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A Dynamic Cooperation Model for Interregional Emergency Response

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Abstract: Large-scale catastrophic events impose a great challenge to a regional emergency service system, and thus improving the ability to cope with the emergencies has become an urgent issue. Due to the scarcity of emergency resources for a single region, so it is highly necessary to establish emergency response teamwork of multiple emergency organizations through interregional cooperation. In this study, the cooperative teamwork of emergency response is formulated as a multi-stage integer programming model with the objective of minimizing total response time to consider the most timely handle emergencies possible. Then a solution procedure based on genetic algorithm is proposed to solve the presented mathematical model, and a hypothetical scenario is given to illustrate how this proposed model can be applied into practice finally.

Keywords: Cooperation; Emergency response; Interregional; Teamwork; Genetic algorithm

1. Introduction

Recent occurrences of natural disasters such as hurricanes, earthquakes or severe manmade hazards can strike a region with little warning and leave much devastation and many casualties behind (Comfort, 2002), which have increased awareness of the need for effective mitigation and effective response to these extreme events. However, local emergency agencies typically do not have sufficient emergency response capacity to effectively deal with the consequences of such large-scale natural or manmade disasters without significant external aid (Basalo, 2003; Kettl, 2006; American Bar Association, 2006). As a result, local emergency agencies temporarily require staffing and equipment more than their existing emergency capacity to control the consequences of such extreme events (Congressional Research Service, 2006; Forsman, 2002; Loflin and Saunders, 2002). However, according to the survey of the United States' Fire Administration, only 12% of local emergency departments had sufficient resources to effectively respond to a hazardous materials incident (United States Fire Administration, 2006), so it is useful and necessary to construct the interregional cooperative teamwork for responding to large-scale disasters at present.

There are a plenty of efforts in emergency response research focuses on disaster management following emergency events (Al-qurashi, 2004; Tsai et al., 2002; Sherali et al., 2004; Barbarosogcaronlu and Arda, 2004; Chiu and Zheng, 2007; Houming et al., 2008; Sheu, 2007, 2010). But the focus of these efforts is still emergency response within a single region, and do not reflect the interregional cooperative response. Since many regions are unwell equipped to respond disasters effectively without an expanded emergency response capacity. To achieve higher levels of readiness for disaster, it has become necessary that the local regional emergency agencies must work together and form teamwork to achieve their aims of sufficient preparedness for large-scale emergency events (Agranoff and McGuire, 2003). Hence, in order to enhance the local regional emergency response capacity and more effective use various emergency resources; many local regional emergency response agencies have engaged emergency response of interregional cooperative (Iaeger, 2004; Bryson et al., 2006; Zhao and Lu, 2008; Poulin, 2009; Jiang and Zhao, 2009).

In this paper, we firstly present a conceptual framework of emergency response of interregional cooperation. Then propose a dynamic integer programming model supported by the efficient use of emergency resources and information to assist multiple regional emergency response agencies in coordinating their teamwork more effectively during states of emergency response. The model can help the disaster region to expand the emergency response capacity to adapt to disaster conditions as well as the ability to maintain the continuity of basic operations for the local region emergency response until the state of extreme event is transferred into a normal disaster. Lastly, a hypothetical numerical case of emergency operations are examined to assess whether emergency response cooperation among multiple response team can be improved by using the interregional cooperation model.

The remainder of this paper is organized as follows. Section 2 describes the background of emergency response of interregional cooperation and constructs a theoretical framework of interregional teamwork, which will be used as a basis for subsequent analysis. Section 3 focuses on the modeling, including modeling assumptions, the proposed a dynamic integer programming formulation, and provides an efficiency solution algorithm to solve the model. Numerical examples and some computational results will be given in Section 4. Finally, we give concluding remarks and directions for future research in Section 5.

2. Theoretical Framework

Extreme disasters are highly destructive events and are somewhat unpredictable in their behaviors. Due to the severe consequences of large-scale disaster and limited emergency response capacity of one single region, it is an inevitable choice to establish a cooperative teamwork of emergency response among multiple regions. Emergency response operations are more effective when multiple emergency agencies interact with each and work together. While information communications, resources sharing as well as organizational cooperation are the key points to form interregional teamwork effectively, these can realize cooperative emergency responses and disaster clear. Therefore, this paper proposes a conceptual framework of emergency response of interregional cooperation, as shown in Fig.1. The cooperative framework can be illustrated from three aspects, information communication, resources sharing, and organizational cooperation.

Information communication in interregional cooperation has great significance in forming of partnership between multi-regional emergency agencies, as well as transferring the disaster information and the condition of emergency response team in each region. Due to the wide geographical distribution of multi-regional emergency response teams, it is also necessary to integrate plenty of information based on the interregional data exchanging and information communication, so as to support the various activities of emergency response teamwork of multi-regional cooperation. On the other hand, the capability of emergency response team is composed by various resources, such as emergency staff, security infrastructure, safety monitoring equipment and emergency rescue material, can be used to master, relief and eliminate disasters happened in the disaster region. All of these resources need to be shared and coordinated in scientific way for the using time, locations, scheduling method and so on. The resources sharing of interregional cooperative emergency response in this paper is refer to integrate and share the emergency response team from each region, in order to solve the issue of resources limitation for a single disaster region and maximize the utility of emergency resources through the team formation.

