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A cost- efficiency equilibrium problem of regional single emergency resource guarantee with multi-objective programming

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Abstract

In the background of regional emergency resource guarantee engineering to respond to earthquake disasters, a multi-objective model of cost-efficiency equilibrium problem is built to guarantee the supply of single emergency resource in an area, combined with qualitative analysis of key factors affecting the resource layout. The model quantifies constitutional indexes about emergency resource guarantee cost and rescue efficiency. With robust optimization ideas, the model is transformed to single-objective programming model according to three decision criteria, and solved with branch-and-bound algorithm by Lingo software. Finally， a numerical example is illustrated to verify the model and decision criteria.

tee engineering; Emergency resource reserve
Keywords: Cost-efficiency equilibrium; Multi-objective programming; Regional resource guaran

1. Introduction

In recent years, earthquake disasters are very frequent all over the world. For example, the Wenchuan earthquake happened on May 12, 2008 in China, which was the most destructive since new China was founded. There were 69,227 people killed, 374,643 injured, 17,923 missing, causing economic loss of 845.2 billion RMB directly. The affected areas extended to Shaanxi, Gansu, Ningxia, Zhejiang, Hubei, Guangdong and other 10 provinces. During the rescue process, supply sectors of regional emergency resources at all levels play a major role. And efficient allocation of the emergency resource is very necessary to study.

Regional resource guarantee engineering is a very pressing task in order to prevent losses caused by large disasters. Earthquake emergency rescue development plan (draft) in the 12th Five-Year Plan of China indicates that earthquake emergency areas of cooperation must strengthen the linkage mechanism, perfect six areas of cooperation, strengthen the regional emergency coordination and inter-regional collaboration, and promote the linkage among government departments gradually. The United States has formed reserve systems to deal with sudden disasters, and the systems are base on different levels and areas divided by subordination. Britain has developed a regional emergency plan including nine regional bureaus. So the regional emergency resource guarantee has become inevitable and effective measures to respond to great earthquakes. At the same time, the construction of emergency resources repository has attracted more and more attention. "Construction standards of relief materials repository " edited by the Chinese Ministry of civil affairs in 2009 proposed that 31 capital cities will be screened to determine 21 cities as the central repository, according to the natural disasters distribution, the traffic access ability and the level of economic development.

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In the earthquake context, the evaluation of guarantee ability for the regional emergency resource is an important basis for emergency region division and adjustment. And factors affecting region division contain the frequency and intensity of earthquakes, the level of economic development, the traffic access ability, the seismic capacity, material storage conditions, and so on. In this paper, there are at least three key factors related to the layout of emergency resource within a region:

(1) Traffic access ability

It is the key factor impacting time efficiency assessment of regional emergency resource. At the same time, it will affect the number of emergency resource repository and the number of inventory.

(2) Demand for emergency resource

This is the primal basis to make decision of types and quantity of regional emergency resource to reserve, and it is the direct factor to study the repository building of regional emergency resource and related emergency services.

(3) Layout targets of emergency resource

It will lead to different aggregation tendency of emergency resource. For example, in the context of earthquakes in China, when the target is to rescue the wounded as many as possible, the resource reserves will tend to be in the west, but if the goal is to minimize economic losses, resource reserves will tend to be in the east. Therefore, the guarantee of emergency resource has to achieve a multi-objective balance, and the balance will vary according to different criteria. So quantifications of these criteria become very critical.

More analysis of the factors must be considered for the actual circumstances. But in order to build our mathematical models concisely, part of the analysis process is omitted.

2. Literature Review

The final realization of multi-agent optimization is a "binding compromise", that is equilibrium. Equilibrium is a core concept to quantify in our problem. Many papers dealt with it by multi-objective programming or game theory. Jun Li [1] considered the transportation problem from any supply point to any demand point, which was based on modern marketing philosophy, and proposed a mathematical model with multi-constraint levels and time-cost trade-off objective mode. In [2] a trade-off model based on the network improvement by adjusting weight of arcs (distribution time) to optimize the service of the network was described. Bo Wang [3] considered how the decision makers can met the optimal demand of each location under the principle of time priority, when there were more than one crisis locations, and established a multi-stage dynamic decision-making model of emergency resources scheduling. In [4] a cost–time trade-off bulk transportation problem was considered in order to minimize the total cost and duration of bulk transportation without priorities. Karl [5] presented a multi-objective programming model about the location decision of public facilities like schools near coasts, taking risks of inundation by tsunamis into account.

