Optimising hazardous materials transport network based on multi-objective hybrid intelligence algorithm

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Abstract: Hazardous materials transport network optimisation is the basis of ensuring the safety of hazardous materials transport. Considering the uncertainty of much basic information in hazardous materials transport system, this paper proposes the multi-objective chance-constrained programming model for hazardous materials transport network under uncertainty optimisation theory framework. Then, the paper builds the multi-objective hybrid intelligent algorithm to solve the model. The algorithm applies the stochastic simulation and fuzzy simulation to simulate uncertain parameters, adopts the priority coding way to code chromosome, applies the chromosome marker selection strategy to complete the selection operation, adopts the priority index crossover operator to ensure offspring’s inheritance and advantages for the parent, uses the single parent vicinal swap method to complete mutation and applies the exclusive method to build dominating sets. Finally, the case study shows the model and algorithm are feasible.

Keywords: optimisation; multi-objective hybrid intelligent algorithm; hazardous materials transport; chance-constrained programming model.


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1 Introduction

Hazardous materials transport is not only a sensitive public security problem, but also an important strategic and tactical decision-making problem with great attention by governments and the public (Cao and Ma, 2014); many experts and scholars carried out research on this problem. Jassbi and Makvandi (2010) studied the hazardous materials transport multi-objective optimisation framework, the objectives including shortest mileage, minimum number of affected inhabitants, minimum social risk and minimum probability of accidents. Gao (2010) presented hazardous materials transport risk model and network optimisation model, and made simulation analysis with an example. Minciardi and Robba (2011) put forward a hazardous materials transport route optimisation model by minimising the transport cost and risk. Ma et al. (2012, 2013a, 2013b) studied the route selection problem of hazardous materials transport, and established multi-objective route planning model for hazardous materials transport; an improved label algorithm was adopted to solve the model. He et al. (2013a, 2013b) presented the multi-objective travelling salesman problem for hazardous materials transportation based on improved genetic algorithm, and studied the hazardous materials vehicle scheduling route based on uncertain operator. Liu (2013) considered three influence factors, including risks, route length and transport costs, and established a comprehensive objective model, and the Dijkstra algorithm was adopted to solve the model.

However, owing to many subjective and objective reasons, hazardous materials transport risk and vehicle transport time parameters are uncertain, and hazardous materials transport network design is also a typical multi-objective optimisation problem. At present, there are some typical algorithms to solve multi-objective optimisation problem, such as niche Pareto genetic algorithm (Horn et al., 1994), non-dominated sorting genetic algorithm (Deb et al., 2002), swarm intelligence and bio-inspired computation method (Cui and Gao, 2012; Cui and Xiao, 2014). These algorithms have good efficiency on a particular problem; however, these algorithms cannot be directly applied for multi-objective optimisation design problems of hazardous materials transport network under uncertain environment. Through combining hazardous materials transport problem features and multi-objective optimisation ideas, the paper presents a multi-objective hybrid intelligent algorithm for multi-objective optimisation design problems of hazardous materials transport network under uncertainty environment.

This paper is organised as follows. Problem description and mathematical model are put forward in Section 2, a multi-objective hybrid intelligent algorithm is designed in Sections 3 and 4 is the case study, and the last section is the conclusion.

2 Problem description and mathematical model

In general, hazardous materials transport network optimisation design problem can be described as follows: in the road traffic network $G = (V, E)$, $V$ is the node set, $V = \{v_1, v_2, \ldots, v_n\}$, $E$ is the road set between nodes, $E = \{e_1, e_2, \ldots, e_m\}$. Assuming source point is $v_1$, confluence point is $v_n$, there is a random section $(i, j) \in E$, it endows with a two-dimensional impedance vector $(\xi_1, \xi_2)$, $\xi_1$ and $\xi_2$ are the random number or fuzzy number, $\xi_1$ is the hazardous materials transport risk on the road $(i, j)$.
and $\xi_{i,j}^{(i,j)}$ is the hazardous materials vehicles transport time on the road $(i, j)$, $\xi_{i,j}^{(k)} = \{\xi_{i,j}^{(i,j)} | (i, j) \in E\}$. The optimisation objective of hazardous materials transport network is to choose hazardous materials transport route with the lowest transport risk and the shortest transport time between $v_1$ and $v_n$ in the network $G$. Multiple objectives are transferred to a mathematical model.

