often treated as an objective function. Customer satisfaction is therefore, considered as one of the optimization objectives in this work. Having taken notice that customers usually offer multiple delivery times in long-haul transportation (Rancourt et al., 2013), we adapt multiple soft time windows in response to their individual demands instead of just a single hard or soft time window.

3. Problem description

In this section, a generic transportation network in which there are more than one alternative path between every possible origin-destination pair node is considered. Suppose that the potential sites for warehouses with different rents and capacities have already been identified. A fleet of vehicles of homogeneous capacity are assigned to service the customers with known demands and soft time windows. The problem herein addressed consists of: (a) renting a subset of warehouses; (b) assigning customers to these rented warehouses; and (c) determining a route for each group of warehouse and customers. To simplify the modelling of the problem, we assume that: 1) each vehicle originates and terminates at (i.e., returns to) the same warehouse, and each warehouse has only one vehicle for transportation service; 2) each vehicle departs from warehouse in a fixed departure time; 3) each customer must be visited once and only once, and the demand of each customer must be satisfied; 4) the transportation risk in each route is defined by the risk generated by the full load of the vehicle.

In the proposed hazardous material logistics problem, three criteria are considered: (a) minimizing the total risk, which includes site risk for the population around warehouses and transportation risk related to the population exposure along the paths; (b) minimizing the total cost, which includes warehouses rent and transportation cost; and (c) maximizing the satisfaction level for customers. An important constraint is the traffic restriction imposed in inter-city roads, which is absent in traditional hazardous material logistics studies. The frame of the proposed hazardous material logistics problem is illustrated in Fig. 1. For conciseness and comprehensibility, the notations we used are listed in Table 1.

[Please insert Figure 1 here]
[Please insert Table 1 here]

3.1. Customer satisfaction model

In the transportation business, a given time window $[e, l]$ is not always strictly obeyed and the deviation of service time from the customer-specified time window determines the customer's satisfaction level. For decision makers, a little earliness or lateness for some customers is acceptable in order to obtain an overall executable delivery plan. However, there exist certain bounds on the violation that a customer can endure. Tang et al. (2009) introduced two concepts to describe these bounds. Endurable earliness time t_1 is the earliest service time that a customer can endure when a service starts earlier than t_2 (t_2=e). Endurable lateness time t_4 is the latest service time that a customer can endure when a service starts later than t_3 (t_3= l). With the introduced concepts of t_1 and t_4, the satisfaction level for each customer can be described by a trapezoidal piecewise function, and the corresponding time window is a soft time window.

In addition, customers usually offer a choice of delivery periods due to their work time in real-world settings, especially commonly occurring in long-haul transportation. In this work, while multiple soft time windows are considered to be assigned to each customer, a single time window has to be chosen for each customer delivery. An example of customer satisfaction function with three soft time windows for customer i is shown in Fig. 2, for which the customer satisfaction function can be intuitively expressed as follows:

[Please insert Figure 2 here]

$$\varphi_i(a_i) = \begin{cases} 0, & \text{if } a_i \le t_{i1}^p \\ \dfrac{a_i - t_{i1}^p}{t_{i2}^p - t_{i1}^p}, & \text{if } t_{i1}^p \le a_i \le t_{i2}^p \\ 1, & \text{if } t_{i2}^p \le a_i \le t_{i3}^p \\ \dfrac{t_{i4}^p - a_i}{t_{i4}^p - t_{i3}^p}, & \text{if } t_{i3}^p \le a_i \le t_{i4}^p \\ 0, & \text{if } t_{i4}^p \le a_i \end{cases} \tag{1}$$

where $p = 1, 2, 3$. As can be seen from Fig. 2, for each soft time window, the customer satisfaction level may run at 100% which a service occurring within their desired time interval, as opposed to a degraded customer satisfaction level as service takes place earlier or later than expected. Reflecting this underlying intuitive design intention, the customer average satisfaction level is herein defined by

$$S = \frac{1}{|N_c|} \sum_{i \in N_c} \varphi_i \ . \tag{2}$$

3.2. Risk model

An important objective for hazardous material logistics is to control risk. There are plenty of risk criteria in the existing literature. Choosing different risk criteria normally leads to different solutions. The most popular criteria are perhaps, population exposure (the number of people exposed to hazardous materials) and societal risk (the probability of a hazardous material accident multiplied by the possible consequences). The risk criterion used in this study is the social risk, which has been taken by Erkut and Ingolfsson (2000) and Chang et al. (2005).

In general, possible consequences associated with an accident may include risk facing people and properties in the surrounding areas among other factors. In this work, a consequence is defined by the number of people may be at risk. The transportation risk on an arc can be determined as a function of the estimated incident probability and the number of people may be at risk along this arc, which is given by the following formula:

$$R^k_{ij}(u_i) = P^k_{ij}(u_i)\rho^k_{ij}(u_i). \tag{3}$$

Note that $R^k_{im}(u_i) \equiv 0$. It means that there is no transportation risk on the return path to warehouse due to no-loading.

Obviously, the number of people exposed to the transportation risk may vary during different parts of the day due to the daily mobility of the people. Taking into account the impact of population density upon traffic congestion, the cargo transport time is usually depicted using five time intervals ($H_\tau = \{H_1, H_2, H_3, H_4, H_5\}$) corresponding to the traffic peak and off-peak hours during each day. Thus, the number of people may be at risk between any pair of nodes is expressed as a function of the departure time (see Table 1 for notations):

$$\rho^k_{ij}(u_i) = \begin{cases} \mu^{k1}_{ij}, & \text{if } u_i \in H_1 \\ \mu^{k2}_{ij}, & \text{if } u_i \in H_2 \\ \mu^{k3}_{ij}, & \text{if } u_i \in H_3 \\ \mu^{k4}_{ij}, & \text{if } u_i \in H_4 \\ \mu^{k5}_{ij}, & \text{if } u_i \in H_5. \end{cases} \tag{4}$$

The warehouse site risk is defined in a similar way, as a function of the incident probability and the number of people may be at risk around the warehouse, such that

$$R_m = \rho_m P_m. \tag{5}$$

This reflects the observation that warehouses are often located in remote areas and the pedestrian flow volume around these warehouses is low, therefore, the number of people may be at risk around the warehouse is relatively constant.

A key objective of the proposed hazardous material logistics studies is to minimize the total risk, including the total site risk and total transportation risk (in addition to minimizing the costs and maximizing the customer satisfaction level). Thus, the total risk can be defined by

$$R = \sum_{m \in N_w} R_m y_m + \sum_{u_i \in H_t} \sum_{k \in K_{ij}} \sum_{(i,j) \in A} R^k_{ij}(u_i) x^k_{ij}. \tag{6}$$

3.3. Cost model

Apart from the consideration of risk, decision makers are naturally in the pursuit of their economic benefits by lowering the potential cost owing to their strategic and operational decisions. Another key objective is cost, which contains warehouse rent and transportation cost, with the transportation cost consisting of two parts: fuel charge and toll. Thus, we can define the following (again, see Table 1 for notations):

$$C = \sum_{m \in N_w} C_m y_m + \sum_{u_i \in H_\tau} \sum_{k \in K_{ij}} \sum_{(i,j) \in A} [\varepsilon F_{ij}^k(u_i) + \bar{C}_{ij}^k] x_{ij}^k. \tag{7}$$

In China, both state and local governments impose tolls to all sorts of vehicles, and different specifications are charged differently. In terms of fuel charges, we use the general format of the vehicle fuel consumption function that has been reported in 'Road Vehicle Emission Factors 2009', namely,

$$F_{ij}^k(u_i) = k(a + bV_{ij}^k(u_i) + c(V_{ij}^k(u_i))^2 + d(V_{ij}^k(u_i))^3 + e(V_{ij}^k(u_i))^4 + f(V_{ij}^k(u_i))^5 + g(V_{ij}^k(u_i))^6)/(V_{ij}^k(u_i)). \tag{8}$$

Also, the delivery speed varies with respect to the departure time of the day since the traffic conditions vary throughout the day, thus, it is a time-dependent factor:

$$V_{ij}^k(u_i) = \begin{cases} \alpha_{ij}^{k1}, & u_i \in H_1 \\ \alpha_{ij}^{k2}, & u_i \in H_2 \\ \alpha_{ij}^{k3}, & u_i \in H_3 \\ \alpha_{ij}^{k4}, & u_i \in H_4 \\ \alpha_{ij}^{k5}, & u_i \in H_5. \end{cases} \tag{9}$$

3.4. Mathematical formulation

Putting the above discussions and intuitive definitions together, the overall optimization problem can be summarized as follows:

$$\min \quad R = \sum_{m \in N_w} R_m y_m + \sum_{u_i \in H_\iota} \sum_{k \in K_{ij}} \sum_{(i,j) \in A} R_{ij}^k(u_i) x_{ij}^k \tag{10}$$

$$\min \quad C = \sum_{m \in N_w} C_m y_m + \sum_{u_i \in H_\tau} \sum_{k \in K_{ij}} \sum_{(i,j) \in A} [\varepsilon F_{ij}^k(u_i) + \bar{C}_{ij}^k] x_{ij}^k \tag{11}$$

$$\max \quad S = \frac{1}{|N_c|} \sum_{i \in N_c} \varphi_i \tag{12}$$

$$\text{s. t.} \quad \sum_{m \in N_w} z_{im} = 1, \quad \forall i \in N_c \tag{13}$$

$$\sum_{k \in K_{ij}} \sum_{i \in N} x_{ij}^k = 1, \quad \forall j \in N_c \tag{14}$$

$$\sum_{k \in K_{ij}} \sum_{j \in N} x_{ij}^k - \sum_{k \in K_{ij}} \sum_{j \in N} x_{ji}^k = 0, \quad \forall i \in N \tag{15}$$

$$\sum_{k \in K_{ij}} \sum_{(i,j) \in A^*} x_{ij}^k = |A^*| - 1, \quad \forall A^* \subseteq A, \ |A^*| \geq 2 \tag{16}$$

$$\sum_{k \in K_{im}} x_{im}^k \leq y_m z_{im}, \quad \forall i \in N_c, \ m \in N_w \tag{17}$$

$$\sum_{i \in N_c} d_i z_{im} \leq Q_m y_m, \quad \forall m \in N_w \tag{18}$$

$$a_j \geq \left(u_i + \sum_{k \in K_{ij}} \frac{D_{ij}^k}{V_{ij}^k(u_i)} \right) - \left(1 - \sum_{k \in K_{ij}} x_{ij}^k \right) M, \quad \forall i, j \in N \tag{19}$$

$$a_j \leq \left(u_i + \sum_{k \in K_{ij}} \frac{D_{ij}^k}{V_{ij}^k(u_i)}\right) + \left(1 - \sum_{k \in K_{ij}} x_{ij}^k\right) M, \quad \forall i, j \in N \tag{20}$$

