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Site selection of emergency material warehouse under fuzzy environment

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Abstract: The objective of this work was to determine the location of emergency material warehouses. For the site selection problem of emergency material warehouses, the triangular fuzzy numbers are respectively demand of the demand node, the distance between the warehouse and demand node and the cost of the warehouse, a bi-objective programming model was established with minimum total cost of the system and minimum distance between the selected emergency material warehouses and the demand node. Using the theories of fuzzy numbers, the fuzzy programming model was transformed into a determinate bi-objective mixed integer programming model and a heuristic algorithm for this model was designed. Then, the algorithm was proven to be feasible and effective through a numerical example. Analysis results show that the location of emergency material warehouse depends heavily on the values of degree α and weight w_1. Accurate information of a certain emergency activity should be collected before making the decision.

Key words: bi-objective; mixed-integer programming; emergency material warehouse; triangular fuzzy number; site selection

1 Introduction

Emergency material warehouse is an essential infrastructure for emergency aid. China's network of emergency material warehouses has already taken shape, and a certain number and varieties of disaster relief supplies are stored. Despite their important role in the emergency rescue, there are still many problems in the layout of relief material warehouses. Therefore, it is of great significance to study the site selection of emergency material warehouse. The scientific and reasonable site selection of emergency material warehouse will provide theoretical guidance and technical support for the programming of emergency material warehouse, and to improve the efficiency of emergency rescue and reduce the cost. The site selection of emergency material warehouse belongs to the problem of site selection of facility warehouse. Since HAKIMI [1] researched site selection of multiple facilities in the network, scholars have done a lot of research on site selection of facility, and push the theoretical research of site selection of facility into prosperity. VIDAL and GOETSCHALCKX [2] summarized the current status of site selection research, and note out the research orientation of emergency logistics system. LIN et al [3] proposed the location of temporary depots around the disaster-affected area and a two-phase heuristic approach. BERALDI and BRUNI [4] established a probability along with the required vehicles and resources, to improve logistical efficiency and model of rapid decision-making concerning site selection in emergency situation. The model revealed the uncertainty of decision-making process by embedding stochastic programming into the conventional two-stage programming. Moreover, a suitable heuristic algorithm was proposed. LIU and ZHANG [5] studied on location selection of multi-objective emergency logistics center based on AHP, it applied the interrupt delay constraint on the basis of considering the environment, economy and technical factor, and it considered that the time objective is priority to the cost objective. LIU and SHEN [6] and FANG and HE [7] respectively examined continuous consumption and optimization of site selection of emergency system. HUANG et al [8] proposed a variation of the P-center problem and designed a dynamic programming approach. In the P-center problem, it is assumed that the facility located at a node responds to demands originated from the node. Considering that this assumption was not valid for large-scale emergencies where most of the facilities in a whole city may become functionless. ZHANG et al [9] took the model of multilevel fuzzy optimization into location decision on distribution center of emergency logistics for emergency event, and used information entropy and analytical hierarchy process to determine the combined weight of the indexes, which provided a new way for location decision on distribution center of

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emergency logistics. TREVOR and CHRISTOPOHER [10] focused on the choice of emergency logistics nodes, and established a quantitative model depending on the storage amount of emergency material of the node. ZHANG and YANG [11] considered perishable commodities, time constraint, demand constraint, in order to minimize the total cost. YASANUR [12] considered the location problem based on a combination of the fuzzy-analytical hierarchy process and artificial neural networks methods in the process of decision-making. WANG and HE [13] focused on the logistics center location and allocation problem under uncertain environment and proposed a robust optimization model using the formation of regret model. GUO and QI [14] considered the transportation costs to be interval numbers and minimized the total cost to select the emergency material warehouses. The multi-objective model is transformed into a single-objective problem and mainly pursues the goal of efficiency and fairness, METR and ZABINSKY [15] analyzed the earthquake scenarios of the Seattle area and developed a two-stage stochastic programming model for the storage and distribution problem of medical supplies.

