Research Article

A Multiobjective Allocation Model for Emergency Resources That Balance Efficiency and Fairness

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Efficiency and fairness are two important goals of disaster rescue. However, the existing models usually unilaterally consider the efficiency or fairness of resource allocation. Based on this, a multiobjective emergency resource allocation model that can balance efficiency and fairness is proposed. The object of the proposed model is to minimize the total allocating costs of resources and the total losses caused by insufficient resources. Then the particle swarm optimization is applied to solve the model. Finally, a computational example is conducted based on the emergency relief resource allocation after Ya'an earthquake in China to verify the applicability of the proposed model.

1. Introduction

Major sudden disaster often affects many areas and causes a lot of casualties and a great loss of property [1, 2]. For example, in 2008, more than 100 thousand square kilometers were seriously damaged by the Wenchuan earthquake on May 12, resulting in a number of seriously affected disaster areas, including Wenchuan, Beichuan, Qingchuan, Mianzhu, and other hard-hit areas [3]. After a disaster, a large demand for emergency resources, such as food, drugs, and other supplies, is inevitably generated at the multiple affected sites [4]. At this time, how to allocate emergency resources will directly affect the rescue effect. Efficiency and fairness are two important but conflicting goals in emergency rescue [5]. The most efficient allocation scheme is not necessarily the fairest, and the fair allocation scheme may result in very high allocating costs. Therefore, appropriate trade-off between efficiency and fairness may be needed in the context of different disasters. Based on this, it is very necessary to construct a resource allocation model that considers both efficiency and fairness to meet the demands of all affected sites.

The goals of most existing models for emergency resource allocation mainly reflect the efficiency, such as the lowest total allocation costs. Equi et al. [6] proposed a product delivery

model that minimizes the total costs, including loading costs, transportation costs, unloading costs, and storage costs. Viswanath and Peeta [7] developed low-cost routes that cover the maximum population while satisfying budget constraints for earthquake rescue. Zhan and Liu [8] presented a model that aims to minimize both the transportation costs and the rescue time. Barbarosoglu et al. [9] proposed a mathematical model for minimizing the cost of different helicopters in a disaster relief operation. Haghani et al. [10, 11] analyzed the multicommodity allocation models that aim to minimize the sum of the vehicular flow costs and the transfer costs. Bai [12] used the minimum total costs of allocation as one of the objectives to consider the issue of emergency resource allocation under integrated uncertainty. Yang et al. [13] constructed a bilevel programming model of resource allocation for sudden disaster with the minimum allocation cost as the goal of the upper level. However, in the actual allocation of resources, the low-cost allocation plan is not necessarily the fairest and often leads to inaccurate allocation of resources among disaster locations.

With the continuous development of research, the issue of fairness has gradually been considered in the resource allocation process. Mandell [14] put the Gini coefficient as the fairness index to build the resource allocation model of

FIGURE 1: The diagram of emergency resource allocation.

public service facilities system. Wang et al. [15] constructed a fair allocation model for emergency resource based on the double-layer decision-making method. Pang et al. [16] set a fair coefficient within (0,1) to ensure the fairness of resource allocation. Chen and Fu [17] proposed an emergency resource allocation model with the minimum total weighted envy value as the fairness goal and the proportional fairness as constraints. Ye et al. [18] developed an equilibrium decision model for earthquake rescue based on demand information update that aims to realize a fair allocation to all disaster locations. Zhan et al. [19] presented a fair decision-making model for resource allocation by introducing Bayesian demand updating method, but the dynamic change characteristics of supply were not considered.

From the perspective of stage of emergency resource allocation, the above researches mainly focused on single-stage resource allocation. There are few related studies although the issue of multistage resource allocation has gradually received more emphasis. For example, Linet [20] constructed a multistage emergency resource allocation model with the goal of minimizing transportation time, but this model did not consider the issue of fairness. Feng et al. [5] proposed multiobjective optimization model of the emergency resource allocation with multicycle and multi-item; it deals with the allocation of resources between a single supply site and multiple disaster sites, but in the actual rescue process, the resource reserves of a single allocation center are usually limited, and it is not possible to meet the needs of multiple disaster sites at the same time. Thus, the study of resource allocation between multiple supply sites and multiple affected sites may be more in line with the actual situation of rescue.