$$u_i = a_i + s_i, \quad \forall i \in N_c \tag{21}$$

$$x_{ij}^k \leq sgn\left(|(u_i - pt_{ij}^{k1})(pt_{ij}^{k2} - u_i)| - (u_i - pt_{ij}^{k1})(pt_{ij}^{k2} - u_i)\right) \tag{22}$$

$$x_{ij}^k \in \{0, 1\}, \quad \forall (i, j) \in A, \ k \in K_{ij} \tag{23}$$

$$y_m \in \{0, 1\}, \quad \forall m \in N_w \tag{24}$$

$$z_{im} \in \{0, 1\}, \quad \forall m \in N_w, \ i \in N_c \tag{25}$$

where M is a sufficiently large constant. In particular, Constraint (13) ensures that each customer is assigned to only one warehouse. Constraint (14) guarantees that each customer must be visited exactly once. Constraint (15) imposes a flow balance for each node. Constraint (16) ensures sub-tour elimination. Constraint (17) presents route requirements for warehouse and customers. Constraint (18) describes the capacity limit for warehouse. Constraints (19)-(20) are those imposed over time; if the arc from node i to node j is selected, the value in the bracket which is multiplied by M is equal to zero, and the two inequalities convert to the same equation; otherwise, that value is equal to one, and the inequalities hold. Constraint (21) expresses that the required relationships among the arrival time, departure time and service time with respect to each customer. Constraint (22) is the traffic restriction constraint, which means that the k-th route from node i to node j is restricted if and only if the departure time $u_i \in [pt_{ij}^{k1}, pt_{ij}^{k2}]$. Constraints (23)-(25) define the domains of the decision variables.

4. Optimization algorithm

The above-formulated LRP is essentially a multiple traveling salesman problem (MTSP) regarding warehouse and customer locations. As with classical TSP, MTSP is NP-hard. Gavish and Srikanth (1986) proposed a branch-and-bound algorithm for solving problems involving large-scale symmetric MTSP instances. After that, many researchers have attempted to use deterministic methods to solve such problems, but the results are generally unsatisfactory (Bektas, 2006). Due to their combinatorial complexity, more and more researchers have chosen heuristic algorithms to find solutions (e.g., Laporte, 1992; Yuan et al., 2013). Genetic algorithm offers a stochastic search mechanism mimicing the characteristics of natural selection and genetics. They are commonly used to generate high-quality solutions for optimization and search problems by relying on bio-inspired operators such as mutation, crossover and selection. In particular, they are widely exploited in location and routing problems (Gen and Syarif, 2005; Weckman et al., 2015).

In the following section, a simple genetic algorithm is proposed to solve the proposed compromise model, to demonstrates the efficiency of considering the real-life aspects. Then, we design a adaptive weight genetic algorithm to obtain the Pareto solution of the problem. The questions attempted to solve in this algorithm are: (1) where to rent the warehouses; (2) to which warehouse every customer should be assigned; (3) which route a warehouse should choose to serve the customers; and (4) which arc should be chosen between the two nodes in transportation route.

4.1. A simple genetic algorithm

As the proposed model is multi-objective, in this section, we can apply the weighted compromise method to solve it, which is the most common multi-objective optimization mechanism adopted in hazardous material logistic management. The weight coefficients would be determined by the decision makers according to the category and danger classes of hazardous materials. The following outlines the principal steps in solving this problem. First, normalization is performed on the given objectives. Let $R_{\max}$, $R_{\min}$, $C_{\max}$, $C_{\min}$, $S^*_{\max}$, and $S^*_{\min}$ denote the maximum and minimum values for R, C and S^*, respectively, then the normalized terms are

$$R' = \frac{R - R_{\min}}{R_{\max} - R_{\min}}, \quad C' = \frac{C - C_{\min}}{C_{\max} - C_{\min}}, \quad S^{*'} = \frac{S^* - S^*_{\min}}{S^*_{\max} - S^*_{\min}}, \tag{26}$$

where $S^* = 1 - S$.

Next, given pre-specified parameter λ_1, λ_2, and λ_3, the multi-objective function is transformed into a compromise single objective function as follows:

$$\min \qquad \lambda_1 R^{'} + \lambda_2 C^{'} + \lambda_3 S^{*'}. \tag{27}$$

4.1.1. Representation scheme

A solution to the current problem consists of a service order of warehouses and a choice of transportation path. Without losing generality, suppose that there are t warehouses and n customers. In this problem, we design each chromosome structure as $U = (c_1, c_2, ..., c_n; l_1, l_2, ..., , l_{n+t}; b_1, b_2, ..., b_{t-1})$, which contains the service order of the customers c_i, the choice of the transportation road l_j between certain two given nodes, and the customer piecewise points b_k in relation to different warehouse services (See Fig. 3).

[Please insert Figure 3 here]

4.1.2. Initialization process

Randomly generate a vector U_1. If U_1 that satisfies constraints (13)-(25) according to the mathematical model. This results in a feasible chromosome (i.e., a possible solution to the problem at hand). Obviously, repeat the random generation if any constraints is failed. Repeat the above process pop_size times. Denote the generated chromosomes as $U_1, U_2, ..., U_{pop\_size}$.

4.1.3. Evaluation function

Let U_i be a feasible chromosome. Calculate the normalized values $R^{'}$, $C^{'}$ and $S^{*'}$ to get the objective value $\lambda_1 R^{'} + \lambda_2 C^{'} + \lambda_3 S^{*'}$ together with the given coefficients λ_1, λ_2 and λ_3. This leads to the objective value of each of the pop_size chromosomes. Since a chromosome with a smaller objective value is better, reorder them according to the ascending rank of the objective value $\lambda_1 R^{'} + \lambda_2 C^{'} + \lambda_3 S^{*'}$, and define the evaluation function as follows:

$$Eval(U_i) = \theta(1-\theta)^{i-1}, \quad i = 1, 2, ..., pop\_size$$

where θ is a real number taking value in interval (0,1).

4.1.4. Selection process

The popular roulette wheel selection method is adopted here. For any $i = 1, 2, \cdots, pop\_size$, we calculate the cumulative q_i for U_j,

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

Generate a random number $r \in (0, q_{pop\_size}]$. Select the ith chromosome U_i if $q_i < r \leq q_{i+1}$. Repeat this process pop_size times, thereby obtaining an emerging population of pop_size chromosomes.

4.1.5. Crossover process

A parameter P_c is defined as the probability of crossover and based on it, chromosomes are divided into pairs. We introduce the specifically designed crossover operation for the present problem, applied to a pair of chromosomes U and U', as illustrated in Fig. 4 (where there are 3 warehouses and 9 customers). First, randomly select some genes in the chromosome U, as those pointed to by a blue arrow in the illustration. Then, in the chromosome U', we find these genes, as pointed to by a red arrow. Generate one child as the combination of blue-pointed genes in U and the rest of green genes in U', and generate another child as the combination of red-pointed genes in U' and the rest green genes in U. Meanwhile, exchange the piecewise points of chromosomes U and U'. Finally, find the optimal arc between any two nodes using enumeration method which enables a child to have the lowest objective value, and obtain chromosomes V and V', as shown in Fig. 4. Select two chromosomes from the parents and children with the smallest objective values to replace the parents.

[Please insert Figure 4 here]

4.1.6. Mutation process

Define a parameter P_m as the mutation probability and repeat the following process *pop_size* times. Randomly generate a number r_i in the unit interval [0,1]. If $r_i < P_m$, select the ith chromosome U_i to perform the mutation operation. For illustration, we continue to use the example where there are 3 warehouses and 9 customers. Randomly select 2 genes located on the chromosome U_i and swap their positions to obtain a possible child. Then, find the optimal arc between any two nodes using enumeration method which enables the child to have the lowest objective value, and return the chromosome U^*, as shown in Fig. 5. Finally, if U^* has a smaller objective value than U_i then replace U_i with U^*, else retain U_i.

[Please insert Figure 5 here]

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

4.2. Adaptive weight genetic algorithm

Gen et al. (2008) gave a detailed introduction to the application of genetic algorithm in network optimization problems, and summed up the typical multi-objective genetic algorithms according to proposed years of different approaches. Inspired by Gen's work, we design an Adaptive Weight Genetic Algorithm(AWGA) to solve the model. The characteristic of AWGA is re-adjusting the weights to obtain search pressure towards the ideal point using some useful information of the current population.

For the feasible chromosome, define two extreme points for the objectives at each generation as follows:

$$z_1^{\min} = \min\{R_i\}, z_2^{\min} = \min\{C_i\}, z_3^{\min} = \min\{S_i^*\},$$

$$z_1^{\max} = \max\{R_i\}, z_2^{\max} = \max\{C_i\}, z_3^{\max} = \max\{S_i^*\},$$

where $S_i^* = 1 - S_i, i = 1, 2, ..., pop\_size$. The weighted-sum fitness function (Gen et al. 2017) is chosen for a given chromosome U_i given by the following equation:

$$Eval(U_i) = \sum_{j=1}^{3} w_j(z_j - z_j^{\min}) = \sum_{j=1}^{3} \frac{z_j - z_j^{\min}}{z_j^{\max} - z_j^{\min}} = \frac{R_i - z_1^{\min}}{z_1^{\max} - z_1^{\min}} + \frac{C_i - z_2^{\min}}{z_2^{\max} - z_2^{\min}} + \frac{S_i^* - z_3^{\min}}{z_3^{\max} - z_3^{\min}} \tag{28}$$

where w_j is adaptive weight for the jth objective function as shown in the following equation:

$$w_j = \frac{1}{z_j^{\max} - z_j^{\min}}, j = 1, 2, 3.$$

Fig. 6 shows the general working procedure of a AWGA, involving the following steps, each of which (including the overall representation scheme) is briefly described with respect to the present application problem next:

Step 1. Randomly initialize *pop_size* chromosomes.
Step 2. Calculate fitness value using Eqn. (28) for each chromosome.
Step 3. Update the Pareto solution set.
Step 4. Spin the roulette wheel and select *pop_size* chromosomes.

Step 5. Update the chromosomes using both crossover operation of 4.1.5 and mutation operation of 4.1.6.
Step 6. Repeat the cycle G times, and output the end solution. Otherwise, return to the step 2.

[Please insert Figure 6 here]

5. Case study

To illustrate the efficacy of the proposed model and solution algorithm, we present a real-world case study on hazardous material logistics in Shandong, China. We first describe the problem data and then discuss our experimental findings.