Scenario analysis and robust optimization methods are effective to build and solve mathematical models with uncertain parameters. Earthquake disasters have a lot of uncertain information, such as the demand for emergency resource, transportation time, various cost, etc. These uncertain parameters can be achieved through the “scenario”. Scenario analysis method originated in the late 1970s as a forecasting technique [6]. And the management idea with "scenario-response" is gradually formed based on the method, which is to make decisions according to different scenarios [7-9]. Robust optimization is a new modeling method to solve problems with uncertainty parameters. It is not expressed with the probability distribution of uncertain data, but with uncertain data set of known values. Yu Gang [10] proposed robust idea based on the scenario method and defined three concepts of robust decision, including the absolute robust decision, the robust deviation decision and the relative robust decision. With these concepts, a scenario relaxation algorithm was proposed for solving min–max regret and min–max relative regret robust optimization problems in [11]. Here we use the idea of the absolute robust decision, because it is simple and tractable for large-scale emergency management problems.

This paper is organized as follows. In Section 3， key parameters are extracted according to the problem background. And a multi-objective programming model of cost-efficiency equilibrium problem is built to guarantee single emergency resource supply in a region. Then numerical experiments verify the validity of our model in section 4. Finally, a summary of the issues and further researches are discussed in section 5.

3. Cost-efficiency equilibrium model based on multi-objective programming

We consider the single resource guarantee problem when earthquake disasters happen. There are some repositories in the emergency region. When the earthquake occurs in the region, there may be several affected points. The locations and capacities of repositories are known, but the demand and locations of affected points are uncertainty. We describe the uncertain parameters by scenarios. That is each scenario represents determined locations of affected points and their demand. At the same time, assume the time and cost of transportation between repositories and affected points for different scenarios have been predicted, and related resource costs have been obtained according to local conditions. So our research is how to achieve cost-efficiency equilibrium between resource guarantee cost and rescue efficiency under conditions of meeting the demand as far as possible.

Resource guarantee cost and rescue efficiency of regional emergency resource reserve are checks and balances. The two factors are both related with the location and amount of emergency resource. Great amount of resource and rare transportation time between repositories and affected points will earn good rescue efficiency. However, Great amount of resource and much transportation time between repositories and affected points will result in high guarantee cost. So our equilibrium research should use several decision-making criteria according to the actual needs.

Through the above analysis, we set the model parameters and variables as follows:

I : Set of resource repositories, $i \in I$

J : Set of affected points by earthquake disasters, $j \in J$

S : Set of earthquake scenarios, $s \in S$

x_{is} : Amount of resource in repository i in scenario s

y_{ijs} : Amount of resource transporting from repository i to affected point j in scenario s

t_s : Gold rescue time in scenario s

T_s : Latest rescue time in scenario s

T_{ijs} : Transportation time from repository i to affected point j in scenario s

C_{is}: Unit resource cost of repository i in scenario s

CS_{is} : Annual cost of reserves for unit resource of repository i in scenario s

CT_{ijs} : Transportation cost for unit resource from repository i to affected point j in scenario s

v_i : Capacity of repository i , $v_i \in V$

d_{js} : Amount of demand resource for affected point j in scenario s

δ_{js} : Fluctuations in the amount of resource satisfying demand of affected point j in scenario s , $\delta_{js} \geq 0$

3.1. Description of objective function

The objectives of this paper are maximizing guarantee rate of emergency resource rescue efficiency and minimizing emergency resource guarantee cost.

3.1.1. Description of guarantee rate of emergency resource rescue efficiency

The objective contains two parts. One part is satisfaction rate α_{ijs} of emergency resource for affected point j supplied by repository i in scenario s :

$$\alpha_{ijs} = min\left\{\frac{y_{ijs}}{d_{js}}, 1\right\} \quad \forall i \in I, j \in J, s \in S \tag{1}$$

The other part is time rate of emergency resource β_{ijs} for affected point j supplied by repository i in scenario s :

$$\beta_{ijs} = \begin{cases} 1 & T_{ijs} \le t_s \\ \dfrac{T_s - T_{ijs}}{T_s - t_s} & t_s < T_{ijs} \le T_s, \quad \forall i \in I, j \in J, s \in S \\ 0 & T_{ijs} > T_s \end{cases} \tag{2}$$

Then the guarantee rate of emergency resource rescue efficiency for affected point j in scenario s can be described as follows:

$$\rho_{js}(x) = \sum_{i \in I} (\lambda_{ijs}\alpha_{ijs} + \gamma_{ijs}\beta_{ijs} / |I|) \quad \forall j \in J, s \in S \tag{3}$$

and $\lambda_{ijs} + \gamma_{ijs} = 1, 0 \le \lambda_{ijs} \le 1,\ 0 \le \gamma_{ijs} \le 1, \forall i \in I, j \in J, s \in S$ are weight factors of α_{ijs} and β_{ijs} respectively.

