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Research on Location and Transportation Route Optimization for Hazardous Chemical Waste Based on Multi-objective Constraints

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Traditional literature has only considered the dual constraints of waste stacking and storage and vehicle transportation, and given little thought on environmental risk control. In light of this problem, this paper proposes a multi-objective optimization model considering cost, environmental risk and social risk and verifies the feasibility of the proposed model through an instance. The proposed cost-environment risk-social risk multi-objective optimization model is a multi-layer network structure. It considers the environmental capacity constraint and the environmental and social risks for recycling hazardous chemicals and performs clustering analysis based on the multi-layer genetic algorithm. The results show that compared with the optimization solution considering social risk only, the one considering environmental risk only reduces the total cost by about 66.98% and that the multi-objective optimization solution considering construction cost, environmental risk and social risk reduces the total cost by about 71.39%, indicating that environmental risk is the most important factor for the location-transportation route optimization scheme. In summary, the multi-objective optimization solution considering construction cost, environmental risk and social risk established in this paper can achieve the best overall optimization.

1. Introduction

Hazardous chemical waste refers to hazardous substances (including solids, liquids and gases) that are flammable, explosive, easily corrosive, and infectious (Atlas, 2001; Uğurlu and Kahraman, 2011; Ghezavati and Morakabatchian, 2015). The recycling and logistic transport of hazardous chemical waste are different from those of general goods - the planning of logistic location and transportation route will have a serious impact on the surrounding environment, economy and regional development and the potential hazards in waste storage and transportation are also public concerns (Alumur and Kara, 2007; Zhao, 2011; Huang and Prof, 2005).

The location-routing problem (LRP) for hazardous waste is a dual constrained problem that optimizes waste storage and vehicle transport (Anandalingam and Westfall, 2010; Berman et al., 2007). Researchers have conducted extensive research on the LRP problem and constructed a large number of computation models (Alshammari et al., 2008; Zhao et al., 2016), such as the bi-objective model that considers transportation time and risk; the multi-objective model that considers cost, storage centre and transportation route; and the equitable risk distribution model. The above literatures only focused on one kind of hazardous chemicals, but in actual management, the hazardous chemicals often have many kinds of characteristics. Some researchers have designed whole-process logistic systems for treatment of hazardous chemicals, including the collection, storage, processing and transportation of hazardous substances; or subdivided the problem into several sub-problems such as location of storage and processing centre and planning of logistics and transportation routes.

Traditional literature has only considered the dual constraints of waste stacking and storage and vehicle transportation, and given little thought on environmental risk control; therefore, this paper proposes a multi-objective optimization model considering cost, environmental risk and social risk and verifies the feasibility of the proposed model through an instance.

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2. Location-routing model for hazardous chemical recycling considering environmental factors

The storage location and logistics transport of hazardous chemicals have particularities. If there is any hazardous chemical leakage or explosion in the process of storage and transportation, it may lead to significant environmental and social hazards. In the preliminary storage location and logistics transport planning, the impacts of environmental factors must be taken into account.

Figure 1 shows the flow circulation diagram for the recycling system and location-logistics transportation model for hazardous chemical waste proposed in this paper. The whole system is a multi-layer network structure consisting of upstream production plants, midstream recycling centres and processing centres and a downstream chemical treatment centres. The hazardous substances are transported by vehicle between the four centres. During the production of hazardous chemicals, the production plants would also generate some waste chemicals, processible chemicals and recyclable chemicals. The three types of hazardous chemical derivatives will be transported to the recycling centres, processing centres and downstream chemical treatment centres, respectively, depending on their applications. The flow process is similar at the recycling centres and processing centres.

In Figure 1, x_{wij}, y_{wij}, z_{wij}, l_{wij}, m_{wij} and n_{wij} are continuous decision variables, representing the total amount of hazardous chemical waste transported between two centres (such as the production centre and the recycling centre); r_{wi}, t_{wil} and d_{wi} represent respectively the total amount of chemical waste treated at the recycling centre, the processing centre and the processing centre.