Through the analysis of the above literatures we found that most of the existing researches usually unilaterally take the efficiency or fairness as one of the goals of model for the resource allocation and the issue of balancing efficiency and fairness of resource allocation is rarely studied. However, efficiency and fairness are important goals and should be considered in the process of resource allocation.

On the basis of existing studies, this paper constructs a multiobjective allocation model for emergency resources,

which aims to balance the efficiency (the total allocating costs) and fairness (the total losses caused by insufficient resources) of resource allocation. Then, a case study for the Ya'an earthquake in China is applied to verify the effectiveness and feasibility of the proposed model.

The main contributions of this paper can be summarized as follows:

- (1) The proposed model can consider both efficiency and fairness and can provide support for resource allocation decisions in different emergency contexts
- (2) The unmet proportion of required resources is used to quantify the fairness, which will facilitate the fair allocation of emergency resources among multiple affected sites during large-scale disasters

The rest of this paper is organized as follows: Section 2 describes the general problem and assumptions. Section 3 proposes the mathematical model. Section 4 presents the solution algorithm. In Section 5, a computational example is given to illustrate the applicability and potential advantages of the proposed model. Finally, conclusions are drawn in Section 6.

2. The General Problem Description and Assumptions

2.1. Problem Description. The multiobjective emergency resource allocation discussed in this paper is about dealing with the multiple supply sites, multiple affected sites, and multistage allocation for large-scale sudden disasters; the decision makers should consider both efficiency and fairness of resource allocation at each stage to meet the needs of all affected sites as soon as possible with the least cost, as shown in Figure 1.

2.2. Assumptions. Combined with the actual situation of emergency resource allocation, the following assumptions are made:

- (1) The emergency response center has an advanced information platform that can timely grasp and update

the related disaster information at every stage, such as the number of affected sites, road conditions, casualties, resource demands, and available resources

(2) All types of emergency resources are irrelevant items; that is, whether a certain type of resource arrives at the affected area has no effect on the allocation of other types of resources

(3) The impact of secondary disasters on resource allocation is not considered in this paper

3. The Multiobjective Allocation Model for Emergency Resources

3.1. Notations. For the sake of simplicity, we adopt the notations displayed as follows.

Sets:

I : set of affected sites, $i \in I$, $I = \{i/1, 2, \dots, n\}$, where n is the total number of affected sites

J : set of supply sites, $j \in J$, $J = \{j/1, 2, \dots, m\}$, where m is the total number of supply sites

Q : set of types of emergency resources, $q \in Q$, $Q = \{q/1, 2, \dots, Q\}$, where Q is the total number of types of resources

R : set of stages of rescue, $r \in R$, $R = \{r/1, 2, \dots, R\}$, where R is the maximum number of stages

Parameters:

X_{ijqr} : demand for resource $q \in Q$ in $i \in I$ at stage $r \in R$; Y_{jqr} : new supply of resource $q \in Q$ in $j \in J$ at stage $r \in R$; U_{ijr} : fixed cost of transportation for using $j \in J$ to $i \in I$ at stage $r \in R$; V_{ijqr} : variables cost of allocating resource $q \in Q$ from $j \in J$ to $i \in I$ at stage $r \in R$; H_{ijr} : maximum total amount of resource that can go from $j \in J$ to $i \in I$ at stage $r \in R$

Variables. There are one binary variable and three continuous variables for this model:

s_{ijr} : binary variable indicating whether $j \in J$ allocates resource to $i \in I$ at stage $r \in R$ or not

x_{ijqr} : amount of $q \in Q$ that allocates from $j \in J$ to $i \in I$ at stage $r \in R$; l_{jqr} : inventory of resource $q \in Q$ in $j \in J$ at the end of stage $r \in R$; $p_{iq,r}$: unmet proportion of required resource $q \in Q$ in $i \in I$ at the end of stage $r \in R$; it can be measured by $p_{iq,r} = X_{iq,r} - \sum_{j \in J} x_{ijqr}$.