3.1.2. Description of emergency guarantee cost

The objective contains resource cost, resource reserve cost and resource transportation cost. Emergency guarantee cost $c_{is}(x)$ of repository i in scenario s can be described as follows:

$$c_{is}(x) = \omega_{is} C_{is} x_{is} + \xi_{is} CS_{is} x_i + \theta_{is} \sum_{j \in J} CT_{ijs} y_{ijs} \quad \forall i \in I, s \in S \tag{4}$$

and $0 \le \omega_{is} \le 1, 0 \le \xi_{is} \le 1, 0 \le \theta_{is} \le 1 \ \forall i \in I, s \in S$ are influence factors of resource location.

3.1.3. Objective function and transformation criteria

By above analysis and definitions, our objective functions can be expressed as follows:

$$\begin{cases} \max \sum_{j \in J} \rho_{js}(x) \\ \min \sum_{i \in I} c_{is}(x) \end{cases} \quad \forall s \in S \tag{5}$$

So the average guarantee rate of rescue efficiency is $\frac{1}{|J|}\sum_{j \in J} \rho_{js}(x)$, noted as $\mathrm{obj}_1(s)$. And total guarantee cost is $\sum_{i \in I} c_{is}(x)$, noted as $\mathrm{obj}_2(s)$.

According to absolute robust optimization [10], we have

$$\begin{cases} \max \min_{s \in S} \sum_{j \in J} \rho_{js}(x) \\ \min \max_{s \in S} \sum_{i \in I} c_{is}(x) \end{cases} \tag{6}$$

In order to solve concisely and consider the priority of the two objections, we propose three criteria and transform the multi-objective to single objective.

(1) Maximize cost- efficiency rate at the worst-case scenario (noted as “criterion 1”):

$$\min \max_{s\in S} \frac{\sum_{i\in I} c_{is}(x)}{\sum_{j\in J} \rho_{js}(x)} \tag{7}$$

(2) Maximize guarantee rate of rescue efficiency at the worst-case scenario (noted as "criterion 2"):

$$\begin{aligned} &\max \min_{s\in S} \sum_{j\in J} \rho_{js}(x) \\ &s.t.\ \max_{s\in S} \sum_{i\in I} c_{is}(x) \le c_{\max} \end{aligned} \tag{8}$$

and make the guarantee cost as the constraint of our model, $c_{\max}$ is the maximum budget of the guarantee cost.

(3) Minimize guarantee cost at the worst-case scenario(noted as "criterion 3"):

$$\begin{aligned} &\min \max_{s\in S} \sum_{i\in I} c_{is}(x) \\ &s.t. \min_{s\in S} \frac{1}{|J|} \sum_{j\in J} \rho_{js}(x) \ge \rho_{\min} \end{aligned} \tag{9}$$

And make the guarantee rate of rescue efficiency as the constraint of our model, $\rho_{\min}$ is the minimum requirement of the guarantee rate of rescue efficiency.

3.2. Common constraints of multi-criteria objectives

(1) Transportation volume constraints

$$\sum_{j\in J} y_{ijs} \le x_{is} \le V_i \quad \forall i \in I, s \in S \tag{10}$$

(2) Rescue time constraints

$$y_{ijs} \begin{cases} \ge 0, & T_{ijs} \le T_s \\ = 0, & T_{ijs} > T_s \end{cases}, \ \forall i \in I, j \in J, s \in S \tag{11}$$

(3) Demand satisfaction volume constraints

$$d_{js} - \delta_{js} \le \sum_{i\in I} y_{ijs} \le d_{js} + \delta_{js} \quad \forall j \in J, s \in S \tag{12}$$

(4) Decision variables constraints

$$x_{is} \ge 0,\ y_{ijs} \ge 0 \text{ and integer}, \quad \forall i \in I, j \in J, s \in S \tag{13}$$

Then we build a multi-criteria model based on multi-objective programming of cost-efficiency equilibrium problem to guarantee single emergency resource supply in an area.

4. Numerical computation

We design a simple instance in the background of section 1 here, as shown in the diagram Fig.1. below. Assume there are three resource repositories called i_1, i_2 and i_3. Consider two scenarios s_1 and s_2. There exist three affected points in s_1 and there exist another three affected points in s_2.