Most of the existing literature studied the problem of site selection of the distribution center either with the minimum cost of the system or the minimum total distance in a determinate environment. Few researches investigate site selection of distribution center by meeting both of the requirements. Though GUO and QI [14] considered the location problem which treated the transportation cost as interval number, it didn't consider the distance between the material warehouse and each demand node, but the total distance plays a very important role in real emergency activities. The demand of the demand node, the distance from emergency material warehouse to the demand node and the cost of the warehouse were treated as triangular fuzzy numbers, the site selection of bi-objective emergency material warehouse with minimum total distance and lowest cost of the system were discussed.

2 Problem description and model building

2.1 Problem description

Suppose that $J=\{1, 2, \cdots, n\}$ is the set of serial numbers of n candidate sites of warehouses in the emergency logistics system, and $I=\{1, 2, \cdots, m\}$ is the set of serial numbers of m emergency material demand nodes in the emergency logistics system. A warehouse with the reserve capacity of S_j is built on the j-th site; the unit transportation cost from the j-th site to the i-th demand node is c; the cost (variable cost and fixed cost) of building warehouse in the j-th site is $\tilde{f}_j$ ($\tilde{f}_j=(f_j^{\mathrm{p}}, f_j^{\mathrm{m}}, f_j^{\mathrm{o}})$ is a triangular fuzzy number). Considering that emergency logistics system is formed specifically to manage emergency event, the demand amount of emergency materials in the i-th demand node is a fuzzy parameter, denoted as $\tilde{D}_i$ ($\tilde{D}_i=(D_i^{\mathrm{p}}, D_i^{\mathrm{m}}, D_i^{\mathrm{o}})$ is a triangular fuzzy number). The distance from the j-th candidate warehouse to the i-th demand node is also a fuzzy parameter, denoted as $\tilde{d}_{ij}$ ($\tilde{d}_{ij}=(d_{ij}^{\mathrm{p}}, d_{ij}^{\mathrm{m}}, d_{ij}^{\mathrm{o}})$ is a triangular fuzzy number). p sites are selected among the n candidate warehouse sites to build the warehouse (supposing that there are at least p warehouse sites which enable the warehouse built in these sites to satisfy the demand of each demand node), so that the demand amount of each demand node is satisfied, and the supply amount of the warehouse does not exceed its capacity limit. The question is how to select the sites of emergency material warehouses and how to determine the supply amount of the demand node, to ensure the minimum total distance between the selected warehouse sites and the demand nodes and the lowest total cost of the system.

2.2 Model building

Suppose that x_{ij} is the amount of emergency materials supplied from the j-th warehouse to the i-th demand node; $y_j=\{0,1\}$, when $y_j=1$, it is indicated that the j-th candidate warehouse site is selected, and when $y_j=0$, it is indicated that the j-th candidate warehouse site is not selected. Based on the description and presumptions above, the mathematical model of site selection of emergency material warehouses under fuzzy environment can be obtained.

Model I:

$$\min z_1=\sum_{i=1}^{m}\sum_{j=1}^{n}\tilde{d}_{ij}y_j \tag{1}$$

$$\min z_2=\sum_{i=1}^{m}\sum_{j=1}^{n}c\,\tilde{d}_{ij}x_{ij}+\sum_{j=1}^{n}\tilde{f}_j y_j \tag{2}$$

$$\text{s.t.}\ \sum_{i=1}^{m}x_{ij}\le S_j y_j\ \ (j=1,\ 2,\ \cdots,\ n) \tag{3}$$

$$\sum_{j=1}^{n}y_j=p \tag{4}$$

$$\sum_{j=1}^{n}x_{ij}\ge\tilde{D}_i\ (i=1,\ 2,\ \cdots,\ m) \tag{5}$$

$$y_j\in\{0,1\}\ (j=1,\ 2,\ \cdots,\ n) \tag{6}$$

$$x_{ij}\ge 0(i=1,\ 2,\ \cdots,\ m;\ j=1,\ 2,\ \cdots,\ n) \tag{7}$$

The objective function Eq. (1) represents the total distance between the warehouses and the demand nodes; Another objective function Eq. (2) represents the total cost of the system, including transportation costs and warehouse cost. The constraint condition (Eq. (3)) specifies that the supply amount of the selected warehouse cannot exceed the amount that can be supplied; Constraint condition (Eq. (4)) specifies that p sites must be selected to build the emergency material warehouse; Equation (5) specifies that the demand of each demand node should be satisfied.