Moreover, the organizational cooperation generally involves several emergency departments in multiple regions. Its purpose is optimizing the unreasonable emergency response process, so as to improve the efficiency of interregional cooperation and reduce the deployment of emergency response team. Due to the regional differences, it caused the emergency response teams at different region with different emergency capacity superiority during interregional cooperation. Therefore, different ideas will be existed in an actual cooperative activity for one same emergency response process, and more original opinions or ideas can be proposed through communication of these ideas by using organizational cooperation methodology. Generally, the organizational cooperation can be demonstrated from four aspects: emergency plan, emergency resource, emergency command and emergency response, and the relationship among them can be illustrated from three aspects. First of all, emergency plan can guide the organizational cooperation orderly and high efficiently during the cooperation; then, emergency resource is an important guarantee of interregional organizational cooperation, and it is necessary to enhance the utilization of resources through emergency resources sharing; moreover, due to several emergency departments involved in the organizational cooperation, the command and coordination of emergency activity is the key to ensure the emergency organizational cooperation effectively; finally, the achievement of organizational cooperation is illustrated by emergency response teamwork. Therefore, an effective organizational cooperation mechanism can produce a preplan about commanding decision quickly after extreme disasters happened.

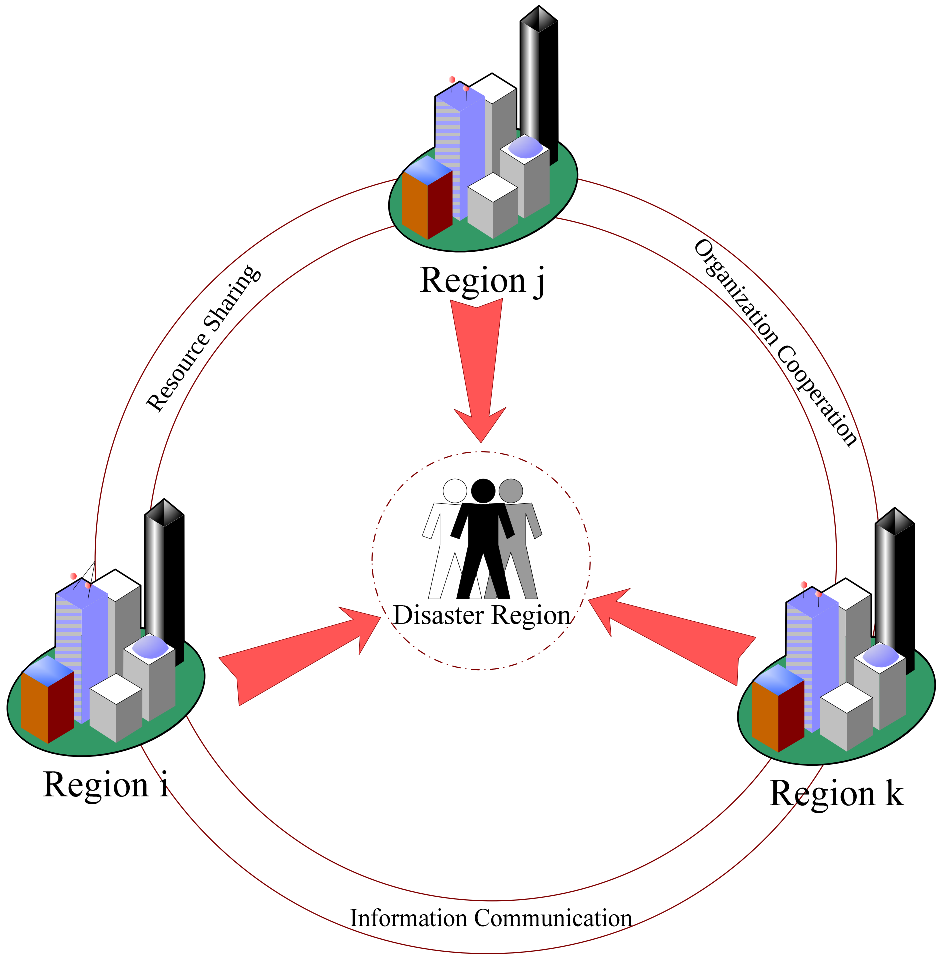

Fig.1 Conceptual framework of emergency response of interregional cooperation

3. Mathematical Formulation and Solution

In order to solve the emergency response of interregional cooperation problem mentioned in Section 2, this section propose a dynamic integer programming model to solve the emergency response team formation through how to deploy emergency response team from multiple regions. As a starting point of model formulations, the basic assumptions of this paper are described as follows:

(1) We only consider the emergency response team formation problem after a large-scale extreme event happened in a single region.