Assuming

\[ x_{ij} = \begin{cases} 1 & \text{road}(i, j) \text{ on route } 1 \\ 0 & \text{or} \end{cases}, \]

the transport risk and vehicle transport time of hazardous materials transport route and vehicle transport time are as follows:

\[ Z_1(x, \xi_i) = \sum_{i=1}^{n} \sum_{j=1}^{m} \xi_{i,j}^{(i,j)} x_{ij} \]  
(1)

\[ Z_2(x, \xi_i) = \sum_{i=1}^{n} \sum_{j=1}^{m} \xi_{i,j}^{(i,j)} x_{ij}. \]  
(2)

**Definition:** The $\alpha$ optimal transport route of hazardous materials: in hazardous materials transport network $G$, and among all the transport routes from node 1 to node $n$, if there is a transport route meanwhile satisfy equations (3) and (4):

\[ \min \{Z_1 | Ch[Z_1(x, \xi_i) \leq \bar{R}] \geq \alpha \} \leq \min \{Z_2 | Ch[Z_2(x, \xi_i) \leq \bar{F}] \geq \alpha \} \]  
(3)

\[ \min \{Z_2 | Ch[Z_2(x, \xi_i) \leq \bar{F}] \geq \alpha \} \leq \min \{Z_1 | Ch[Z_1(x, \xi_i) \leq \bar{R}] \geq \alpha \} \]  
(4)

Then, the transport route will be the optimal transport of hazardous materials (Liu, 1999, 2002). $Ch$ refers to the occurrence opportunity of uncertainty incident (in a fuzzy environment, it refers to the credibility measure $Cr$; in a random environment, it refers to the probability measure $Pr$) and $\alpha$ is a given confidence level by makers in advance. $\bar{R}$ is the pessimistic value $\alpha$ of hazardous materials transport risk and $\bar{F}$ is the pessimistic value $\alpha$ of vehicle transport time.

When decision-makers choose the transport route, hazardous materials transport risk and vehicle transport time are required to satisfy a certain confidence level, and the chance-constrained programming model of hazardous materials transport network can be set up; the model is as follows:

\[ \min \{\bar{R}, \bar{F}\} \]  
(5)

\[ \text{s.t. } Ch[Z_1(x, \xi_i) \leq \bar{R}] \geq \alpha \]  
(6)

\[ Ch[Z_2(x, \xi_i) \leq \bar{F}] \geq \alpha \]  
(7)

\[ Z_1(x, \xi_i) = \sum_{i=1}^{n} \sum_{j=1}^{m} \xi_{i,j}^{(i,j)} x_{ij} \]  
(8)

\[ Z_2(x, \xi_i) = \sum_{i=1}^{n} \sum_{j=1}^{m} \xi_{i,j}^{(i,j)} x_{ij}. \]  
(9)
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\[ \sum_{j=1}^{n} x_{ij} - \sum_{k=1}^{n} x_{kj} = 1 \]  \hspace{1cm} (10)

\[ \sum_{j=1}^{n} x_{ij} - \sum_{k=1}^{n} x_{kj} = 0, \hspace{0.5cm} i = 2, 3, \ldots, n-1 \]  \hspace{1cm} (11)

\[ \sum_{j=1}^{n} x_{ij} - \sum_{k=1}^{n} x_{in} = -1 \]  \hspace{1cm} (12)

\[ Ch \{ \max_{(i,j) \in E} \{ \xi_{ij} x_{ij} \} \leq r \} \geq \beta \]  \hspace{1cm} (13)

\[ Ch \left\{ \max_{(i,j) \in E} \left\{ \sum_{i=1}^{n} \sum_{j=1}^{n} \xi_{ij} x_{ij} \right\} \leq R \right\} \geq \beta \]  \hspace{1cm} (14)

\[ x_{ij} \in \{0,1\} \]  \hspace{0.5cm} \forall (i,j) \in E, \hspace{1cm} (15)

where \( \bar{R} \) is the pessimistic value \( \alpha \) of hazardous materials transport risk and \( \bar{T} \) is the pessimistic value \( \alpha \) of vehicle transport time. In the fuzzy environment, \( \xi_1 \) and \( \xi_2 \) are the fuzzy variable; \( Ch \) is the credibility measure or probability measure; in a fuzzy environment, \( Ch \) refers to the credibility measure, and in a random environment, \( Ch \) refers to the probability measure; \( \alpha \) and \( \beta \) are the confidence level; \( r \) is the biggest risk threshold of any transport section; \( R \) is the biggest risk threshold of any transport path. Formula (5) is the optimisation objective; formula (6) denotes that the transport risk must meet a certain confidence level; formula (7) denotes that the transport time must meet a certain confidence level; formula (8) is the expression of transport risk; formula (9) is the expression of transport time; formula (10) is the starting point constraint; formula (11) is intermediate node constraint; formula (12) is the terminal constraint; formula (13) is the confidence level, which meets the risk threshold; formula (14) is the confidence level, which must meet the risk threshold; formula (15) is the decision variable constraint.