2.3 Model solution

2.3.1 Model transformation

Model I is a fuzzy programming model. In order to solve it, the model should be transformed into a determinate one. According to Ref. [16], it is supposed that $\tilde{c}=(c^{\mathrm{p}},c^{\mathrm{m}},c^{\mathrm{o}})$ is a triangular fuzzy number. Then the membership function can be defined as follows:

$$\mu_{\tilde{c}}(x)=\begin{cases} f_c(x)=\dfrac{x-c^{\mathrm{p}}}{c^{\mathrm{m}}-c^{\mathrm{p}}} & \text{if } c^{\mathrm{p}}\le x\le c^{\mathrm{m}} \\ 1 & \text{if } x=c^{\mathrm{m}} \\ g_c(x)=\dfrac{x-c^{\mathrm{p}}}{c^{\mathrm{m}}-c^{\mathrm{p}}} & \text{if } c^{\mathrm{m}}\le x\le c^{o} \\ 0 & \text{if } x\le c^{\mathrm{p}} \text{ or } x\ge c^{o} \end{cases} \tag{8}$$

According to Ref. [17], the expectation range and expectation value of the triangular fuzzy number $\tilde{c}=(c^{\mathrm{p}},c^{\mathrm{m}},c^{\mathrm{o}})$ can be defined as

$$E_{\mathrm{I}}(\tilde{c})=[E_1^{\mathrm{c}},E_2^{\mathrm{c}}]=[\int_0^1 f_c^{-1}(x)\mathrm{d}x,\int_0^1 g_c^{-1}(x)\mathrm{d}x]= [\frac{1}{2}(c^{\mathrm{p}}+c^{\mathrm{m}}),\frac{1}{2}(c^{\mathrm{o}}+c^{\mathrm{m}})] \tag{9}$$

$$E_{\mathrm{V}}(\tilde{c})=\frac{E_1^{\mathrm{c}}+E_2^{\mathrm{c}}}{2}=\frac{c^{\mathrm{p}}+2c^{\mathrm{m}}+c^{\mathrm{o}}}{4} \tag{10}$$

According to Ref. [17], for any pair of fuzzy numbers $\tilde{a}$ and $\tilde{b}$, the degree of $\tilde{a}$ bigger than $\tilde{b}$ can be defined as

$$\mu_M(\tilde{a},\tilde{b})=\begin{cases} 0, \text{ if } E_2^a-E_1^b<0 \\ \dfrac{E_2^a-E_1^b}{E_2^a-E_1^b-(E_1^a-E_2^b)}, \\ \quad \text{if } E_1^a-E_2^b\le 0\le E_2^a-E_1^b \\ 1, \text{ if } E_1^a-E_2^b>0 \end{cases} \tag{11}$$

When $\mu_M(\tilde{a},\tilde{b})\ge\alpha$, we say that $\tilde{a}$ is greater than or equal to $\tilde{b}$ by at least α degree (written as $\tilde{a}\ge_\alpha\tilde{b}$), and $\alpha\in(0,1]$ is given by the decision makers.

According to Ref. [15], if $\tilde{a}\ge\alpha/2\tilde{b}$, $\tilde{a}\le_{\alpha/2}\tilde{b}$, we say that $\tilde{a}$ is equal to $\tilde{b}$ by at least α degree.

Thus, Model I can be transformed into the following determinate bi-objective programming model.

Model II:

$$\min z_1=\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{d^p{}_{ij}+2d^m{}_{ij}+d^o{}_{ij}}{4}\right)y_j \tag{12}$$

$$\min z_2=\sum_{i=1}^{m}\sum_{j=1}^{n}\left(\frac{d^p{}_{ij}+2d^m{}_{ij}+d^o{}_{ij}}{4}\right)cx_{ij}+ \sum_{j=1}^{n}\left(\frac{f^p{}_j+2f^m{}_j+f^o{}_j}{4}\right)y_j \tag{13}$$