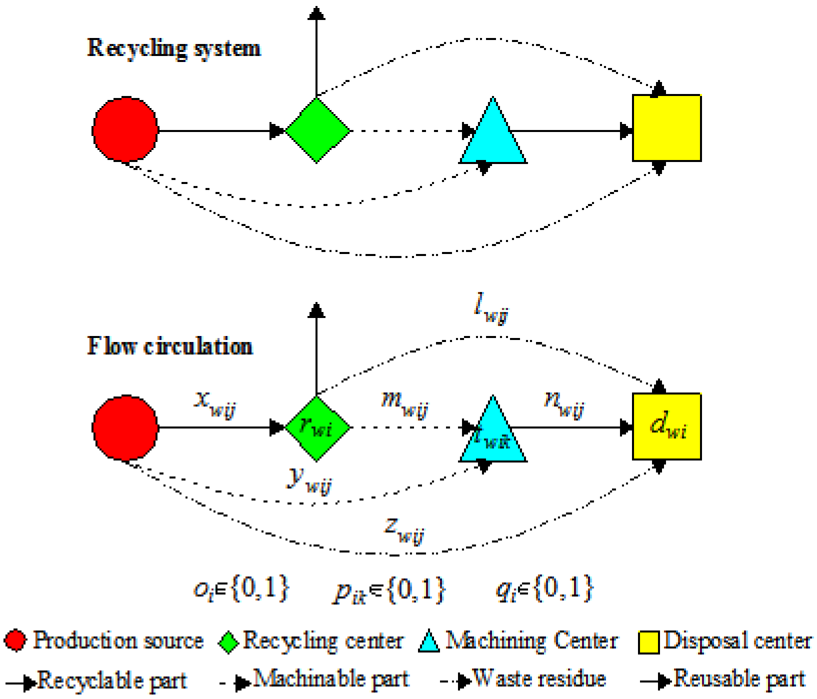

Figure 1: Flow circulation of the hazardous chemical waste recycling system and location-logistics transportation

According to the hazardous chemical waste recycling system in Figure1, a mathematical model is established with cost, environmental risk and social risk taken into account. The corresponding objective functions are as follows:

$$\min f_1 = \sum_{i\in R} RFC_i o_i + \sum_{i\in T}\sum_{k\in K} TFC_{ik} p_{ik} + \sum_{i\in D} DFC_i q_i + \sum_{w\in W}\sum_{(i,j)\in E} TC_w \left(x_{wij} + y_{wij} + z_{wij} + l_{wij} + m_{wij} + n_{wij}\right) \tag{1}$$

$$\min\ f_2 = \sum_{w\in W}\sum_{i\in R}\frac{r_{wi}}{NEC_{wi}} + \sum_{w\in W}\sum_{i\in T}\frac{\sum_{k\in K} t_{wik}}{NEC_{wi}} + \sum_{w\in W}\sum_{i\in D}\frac{d_{wi}}{NEC_{wi}} + \sum_{w\in W}\sum_{(i,j)\in E}\frac{\left(x_{wij} + y_{wij} + z_{wij} + l_{wij} + m_{wij} + n_{wij}\right)}{EEC_{wij}} \tag{2}$$

$$\min\ f_3 = \sum_{w\in W}\sum_{i\in R} r_{wi}N_i + \sum_{w\in W}\sum_{i\in T}\sum_{k\in K} t_{wik}N_i + \sum_{w\in W}\sum_{i\in D} d_{wi}N_i + \sum_{w\in W}\sum_{(i,j)\in E}\left(x_{wij} + y_{wij} + z_{wij} + l_{wij} + m_{wij} + n_{wij}\right)NN_{ij} \tag{3}$$

minf_1, minf_2 and minf_3 represent the minimization of the total cost, environmental risk and social risk of hazardous chemical waste.

$$\begin{cases} NEC_{wi} = N_i \times C_w \times CF \\ EEC_{wij} = NN_{ij} \times C_w \times RR \times CF \end{cases} \tag{4}$$

$$\begin{cases} \alpha_w g_{wi} = \sum_{j\in R} x_{wij}, \forall w\in W, \forall i\in G \\ r_{wi} = \sum_{j\in R} x_{wji}, \forall w\in W, \forall i\in R \\ \beta_w g_{wi} = \sum_{j\in T} y_{wij}, \forall w\in W, \forall i\in G \end{cases} \tag{5}$$

$$\begin{cases} (1-\alpha_w-\beta_w)\, g_{wi} = \sum_{j\in T} z_{wij}, \forall w\in W, \forall i\in G \\ (1-\delta_w-\varepsilon_w)\, r_{wi} = \sum_{j\in D} l_{wij}, \forall w\in W, \forall i\in R \\ \delta_w c_{wi} = \sum_{j\in T} m_{wij}, \forall w\in W, \forall i\in R \end{cases} \tag{6}$$

