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Original Research Paper

Collaborative Optimization of Emergency Rescue Under Sudden Inter-City Natural Disaster

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ABSTRACT

This paper combines the characteristics of sudden inter-city natural disaster, and finds out the emergency rescue principles based on the theory of collaborative. Disaster situation and distribution of rescue resources, the rescue efficiency, the rescue reliability, the rescue time and other factors are considered comprehensively, and then a multi-objective assignment model is constructed. Attribute value matrices are transformed into fuzzy relationship matrices according to the theory of fuzzy mathematics and the reserve point method is applied according to the characteristic of the optimization model. With purpose of showing the validity and feasibility of the algorithm Hungarian method is adopted to prove it. The results of the numerical example illustrate that the proposed multi-objective plan does well in task allocation and can satisfy the inter-city emergency rescue task.

INTRODUCTION

In the past decades, various natural disasters frequently occurred around the world including earthquake, tsunami, typhoon, so and so forth. China is also labelled as a country with diversified disaster categories, wide disaster coverage, high occurrence frequency, as well as heavy loss caused by disasters. These sudden and severe natural disasters always result in a large sum of casualties and property loss. A particular example is the rainstorm happened in July 21st, 2012 in Beijing, which had triggered a long debate on waterproof ability of city infrastructure. The heavy rainfall caused mud-rock flow in mountain areas and fiercely attacked urban transport system. Moreover, it took lives of 77 people and forced over 60,000 residents to escape from home, and the direct economic loss reached 10 billion RMB.

To overcome the tragedies and diminish the negative influences, plenty of researches have been conducted and have got considerable achievements. Kannan investigated the network layout with the maximal covering set for different freights (Kannan et al. 2003). Oded Berman found out that the reliability of service facilities location relies on the distance (Oded Berman et al. 2003). Asad's study related to the location and layout of emergency department (Asad et al. 2004). Chen Zhizong focused on the urban disaster prevention and mitigation facilities location (Chen Zhizong et al. 2005, 2006). It developed the two-stage facility locating model and the multi-objective decision model to set the emergency rescue facilities. Wei Yi used a heuristic ant colonies optimization algorithm to solve the logistics problems in disasters (Wei Yi & Arun Kumar 2007). The initial problem is transformed into two sub-questions (vehicle routes and large amount products allocation) and then was processed separately. Moreover, Mei-Shiang Chang presented an approach of emergency logistics planning under uncertainty conditions, and the approach assisted the government to locate the material storage, determine the rescue equipment amount and transportation (Mei-Shiang Chang et al. 2007). Arun Jotshi examined disaster relief resources optimization, the model had its goals as the least transport time for the wounded and maximal expectation for people survive, and then calibrated the parameters by numerical examples (Aran Jotshi et al. 2009). Yuan Yuan modeled the route choice for emergency logistics (Yuan Yuan et al. 2009) and Zhi-Hua Hu designed the supply chain of container network flow and the optimized path. It then formulated a linear integer programming model under disasters and tested the feasibility by computer simulation (Zhi-Hua Hu 2011). The focus of his research are on two major problems in emergency logistics system optimization, there exists close relationship of these two elements and have to be optimized and managed with consideration of the overall optimization of the system. Therefore, some researchers addressed the integration of facility location and vehicle route choice. Wei Yi's method took the minimal relief goods distribution and delay in the wounded treatment as objectives to operate the resource supply and rescue (Wei Yi & Ozdamar 2007). Dai Ying considered the LRP with fuzzy demand for emergency rescue and rescue time range, the model objectives are the biggest rescuing station time satisfaction and the least total cost of the system. It then formed the multi-objective optimizing model and a hybrid multi-objective genetic algorithm (Dai Ying 2010). Citing the location-path problem for disaster reduction system, Zeng Min-gang divided the problem into two small questions as emergency service facility location and path design for emergency resources transportation (Zeng Min-gang et al. 2010). Wang Shao-ren formulated a double-layer location-transportation model and proposed a two stage triangle heuristic algorithm and analysed the complicacy and compared the method with improved genetic algorithm (Wang Shao-ren & Ma Zu-jun 2011).