5.1. Dataset and experimental setup

The data obtained by the Department of Transportation in Shandong Province, is related to the administrative districts and road network within Shandong. We use the existing warehouses located in Jinan (the capital city of Shandong) as candidate sites. There are three large-scale and professional hazardous material warehouses in Jinan, which are located in Shanghe Economic Development Zone, New Material Industrial Park and Diaozhen Chemical Industry Park, respectively. Nine customers are located in different administrative districts. The requirements of customers are presented in Table 2. For convenience, these 3 warehouses and 9 customers are listed and numbered from 1 to 12 respectively as follows: Shanghe Economic Development Zone (1), New Material Industrial Park (2), Diaozhen Chemical Industry Park (3), Dezhou city (4), Liaocheng city (5), Heze city (6), Jinan changqing district (7), Taian city (8), Laiwu city (9), Binzhou city (10), Zibo city (11) and Weifang Fangzi district (12).

[Please insert Table 2 here]

The network illustrating the entire problem is shown in Fig. 7, where the expressways, the national roads and the provincial roads are highlighted. To simply experimental computation, we only select two alternative paths between every possible origin-destination pair (with one being an ordinary road and the other expressway). The application focuses on a single departure time such that shipments depart from warehouses at 6 am (although it is straightforward to extend this to simultaneously considering a variety of different departure times). The work day is divided into 5 periods based on the state of traffic jam, 6:00-11:00, 11:00-14:00, 14:00-19:00, 19:00-23:00 and 23:00-6:00, denoted as H_1, H_2, H_3, H_4, H_5, respectively. The hazardous material vehicles are banned crossing the expressway from 19:00 pm to 6:00 am. As shown in Table 2, customers permit different soft time windows for delivery. For example, customer number 4 gives 3 soft time windows, (8,9,11,12), (14,15,17,18) and (20,21,22,23), meaning that if the service starts in interval 9:00-11:00, 15:00-17:00 or 21:00-22:00, customer satisfaction level would run at 100% and otherwise, they would have a degraded satisfaction level.

[Please insert Figure 7 here]

Information regarding the risk of the warehouse sites and transportation is not available presently. In this study, we assume that the probability of the incident is estimated according to the work of Erkut and Verter (1998) (noting that estimating the probability of a transportation incident or a warehouse incident requires very complex analysis, involving a thorough study for each specific case which is beyond the scope of this paper). Consequently, the transportation risk assessment is inevitably approximate or inaccurate. The relevant data concerning transportation risk are listed in three parts (due to space limit in pages) as presented in Tables 3, 4 and 5. For example, there are two alternative paths of different risk vales from Shanghe Economic Development Zone (1) to Dezhou city (4), as shown in Table 3. The lowest population exposure path is the first path with a total of 50 people at risk from 8:30 to 9:30 am. However, the transportation risk of selecting the 1st path is higher due to a higher incident probability. In turn, selecting the second path from 14:00-19:00 is a better decision.

[Please insert Table 3 here]
[Please insert Table 4 here]
[Please insert Table 5 here]

Information regarding warehouse site risk is shown in Table 6. In particular, the unit rent and capacity of each warehouse are presented in this table, where the rent of a warehouses is calculated according to its storage capability. The total cost of transporting hazardous materials is related to the distance, the speed, the average cost of fuel and the toll. In this paper, Euro II diesel rigid Heavy Goods Vehicles (HGVs) with gross weight between 12 and 14 tonnes is taken as an example, and the fuel consumption for every 100 kilometres transported is calculated by Eqn. (8) whose coefficients are $k = 0.037032086, a = 2391.533919, b = 916.9084472, c = -19.16345647, d = 0.100967691, e = 0.004462903, f = -7.13588E-05, g = 3.2168E-07$ (noting that this formula is only valid when speed is between 6km/h and 90km/h). It is assumed that the average diesel costs 5.3RMB/Litre in China. The data about toll is taken from Shandong Traffic Management Bureau website. In addition, the distances of the alternative paths, the time-dependent speeds and the transportation times are shown in three parts in Tables 7, 8 and 9 (again, due to the physical space limit in presentation).

[Please insert Table 6 here]
[Please insert Table 7 here]
[Please insert Table 8 here]
[Please insert Table 9 here]

5.2. Results and discussions

Firstly, to illustrate the efficacy of the proposed model, we solve the problem in four different cases (5.2.1-5.2.4) using the simple genetic algorithm in subsection (4.1), and compare the solutions. Set $\lambda_1 = \lambda_2 = \lambda_3 = 1$ given in Eqn. (27). Whilst different weights may be assigned to λ_1, λ_2, λ_3 based on different decision makers' preferences, no such further investigation (which bears the same conceptual work) is carried out here for experimental simplicity. Then, the Pareto frontier is given using adaptive weight genetic algorithm (5.2.5).

5.2.1. Case 1: With traffic restrictions

The particular traffic restrictions considered, together with the optimal results for warehouses location selected and routing strategies computed under these restrictions are summarized in Table 10. It also gives the characteristics of the routing strategies regarding the total risk (TR), total cost (TC), customer average satisfaction level (CASL) and compromise objective function value (COFV). There are two routes in this case: One route originates from and terminates at warehouses (1), in which the delivery sequence for customers and the selected alternative arcs are $1 \xrightarrow{2} 7 \xrightarrow{2} 8 \xrightarrow{2} 9 \xrightarrow{2} 11 \xrightarrow{1} 12 \xrightarrow{2} 10 \xrightarrow{1} 1$. The number above an arrow represents the choice of path between the two locations, with 1 representing an expressway and 2 an ordinary road. Another route originates from and terminates at warehouses (2), where the delivery sequence for customers and the selected alternative paths are $2 \xrightarrow{1} 5 \xrightarrow{1} 4 \xrightarrow{1} 6 \xrightarrow{1} 2$.

[Please insert Table 10 here]

5.2.2. Case 2: Without traffic restrictions

In order to better reflect the adverse effects of traffic restrictions, we compute the location and routing solutions in this second scenario without involving any traffic restriction, as shown in Table 11. The bold digit above an arrow indicates that the arc is illegal if the path is selected under traffic restriction, implying that such paths only exist in the case there is no traffic restriction. As expected, this case has a better objective function value than case 1. This is because carriers have more choices to select the road paths in this case. However, it can be computed that the overall risk in case 2 is increased by 11.1% as compared to case 1, which means that traffic restrictions indeed play a role. In addition, case 2 has a higher overall cost, which is increased by 1.1%. Although the customer satisfaction level of case 1 is lower than that of case 2, it is within the acceptable limits. In short, imposing necessary traffic restrictions effectively reduces the risk and produces overall better results.

[Please insert Table 11 here]

5.2.3. Case 3: Customer satisfaction

This case discusses the effects of introducing the consideration of customer satisfaction, for which the compromise function is changed as follows:

$$\min \qquad \lambda_1 R^{'} + \lambda_2 C^{'} \tag{29}$$

where $\lambda_1 = \lambda_2 = 1$ (namely, without optimizing the customer satisfaction factor). As shown in Table 12, the risk computed in this case is increased by 11.2% as compared to case 1, while the situation regarding the cost is just the opposite and is reduced by 14.6%. The customer satisfaction level in this case can be calculated by the results in Table 5 using the customer satisfaction function, which is 43.44% and reduced by 44.2%. This means that the overall risk and customer satisfaction have both been sacrificed in order to reduce the cost, which is obviously not a good choice to hazardous material logistics management in real-world practice. This result clearly shows the necessity of considering customer satisfaction in the model.

[Please insert Table 12 here]

5.2.4. Case 4: One path per origin-destination pair only

Traditional hazardous material logistics studies usually presume that there is one and only one path from each origin to each destination, and typically assumes the path being an ordinary road. In order to reflect the effects of route choices, this case considers the location and routing solutions of a scenario where only one ordinary path is assumed between any pair of origin-destination. The results are listed in Table 13. Compared to the solutions of case 1 the results are completely different fin this case, except for the warehouse location. It is crystally clear that the objective function value in case 1 is smaller than that in the present case, in virtue of the lower risk and higher customer satisfaction. The risk computed in this case is increased by 2% as compared to case 1, and the customer satisfaction is reduced by 16.3%. Thus, multiple paths are important to consider in dealing with the hazardous material LRPs.

[Please insert Table 13 here]

5.2.5. Case 4: Pareto frontier

Although the compromise single objective function and simple genetic algorithm has illustrated the efficacy of the proposed model, the solution obtained by this method are relatively single, and the effect is very poor in practical application. Thus, in case 4, the adaptive weight genetic algorithm is selected to solve the proposed model under the traffic restrictions. Table 14 lists 30 non-dominated solutions, and Fig. 8 shows the Pareto frontier. Decision makers can determine the warehouses and transportation routes according to actual situation.

[Please insert Table 14 here]

6. Conclusion and future research directions

This paper has proposed a new multi-objective location-routing model which works by minimizing both the total risk and the total cost, while maximizing customer satisfaction. The model is flexible, as it is applicable to various cost and risk measures. The work considers important real-life aspects of hazardous material logistics management that were observed in the literature but not incorporated into existing models, such as traffic restrictions, multiple imprecisely imposed time windows, alternative paths between possible node pairs, and time-dependent modelling parameters. The aim for such a novel development has been to answer the following questions for corporate decision makers: where to rent warehouses, how to assign customers to the rented warehouses, and how to route vehicles to customers. The work is not only helpful for corporate decision makers, but also useful for relevant government departments, e.g., to consider a certain introduction of traffic restriction schemes: when and which road segment is to be set for no entry for hazardous material vehicles.

Further research is required to improve the efficiency of running the algorithms in order to solve problems of a much larger scale than experimentally evaluated. It would also be interesting to examine what alternative heuristic algorithms may be developed to solve the model. Another significant extension of this work is to consider the addition of vehicle capacity constraints to make the proposed model more practical.