3 Multi-objective hybrid intelligence algorithm design

Because of the chance constraints and uncertain parameters of hazardous materials transport network, it is difficult to solve the model by using traditional method. Liu (2002) set up the hybrid intelligence algorithm to solve general chance constraints programming model, but it can only be used to solve the single-objective chance constraints programming model. To solve the multi-objective chance-constrained programming model of hazardous materials transport, the section will present a new multi-objective hybrid intelligent algorithm.

3.1 The processing of chance constraints

For some simple stochastic and fuzzy parameters (such as normal distribution and triangular fuzzy number), we can use analytic approach to change chance constraints into their deterministic equivalent form.
3.1.1 Stochastic simulation

We take random time, for example, assume that a route has been obtained, the total number of roads is $m$, random transit time of each section is $t_1, t_2, \ldots, t_m$, so the pessimistic value simulation steps for a given confidence level $\alpha$ are as follows (Liu, 2002):

**Step 1:** Set the total number $N$ of simulations, $i = 1$.

**Step 2:** Generate random number $p_j$ between 0 and 1, the number of $p_j$ is $m$, according to the probability distribution function of road, respectively, corresponding passing time $t_j$ can be obtained, $j = 1, 2, \ldots, m$, and calculate $T_i = \sum_{j=1}^{m} t_j$.

**Step 3:** Set $i = i + 1$, if $i \leq N$, go to step 2, or arrange $T_1, T_2, \ldots, T_N$ according to the order of sequence, $[\alpha N]$ is the pessimistic value.

3.1.2 Fuzzy simulation

We take fuzzy transport risk, for example, assume that a route has been obtained, the total number of roads is $m$, fuzzy transport risk of each section is $r_1, r_2, \ldots, r_m$, so the pessimistic value simulation steps based on credibility measure are as follows (Liu, 2002):

**Step 1:** Set the total number $N$ of simulations, $i = 1$.

**Step 2:** Generate sample time (its potential is greater than 0) from the distribution of the fuzzy variables $\tilde{r}_1, \tilde{r}_2, \ldots, \tilde{r}_m$, calculate the possibility $\text{Pos}_j(r_j)$, respectively, definite $v_i = \text{Pos}_1(r_1) \wedge \text{Pos}_2(r_2) \wedge \cdots \wedge \text{Pos}_m(r_m)$, at the same time, calculate the corresponding total transport risk $R_i = \sum_{j=1}^{m} r_j$.

**Step 3:** Set $i = i + 1$, if $i \leq N$, go to step 2.

**Step 4:** According to the definition of credibility, establish $L(R) = \frac{1}{\alpha} \left( \max \{ v_i \mid R_i \leq R \} + \min \{ 1 - v_i \mid R_i > R \} \right)$. Owing to the monotonicity of $L(R)$, minimum value, which meet $L(R_{\alpha}) \geq \alpha$, can be found by dichotomy, and the minimum value is the pessimistic value.

3.2 Chromosome coding and genetic operator design

We adopt chromosome coding way based on priority (Wang and Cai, 2008), use gene location to mark node number, use gene value to mark relative nodes priority to the other nodes, the priority of the starting node is set to 1 and the end node priority is set to the total number of nodes.

We adopt chromosome marker selection strategy to complete selection operation. First of all, copy different individuals to the construct set, solve dominant individual of current generation, and put individual into the Pareto pool by the domination relationship. Then, we conduct roulette wheel selection to the whole population by using a random sub-objective, and mark the selected individuals in the corresponding chromosomal mark domain, if chromosome has certain priorities after marking, it will be copied into the corresponding non-dominated solutions. When the whole population end roulette wheel selection, elite reservation operation will be implemented, then conduct the same operation for population by another random sub-objective until all the individuals were
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marked and taken by elite reservation. Finally, the elite individual will be put into the next generation, and the next generation of population will be formed according to the population size, non-dominated individuals number in the Pareto pool, the priority of non-dominated objective set and the number of individuals in the non-dominated objective set.