$$\begin{cases} \sum_{k\in K}\phi_{wk}t_{wik} = \sum_{j\in D} n_{wij}, \forall w\in W, \forall i\in T \\ \sum_{i\in R} y_{wij} + \sum_{j\in R} m_{wij} = \sum_{k\in K} t_{wjk}, \forall w\in W, \forall j\in T \\ \sum_{i\in R} z_{wij} + \sum_{j\in R} l_{wij} + \sum_{i\in T} n_{wij} = d_{wj}, \forall w\in W, \forall j\in D \end{cases} \tag{7}$$

$$\begin{cases} \sum_{w\in W} r_{wi} \le o_i RC_i, \forall i\in R \\ \sum_{w\in W} t_{wik} \le p_{ik} TKC_{ik}, \forall i\in T, \forall k\in K \\ \sum_{w\in W} d_{wi} \le q_i DC_i, \forall i\in D \\ \sum_{w\in W} t_{wik} \ge p_{ik} TKM_{ik}, \forall i\in T, \forall k\in K \end{cases} \tag{8}$$

NEC_{wi} and EEC_{wij} represent the environmental capacity of network nodes and network arcs; N_i and NN_{ij} represent the number of inhabitants at the four treatment centres and in their surroundings; C_w is the atmospheric standard concentration of chemical ions; CF is the conversion factor; TKC_{ik} represents the ultimate processing capacity; DC_i is the maximum amount of waste treated; α_w and β_w are the percentages of recyclable and processible waste in the waste chemicals produced at the production plant; δ_w and ε_w are the percentages of reusable or processible waste in the recyclable waste; RFC_i and DFC_i are the construction costs of the recycling centre and the processing centre, respectively; TC_i is the transportation cost of waste; and g_{wt} is the production of hazardous chemical waste at the production plant.
Equations 4-8 are the constraints for minf_1, minf_2 and minf_3, respectively. Equation 4 represents the environmental capacity constraint of the areas where the four centres are located; Equation 5-7 represent the conservation of transport flow of hazardous chemical waste in the whole system; and Equation 8 represents the maximum processing, recycling and treatment capacity of the 4 centres.
The established model comprehensively considers environmental risk, social risk and total cost, which is a typical multi-objective function optimization problem. The extremum method is used to eliminate the dimensions of the three objective functions so that the three objective functions can be combined to form a new single-objective optimization model. The conversion coefficient η is as follows:

$$\eta_z = \frac{f_z(X) - f_z^*}{f_z(X)} \tag{9}$$

z=1, 2, 3, representing the three objective functions. The TOPSIS method is used to combine the multi-objective optimization problems into a new single-objective optimization problem. And then there is:

$$\min F(X) = \sqrt{\sum_z \left\{ \eta_z \left[f_z(X) - f_z^* \right] \right\}} \tag{10}$$

3. Instance analysis

The hazardous chemical waste location-transport routing model is shown in Figure2. There are 35 production centres and 4 candidate processing centres in the model. At the 4 candidate points, recycling centres, processing centres and downstream chemical treatment centres can be constructed simultaneously. Suppose the average transport cost of hazardous substances per kilometre is 230 Yuan/ton, that CF=1.1×10^6, and that the average concentration of major wastes in the chemicals is 4.5×10^{-4}mg/L. Table 1 and Table 2 list the relevant information on 4 candidate centres as chemical recycling centres or chemical treatment centres, respectively.

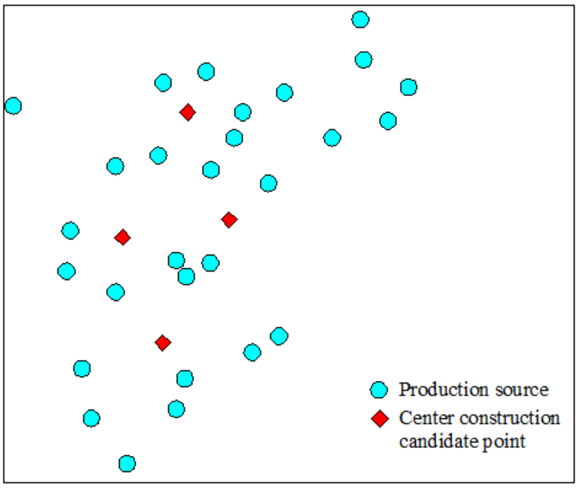

Figure 2: Transportation planning model for hazardous chemical waste recycling

According to relevant information in Equation 1-8 and Table 1 and 2, iterative calculation is performed using the genetic algorithm, with the initial population set to 3-. The crossover probability and mutation probability are 0.75 and 0.05, respectively, and the maximum number of iterations is 120. The calculated total cost, environmental risk and social risk and the optimal centre locations are shown in Table 3.