$$\text{s.t. } \sum_{i=1}^{m}x_{ij}\le S_jy_j\ (j=1,\ 2,\ \cdots,\ n) \tag{14}$$

$$\sum_{j=1}^{n}y_j=p \tag{15}$$

$$\sum_{j=1}^{n}x_{ij}\ge\alpha\left(\frac{D_i^p+D_i^m}{2}\right)+(1-\alpha)\left(\frac{D_i^o+D_i^m}{2}\right)\quad (i=1,\ 2,\ \cdots,\ m) \tag{16}$$

$$y_j\in\{0,1\}\ (j=1,\ 2,\ \cdots,\ n) \tag{17}$$

$$x_{ij}\ge 0\ (i=1,\ 2,\ \cdots,\ m;\ j=1,\ 2,\ \cdots,\ n) \tag{18}$$

2.3.2 Algorithm design

Model II is an NP-hard problem. The bi-objective programming model can be transformed into a single-objective one. Given the different dimensions of the two objective functions, we first made the objective function dimensionless, and then transformed bi-objective model into a single-objective one by liner weighting method, as shown below:

Step 1: Look for the set of feasible solution $\Phi=\{Y_1,Y_2,\cdots,Y_q\}(q\le C_n^{\mathrm{p}})$ of $Y=\{y_1,\ y_2,\ \cdots,\ y_n\}$, where $Y_i=\left(0,\cdots,\underset{i_1}{1},0,\cdots,\underset{i_2}{1},\cdots 0,\underset{i_p}{1},\cdots 0\right)$ represents that in the i-th feasible solution, the address set $\Theta=\{i_1,i_2,\cdots,i_p\}$ satisfies the condition that the number of the warehouse sites is p and the warehouses built on these p warehouse sites can meet the total demand of the demand nodes.

Step 2: For each $Y_i(i=1,2,\cdots,q)$, calculating the value of z_1, which can be successively denoted as z_{11}, z_{12}, ⋯, z_{1q}, and notes $z_1^{\max}=\max\{z_{11},z_{12},\cdots,z_{1q}\}$.

Step 3: For each $Y_i(i=1,2,\cdots,q)$, treating z_2 as the objective function separately to solve the following transportation problem:

$$\min z_2=\sum_{i=1}^{m}\sum_{j\in\Theta}\left(\frac{d^{\mathrm{p}}{}_{ij}+2d^{\mathrm{m}}{}_{ij}+d^{\mathrm{o}}{}_{ij}}{4}\right)cx_{ij}+ \sum_{j\in\Theta}\left(\frac{f^{\mathrm{p}}{}_j+2f^{\mathrm{m}}{}_j+f^{\mathrm{o}}{}_j}{4}\right)$$

$$\text{s.t.} \sum_{i=1}^{m} x_{ij} \le S_j\,(j\in\Theta)$$

$$\sum_{j\in\Theta} x_{ij} \ge \alpha\left(\frac{D_i^{\mathrm{p}}+D_i^{\mathrm{m}}}{2}\right)+(1-\alpha)\left(\frac{D_i^{\mathrm{o}}+D_i^{\mathrm{m}}}{2}\right)$$

$$(i=1,\ 2,\ \cdots,\ m)$$

$$x_{ij}\ge 0\,(i=1,\ 2,\ \cdots,\ m;\ j\in\Theta)$$

The value of z_2 can be obtained, and denoted successively as z_{21}, z_{22}, ⋯ , z_{2q}, and notes $z_2^{\max}=\max\{z_{21},z_{22},\cdots,z_{2q}\}$;

Step 4: For each $Y_i\,(i=1,2,\cdots,q)$, treating Eq. (15) as the objective function, to solve the following model $(w_1+w_2=1, 0<w_1,w_2<1)$.

$$\min z=\frac{w_1}{z_1^{\max}}\sum_{i=1}^{m}\sum_{j\in\Theta}\left(\frac{d^{\mathrm{p}}_{ij}+2d^{\mathrm{m}}_{ij}+d^{\mathrm{o}}_{ij}}{4}\right)+$$
$$\frac{w_2}{z_2^{\max}}\sum_{j\in\Theta}\sum_{i=1}^{m}\left(\frac{d^{\mathrm{p}}_{ij}+2d^{\mathrm{m}}_{ij}+d^{\mathrm{o}}_{ij}}{4}\right)cx_{ij}+$$
$$\frac{w_2}{z_2^{\max}}\sum_{j\in\Theta}\frac{f^{\mathrm{p}}_{j}+2f^{\mathrm{m}}_{j}+f^{\mathrm{o}}_{j}}{4} \quad (19)$$