We use priority index crossover operator to ensure offspring’s inheritance and advantages to the parent (Chang, 2002; Retvari and Biro, 2007; Gen et al., 2008). The single parent vicinal swap method is used to complete mutation. First of all, select two different gene locations in chromosomes randomly, confirm vicinal swap position according to the order of two genes, position. Then, if the number of genes is even number within start-stop position, all odd number genes and its right neighbouring even number genes will be swapped within the segment; if the number of genes is odd number within start-stop position, all odd number genes and its right neighbouring even number genes will be swapped within the segment apart from the last genes.

For example, chromosome $P_a = 1 2 3 | 4 5 6 7 | 8 9$ will be changed into $P_a' = 1 2 3 | 5 4 7 6 | 8 9$ and $P_b = 4 5 | 2 1 8 7 6 | 9 3$ will be changed into $P_b' = 4 5 | 1 2 7 8 6 | 9 3$. Obviously, it must generate feasible solution by such mutation method.

The specific steps of building dominated sets by exclusive method (Hsieh et al., 2013) are as follows:

**Step 1:** Initialise the non-dominated set paretos and construction set paretos1.

**Step 2:** Copy all the different individuals of population pops into paretos1.

**Step 3:** Compare different individual $X$ with $Y$ (it belongs to paretos1). If $X$ dominates $Y$, $Y$ will be removed from the construction set paretos1; If $Y$ dominates $X$, $X$ will be removed from the construction set paretos1, then exit current comparison to next comparison; when a round comparison is ended, if $X$ is not dominated by any other individual, then copy $X$ into the dominated sets paretos.

**Step 4:** Assign the individual (it is behind $X$) to $X$ in paretos1.

**Step 5:** Repeat steps 3 and until $X$ is the last individual of paretos1.

**Step 6:** Copy last individuals of paretos1 into the dominated sets paretos.

In any case, the individual must be non-dominated by using this method to construct the dominating sets. But, it is just the dominated sets of current generation, it is not the global dominant individual, therefore, each individual of current generation will be compared with all individuals of paretos0, judge whether it is the global dominant individual and conduct corresponding operation.

### 3.3 Steps of the multi-objective hybrid intelligence algorithm

**Step 1:** Initialise and set crossover and mutation rate, confidence level, simulation frequency and genetic algebra, etc.

**Step 2:** Build initial population based on the priority chromosome coding way.

**Step 3:** Use analytic method or computer simulation techniques to calculate objective and fitness value of chromosomes.
Step 4: Use exclusive method to construct non-dominated set.

Step 5: Get new population through roulette method to select chromosome, and retain optimal individual under single objective.

Step 6: Conduct matching crossover operation and swapping mutation operation for new population according to different probabilities.

Step 7: Repeat steps 3–6 until it meets the given maximum generation.

Step 8: Get the final non-dominated set.

The flow chart of algorithm is shown in Figure 1.

**Figure 1** Flow chart of the multi-objective hybrid intelligence algorithm (see online version for colours)
4 Case study

Figure 2 is an abstract figure of a road traffic network, and hazardous materials transport risk and transport time parameters are shown in Table 1. The transport risk is a triangular fuzzy number, and the transport time is random numbers, which obey the normal distribution.

**Figure 2** Road traffic network

![Road traffic network diagram]