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List of Figure and Table Captions

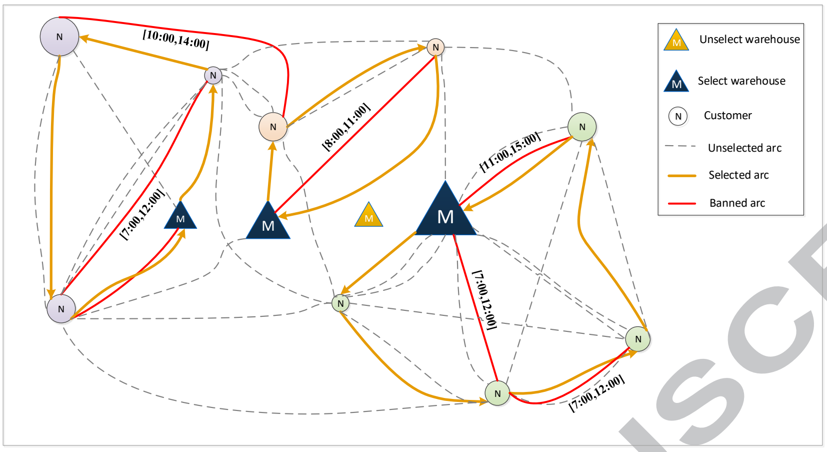

Figure 1: Illustrative problem of proposed hazardous material logistics

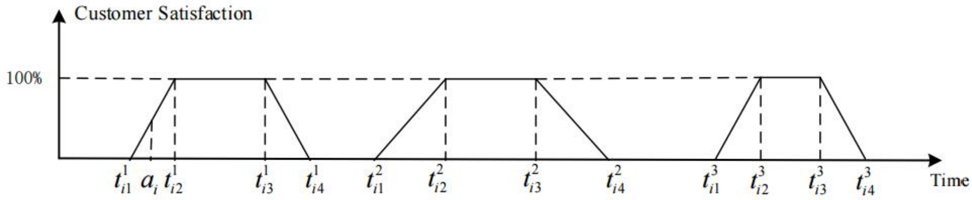

Figure 2: A customer satisfaction function with three soft time windows for customer i

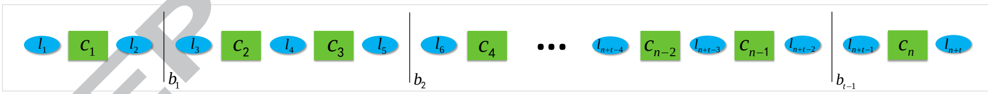

Figure 3: Chromosome structure

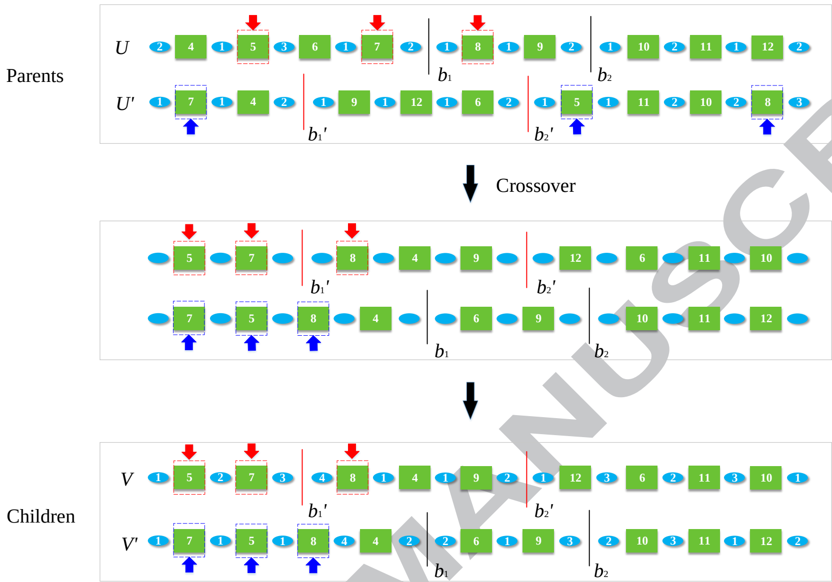

Figure 4: Crossover

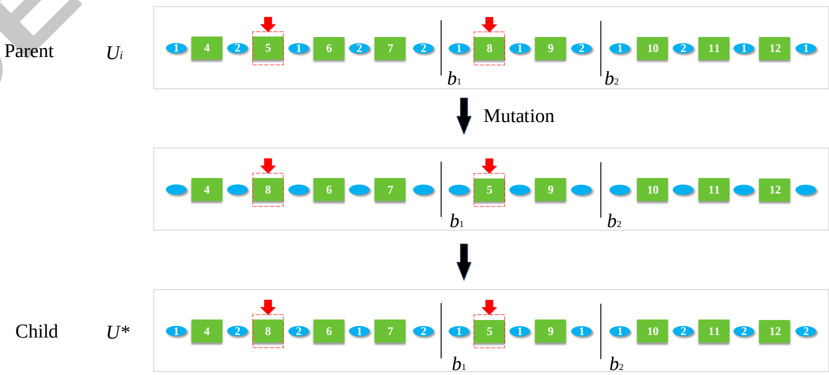

Figure 5: Mutation

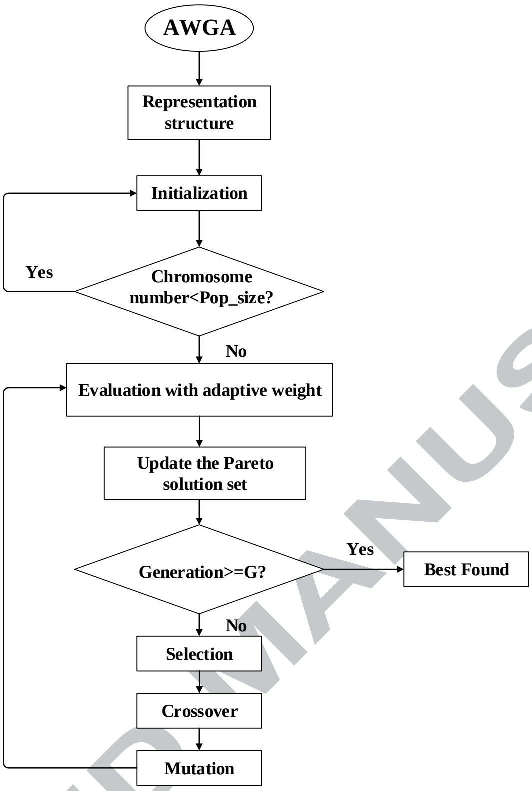

Figure 6: General procedure of an AWGA

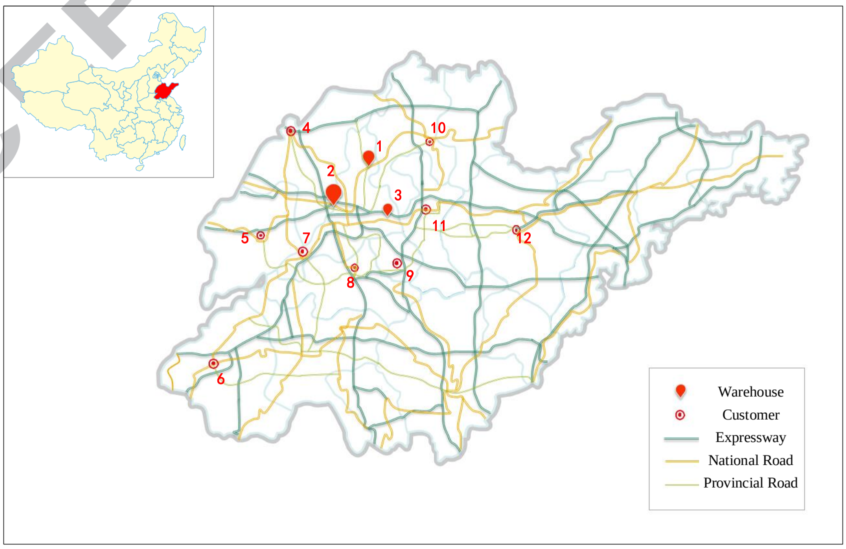

Figure 7: Candidate Warehouses Nodes, Customers Nodes and Road Network in Shandong

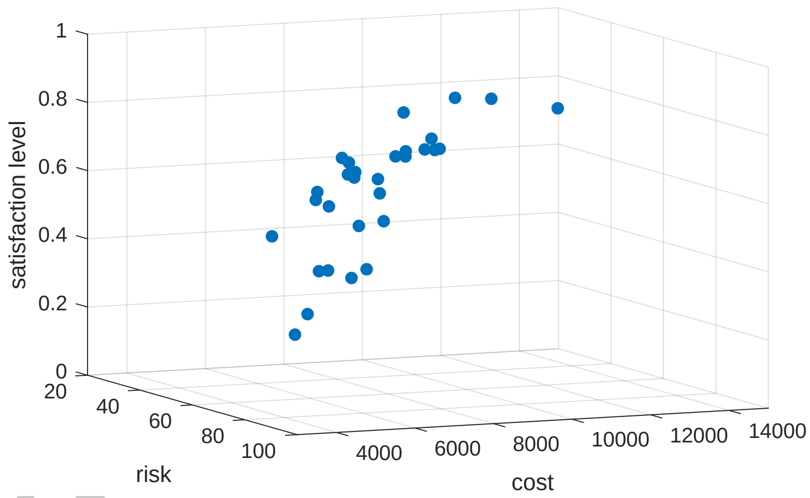

Figure 8: The Pareto frontier under traffic restrictions

Table 1: List of notations

Notations	
Sets and indices	
N_w	set of potential warehouse nodes
N_c	set of customer nodes
N	set of all nodes, $N = N_w \cup N_c$
H_τ	set of five time interval, $H_\tau = \{H_1, H_2, H_3, H_4, H_5\}$
K_{ij}	set of alternative arcs connecting node i to node j, $K_{ij} = \{(i, j)^1, (i, j)^2, \cdots, (i, j)^{\vert K_{ij}\vert}\}$
A	set of arcs in the network, $A = \underset{i,j\in N, i\neq j}{\cup} K_{ij} \setminus \underset{i,j\in N_w, i\neq j}{\cup} K_{ij}$
Parameters	
u_i	departure time from node i
a_i	arrival time to node i
$[pt_{ij}^{k1}, pt_{ij}^{k2}]$	prohibited time interval of k-th arc from node i to node j
s_i	service time for customer i
D_{ij}^k	length of the k-th arc from node i to node j
$V_{ij}^k(u_i)$	vehicle speed at the k-th arc from node i to node j with departure time u_i
W_i	the time windows set of customer i, $W_i = \{[t_{i1}^p, t_{i2}^p, t_{i3}^p, t_{i4}^p], p = 1, \cdots, p_i\}$
R_m	site risk of warehouse m
$R_{ij}^k(u_i)$	transportation risk associated with the k-th arc from node i to node j with departure time u_i
ρ_m	number of people around warehouse m
$\rho_{ij}^k(u_i)$	number of people along the k-th arc from node i to node j with departure time u_i
P_m	incident probability associated with warehouse m
P_{ij}^k	incident probability associated with the k-th arc from node i to node j
C_m	rent of warehouse m
$F_{ij}^k(u_i)$	vehicle fuel consumption of the k-th arc from node i to node j with departure time u_i
ε	the unit price of fuel
$\bar{C}_{ij}^k$	toll of the k-th arc from node i to node j
Q_m	capacity of warehouse m
d_i	demand of customer i
Decision variables	
x_{ij}^k	1, if the k-th arc from node i to node j is selected; 0 otherwise
y_m	1, if warehouse m is selected; 0 otherwise
z_{im}	1, if customer i is allocated to warehouse m; 0 otherwise