To summarize the above researches, academicians and scholars paid more attention to logistics management and especially the transportation of rescue materials, which have been intensively studied. It should be noted that disasters usually cover a wide region and after it took place, all the rescuers should be sent to the places with incidents to carry out the rescue at the first time and reduce the loss as much as possible. Hence, the optimal rescuer allocation plan which guarantees rescuers completing tasks effectively and efficiently is of great significant. But we still find few studies focusing on this field.

SUDDEN NATURAL DISASTERS IN CITY AND INTER-CITY

Urban area: Urban areas are defined as cities and certain regions, which are combined together in face of the disasters. Its definition covers a wide range and can be referred to a city, a certain region, as well as the integration of city and city, city and region, and region and region. City, a complicated and dynamic system for human living, embraces some elements like society, economy, resource, environment, disasters, etc. The definition of region can be understood from the following aspects: (i) the region consists of several cities with close relations and need to achieve the same target, when considering factors of administration, economy and geography factors. This kind of region expands larger than cities, such as the Yangtze River Delta region, the Pearl River Delta region in China; (ii) the regions have relatively independent and specific geographical entity, this kind of region is represented by some economic and technological development zones and special economic zone, such as Guangzhou Nansha Economic and Technological Development Zone, Zhuhai Special Economic Zone, Liuzhi Zone and Wanshan Zone in China; (iii) the region is the major hazard source that situated inside one city, such as the Chemical Industrial Park in Shanghai and Guangzhou of China, which is the comprehensive product of society development and industrialization. No matter the city or the region, they share some common features including huge population, complex people composition, the concentration of wealth, and numerous risks. The expansion and evolution of cities make the urban areas acting as the core of contemporary construction and a big hazard bearing body as well. It becomes extremely weak whenever disasters happen and will inevitably face great loss of people and money.

Inter-city natural disasters: The inter-city natural disaster presented here is the situation that when disasters take place, it needs the joint efforts from departments of emergency management in two or more urban areas. There are mainly three circumstances for the inter-city disasters: (1) the disaster occurs on or near the boundaries across two or more urban areas; (2) when the disaster happens in one region, the local department cannot tackle it on its own, it calls for the help from other regions; (3) the disaster spreads to nearby regions and needs the cooperation to solve the problem. Besides the characteristics for usual disasters, the inter-city disaster requires the cooperation from differed departments and regions and to work together for the common purpose.

Collaborative rescue for inter-city natural disaster: The collaborative rescue refers to all the emergency management actions that are taken under the inter-city disasters, the final aim is to lower the damages as much as possible. Once the disaster occurs, the reasonable allocation of rescuers will effectively reduce the loss, and lessen the harm to the whole society. However, the academic research in this field is seldom conducted and there is a phenomenon that in real disasters, some areas lack rescuers severely but some regions have excessive resources due to ineffective communication and information missing. In view of this, this study investigates the collaborative rescue under catastrophic disasters, and models the allocation with multi objectives as maximal rescue efficiency, maximal reliability and minimal rescue time, in order to make the most of the rescuing resources.

PROBLEM DESCRIPTIONS

In traditional allocation problems, the incident places m and the number of rescue team n are set as the same value, but in real circumstances, we usually need to select k rescue teams from n regions and send them to k incident places, $0<k \le Min\{m,n\}$. The convention is that for each rescue team, it can only take operation for one place and there is only one rescue team for each place. Considering there are time differences for different teams to travel and the efficiency and reliability are also distant accordingly, thus we set the optimizing goal as maximal rescue efficiency, maximal reliability and minimal rescue time.