3.2. Model Formulation

3.2.1. Objective Function. This paper proposes to use a (convex) utility function $f_{iq,r}[\cdot]: R_+ \rightarrow R_+$ to measure the penalty (or loss) for the insufficient resources $q \in Q$ in affected site $i \in I$ at stage $r \in R$.

$$f_{iq,r}[p_{iq,r}] = \frac{[1 - e^{-\alpha p_{iq,r}}]}{\alpha} \quad \alpha < 0 \quad (1)$$

where the parameter α is used to show the importance placed on large losses.

Then the objective functions can be written as the following:

$$F_1 = \min \sum_{i \in I} \sum_{j \in J} \sum_{r \in R} U_{ijr} s_{ijr} + \sum_{i \in I} \sum_{j \in J} \sum_{q \in Q} \sum_{r \in R} V_{ijqr} x_{ijqr} \quad (2)$$

$$F_2 = \min \sum_{i \in I} \sum_{q \in Q} \sum_{r \in R} f_{iq,r}[p_{iq,r}] \quad (3)$$

The first objective function (2) is to minimize the total allocating costs and stands for “efficiency” in process of relief resources allocation. The second objective function (3) is to minimize the total losses caused by insufficient resources and represents “fairness” of relief resources allocation.

3.2.2. Constraints. The emergency resource allocation model formulated should satisfy the following six constraints.

① The total amount of resources that can be allocated should not exceed the sum of the inventory and the new supply. Here is the mathematical expression of the following constraint equation (4); $l_{j,q,r-1}$ is the inventory of resources at supply sites at the end of stage $r - 1$:

$$\sum_{i \in I} x_{ijqr} \leq Y_{jqr} + l_{j,q,r-1} \quad \forall j \in J, q \in Q, r \in R \quad (4)$$

② The total amount of resource allocated to all affected sites should not exceed the sum of the current demand and the unmet proportion remaining from previous stages. It is given by (5); $p_{iq,r-1}$ is the unmet proportion of required resources at affected sites at the end of stage $r - 1$:

$$\sum_{j \in J} x_{ijqr} \leq X_{iq,r} + p_{iq,r-1} \quad \forall i \in I, q \in Q, r \in R \quad (5)$$

③ The fixed cost should be paid as long as the supply site allocates resources to the affected site. This constraint limits the capacity for transportation and also enforces the fixed charge, as shown in

$$\sum_{q \in Q} x_{ijqr} \leq H_{ijr} s_{ijr} \quad \forall i \in I, j \in J, r \in R \quad (6)$$

④ The binary variable must be equal to 0 or 1, as demonstrated in

$$s_{ijr} \in \{0, 1\} \quad \forall i \in I, j \in J, r \in R \quad (7)$$

⑤ The variables for the amount of allocation, inventory, and unmet proportion of required resource must be nonnegative, as shown in

$$x_{ijqr} \geq 0, \quad \forall i \in I, j \in J, q \in Q, r \in R \quad (8)$$

$$l_{jqr} \geq 0, \quad \forall j \in J, q \in Q, r \in R \quad (9)$$

$$p_{iq,r} \geq 0, \quad \forall i \in I, q \in Q, r \in R \quad (10)$$

4. Solution Algorithm

4.1. The Basis for the Selection of Algorithm. The model proposed in this paper contains many parameters which are dynamically changing. The traditional optimization methods (such as gradient descent, Newton's method and quasi-Newton methods, and conjugate gradient) are limited in

the process of solving the model [22]. Therefore, we need to explore the adaptive intelligent optimization method. Currently, the intelligent algorithms for solving optimization problems mainly include genetic algorithm (GA), ant colony algorithm (ACO), and particle swarm optimization (PSO). This paper selects the particle swarm optimization algorithm to solve the model. The reasons are as follows: Compared with GA, the advantage of PSO is that the rule is simpler. It does not have the "Crossover" and "Mutation" operations of GA and is easy to implement. There are not many parameters that need to be adjusted, and all particles can converge to the optimal solution quickly [23]. Compared with ACO, the advantage of PSO is that it is quick to approximate the optimal solution, the solution speed is fast, and the parameters of the system can be effectively optimized [24].