Table 2: Requirements of Customers

Customer	Demand (unit)	Service Time (h)	Time Windows
4	1	0.16	(8,9,11,12) (14,15,17,18) (20,21,22,23)
5	1.5	0.25	(8,9,11,12) (14,15,17,18)
6	2.5	0.42	(8,9,11,12) (14,15,17,18) (20,21,22,23)
7	3	0.50	(8,9,11,12) (14,15,17,18)
8	3	0.50	(8,9,11,12) (14,15,17,18) (20,21,22,23)
9	3.5	0.58	(8,9,11,12) (14,15,17,18) (20,21,22,23)
10	2.5	0.42	(8,9,11,12) (14,15,17,18)
11	1	0.16	(8,9,11,12) (14,15,17,18) (20,21,22,23)
12	1	0.16	(8,9,11,12) (14,15,17,18) (20,21,22,23)

Table 3: Time-dependent Transportation Risk - Part 1

Node Pair	Alternative Path	Incident Probability	Population Exposure			Transportation Risk		
			$H_1\&H_3$	$H_2\&H_4$	H_5	$H_1\&H_3$	$H_2\&H_4$	H_5
(1,4)	1	0.06155	50	30	90	3.07755	1.84653	5.53959
	2	0.03828	78	50	154	2.98596	1.91408	5.89535
(1,5)	1	0.07677	50	33	96	3.83850	2.53341	7.36992
	2	0.07443	85	54	150	6.32655	4.01922	11.16450
(1,6)	1	0.14811	35	24	73	5.18380	3.55460	10.81192
	2	0.14432	54	36	112	7.79350	5.19566	16.16429
(1,7)	1	0.05323	30	20	78	1.59678	1.06452	4.15163
	2	0.04988	52	35	142	2.59366	1.74573	7.08268
(1,8)	1	0.07501	32	25	79	2.40034	1.87526	5.92583
	2	0.06953	57	42	153	3.96344	2.92043	10.63870
(1,9)	1	0.07543	43	23	75	3.24364	1.73497	5.65751
	2	0.07243	69	32	128	4.99781	2.31782	9.27130
(1,10)	1	0.03755	40	25	78	1.50210	0.93881	2.92910
	2	0.03843	74	41	132	2.84349	1.57545	5.07217
(1,11)	1	0.07165	35	24	73	2.50772	1.71958	5.23038
	2	0.05702	53	33	115	3.02203	1.88164	6.55724
(1,12)	1	0.11597	34	23	68	3.94296	2.66730	7.88593
	2	0.10566	49	29	125	5.17712	3.06401	13.20694
(2,4)	1	0.06974	36	23	70	2.51051	1.60394	4.88156
	2	0.06026	56	34	122	3.37478	2.04898	7.35221
(2,5)	1	0.07317	46	30	95	3.36582	2.19510	6.95115
	2	0.07396	78	46	163	5.76869	3.40205	12.05507
(2,6)	1	0.13737	46	20	75	6.31909	2.74743	10.30286
	2	0.13549	70	34	132	9.48434	4.60668	17.88475
(2,7)	1	0.04528	45	27	92	2.03776	1.22265	4.16608
	2	0.04104	90	45	150	3.69401	1.84700	6.15668
(2,8)	1	0.06427	46	31	98	2.95658	1.99248	6.29880
	2	0.05407	98	76	153	5.29862	4.10913	8.27233
(2,9)	1	0.03978	37	29	90	1.47203	1.15375	3.58061
	2	0.03895	59	38	143	2.29790	1.48001	5.56949
(2,10)	1	0.05253	33	21	66	1.73344	1.10310	3.46688
	2	0.04260	48	30	103	2.04487	1.27805	4.38795
(2,11)	1	0.03073	43	22	68	1.32141	0.67607	2.08967
	2	0.03158	64	32	114	2.02118	1.01059	3.60023
(2,12)	1	0.07754	45	18	67	3.48908	1.39563	5.19485
	2	0.08027	76	26	104	6.10025	2.08693	8.34772
(3,4)	1	0.07098	37	25	74	2.62620	1.77446	5.25241
	2	0.05979	54	48	108	3.22850	2.86978	6.45700
(3,5)	1	0.07441	42	26	68	3.12512	1.93460	5.05971
	2	0.07349	64	38	114	4.70304	2.79243	8.37729
(3,6)	1	0.13861	38	15	54	5.26731	2.07920	7.48513
	2	0.13501	54	28	86	7.29073	3.78038	11.61116
(3,7)	1	0.04652	40	20	57	1.86084	0.93042	2.65170
	2	0.04057	78	39	90	3.16427	1.58213	3.65108
(3,8)	1	0.06552	25	20	35	1.63789	1.31031	2.29304
	2	0.05531	58	45	87	3.20795	2.48893	4.81193

Table 4: Time-dependent Transportation Risk - Part 2

Node Pair	Alternative Path	Incident Probability	Population Exposure			Transportation Risk		
			$H_1\&H_3$	$H_2\&H_4$	H_5	$H_1\&H_3$	$H_2\&H_4$	H_5
(3,9)	1	0.04014	40	26	78	1.60560	1.04364	3.13092
	2	0.04019	63	34	120	2.53166	1.36629	4.82220
(3,10)	1	0.05377	46	31	90	2.47324	1.66675	4.83894
	2	0.04212	60	41	165	3.12747	2.22710	6.95054
(3,11)	1	0.03197	40	23	87	1.27872	0.73526	2.78122
	2	0.03282	56	45	159	1.83784	1.47683	5.21814
(3,12)	1	0.07878	45	34	88	3.54497	2.67842	6.93238
	2	0.08150	86	53	142	7.00934	4.31971	11.57357
(4,5)	1	0.07810	30	20	76	2.34293	1.56195	5.93541
	2	0.05913	52	38	148	3.07499	2.24711	8.75191
(4,6)	1	0.14854	35	28	68	5.19892	4.15913	10.10075
	2	0.13627	49	44	130	6.67740	5.99603	17.71556
(4,7)	1	0.05366	33	20	66	1.77086	1.07325	3.54173
	2	0.05582	56	38	112	3.12581	2.12108	6.25162
(4,8)	1	0.07544	44	23	74	3.31947	1.73518	5.58275
	2	0.08504	87	44	140	7.39857	3.74180	11.90574
(4,9)	1	0.09693	39	20	70	3.78045	1.93869	6.78542
	2	0.10198	74	40	132	7.54645	4.07916	13.46123
(4,10)	1	0.08792	45	23	65	3.95645	2.02218	5.71487
	2	0.08123	84	39	130	6.82366	3.16813	10.56042
(4,11)	1	0.09315	36	22	64	3.35340	2.04930	5.96160
	2	0.09104	68	54	124	6.19038	4.91589	11.28834
(4,12)	1	0.13747	41	20	78	5.63629	2.74941	10.72270
	2	0.13972	29	54	124	4.05189	7.54491	17.32534
(5,6)	1	0.07349	35	25	83	2.57229	1.83735	6.10000
	2	0.07760	64	44	154	4.96627	3.41431	11.95009
(5,7)	1	0.05356	47	33	78	2.51748	1.76760	4.17795
	2	0.04445	108	87	178	4.80022	3.86685	7.91148
(5,8)	1	0.07534	41	20	70	3.08908	1.50687	5.27405
	2	0.05348	75	38	130	4.01085	2.03216	6.95214
(5,9)	1	0.09855	31	20	71	3.05505	1.97100	6.99705
	2	0.07881	54	38	118	4.25590	2.99489	9.29993
(5,10)	1	0.11793	35	28	68	4.12745	3.30196	8.01904
	2	0.10194	87	76	176	8.86865	7.74733	17.94118
(5,11)	1	0.09613	46	22	65	4.42214	2.11494	6.24868
	2	0.09832	68	40	98	6.68549	3.93264	9.63497
(5,12)	1	0.14046	37	26	75	5.19713	3.65204	10.53473
	2	0.14792	85	66	116	12.57354	9.76298	17.15918
(6,7)	1	0.09505	33	24	78	3.13677	2.28128	7.41417
	2	0.09460	52	43	96	4.91938	4.06795	9.08194
(6,8)	1	0.10775	44	23	74	4.74091	2.47820	7.97335
	2	0.09962	76	45	134	7.57120	4.48295	13.34921
(6,9)	1	0.13058	33	34	78	4.30917	4.43975	10.18532
	2	0.12400	68	70	153	8.43214	8.68014	18.97231
(6,10)	1	0.18252	44	21	70	8.03068	3.83283	12.77609
	2	0.16815	70	45	102	11.77029	7.56662	17.15099

Table 5: Time-dependent Transportation Risk - Part 3

Node Pair	Alternative Path	Incident Probability	Population Exposure			Transportation Risk		
			$H_1\&H_3$	$H_2\&H_4$	H_5	$H_1\&H_3$	$H_2\&H_4$	H_5
(6,11)	1	0.16072	35	20	71	5.62511	3.21435	11.41094
	2	0.15494	64	58	144	9.91642	8.98675	22.31194
(6,12)	1	0.20504	46	24	70	9.43175	4.92091	14.35266
	2	0.20456	134	68	154	27.41117	13.91015	31.50239
(7,8)	1	0.02575	46	22	91	1.18466	0.56658	2.34357
	2	0.02888	38	30	88	1.09748	0.86643	2.54153
(7,9)	1	0.05616	36	29	88	2.02160	1.62851	4.94168
	2	0.05241	49	34	115	2.56794	1.78184	6.02681
(7,10)	1	0.08789	31	20	70	2.72444	1.75770	6.15195
	2	0.07396	55	34	134	4.06766	2.51456	9.91031
(7,11)	1	0.06609	40	28	78	2.64366	1.85056	5.15514
	2	0.06075	51	24	98	3.09825	1.45800	5.95350
(7,12)	1	0.11041	35	26	88	3.86442	2.87071	9.71626
	2	0.11035	54	46	142	5.95909	5.07626	15.67020
(8,9)	1	0.02581	30	22	71	0.77436	0.56786	1.83265
	2	0.02603	54	49	96	1.40576	1.27559	2.49912
(8,10)	1	0.09363	46	25	88	4.30705	2.34079	8.23957
	2	0.09325	55	31	141	5.12894	2.89086	13.14874
(8,11)	1	0.06592	52	28	71	3.42787	1.84577	4.68036
	2	0.07955	87	35	128	6.92094	2.78429	10.18253
(8,12)	1	0.11633	47	24	85	5.46770	2.79202	9.88839
	2	0.10311	106	47	178	10.92950	4.84610	18.35331
(9,10)	1	0.06767	44	26	68	2.97752	1.75945	4.60163
	2	0.07846	108	51	174	8.47341	4.00133	13.65161
(9,11)	1	0.03996	33	22	72	1.31853	0.87902	2.87680
	2	0.03901	108	53	170	4.21313	2.06756	6.63179
(9,12)	1	0.09285	47	21	77	4.36409	1.9499	7.14968
	2	0.07879	75	35	133	5.90929	2.75767	10.47914
(10,11)	1	0.03759	31	31	64	1.16538	1.16538	2.40595
	2	0.03591	80	41	138	2.87244	1.47213	4.95496
(10,12)	1	0.08440	39	25	86	3.29150	2.10994	7.25819
	2	0.06657	32	22	80	2.13019	1.46451	5.32548
(11,12)	1	0.05283	40	35	85	2.11320	1.84905	4.49055
	2	0.05169	111	74	179	5.73726	3.82484	9.25197