COLLABORATIVE OPTIMIZATION MODEL OF MULTIPLE OBJECTIVES

As illustrated above, we set the following objectives in terms of the minimal rescue time, maximal rescue efficiency, and maximal reliability:

$$Max\, f_1 = \sum_{i=1}^{m}\sum_{j=1}^{n} w_{ij}x_{ij} \qquad ...(1)$$

$$Max\, f_2 = \sum_{i=1}^{m}\sum_{j=1}^{n} v_{ij}x_{ij} \qquad ...(2)$$

$$Min\, f_3 = \sum_{i=1}^{m}\sum_{j=1}^{n} t_{ij}x_{ij} \qquad ...(3)$$

s.t.

$$\sum_{j=1}^{n} x_{ij} \le 1, \qquad i = 1,2\cdots m \qquad ...(4)$$

$$\sum_{i=1}^{m} x_{ij} \le 1, \qquad j = 1,2\cdots n \qquad ...(5)$$

$$\sum_{i=1}^{m}\sum_{j=1}^{n} x_{ij} = k \qquad ...(6)$$

$$x_{ij} = 1 \text{ or } 0 \quad i = 1,2\cdots m; j = 1,2\cdots n \qquad ...(7)$$

Where i is the incident place, $i=1,2,\cdots m$; j is rescue team; $j=1,2\cdots n$; w_{ij} is the efficiency of team j in place i; %, x_{ij} is the 0-1 decision variable, when $x_{ij}=1$, team j is working in place i, when $x_{ij}=0$, team j is not in place i, v_{ij} is the reliability for team j to arrive at i and work there, %, t_{ij} is the response time for team j arrive at place i, h; k is the total number of rescue tasks, $0<k \le Min\{m,n\}$.

Formulas (1) to (3) are the objective functions. Formula (1) represents the maximal rescue efficiency, formula (2) denotes the maximal reliability, and formula (3) is the minimal rescue time. Formula (4) to (6) are constrains where formula (4) means that there is only one team for one incident place, (5) indicates that one rescue team can only complete the task for one place, and formula (6) is the total number of tasks for rescuing. Formula (7) shows the value ranges for decision variables.

MODEL SOLUTION

The above-mentioned model is a typical multi-objective programming problem. In this paper, the target attribute value matrix for each objective are transformed into fuzzy relationship matrix, and then the fuzzy relationship matrix and reserve point method are integrated to solve the model.

Model Transformation

With the property value a^l_{ij} under objective l, rescue team j works for place I, we can get the property matrix under objective:

$$A^l = \begin{bmatrix} a^l_{11} & a^l_{12} & \cdots & a^l_{1m} \\ a^l_{21} & a^l_{22} & \cdots & a^l_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ a^l_{n1} & a^l_{n2} & \cdots & a^l_{nm} \end{bmatrix} = \left(a^l_{ij}\right)_{m\times n} \qquad ...(8)$$

Compute the maximal and minimal values for the property matrix under different objectives, and get the relative attribute value r^l_{ij} based on formula (9)-(10).

When the objective value is the maximum:

$$r^l_{ij} = \frac{a^l_{ij} - a^l_{min}}{a^l_{max} - a^l_{min}} \qquad ...(9)$$

When the objective value is the minimal:

$$r^l_{ij} = \frac{a^l_{max} - a^l_{ij}}{a^l_{max} - a^l_{min}} \qquad ...(10)$$

Where a^l_{max}, a^l_{min} are respectively the maximal value and minimal value for property matrix l.

The weights of variables α are calculated considering the degrees of each sub objectives, $\alpha=\left(\alpha_1, \ \alpha_2, \ldots \alpha_L\right)$, the value can be determined by the analytic hierarchy process, etc.

$$\sum_{l=1}^{L} \alpha_l = 1 \qquad ...(11)$$

Where $\alpha_1, \ \alpha_2, \ldots \alpha_L \ge 0$

Thus, we can obtain the synthesis of the relative membership degree of each attribute value considering L targets,

$$r_{ij} = \sum_{l=1}^{L} \alpha_l r^l_{ij} \qquad i=1,2,\cdots m; j=1,2\cdots n \qquad ...(12)$$