Meanwhile, resource allocation under emergency situations is often subjected to severe time pressure, which places stringent requirements on the efficiency of solving the model. The chosen algorithm should be able to quickly solve for dynamic changes of parameters, while the accuracy requirements of the solution may be relatively loose. Therefore, the selection of the algorithm for solving the model should follow the principles of fast convergence, less resource usage, and good robustness. Combined with the characteristics of the model proposed in this paper, PSO can meet the need for solving this kind of problem. It can avoid complex genetic operations like evolutionary algorithms and is simple, easy to implement, and fast to converge. Therefore, this paper selects the PSO to solve the proposed model.

4.2. The PSO Algorithm. PSO is a new evolutionary algorithm proposed by Kennedy and Eberhart, which was inspired by the bird foraging behavior [25]. It uses a simple velocity-displacement model to achieve population-based global search guided by fitness function information, while its memory function can track the search path and dynamically adjust the search strategy [26]. The mathematical description of standard PSO is as follows: there are m particles in a D -dimensional space, the position of each particle i is denoted as $X_i = [x_{i1}, x_{i2}, \dots, x_{iD}]$, and each position corresponds to a fitness function $F_{k-1}(i)$ related to the optimization objective function. The velocity of each particle i is denoted as $V_i = [v_{i1}, v_{i2}, \dots, v_{iD}]$, the best position that the particle i has experienced is denoted as $Pbest_i = [p_{i1}, p_{i2}, \dots, p_{iD}]$, and the best position that the population has experienced is denoted as $Gbest_j = [g_{j1}, g_{j2}, \dots, g_{jD}]$. The velocity and position updating formula for particle i in the D -dimensional space are as follows:

$$V_{id}^{(k)} = wV_{id}^{(k-1)} + c_1r_1(Pbest_{id} - X_{id}^{(k-1)}) + c_2r_2(Gbest_{jd} - X_{id}^{(k-1)}) \quad (11)$$

$$X_{id}^{(k)} = X_{id}^{(k-1)} + V_{id}^{(k-1)} \quad (12)$$

where d is the dimension of the particle position, $d \in \{1, 2, \dots, d, \dots, D\}$; w is the inertial weight factor; $k-1$ is the present iteration; c_1 and c_2 are positive acceleration constants; and r_1 and r_2 are random numbers uniformly allocated within $[0, 1]$. Moreover, in order to reduce the

possibility of particles leaving the search space, the movement of particles is appropriately limited by setting the velocity interval $[V_{\min}, V_{\max}]$ and the position range $[X_{\min}, X_{\max}]$.

The detailed algorithmic steps are described as follows.

Step 1 (initialization). Set the parameters (m , X_i , V_i , c_1 , c_2 , etc.); randomly generate the velocity and position of each particle in initial population.

Step 2. Calculate the fitness degree $F_i(k-1)$ of every particle.

Step 3. Compare $F_{k-1}(i)$ and individual extremum $Pbest(i)$ of each particle; if $F_{k-1}(i) > Pbest(i)$, then replace $F_{k-1}(i)$ with $Pbest(i)$.

Step 4. Compare $F_{k-1}(i)$ of each particle and global extremum $Gbest$; if $F_{k-1}(i) > Gbest$, then replace $F_{k-1}(i)$ with $Gbest$.

Step 5. Update the velocity V_i and position X_i of each particle according to formula (11) and (12).

Step 6. If the algorithm attains the maximum iterations, turn to Step 7; otherwise turn to Step 2.

Step 7. Stop optimization and output the result.

5. Computational Example

In this section, we provide a computational example to illustrate the applicability of the proposed model in solving the problem of emergency resources allocation for realistic large-scale disasters. Here, take the Ya'an earthquake as a case. A magnitude 7.0 earthquake suddenly occurred at 8:02:46 AM, China Standard Time, on April 20, 2013, in Lushan County of Ya'an city, Sichuan Province. The maximum intensity was 9. A total of 18,682 square kilometers was affected, 196 lost their lives, 11,470 were injured, and 21 were still missing [27]. Lushan County (LS), Yucheng District (YC), Baoxing County (BX), Tianquan County (TQ), and Yingjing County (YJ) were seriously affected in this earthquake. The general disaster information on these affected sites is shown in Table 1. Chengdu (CD) and Ziyang (ZY) were selected as supply sites, and the tents and blankets are selected as the required emergency resources. We take one day as a stage, to analyze the emergency resources allocation in the first 5 days after the large-scale disaster. The relevant data for computational example were chosen using a combination of real and hypothetical data, since some disaster data could not be obtained through official reports. The estimated demand for resources at each affected site and the supply at each supply site are shown in Tables 2 and 3, respectively. Tables 4 and 5, respectively, show the fixed costs of transportation and variable costs of allocating resources.