Table 6: Information of Warehouses

Warehouse	Capacity	Unit Rent	Incident Probability	Population	Site Risk
1	50	300	0.0001	800	0.08
2	50	500	0.0001	700	0.07
3	40	450	0.00012	600	0.072

Table 7: Time-dependent Transportation Time and Cost - Part 1

Node Pair	Alternative Path	Distance (km)	Speed (km/h)			Toll (RMB)	Fuel Cost (RMB)			Transportation Time (h)			Transportation Cost (RMB)		
			H_1&H_3	H_2&H_4	H_5		H_1&H_3	H_2&H_4	H_5	H_1&H_3	H_2&H_4	H_5	H_1&H_3	H_2&H_4	H_5
(1,4)	1	136.78	83	85	89	140	129.69	131.21	135.11	1.65	1.61	1.54	269.69	271.21	275.11
	2	85.86	50	54	58	0	79.44	78.27	77.63	1.72	1.59	1.48	79.44	78.27	77.63
(1,5)	1	170.6	79	81	83	150	158.78	160.14	161.37	2.16	2.11	2.07	308.78	310.14	311.37
	2	165.4	50	52	54	0	153.02	151.76	150.78	3.31	3.18	3.06	153.02	151.76	150.78
(1,6)	1	329.13	84	88	90	290	313.83	322.47	327.97	3.92	3.74	3.66	603.83	612.47	617.97
	2	320.72	42	47	50	0	313.31	301.56	296.72	7.64	6.82	6.41	313.31	301.56	296.72
(1,7)	1	118.28	65	68	75	100	106.73	107.04	108.60	1.82	1.74	1.58	206.73	207.04	208.60
	2	110.84	49	54	57	0	103.05	101.04	100.37	2.26	2.05	1.94	103.05	101.04	100.37
(1,8)	1	166.69	76	77	80	145	153.50	154.00	155.78	2.19	2.16	2.08	298.50	299.00	300.78
	2	154.52	37	47	54	0	159.33	145.29	140.86	4.18	3.29	2.86	159.33	145.29	140.86
(1,9)	1	167.63	76	79	83	145	154.37	156.01	158.94	2.21	2.12	2.02	299.37	301.01	303.94
	2	160.96	48	53	54	0	150.45	147.18	146.73	3.35	3.04	2.98	150.45	147.18	146.73
(1,10)	1	83.45	47	48	50	0	78.57	78.00	77.18	1.78	1.74	1.67	78.57	78.00	77.18
	2	85.39	49	52	53	0	79.39	78.35	78.08	1.74	1.64	1.61	79.39	78.35	78.08
(1,11)	1	159.22	75	79	80	145	146.19	148.18	148.80	2.12	2.02	1.99	291.19	293.18	293.80
	2	126.71	46	47	50	0	119.85	119.14	117.23	2.75	2.70	2.53	119.85	119.14	117.23
(1,12)	1	257.71	73	79	87	215	235.37	239.85	250.59	3.53	3.26	2.96	450.37	454.85	465.59
	2	234.79	39	36	49	0	236.45	245.22	218.28	6.02	6.52	4.79	236.45	245.22	218.28
(2,4)	1	154.97	81	85	88	145	145.47	148.66	151.83	1.91	1.82	1.76	290.47	293.66	296.83
	2	133.92	50	52	55	0	123.90	122.88	121.77	2.68	2.58	2.43	123.90	122.88	121.77
(2,5)	1	162.6	76	81	83	145	149.74	152.64	154.17	2.14	2.01	1.96	294.74	297.64	299.17
	2	164.35	48	50	51	0	153.62	152.05	151.39	3.42	3.29	3.22	153.62	152.05	151.39
(2,6)	1	305.27	83	86	88	280	289.45	294.76	299.09	3.68	3.55	3.47	569.45	574.76	579.09
	2	301.09	46	48	50	0	284.94	281.43	278.56	6.55	6.27	6.02	284.94	281.43	278.56
(2,7)	1	100.63	66	67	69	85	90.87	90.96	91.19	1.52	1.50	1.46	175.87	175.96	176.19
	2	91.21	41	42	45	0	89.95	89.10	86.93	2.22	2.17	2.03	89.95	89.10	86.93
(2,8)	1	142.83	71	74	76	120	129.88	130.78	131.53	2.01	1.93	1.88	249.88	250.78	251.53
	2	120.15	44	46	47	0	115.39	113.71	112.97	2.73	2.61	2.56	115.39	113.71	112.97
(2,9)	1	88.41	55	56	59	45	80.39	80.21	79.85	1.61	1.58	1.50	125.39	125.21	124.85
	2	86.55	43	44	46	0	83.81	83.12	81.91	2.01	1.97	1.88	83.81	83.12	81.91
(2,10)	1	116.73	72	76	78	100	106.37	107.49	108.23	1.62	1.54	1.50	206.37	207.49	208.23
	2	94.67	45	49	56	0	90.23	88.01	85.89	2.10	1.93	1.69	90.23	88.01	85.89
(2,11)	1	68.29	53	59	66	60	62.44	61.68	61.66	1.29	1.16	1.03	122.44	121.68	121.66
	2	70.18	41	43	44	0	69.21	67.95	67.40	1.71	1.63	1.60	69.21	67.95	67.40
(2,12)	1	172.3	65	70	77	150	155.47	156.40	159.18	2.65	2.46	2.24	305.47	306.40	309.18
	2	178.37	44	45	46	0	171.30	170.00	168.80	4.05	3.96	3.88	171.30	170.00	168.80
(3,4)	1	157.73	80	85	87	145	147.40	151.31	153.37	1.97	1.86	1.81	292.40	296.31	298.37
	2	132.86	48	52	55	0	124.19	121.91	120.80	2.77	2.56	2.42	124.19	121.91	120.80
(3,5)	1	165.35	78	80	82	145	153.30	154.53	155.97	2.12	2.07	2.02	298.30	299.53	300.97
	2	163.3	48	52	54	0	152.64	149.84	148.87	3.40	3.14	3.02	152.64	149.84	148.87
(3,6)	1	308.03	82	85	88	280	290.55	295.49	301.80	3.76	3.62	3.50	570.55	575.49	581.80
	2	300.03	43	44	47	0	290.52	288.13	282.11	6.98	6.82	6.38	290.52	288.13	282.11

Table 8: Time-dependent Transportation Time and Cost - Part 2

Node Pair	Alternative Path	Distance (km)	Speed (km/h)			Toll (RMB)	Fuel Cost (RMB)			Transportation Time (h)			Transportation Cost (RMB)		
			$H_1\&H_3$	$H_2\&H_4$	H_5		$H_1\&H_3$	$H_2\&H_4$	H_5	$H_1\&H_3$	$H_2\&H_4$	H_5	$H_1\&H_3$	$H_2\&H_4$	H_5
(3,7)	1	103.38	65	68	70	85	93.28	93.55	93.84	1.59	1.52	1.48	178.28	178.55	178.84
	2	90.15	42	44	46	0	88.07	86.58	85.32	2.15	2.05	1.96	88.07	86.58	85.32
(3,8)	1	145.59	70	72	76	120	132.15	132.67	134.07	2.08	2.02	1.92	252.15	252.67	254.07
	2	122.91	44	46	53	0	118.04	116.32	112.39	2.79	2.67	2.32	118.04	116.32	112.39
(3,9)	1	89.2	56	58	62	45	80.92	80.65	80.43	1.59	1.54	1.44	125.92	125.65	125.43
	2	89.3	44	46	54	0	85.76	84.51	81.41	2.03	1.94	1.65	85.76	84.51	81.41
(3,10)	1	119.48	72	75	77	100	108.88	109.70	110.39	1.66	1.59	1.55	208.88	209.70	210.39
	2	93.61	45	48	54	0	89.22	87.50	85.34	2.08	1.95	1.73	109.22	110.50	121.34
(3,11)	1	71.04	56	61	66	60	64.45	64.07	64.15	1.27	1.16	1.08	124.45	124.07	124.15
	2	72.93	42	46	50	0	71.25	69.02	67.47	1.74	1.59	1.46	71.25	69.02	67.47
(3,12)	1	175.06	71	75	77	150	159.19	160.73	161.73	2.47	2.33	2.27	309.19	310.73	311.73
	2	181.12	40	46	48	0	180.44	171.41	169.30	4.53	3.94	3.77	180.44	171.41	169.30
(4,5)	1	173.55	79	80	84	155	161.52	162.19	165.48	2.20	2.17	2.07	316.52	317.19	320.48
	2	131.41	51	53	54	0	121.05	120.16	119.80	2.58	2.48	2.43	121.05	120.16	119.80
(4,6)	1	330.09	83	87	90	295	312.98	320.97	328.92	3.98	3.79	3.67	607.98	615.97	623.92
	2	302.83	48	52	56	0	283.06	277.86	274.74	6.31	5.82	5.41	283.06	277.86	274.74
(4,7)	1	119.25	68	70	72	95	107.91	108.24	108.67	1.75	1.70	1.66	202.91	203.24	203.67
	2	124.04	46	50	52	0	117.39	114.76	113.81	2.70	2.48	2.39	117.39	114.76	113.81
(4,8)	1	167.65	65	74	85	150	151.27	153.50	160.82	2.58	2.27	1.97	301.27	303.50	310.82
	2	188.98	49	51	52	0	175.69	174.08	173.40	3.86	3.71	3.63	175.69	174.08	173.40
(4,9)	1	215.41	69	75	82	185	195.21	197.78	203.19	3.12	2.87	2.63	380.21	382.78	388.19
	2	226.62	45	51	54	0	215.98	208.75	206.59	5.04	4.44	4.20	215.98	208.75	206.59
(4,10)	1	195.38	84	86	90	175	186.29	188.65	194.69	2.33	2.27	2.17	361.29	363.65	369.69
	2	180.52	55	56	58	0	164.14	163.77	163.22	3.28	3.22	3.11	164.14	163.77	163.22
(4,11)	1	207	69	78	86	185	187.59	191.92	199.87	3.00	2.65	2.41	372.59	376.92	384.87
	2	202.3	48	52	53	0	189.09	185.62	184.98	4.21	3.89	3.82	189.09	185.62	184.98
(4,12)	1	305.49	68	79	83	280	276.45	284.32	289.66	4.49	3.87	3.68	556.45	564.32	569.66
	2	310.49	45	47	49	0	295.91	291.94	288.66	6.90	6.61	6.34	295.91	291.94	288.66
(5,6)	1	163.32	70	75	78	120	148.24	149.95	151.42	2.33	2.18	2.09	268.24	269.95	271.42
	2	172.44	40	44	46	0	171.79	165.60	163.19	4.31	3.92	3.75	171.79	165.60	163.19
(5,7)	1	119.03	63	64	69	95	107.32	107.35	107.87	1.89	1.86	1.73	202.32	202.35	202.87
	2	98.77	43	46	49	0	95.64	93.47	91.83	2.30	2.15	2.02	95.64	93.47	91.83
(5,8)	1	167.43	72	76	79	150	152.57	154.18	155.83	2.33	2.20	2.12	302.57	304.18	305.83
	2	166.51	52	56	59	95	152.78	151.06	150.38	3.20	2.97	2.82	247.78	246.06	245.38
(5,9)	1	219	75	76	78	185	201.07	201.67	203.04	2.92	2.88	2.81	386.07	386.67	388.04
	2	175.14	40	42	44	0	174.48	171.09	168.20	4.38	4.17	3.98	174.48	171.09	168.20
(5,10)	1	262.06	79	80	85	235	243.90	244.91	251.39	3.32	3.28	3.08	478.90	479.91	486.39
	2	226.53	49	52	55	0	210.60	207.85	205.97	4.62	4.36	4.12	210.60	207.85	205.97
(5,11)	1	213.63	76	80	85	185	196.73	199.65	204.93	2.81	2.67	2.51	381.73	384.65	389.93
	2	218.48	44	48	57	0	209.82	204.22	197.84	4.97	4.55	3.83	209.82	204.22	197.84
(5,12)	1	312.14	77	78	80	280	288.38	289.40	291.71	4.05	4.00	3.90	568.38	569.40	571.71
	2	328.72	44	45	47	0	315.69	313.29	309.08	7.47	7.30	6.99	315.69	313.29	309.08