And,

$$R = \begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1m} \\ r_{21} & r_{22} & \cdots & r_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nm} \end{bmatrix} = \left(r_{ij}\right)_{m\times n} \qquad ...(13)$$

Accordingly, objective function formula (1) to (3) can be written as:

$$Min\, f = \sum_{i=1}^{m}\sum_{j=1}^{n} r'_{ij}x_{ij} = \sum_{i=1}^{m}\sum_{j=1}^{n}\left(r_{max} - r_{ij}\right)x_{ij} \qquad ...(14)$$

Constrains formula (4)-(7) keep unchanged.

Reserve Point Algorithm

Basic definition and conventions: Definition 1: *n* factorial square matrix, except oneself, all the other elements are 0, such point is named as reserve point.

Theorem 1: To acquire the optimal solution for (*m, n, k*) allocation problem, we can make the coefficient matrix into a *Max*{*m, n*} factorial square matrix, add *Max*{*m, n*}-*k* reserve point and then solve 2*Max*{*m, n*}-*k* standard allocation problem.

Theorem 2: In the *n* factorial standard allocation problem, if there are *k* reserve points, there will be *2k* optimal points locates in the rows and columns of *k,* and the left *n-2k* optimal points sit in different rows and columns and their sums are the minimal after eliminating all the elements in the reserve point row and column among the *n-k* matrix.

Steps of reserve point algorithm: When $m = n = k$, the model can be solved by the Hungarian method, or we employ the reserve point algorithm.

The reserve point algorithm is operated as follows:

Step 1**:** Handle the coefficient matrix after model transformation using model 3.1.

When $m = n$, the coefficient matrix is fixed; or , the coefficient matrix should be adjusted as follows:

Add $|m-n|$ row or columns of M elements, and $M > Max\{r'_{ij}\}$, and get $Max\{m,n\}$ factorial square matrix.

Step 2**:** Calculate the number of reserve points. After the first processing, when, add reserve points outside the square matrix and change it into a factorial square matrix; or add reserve points outside the coefficient matrix and change it into a factorial square matrix.

Step 3**:** To solve the standard allocation problem with the coefficient matrix after the processing in the second step, we can use the corresponding measures for standard location problems.

Step 4**:** Find the optimal solution. Eliminate the optimal points that locate in the row or column and the left optimal points are the optimal solutions for the allocation problem.

NUMERICAL EXAMPLES

One urban area is attacked by rainstorm, and 5 places are devastated. It is hard for this city to tackle this because there are only 2 emergency rescue teams. Fortunately, the rescue teams in the neighbouring area will lend a help hand with respectively 3 and 2 teams. The response time for 7 teams is different and the minimal time for each is shown in Table 1. The distinct rescue efficiency and reliability are listed in Tables 2 and 3. In the allocation, the final objective is minimal rescue time, minimal rescue efficiency and reliability. In this section, we present the calculation steps as below.

Table 1: Response time for each rescue team .

Team *j*	Place *i*				
	1	2	3	4	5
1	0.54	0.57	0.55	0.72	0.21
2	0.66	0.71	0.75	0.9	0.27
3	0.96	0.83	0.97	0.96	0.45
4	0.59	0.63	0.61	0.79	0.23
5	0.76	0.82	0.86	1.04	0.31
6	0.68	0.76	0.74	1.01	0.42
7	1.20	1.04	1.21	1.20	0.56

Model Solution

Transform the attribute matrix into fuzzy matrix:

1. Based on the proposed model, the attribute matrix of three objectives are concerted using formula (8) and (9):

$$\left(r_{ij}^{1}\right)=\begin{bmatrix} 0.67 & 0.64 & 0.66 & 0.49 & 1.00 \\ 0.55 & 0.5 & 0.46 & 0.31 & 0.94 \\ 0.25 & 0.38 & 0.24 & 0.25 & 0.76 \\ 0.62 & 0.58 & 0.6 & 0.42 & 0.98 \\ 0.45 & 0.39 & 0.35 & 0.17 & 0.9 \\ 0.53 & 0.45 & 0.47 & 0.2 & 0.79 \\ 0.01 & 0.17 & 0.00 & 0.01 & 0.65 \end{bmatrix}$$

$$\left(r_{ij}^{2}\right)=\begin{bmatrix} 0.18 & 0.64 & 0.30 & 0.24 & 0.55 \\ 0.00 & 0.39 & 0.09 & 0.58 & 0.73 \\ 0.45 & 0.18 & 0.58 & 0.67 & 0.18 \\ 0.73 & 0.42 & 0.85 & 1.00 & 0.55 \\ 0.12 & 0.79 & 0.21 & 0.39 & 0.85 \\ 0.76 & 0.09 & 0.88 & 0.85 & 0.48 \\ 0.82 & 0.27 & 0.97 & 0.55 & 0.82 \end{bmatrix}$$

$$\left(r_{ij}^{3}\right)=\begin{bmatrix} 0.17 & 0.60 & 0.29 & 0.23 & 0.51 \\ 0.00 & 0.40 & 0.09 & 0.57 & 0.71 \\ 0.46 & 0.20 & 0.57 & 0.69 & 0.20 \\ 0.71 & 0.43 & 0.83 & 0.97 & 0.54 \\ 0.11 & 0.77 & 0.20 & 0.40 & 0.83 \\ 0.77 & 0.11 & 0.89 & 0.86 & 0.49 \\ 0.86 & 0.31 & 1.00 & 0.57 & 0.86 \end{bmatrix}$$

2. Assume that the target weight vector values the same, $\alpha_1 = \alpha_2 = \alpha_3 = 1/3$. Considering three objectives, we get the synthesis relative membership degree of each attribute value according to the formula (10):

$$\left(r_{ij}\right)=\begin{bmatrix} 0.34 & 0.63 & 0.42 & 0.32 & 0.69 \\ 0.18 & 0.43 & 0.21 & 0.49 & 0.79 \\ 0.39 & 0.25 & 0.46 & 0.53 & 0.38 \\ 0.69 & 0.48 & 0.76 & 0.80 & 0.69 \\ 0.23 & 0.65 & 0.25 & 0.32 & 0.86 \\ 0.69 & 0.22 & 0.74 & 0.64 & 0.59 \\ 0.56 & 0.25 & 0.66 & 0.38 & 0.78 \end{bmatrix}$$

Table 2: Rescue efficiency for each team (%).

Team *j*	Place *i*				
	1	2	3	4	5
1	70	85	74	72	82
2	64	77	67	83	88
3	79	70	83	86	70
4	88	78	92	97	82
5	68	90	71	77	92
6	89	67	93	92	80
7	91	73	96	82	91

Table 3: Rescue reliability for each team (%).

Team *j*	Place *i*				
	1	2	3	4	5
1	71	86	75	73	83
2	65	79	68	85	90
3	81	72	85	89	72
4	90	80	94	99	84
5	69	92	72	79	94
6	92	69	96	95	82
7	95	76	100	85	95

Table 4: Results of model solution.

Team *j*	Place *i*				
	1	2	3	4	5
1	0	1	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	1	0
5	0	0	0	0	1
6	1	0	0	0	0
7	0	0	1	0	0

3. With formula (14), the original function can be converted into:

$$\left(r'_{ij}\right)=\begin{bmatrix} 0.52 & 0.23 & 0.44 & 0.54 & 0.17 \\ 0.68 & 0.43 & 0.65 & 0.37 & 0.07 \\ 0.47 & 0.61 & 0.40 & 0.33 & 0.48 \\ 0.17 & 0.38 & 0.10 & 0.06 & 0.17 \\ 0.63 & 0.21 & 0.61 & 0.54 & 0.00 \\ 0.17 & 0.64 & 0.12 & 0.22 & 0.27 \\ 0.30 & 0.61 & 0.20 & 0.48 & 0.08 \end{bmatrix}$$