$$\text{s.t.} \sum_{i=1}^{m} x_{ij} \le S_j\,(j\in\Theta)$$

$$\sum_{j\in\Theta} x_{ij} \ge \alpha\left(\frac{D_i^{\mathrm{p}}+D_i^{\mathrm{m}}}{2}\right)+(1-\alpha)\left(\frac{D_i^{\mathrm{o}}+D_i^{\mathrm{m}}}{2}\right)$$

$$(i=1,2,\cdots,m)$$

$$x_{ij}\ge 0\,(i=1,2,\cdots,m;\ j\in\Theta)$$

The value of z can be obtained, and denoted successively as $z^1,z^2,\cdots,z^q$; the optimal value of z is $z^{\mathrm{opt}}=\min\{z^1,z^2,\cdots,z^q\}$, and the optimal solution is $\{x_{ij}^*\}$.

3 Numerical example

There are six candidate warehouse sites and six emergency demand nodes. three candidate sites will be selected from the six nodes as the sites for emergency facilities. The relevant data are listed in Table 1.

Since the emergency warehouse is used for emergency rescue, the minimization of the total distance should be the priority. We select w_1=0.8 and α=0.5, c=0.15. Using the above algorithm, the results are obtained as follows.

1) The sets of the eligible candidate warehouses are: Y_1={1,1,1,0,0,0}, Y_2={1,0,1,0,1,0}, Y_3={0,1,1,1,0,0}, Y_4={0,1,1,0,1,0}, Y_5={0,0,1,1,1,0}, Y_6={1,0,1,1,0,0}.

2) The values of z_1 calculated for each Y_i(i=1, 2, ⋯, 6) are z_{11}=1 070.25, z_{12}=1 230.5, z_{13}=1 230.75, z_{14}=1 300.25, z_{15}=1 420.75, z_{16}=1 320.5.

From the data above, it can be known that $z_1^{\max}=1\,420.75$.

3) The values of z_2 can be solved by solving the transportation problem for each Y_i(i=1, 2, ⋯, 6). z_{21}=1 052, z_{22}=1 010.375, z_{23}=1 216.375, z_{24}=1 125.531, z_{25}=1 117.75, z_{26}=1 090.5.

From the data above, it can be known that $z_2^{\max}=1\,216.375$.

4) $z_1^{\max}=1\,420.75$ and $z_2^{\max}=1\,216.375$ are introduced to Eq. (19). The values of z are obtained for each Y_i(i=1, 2, ⋯, 6): z^1=0.172, z^2=0.166, z^3=0.199, z^4=0.184, z^5=0.183, z^6=0.188.

From the data above, it can be known that the optimal value of z is 0.166, and the optimal solution is $Y_2=\{1,0,1,0,1,0\}$ and x_{15}=15, x_{23}=2.75, x_{25}=21, x_{31}=10, x_{41}=18, x_{43}=10, x_{53}=7, x_{63}=12.75.

Therefore, the emergency material warehouses are built respectively on the first, third and fifth sites. The specific distribution solution is as follows.

The warehouse built on site 1 supplies respectively 10 and 18 units of emergency materials to demand nodes 3 and 4; the warehouse built on site 3 supplies respectively 2.75, 10 and 12.75 units of emergency materials to demand nodes 2, 6 and 4; the warehouse built on site 3 supplies 15, 2 and 28 units of emergency materials to demand node 1, 2 and 4.

Then, the minimum total distance is 1 215, and the minimum total cost of the emergency system is

Table 1 Distance between candidate warehouse to each demand node

Warehouse site	Demand node					
	1	2	3	4	5	6
1	(20,30,40)	(60,80,90)	(10,30,50)	(60,70,90)	(50,70,09)	(30,60,80)
2	(30,40,60)	(50,70,80)	(40,60,70)	(50,80,90)	(70,90,100)	(20,50,70)
3	(10,30,40)	(30,60,70)	(30,60,80)	(30,40,50)	(40,60,80)	(10,12,13)
4	(50,70,90)	(70,90,100)	(20,50,70)	(70,90,100)	(120,130,150)	(60,80,90)
5	(100,120,130)	(40,60,80)	(40,60,80)	(130,140,160)	(20,50,80)	(80,90,100)
6	(120,130,150)	(20,50,80)	(70,80,100)	(10,40,60)	(40,60,70)	(10,20,40)