Table 9: Time-dependent Transportation Time and Cost - Part 3

Node Pair	Alternative Path	Distance (km)	Speed (km/h)			Toll (RMB)	Fuel Cost (RMB)			Transportation Time (h)			Transportation Cost (RMB)		
			H_1&H_3	H_2&H_4	H_5		H_1&H_3	H_2&H_4	H_5	H_1&H_3	H_2&H_4	H_5	H_1&H_3	H_2&H_4	H_5
(6,7)	1	211.23	82	87	89	185	199.24	205.39	208.65	2.58	2.43	2.37	384.24	390.39	393.65
	2	210.23	46	48	49	0	198.95	196.51	195.45	4.57	4.38	4.29	198.95	196.51	195.45
(6,8)	1	239.44	79	80	85	215	222.84	223.77	229.69	3.03	2.99	2.82	437.84	438.77	444.69
	2	221.38	46	48	54	0	209.51	206.93	201.82	4.81	4.61	4.10	209.51	206.93	201.82
(6,9)	1	290.18	79	83	85	255	270.07	275.14	278.37	3.67	3.50	3.41	525.07	530.14	533.37
	2	275.56	44	45	46	0	264.63	262.62	260.78	6.26	6.12	5.99	264.63	262.62	260.78
(6,10)	1	405.59	84	86	89	365	386.73	391.62	400.63	4.83	4.72	4.56	751.73	756.62	765.63
	2	373.66	43	48	51	0	361.81	349.27	344.19	8.69	7.78	7.33	361.81	349.27	344.19
(6,11)	1	357.15	83	84	88	320	338.64	340.54	349.92	4.30	4.25	4.06	658.64	660.54	669.92
	2	344.32	45	49	50	0	328.16	320.11	318.56	7.65	7.03	6.89	328.16	320.11	318.56
(6,12)	1	455.64	82	86	90	405	429.78	439.95	454.03	5.56	5.30	5.06	834.78	844.95	859.03
	2	454.58	44	45	49	0	436.56	433.24	422.62	10.33	10.10	9.28	436.56	433.24	422.62
(7,8)	1	57.23	50	52	56	0	52.95	52.51	51.92	1.14	1.10	1.02	52.95	52.51	51.92
	2	59.68	51	52	57	30	54.97	54.76	54.04	1.17	1.15	1.05	84.97	84.76	84.04
(7,9)	1	124.79	60	67	69	100	112.61	112.79	113.09	2.08	1.86	1.81	212.61	212.79	213.09
	2	116.46	45	46	49	0	110.99	110.21	108.27	2.59	2.53	2.38	110.99	110.21	108.27
(7,10)	1	195.3	71	76	80	155	177.60	179.85	182.52	2.75	2.57	2.44	332.60	334.85	337.52
	2	164.35	50	54	55	0	152.05	149.83	149.43	3.29	3.04	2.99	152.05	149.83	149.43
(7,11)	1	146.87	60	64	69	120	132.53	132.46	133.10	2.45	2.29	2.13	252.53	252.46	253.10
	2	135	38	40	43	0	137.52	134.49	130.72	3.55	3.38	3.14	137.52	134.49	130.72
(7,12)	1	245.36	68	70	73	190	222.04	222.71	224.09	3.61	3.51	3.36	412.04	412.71	414.09
	2	245.23	41	46	48	0	241.85	232.08	229.22	5.98	5.33	5.11	241.85	232.08	229.22
(8,9)	1	57.36	45	51	56	45	54.67	52.84	52.04	1.27	1.12	1.02	99.67	97.84	97.04
	2	57.85	41	46	51	0	57.05	54.75	53.29	1.41	1.26	1.13	57.05	54.75	53.29
(8,10)	1	208.07	71	75	80	175	189.21	191.04	194.45	2.93	2.77	2.60	364.21	366.04	369.45
	2	207.23	50	52	57	0	191.72	190.14	187.66	4.14	3.99	3.64	191.72	190.14	187.66
(8,11)	1	146.49	61	64	69	120	132.11	132.11	132.75	2.40	2.29	2.12	252.11	252.11	252.75
	2	176.78	44	48	52	0	169.77	165.24	162.20	4.02	3.68	3.40	169.77	165.24	162.20
(8,12)	1	258.52	69	72	75	215	234.28	235.57	237.36	3.75	3.59	3.45	449.28	450.57	452.36
	2	229.13	40	47	53	0	228.27	215.44	209.51	5.73	4.88	4.32	228.27	215.44	209.51
(9,10)	1	150.38	75	76	80	140	138.07	138.48	140.54	2.01	1.98	1.88	278.07	278.48	280.54
	2	174.35	38	40	47	0	177.60	173.70	163.94	4.59	4.36	3.71	177.60	173.70	163.94
(9,11)	1	88.79	55	56	61	65	80.73	80.55	80.08	1.61	1.59	1.46	145.73	145.55	145.08
	2	86.69	36	38	41	0	90.54	88.31	85.49	2.41	2.28	2.11	90.54	88.31	85.49
(9,12)	1	206.34	70	75	76	175	187.29	189.45	190.02	2.95	2.75	2.72	362.29	364.45	365.02
	2	175.09	48	51	55	0	163.66	161.28	159.20	3.65	3.43	3.18	163.66	161.28	159.20
(10,11)	1	83.54	60	64	67	65	75.38	75.34	75.51	1.39	1.31	1.25	140.38	140.34	140.51
	2	79.79	40	42	47	0	79.49	77.95	75.02	1.99	1.90	1.70	79.49	77.95	75.02
(10,12)	1	187.55	76	80	82	155	172.71	175.27	176.91	2.47	2.34	2.29	327.71	330.27	331.91
	2	147.93	40	45	49	0	147.38	140.99	137.53	3.70	3.29	3.02	147.38	140.99	137.53
(11,12)	1	117.4	60	69	71	95	105.94	106.39	106.76	1.96	1.70	1.65	200.94	201.39	201.76
	2	114.86	40	45	48	0	114.43	109.47	107.36	2.87	2.55	2.39	114.43	109.47	107.36

Table 10: Computational results under traffic restrictions

	Warehouse Node	Routes	TR	TC	CASL	COFV
Case 1	1, 2	$1 \xrightarrow{2} 7 \xrightarrow{2} 8 \xrightarrow{2} 9 \xrightarrow{2} 11 \xrightarrow{1} 12 \xrightarrow{2} 10 \xrightarrow{1} 1$ $2 \xrightarrow{1} 5 \xrightarrow{1} 4 \xrightarrow{1} 6 \xrightarrow{1} 2$	21.1105	8302.4	77.89%	0.7283

Table 11: Computational results without traffic restrictions

	Warehouse Node	Routes	TR	TC	CASL	COFV
Case 2	1, 2, 3	$1 \xrightarrow{2} 11 \xrightarrow{1} 12 \xrightarrow{2} 9 \xrightarrow{2} 8 \xrightarrow{2} 10 \xrightarrow{\mathbf{1}} 1$ $2 \xrightarrow{2} 4 \xrightarrow{1} 7 \xrightarrow{2} 2$ $3 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{1} 3$	23.471	8389.6	84.78%	0.7001

Table 12: Computational results without customer satisfaction

	Warehouse Node	Routes	TR	TC	COFV
Case 3	1	$1 \xrightarrow{2} 4 \xrightarrow{2} 5 \xrightarrow{1} 6 \xrightarrow{1} 7 \xrightarrow{1} 8 \xrightarrow{2} 9 \xrightarrow{2} 11 \xrightarrow{2} 12 \xrightarrow{2} 10 \xrightarrow{2} 1$	23.4784	7082.5	0.33

Table 13: Computational results with one ordinary road per origin-destination pair

	Warehouse Node	Routes	TR	TC	CASL	COFV
Case 4	1, 2	$1 \xrightarrow{2} 7 \xrightarrow{2} 8 \xrightarrow{2} 9 \xrightarrow{2} 12 \xrightarrow{2} 10 \xrightarrow{2} 11 \xrightarrow{2} 1$ $2 \xrightarrow{2} 4 \xrightarrow{2} 5 \xrightarrow{2} 6 \xrightarrow{2} 2$	21.53	7646.3	65.22%	0.7503