Solve the transformed model using reserve point method:

1. For $m \neq n$, $Max\{r'_{ij}\} = 0.68$, we have $M = 0.7$, add 2 columns, the square matrix $\left(r'_{ij}\right)$ becomes $\left(c_{ij}\right)$:

$$\left(c_{ij}\right)=\begin{bmatrix} 0.52 & 0.23 & 0.44 & 0.54 & 0.17 & 0.70 & 0.70 \\ 0.68 & 0.43 & 0.65 & 0.37 & 0.07 & 0.70 & 0.70 \\ 0.47 & 0.61 & 0.40 & 0.33 & 0.48 & 0.70 & 0.70 \\ 0.17 & 0.38 & 0.10 & 0.06 & 0.17 & 0.70 & 0.70 \\ 0.63 & 0.21 & 0.61 & 0.54 & 0.00 & 0.70 & 0.70 \\ 0.17 & 0.64 & 0.12 & 0.22 & 0.27 & 0.70 & 0.70 \\ 0.30 & 0.61 & 0.20 & 0.48 & 0.08 & 0.70 & 0.70 \end{bmatrix}$$

2. $m = k = 5$, $n = 7$, thus add 2 reserve point and make $\left(c_{ij}\right)$ to be the standard allocation problem $\left(c'_{ij}\right)$,

$$\left(c'_{ij}\right)=\begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0.52 & 0.23 & 0.44 & 0.54 & 0.17 & 0.70 & 0.70 & 0 & 0 \\ 0.68 & 0.43 & 0.65 & 0.37 & 0.07 & 0.70 & 0.70 & 0 & 0 \\ 0.47 & 0.61 & 0.40 & 0.33 & 0.48 & 0.70 & 0.70 & 0 & 0 \\ 0.17 & 0.38 & 0.10 & 0.06 & 0.17 & 0.70 & 0.70 & 0 & 0 \\ 0.63 & 0.21 & 0.61 & 0.54 & 0.00 & 0.70 & 0.70 & 0 & 0 \\ 0.17 & 0.64 & 0.12 & 0.22 & 0.27 & 0.70 & 0.70 & 0 & 0 \\ 0.30 & 0.61 & 0.20 & 0.48 & 0.08 & 0.70 & 0.70 & 0 & 0 \end{bmatrix}$$

3. Eliminate the optimal point that on the reserve point row and column after solution, and get the final optimal solutions,

$$\left(x_{ij}\right)=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

Comparison of Model Solution

To verify the feasibility of the algorithm, this paper uses the Hungarian method to test the results

$$\left(x_{ij}\right)=\begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

It can be observed that the solution of reserve point method and the Hungarian method are matched, which indicates the feasibility of the method. The rescue scheme is: team 1 works for place 2, team 4 for place 4, team 5 for place 5, team 6 for place 1, team 7 for place 3, and teams 2 and 3 assume no responsibilities. See Table 4 for details.

CONCLUSIONS

When human society steps into the 21 century, we see tremendous advances in nearly every aspect. However, we cannot be inspired when citing the natural disasters. The catastrophic disasters devour millions of lives and properties every year and propose grave threat to human security and survive. Once the disaster occurs, all the governments together with non-government organizations spend huge sum of labour power, physical resources, and financial resources to save lives and diminish loss as much as they can. Nevertheless, in the real rescues, the rescue resources cannot be allocated reasonably because of the ineffective communications. This study focuses on the inter-city disaster rescues, and develops a multi-objective model considering the rescue efficiency, reliability and rescue time. The fuzzy mathematics is introduced to convert the attribute matrix of each objective into fuzzy matrix and the model is solved by the reserve point algorithm. The numerical example demonstrates the validity and feasibility of the method, which provides references for rescue organization and collaboration.

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