This computational example was solved using MATLAB R2016a on a computer with an Intel(R) Core(TM) i90 GHz processor with 16.0 GB of RAM. The parameters of PSO are set as follows: particle size is 50, largest number of iterations is 600, $w=0.9$, and $c_1=c_2=2$. The allocation results and unmet

TABLE 1: General information on the affected sites.

Affected sites	Region area /(km ²)	Population density /(person*km ⁻²)	Number of fatalities	Number of injured
LS	1,364	88	117	5537
YC	1,060	321	15	1109
BX	3,114	19	26	2500
TQ	2,394	63	5	811
YJ	1,781	79	2	341

Data sources: Central government portal website, as of 15:00 on April 21, 2013 [21].

TABLE 2: The resource demand for the affected sites.

Affected sites	Resources	Stages				
		1	2	3	4	5
LS	Tents	2000	600	400	300	100
	Blankets	8000	8000	9000	10000	10000
YC	Tents	1500	400	200	100	100
	Blankets	5000	6000	6000	6000	7000
BX	Tents	1800	600	300	300	100
	Blankets	8000	6000	7000	9000	10000
TQ	Tents	400	200	100	0	0
	Blankets	2000	2000	1000	3000	2000
YJ	Tents	300	200	0	0	0
	Blankets	1000	1000	1000	1000	1000

TABLE 3: The resource supply of the supply sites.

Supply sites	Resources	Stages				
		1	2	3	4	5
CD	Tents	3500	1000	1000	600	600
	Blankets	15000	10000	15000	15000	20000
ZY	Tents	2000	500	500	600	700
	Blankets	10000	10000	10000	14500	15500

TABLE 4: The fixed costs of transportation from supply sites to affected sites (yuan).

Supply sites	Affected sites				
	LS	YC	BX	TQ	YJ
CD	7000	9000	8500	10000	4000
ZY	2000	5000	9500	10000	7000

TABLE 5: The variable costs of allocating resource from supply sites to affected sites (yuan).

Supply sites	Affected sites				
	LS	YC	BX	TQ	YJ
CD	350	500	450	600	200
ZY	100	250	550	600	350

proportion of required resources when $\alpha = -0.007$ are shown in Table 6.

From Table 6, the model allocates resources to every affected site at each stage, and the unmet proportion of required resources at all affected sites are equal at each stage.

The unmet proportion of resources at the previous stage can be replenished in the next stage until all their demands are satisfied (e.g., all demands of every affected site can be fully satisfied until the fifth stage). When demand is significantly greater than supply, the fair allocation can still be guaranteed. When demand is less than supply, the demands of all affected sites are fully satisfied. Obviously, the proposed model can avoid large shortage and huge losses caused by the insufficient resources at any one affected site, which is beneficial to the fair allocation of resources.

In the actual material allocation process, when the fixed transportation costs are high enough, the high transportation costs may exceed the consideration of fairness. To prove this, we now give the following example (all fixed costs increased by 100 times), also assuming $\alpha = -0.007$. The allocation results and unmet proportion of resources are shown in Table 7.

Table 7 shows unequal unmet proportion due to the higher fixed costs of transportation, and the model does not allocate resources to every affected site at each stage. For example, YJ and TQ do not receive any required resources in the second and third stage, respectively. However, in the next stage, they can receive more resources. This can save the costs

TABLE 6: The allocation results and unmet proportion of emergency resources.