Table 14: Non-dominated solutions under traffic restrictions

Warehouse Node	Routes	TR	TC	CASL
1	$1 \xrightarrow{1} 4 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{1} 7 \xrightarrow{1} 8 \xrightarrow{1} 9 \xrightarrow{2} 11 \xrightarrow{2} 10 \xrightarrow{2} 12 \xrightarrow{2} 1$	21.1784	7619.53	38%
1	$1 \xrightarrow{2} 4 \xrightarrow{2} 5 \xrightarrow{1} 7 \xrightarrow{2} 6 \xrightarrow{1} 8 \xrightarrow{2} 9 \xrightarrow{2} 11 \xrightarrow{2} 10 \xrightarrow{2} 12 \xrightarrow{2} 1$	34.3307	7326.4	12.2%
1	$1 \xrightarrow{1} 4 \xrightarrow{2} 5 \xrightarrow{2} 10 \xrightarrow{2} 6 \xrightarrow{2} 8 \xrightarrow{2} 9 \xrightarrow{2} 11 \xrightarrow{2} 7 \xrightarrow{2} 12 \xrightarrow{1} 1$	55.1075	7378.4	33.3%
1	$1 \xrightarrow{1} 4 \xrightarrow{1} 5 \xrightarrow{2} 10 \xrightarrow{1} 11 \xrightarrow{1} 8 \xrightarrow{2} 9 \xrightarrow{2} 6 \xrightarrow{2} 7 \xrightarrow{2} 12 \xrightarrow{2} 1$	43.9591	7880.42	65.78%
1	$1 \xrightarrow{1} 4 \xrightarrow{1} 5 \xrightarrow{1} 11 \xrightarrow{1} 8 \xrightarrow{1} 9 \xrightarrow{1} 6 \xrightarrow{2} 10 \xrightarrow{1} 7 \xrightarrow{2} 12 \xrightarrow{1} 1$	33.1021	8918.88	57%
1	$1 \xrightarrow{1} 4 \xrightarrow{2} 6 \xrightarrow{2} 7 \xrightarrow{2} 8 \xrightarrow{2} 5 \xrightarrow{2} 9 \xrightarrow{2} 11 \xrightarrow{1} 12 \xrightarrow{1} 10 \xrightarrow{1} 1$	35.4729	7570.98	18.33%
1	$1 \xrightarrow{1} 4 \xrightarrow{2} 6 \xrightarrow{2} 9 \xrightarrow{2} 8 \xrightarrow{2} 5 \xrightarrow{2} 10 \xrightarrow{2} 11 \xrightarrow{1} 12 \xrightarrow{1} 7 \xrightarrow{2} 1$	53.286	7687.75	48%
1	$1 \xrightarrow{1} 4 \xrightarrow{2} 6 \xrightarrow{2} 11 \xrightarrow{2} 5 \xrightarrow{2} 9 \xrightarrow{2} 8 \xrightarrow{1} 7 \xrightarrow{2} 10 \xrightarrow{1} 12 \xrightarrow{2} 1$	39.6658	7835.33	50.67%
1	$1 \xrightarrow{1} 4 \xrightarrow{2} 6 \xrightarrow{2} 11 \xrightarrow{2} 8 \xrightarrow{2} 5 \xrightarrow{2} 7 \xrightarrow{2} 9 \xrightarrow{2} 10 \xrightarrow{2} 12 \xrightarrow{1} 1$	46.0987	7384.18	33.56%
1	$1 \xrightarrow{1} 4 \xrightarrow{2} 6 \xrightarrow{2} 11 \xrightarrow{2} 8 \xrightarrow{2} 7 \xrightarrow{2} 5 \xrightarrow{2} 9 \xrightarrow{2} 10 \xrightarrow{2} 12 \xrightarrow{1} 1$	41.1932	7479.37	32.22%
1	$1 \xrightarrow{1} 4 \xrightarrow{1} 7 \xrightarrow{1} 5 \xrightarrow{2} 10 \xrightarrow{2} 6 \xrightarrow{2} 9 \xrightarrow{2} 8 \xrightarrow{2} 12 \xrightarrow{2} 10 \xrightarrow{1} 1$	64.0085	7605.11	51.78%
1	$1 \xrightarrow{1} 4 \xrightarrow{2} 7 \xrightarrow{1} 8 \xrightarrow{2} 11 \xrightarrow{2} 6 \xrightarrow{2} 5 \xrightarrow{2} 12 \xrightarrow{2} 9 \xrightarrow{2} 10 \xrightarrow{1} 1$	59.8911	7444.14	36.9%
1	$1 \xrightarrow{1} 4 \xrightarrow{1} 7 \xrightarrow{2} 12 \xrightarrow{1} 6 \xrightarrow{2} 5 \xrightarrow{2} 11 \xrightarrow{1} 8 \xrightarrow{1} 9 \xrightarrow{2} 10 \xrightarrow{2} 1$	41.5722	8217.54	63.67%
1	$1 \xrightarrow{1} 4 \xrightarrow{1} 8 \xrightarrow{1} 7 \xrightarrow{1} 9 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{2} 12 \xrightarrow{1} 11 \xrightarrow{1} 10 \xrightarrow{1} 1$	32.1064	8043.57	53.11%
1	$1 \xrightarrow{1} 4 \xrightarrow{1} 8 \xrightarrow{1} 7 \xrightarrow{1} 9 \xrightarrow{1} 10 \xrightarrow{1} 11 \xrightarrow{1} 12 \xrightarrow{2} 6 \xrightarrow{1} 5 \xrightarrow{2} 1$	32.0288	8010.59	50.78%
1, 2	$1 \xrightarrow{1} 9 \xrightarrow{1} 11 \xrightarrow{1} 1$ $2 \xrightarrow{1} 8 \xrightarrow{1} 5 \xrightarrow{2} 10 \xrightarrow{1} 6 \xrightarrow{2} 4 \xrightarrow{2} 12 \xrightarrow{2} 7 \xrightarrow{1} 2$	56.6939	12527	80.11%
1, 2	$1 \xrightarrow{1} 8 \xrightarrow{1} 7 \xrightarrow{1} 6 \xrightarrow{1} 5 \xrightarrow{2} 1$ $2 \xrightarrow{1} 11 \xrightarrow{2} 10 \xrightarrow{1} 9 \xrightarrow{1} 4 \xrightarrow{1} 12 \xrightarrow{2} 2$	23.1786	10184.64	53.56%
1, 2	$1 \xrightarrow{1} 4 \xrightarrow{1} 11 \xrightarrow{1} 12 \xrightarrow{2} 10 \xrightarrow{1} 9 \xrightarrow{2} 1$ $2 \xrightarrow{1} 8 \xrightarrow{1} 7 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{2} 2$	21.4032	10349.66	48.89%
1, 2	$1 \xrightarrow{1} 7 \xrightarrow{1} 9 \xrightarrow{2} 11 \xrightarrow{2} 12 \xrightarrow{2} 10 \xrightarrow{2} 1$ $2 \xrightarrow{1} 4 \xrightarrow{1} 8 \xrightarrow{1} 6 \xrightarrow{1} 5 \xrightarrow{2} 2$	25.4382	9269.16	56%
1, 2	$1 \xrightarrow{1} 7 \xrightarrow{1} 10 \xrightarrow{1} 8 \xrightarrow{1} 5 \xrightarrow{2} 6 \xrightarrow{2} 1$ $2 \xrightarrow{2} 4 \xrightarrow{2} 12 \xrightarrow{2} 9 \xrightarrow{2} 11 \xrightarrow{2} 2$	31.0907	10104	62%
1, 2	$1 \xrightarrow{1} 9 \xrightarrow{1} 10 \xrightarrow{1} 6 \xrightarrow{2} 4 \xrightarrow{2} 8 \xrightarrow{2} 1$ $2 \xrightarrow{1} 5 \xrightarrow{1} 7 \xrightarrow{1} 12 \xrightarrow{1} 11 \xrightarrow{1} 2$	36.0694	10024.8	63.11%
1, 2	$1 \xrightarrow{1} 9 \xrightarrow{1} 11 \xrightarrow{1} 10 \xrightarrow{1} 12 \xrightarrow{2} 4 \xrightarrow{2} 1$ $2 \xrightarrow{2} 5 \xrightarrow{2} 8 \xrightarrow{1} 6 \xrightarrow{2} 7 \xrightarrow{2} 2$	28.2611	10499.35	74%
1, 2	$1 \xrightarrow{1} 4 \xrightarrow{1} 8 \xrightarrow{2} 9 \xrightarrow{1} 7 \xrightarrow{2} 12 \xrightarrow{2} 10 \xrightarrow{2} 1$ $2 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{1} 11 \xrightarrow{2} 2$	32.1536	9007.25	58.33%
2, 3	$2 \xrightarrow{1} 4 \xrightarrow{1} 11 \xrightarrow{1} 6 \xrightarrow{1} 12 \xrightarrow{2} 2$ $3 \xrightarrow{1} 8 \xrightarrow{1} 9 \xrightarrow{2} 5 \xrightarrow{1} 7 \xrightarrow{2} 10 \xrightarrow{2} 3$	32.4276	12455.34	77.67%
2, 3	$2 \xrightarrow{1} 4 \xrightarrow{2} 12 \xrightarrow{1} 11 \xrightarrow{1} 6 \xrightarrow{2} 2$ $3 \xrightarrow{1} 8 \xrightarrow{1} 9 \xrightarrow{2} 5 \xrightarrow{1} 7 \xrightarrow{2} 10 \xrightarrow{2} 3$	28.2183	11811.73	77.44%
2, 3	$2 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{1} 4 \xrightarrow{2} 12 \xrightarrow{2} 2$ $3 \xrightarrow{1} 10 \xrightarrow{1} 9 \xrightarrow{2} 8 \xrightarrow{1} 7 \xrightarrow{1} 11 \xrightarrow{2} 3$	25.8238	11373.18	65.22%
2, 3	$2 \xrightarrow{1} 7 \xrightarrow{1} 6 \xrightarrow{1} 4 \xrightarrow{2} 12 \xrightarrow{2} 2$ $3 \xrightarrow{1} 11 \xrightarrow{1} 10 \xrightarrow{1} 5 \xrightarrow{1} 8 \xrightarrow{1} 9 \xrightarrow{1} 3$	25.341	11612.08	62%
1, 2, 3	$1 \xrightarrow{1} 4 \xrightarrow{1} 1$ $2 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{2} 2$ $3 \xrightarrow{1} 8 \xrightarrow{2} 7 \xrightarrow{1} 10 \xrightarrow{1} 11 \xrightarrow{1} 9 \xrightarrow{2} 12 \xrightarrow{2} 3$	23.0447	11386.07	61.44%

1, 2, 3	$1 \xrightarrow{1} 4 \xrightarrow{1} 1$ $2 \xrightarrow{1} 9 \xrightarrow{1} 8 \xrightarrow{2} 7 \xrightarrow{1} 2$ $3 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{1} 11 \xrightarrow{1} 10 \xrightarrow{2} 12 \xrightarrow{2} 3$	21.7852	11725.94	60.78%
1, 2, 3	$1 \xrightarrow{2} 4 \xrightarrow{1} 1$ $2 \xrightarrow{2} 9 \xrightarrow{1} 8 \xrightarrow{1} 7 \xrightarrow{2} 2$ $3 \xrightarrow{1} 5 \xrightarrow{1} 6 \xrightarrow{1} 11 \xrightarrow{1} 10 \xrightarrow{2} 12 \xrightarrow{2} 3$	22.6295	10930.15	61.11%

*Highlights (for review)

- We present a multi-objective optimization method for hazardous material logistics under the constraint of traffic restrictions in inter-city roads.
- We propose to consider multiple paths between every possible origin-destination pair.
- An adaptive weight genetic algorithm is proposed to solve the proposed model.