Table 1: Basic information on 4 chemical recycling centres

Candidate point	Fixed construction costs ($\times 10^6$yuan/year)	Maximum processing capacity (t/year)	Exposed population
1	21	6400	4207
2	19	6400	3219
3	32	3000	6834
4	26	2600	4456

Table 2: Basic information on 4 chemical treatment centres

Candidate point	Fixed construction costs ($\times 10^6$yuan/year)	Maximum processing capacity (t/year)	Exposed population
1	24	30000	4207
2	30	30000	3219
3	30	32000	6834
4	22	32000	4456

Table 3 Calculated results of the total cost, environmental risk and social risk

Cost/yuan	Environmental risk	Social risk	Recycling centre location	Processing centre location	Processing centre location (node, processing technology)
8.62×10^6	2.34×10^9	3.98×10^8	1,2	1,2	(1,1), (1,1)

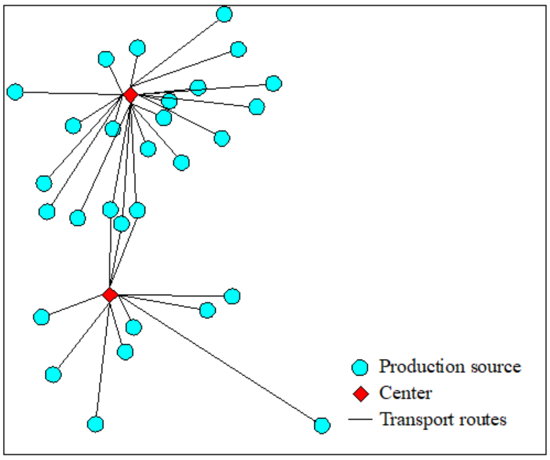

Figure 3: Final location-routing design scheme for hazardous chemical waste recycling

Figure 3 shows the final location-routing design scheme, which selects candidate centre 1 and 2 as the final product treatment centres. The calculation takes a short time and can effectively obtain the optimal solution with multi-objective optimization.

Table 4 lists the calculated results of the total cost in cases of minimized social risk, minimized environmental risk, minimized cost +social risk and minimized cost + social risk + environmental risk, respectively.

Table 4: Comparison of the total costs calculated under different objective functions

Comparison of conditions	Cost/yuan	Rate of change
Minimization of social risk	2.88×10^7	—
Minimization of environmental risk	9.51×10^6	-66.98%
Minimization of cost + social risk	1.48×10^7	-48.61%
Minimization of cost + environmental risk + social risk	8.24×10^6	-71.39%

From Table 4, it can be seen that, the scheme considering social risk only has the highest total cost, followed by the one considering the construction cost + social risk and the one considering environmental risk only and the one that takes construction cost, social risk and environmental risk into account. Compared with the total cost of the scheme considering social risk only, those of the latter three are reduced by about 48.61%, 66.98% and 71.39%, respectively, indicating that the multi-objective optimization solution considering construction cost, environmental risk and social risk established in this paper can achieve the best overall optimization.

4. Conclusions

Traditional literature has only considered the dual constraints of waste stacking and storage and vehicle transportation, and given little thought on environmental risk control. In light of this problem, this paper proposes a multi-objective optimization model considering cost, environmental risk and social risk and verifies the feasibility of the proposed model through an instance. The conclusions are as follows:
(1) The proposed cost-environment risk-social risk multi-objective optimization model is a multi-layer network structure. It considers the environmental capacity constraint and the environmental and social risks for recycling hazardous chemicals and performs clustering analysis based on the multi-layer genetic algorithm.
(2) The calculation results show that compared with the optimization solution considering social risk only, the one considering environmental risk only reduces the total cost by about 66.98% and that the multi-objective optimization solution considering construction cost, environmental risk and social risk reduces the total cost by about 71.39%, indicating that environmental risk is the most important factor for the location-transportation route optimization scheme. In summary, the multi-objective optimization solution considering construction cost, environmental risk and social risk established in this paper can achieve the best overall optimization.

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