Table 2 Cost and reserve capacity of warehouses built on selected sides and demand of demand nodes

Cost ($\tilde{f}_j$)	Capacity (S_j)	Demand ($\widetilde{D}_i$)
(80,100,120)	28	(12,15,18)
(160,180,200)	24	(20,24,27)
(150,170,190)	45	(8,9,12)
(95,115,155)	30	(26,28,20)
(130,150,170)	36	(5.5,6.5,9.5)
(45,60,75)	20	(9,13,16)

1 045.025.

Since the deciders' preferences or local situations are different, so the degree α and the weight w_1 should be taken different values. Using the above algorithm with different values of degree α and weight w_1, the results can be obtained, then by using the plotting function of MATLAB, the following two figures of the total cost and total distance can be got.

According to Figs. 1 and 2, the following conclusions can be got.

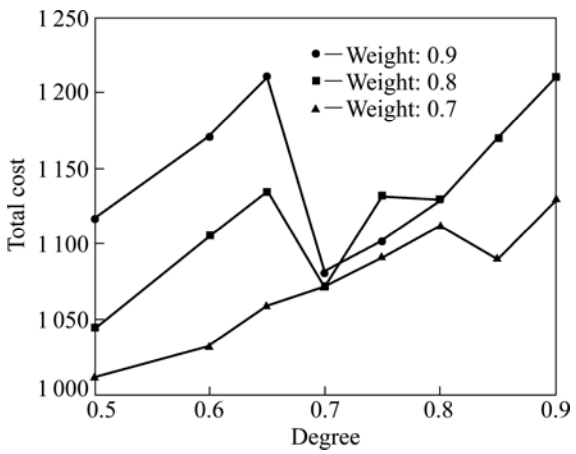

Fig. 1 Different degree α and weight w_1 of corresponding total cost

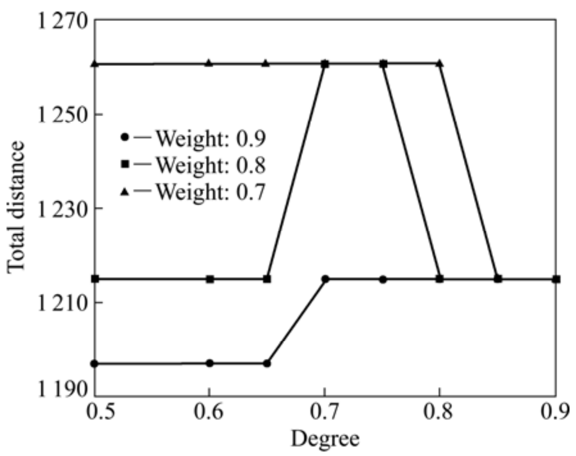

Fig. 2 Different values of degree α and weight w_1 of corresponding total distance

1) Generally, with the degree α and the weight w_1 increasing, the total cost gradually increases;

2) With different values degree α and weight w_1, the total distance changes a lot, and when the degree α decreases to a certain level, the total distance remains unchanged.

So, decision maker should choose appropriate degree α and weight w_1 according to the actual situation to ensure the highest rescue efficiency and reduce rescue cost at the same time.

4 Conclusions

1) Site selection of emergency material warehouse is one of the important problems in emergency managements. It is highly significant to build effective emergency material warehouse network to ensure the supply of emergency materials, to best safeguard people's lives and property safety and to reduce the losses caused by emergencies. This work provides a basis for decision-making related to site selection of emergency material warehouse, with a certain practical significance.

2) Through above analysis, the results of emergency activities rely heavily on the values of degree α and weight w_1, and decision makers play an important role in the location of emergency activities. Therefore, accurate information of a certain emergency activity should be collected before the decision made.

3) The double-level network of distribution centers and demand nodes is discussed. Considering the complete supply chain of emergency activities, the three level network of supply nodes, distribution centers and demand nodes can be discussed in the following work.

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