Affected sites	Resources	Stages				
		1	2	3	4	5
LS	Tents	1900 (100)	500 (200)	500 (100)	400 (0)	100 (0)
	Blankets	8000 (0)	7600 (400)	9200 (200)	10100 (100)	10100 (0)
YC	Tents	1400 (100)	300 (200)	300 (100)	200 (0)	100 (0)
	Blankets	5000 (0)	5600 (400)	6200 (200)	6100 (100)	7100 (0)
BX	Tents	1700 (100)	500 (200)	400 (100)	400 (0)	100 (0)
	Blankets	8000 (0)	5600 (400)	7200 (200)	9100 (100)	10100 (0)
TQ	Tents	300 (100)	100 (200)	200 (100)	100 (0)	0 (0)
	Blankets	2000 (0)	1600 (400)	1200 (200)	3100 (100)	2100 (0)
YJ	Tents	200 (100)	100 (200)	100 (100)	100 (0)	0 (0)
	Blankets	1000 (0)	600 (400)	1200 (200)	1100 (100)	1100 (0)

Note: the numbers in brackets () are the unmet proportion of required resources.

TABLE 7: The allocation results and unmet proportion of resources with higher fixed costs of transportation.

Affected sites	Resources	Stages				
		1	2	3	4	5
LS	Tents	1886 (114)	509 (205)	500 (105)	405 (0)	100 (0)
	Blankets	8000 (0)	7000 (1000)	10000 (0)	10000 (0)	10000 (0)
YC	Tents	1385 (115)	307 (208)	312 (96)	196 (0)	100 (0)
	Blankets	5000 (0)	6000 (0)	6000 (0)	6000 (0)	7000 (0)
BX	Tents	1693 (107)	517 (190)	455 (35)	335 (0)	100 (0)
	Blankets	8000 (0)	6000 (0)	7000 (0)	9000 (0)	10000 (0)
TQ	Tents	334 (66)	167 (99)	0 (199)	199 (0)	0 (0)
	Blankets	2000 (0)	2000 (0)	0 (1000)	3500 (500)	2500 (0)
YJ	Tents	202 (98)	0 (298)	233 (65)	65 (0)	0 (0)
	Blankets	1000 (0)	0 (1000)	2000 (0)	1000 (0)	1000 (0)

of transportation. Thus, the proposed model can effectively trade off efficiency versus fairness and has better flexibility and applicability in emergency resource allocation.

In order to verify the validity of this PSO algorithm, this paper employs MATLAB programming to directly solve the above computational example mentioned (the same data in Tables 2–5). The solutions obtained by the PSO algorithm and direct programming are 43,726,000 and 44,108,000, respectively. The corresponding computing time is 56 seconds and 439 seconds, respectively. Among them, the solution obtained by PSO algorithm is the average value of 20 tests. It can be seen that the PSO algorithm obtains a better objective value, which can reduce the total losses caused by resources shortage and the total costs of allocation. Moreover, the computing time of PSO is only 1/8 of direct programming, indicating that the PSO algorithm can improve the timeliness of resource allocation and save time for emergency rescue.

6. Conclusions

This paper is motivated by the need to solve the allocation problem of emergency resource in large-scale disaster. We propose a multiobjective emergency resource allocation model and the particle swarm optimization algorithm is applied. Then the case study for the Ya'an earthquake in

China verifies the effectiveness and feasibility of the proposed model. This study can provide enlightenment on the emergency resource allocation decisions for emergency decision-makers:

- (1) In emergency resource allocation decision, efficiency and fairness are important goals of disaster relief. Decision-makers must realize a balance between efficiency and fairness to meet the material needs of all disaster-stricken areas as soon as possible with the least cost
- (2) In the case of resource shortage in the initial stage of disaster relief, the primary objective should be to reduce the losses caused by insufficient resources at each affected site, ensuring the fairness of resources allocation. When resources continue to be supplied, the cost of allocation should be considered
- (3) With higher costs of transportation, decision-makers can choose to centralize allocation or allocate resources once every two stages to save the transportation costs

However, the allocation process of emergency resources is affected by many factors, such as the response time, urgency of resources, and disaster severity. Thus, future research on

resource allocation model should comprehensively consider the above constraints.

Data Availability

The [Tables 1–5] data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors claim that there are no conflicts of interest in their research.

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