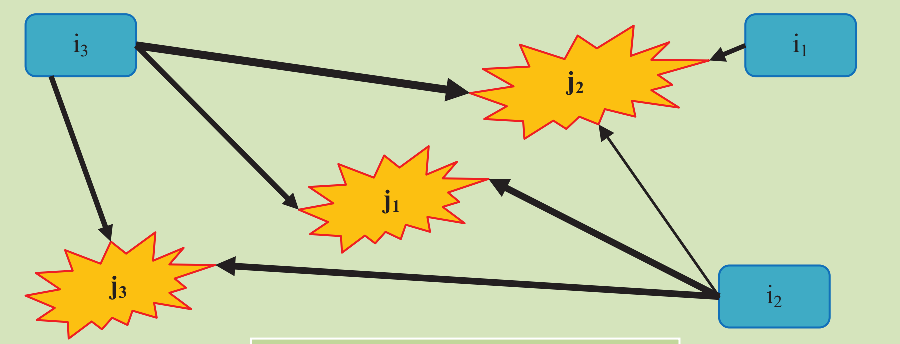

Fig. 1. Relief within region diagram

We set a set of experimental data as the following tables, and set parameters $c_{max}=7000$ and $\rho_{min}=0.7$.

Table 1: Resource capacity of repositories

i_1	i_2	i_3
145	110	85

Table 2: Resource demand amount

	s_1	s_2
j_1	52	61
j_2	38	57
j_3	40	57

Table 3: Transportation time and cost

		s_1		s_2	
		time	cost	time	cost
i_1	j_1	8	10.8	18	16.8
	j_2	9	21.6	10	12
	j_3	16	12.5	7	10.2
i_2	j_1	24	20.4	14	18.6
	j_2	12	13.2	5	9
	j_3	15	16.2	20	18
i_3	j_1	11	17.4	12	13.2
	j_2	17	16.2	13	21.6
	j_3	18	15.5	19	17.4

Table 4: Unit resource cost and annual cost of reserves

	s_1		s_2	
	C	CS	C	CS
i_1	99	4.95	96	4.8
i_2	99	4.95	99	4.95
i_3	100	5	95	4.75

Table 5：values of other parameters（$\forall i \in I, j \in J, s \in S$）

λ_{ijs}	γ_{ijs}	ω_{is}	ξ_{is}	θ_{is}	t_s	T_s	δ_{js}
0.5	0.5	0.1	1	1	12	24	10

According to the model in section 2， we solve the model with above parameters with branch-and-bound algorithm by Lingo9.0, and the results are shown in Table 6.

Table 6: Computation results

objections	criterion 1	criterion 2	criterion 3
$obj_1(1)$	0.847	0.979	0.787
$obj_1(2)$	0.803	0.975	0.803

$obj_2(1)$	3877	6074	3505
$obj_2(2)$	3677	6843	3677

If we change the demand amount of affected points in each scenario in Table 2, for example, the data in value are increased by 10, and the results are listed in Table 7.

Table 7 Computation results when the demands increase

objections	criterion 1	criterion 2	criterion 3
$obj_1(1)$	0.844	0.956	0.795
$obj_1(2)$	0.816	0.962	0.816
$obj_2(1)$	4589	6866	4410
$obj_2(2)$	4436	6884	4436

From the above results, we can see that the objective value under the three criteria have advantages and disadvantages. Criterion 1 highlights the equilibrium between the rescue efficiency and guarantee cost, while criterion 2 considers rescue efficiency is more valued and criterion 3 has more emphasis on cost reduction. The corresponding target value will deteriorate due to the increased demand in Table 7. These indicate that our model is valid, and the proposed criteria can guide decision making according to actual situation.

5. Conclusion and future work

In this paper, some qualitative analysis of key elements, which may affect the layout of regional emergency resource, is proposed at first. And then we build an optimization model for quantitative research according to different scenarios with two emergency effectiveness indicators as objectives and with resource amount, rescue time, guarantee cost as constrains. Three decision-making criteria are given and a numerical example is illustrated to verify the model and decision criteria with part of parameters comparison.

In future research, firstly, various parameters in the model need to be a better assessment, combined with DEA (data envelopment analysis), AHP (Analytic Hierarchy Process) or fuzzy comprehensive evaluation methods to further analysis and test. Secondly, consider situations that some constraints can be relaxed or changed, and propose different evaluation according to different equilibrium conditions in order to establish regional evaluation indicators system. At last, assessing the guarantee ability of multiple regions of emergency resource and adjusting the different regions combined with a number of practical scenarios are very valuable.

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