**Table 1** Transport risk and transport time in the traffic network

<table>
<thead>
<tr>
<th>Road</th>
<th>Transport risk</th>
<th>Transport time</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1,2)</td>
<td>(1,1.5,2)</td>
<td>(25,4)</td>
</tr>
<tr>
<td>(1,3)</td>
<td>(5.6,6.6,4)</td>
<td>(23,3)</td>
</tr>
<tr>
<td>(1,4)</td>
<td>(6,7,8)</td>
<td>(35,5)</td>
</tr>
<tr>
<td>(2,3)</td>
<td>(2.5,3,3.5)</td>
<td>(20,5)</td>
</tr>
<tr>
<td>(2,5)</td>
<td>(4.8,5.5,2)</td>
<td>(18,2)</td>
</tr>
<tr>
<td>(2,6)</td>
<td>(1,1.7,2.4)</td>
<td>(25,7)</td>
</tr>
<tr>
<td>(3,4)</td>
<td>(6.6,3,6.5)</td>
<td>(14,1)</td>
</tr>
<tr>
<td>(3,6)</td>
<td>(5.1,5,7,6.3)</td>
<td>(22,5)</td>
</tr>
<tr>
<td>(3,7)</td>
<td>(4,4,9,5.8)</td>
<td>(20,5)</td>
</tr>
<tr>
<td>(4,7)</td>
<td>(8,9,10)</td>
<td>(25,5)</td>
</tr>
<tr>
<td>(5,8)</td>
<td>(4,4,5,5)</td>
<td>(30,9)</td>
</tr>
<tr>
<td>(6,5)</td>
<td>(5,5,4,5.8)</td>
<td>(20,5)</td>
</tr>
<tr>
<td>(6,8)</td>
<td>(5,1,5,7,6.3)</td>
<td>(10,1)</td>
</tr>
<tr>
<td>(6,9)</td>
<td>(5,6,7)</td>
<td>(23,3)</td>
</tr>
<tr>
<td>(6,10)</td>
<td>(4,5,6)</td>
<td>(20,5)</td>
</tr>
<tr>
<td>(7,6)</td>
<td>(3,4,5)</td>
<td>(40,5)</td>
</tr>
</tbody>
</table>
Now, a batch of hazardous materials are transported from node 1 to node 11, and we want to get the optimal transport network. This problem can be converted into a hazardous materials transport network design problem. We design the computer program in Microsoft Visual C++ environment according to the operation steps of multi-objective hybrid intelligence algorithm, assume $\alpha = \beta = 0.8$, $r = 15$, $R = 30$, $N = 3000$, maximum genetic generation is 100, the number of individuals in each generation population is 100, crossover probability is 0.90, mutation probability is 0.10, computer program was running on the Lenovo laptop (Pentium (R) Dual-core CPU T4200 @ 2.00 GHz, 1.99 GB memory, Windows XP), and the results are shown in Table 2.

Table 2  Pareto solution set

<table>
<thead>
<tr>
<th>Number</th>
<th>Pareto solution</th>
<th>Transport risk</th>
<th>Transport time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1 \rightarrow 3 \rightarrow 6 \rightarrow 10 \rightarrow 11$</td>
<td>19.888</td>
<td>89.170</td>
</tr>
<tr>
<td>2</td>
<td>$1 \rightarrow 3 \rightarrow 6 \rightarrow 8 \rightarrow 11$</td>
<td>19.241</td>
<td>93.093</td>
</tr>
<tr>
<td>3</td>
<td>$1 \rightarrow 2 \rightarrow 6 \rightarrow 10 \rightarrow 11$</td>
<td>11.527</td>
<td>94.406</td>
</tr>
<tr>
<td>4</td>
<td>$1 \rightarrow 2 \rightarrow 6 \rightarrow 8 \rightarrow 11$</td>
<td>10.681</td>
<td>98.623</td>
</tr>
</tbody>
</table>

We can see the transport time is gradually increasing with the decrease in transport risk; it shows that transport time and transport risk are in conflict in the multi-objective optimisation design of hazardous materials transport network; the four solutions form the Pareto frontier curve.

5 Conclusion

Hazardous materials transport vehicles are a lot of flowing danger sources. Once accident happened, the effects for surrounding people and livestock, property and environment are very serious. However, the hazardous material transport is an important part of its life cycle, and it is difficult to omit. To avoid hazardous materials transport accidents, we need to design a scientific transportation network for hazardous materials in advance. On the basis of the review of research status for hazardous materials transport network design problem, the paper considers transport risk and transport time comprehensively, builds multi-objective chance-constrained programming model for hazardous materials transport network, and then adopts multi-objective hybrid intelligent algorithm to solve
the model. The case study shows that the model and algorithm are feasible. And, the obtained optimal design scheme can guide the trucks carrying hazardous materials to arrive at the destination safely and fast.

Although most hazardous materials are transported by trucks, but other transport modes cannot be ignored, so multi-modal transport network optimisation design methods of hazardous materials need to do in-depth research.

Acknowledgements

This work is financially supported by the National Natural Science Foundation of China (Nos. 61364026, 61164003, 51408288) and the Higher School Science Foundation of Gansu Province (No. 2014A-044).

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