(2) Since the response time is primary for interregional cooperation activities, only time element is considered as model objective and other factors are ignored; moreover, we also do not divided the response time into different stages at each time period.

(3) The lead time of emergency response team from different region is assumed as zero; and supposes that the working time for each emergency response team is not more than 9 hours.

3.1 Notation

According to the above explanation and assumptions, the definitions of parameters and variables specified in this paper are summarized in the following.

Q : set of all emergency response team types;

M : set of all regions that can offer emergency capacity for each other;

T : the length of planning horizon (in terms of the total number of emergency response time periods);

$a_{mqi}(t)$: amount of emergency response team i of type q available in region m at time period t , $t \in T, q \in Q, m \in M, i \le a_{mqi}(t)$;

$c_{mqi}(t)$: emergency capacity of response team i of type q in region m at time period t, $t \in T, q \in Q, m \in M, i \le a_{mqi}(t)$;

v_q: total amount of emergency response team of type q, $q \in Q$;

r_{mqi}: total elapsed time requirement to deploy emergency response team i of type q from region m, $q \in Q, m \in M, i \le a_{mqi}(t)$;

$\gamma(t)$: minimum emergency capacity requirement at time period t, $t \in T$;

$x_{mqi}(t)$: a binary parameter (0, 1) whether emergency response team i of type q in region m be deployed on scene at time period t, $t \in T, q \in Q, m \in M, i \le a_{mqi}(t)$.

According to the above analysis, the following model can be formulated.

3.2 Mathematical Model

Based on the description and hypothesis of the model, suppose TRT is the total emergency response time of multiple region cooperation, a integer programming model for this emergency response can be constructed as follows.

$$\text{Min}\, TRT(t) = \sum_{m}\sum_{q}\sum_{i} r_{mqi} x_{mqi}(t) \tag{1}$$

Subject to:

$$\sum_{m}\sum_{q}\sum_{i} c_{mqi}(t) \cdot x_{mqi}(t) \ge \gamma(t), \qquad \forall t \in T, q \in Q, m \in M \tag{2}$$

$$\sum_{q}\sum_{i} x_{mqi}(t) \le \sum_{q} a_{mqi}(t), \qquad \forall t \in T, q \in Q, m \in M \tag{3}$$

$$\sum_{m}\sum_{q}\sum_{i} x_{mqi}(t) \le v_q, \qquad \forall t \in T, q \in Q, m \in M \tag{4}$$

$$x_{mqi}(t) \in \{0,1\}, \qquad \forall\, q \in Q, m \in M \tag{5}$$

The objective of the model, Eq. (1), is to minimize total emergency response time of all regions at each time period. Constraint (2) is an emergency capacity constraint that stipulates that the cumulative emergency requirement at any time period $t \in T$ will be satisfied. Constraint (3) ensures that the emergency response teams i of type q utilize no more than the amount in region m. Constraint (4) shows the upper bound constraint on emergency response team types. Constraint (5) states that whether emergency response team i of type q is deployed at time period t.

3.3 Solution Methodology

In this section, we focus on the solution methodology for the integer programming model of emergency response of interregional cooperation. The interregional teamwork problem is a combinatorial optimization problem, and in the above formulations it is also a mixed integer programming problem. Besides this, it is an NP complete problem. Since the GAs is commonly used to optimize various objective functions, we adopt the genetic algorithm to solve the models in Eq. (1).

GAs is not only an optimized search method based on biological natural selection and genetic principles, but also a highly parallel, random and adaptive search algorithm (Goldberg, 1989). It simulates biological evolution and genetic manipulation, and does not require specific knowledge with regard to the objective. Since the search space of the target is continuously differentiable, GAs has the ability to achieve global optimization (Gen, 1997). This algorithm introduces the principles of biological evolution and the survival of the fittest into the coding serials of the parameters to be optimized. It selects each individual according to a certain fitness function and a series of genetic operations, in order to keep the individuals with high fitness for forming new groups. The new groups contain the main information of the last generation, and introduce new individuals better than the last one. As a repeating process, the fitness of each individual in the group becomes higher until meeting certain limit conditions. At the moment, the highest fitness individual in the groups will be the optimal solution of parameters to be optimized. In what follows, we describe how to apply the genetic algorithm in to solving the dynamic integer programming model for interregional cooperative teamwork.

3.3.1 Chromosome Coding

One of the most important elements of GAs is its chromosome structure that can be coded in binary or real mode. In this research, based on the emergency response team selection for interregional cooperation, the binary mode is selected to code a chromosome. In this regard, each chromosome i contains m genes, where m is the total number of emergency response team of all types. The position of each gene in a chromosome denotes the corresponding emergency response team of type m, and has two values, with 0 indicating the corresponding emergency response team is not to be chosen, and 1 to be chosen. Using a binary system can tell easily which emergency response team is joined in the interregional cooperation. Therefore, the solution encoding scheme proposed in this paper can successfully represent different binary variables for every emergency response team.

3.3.2 Initialization of Population

According to the chromosome coding structure, this step is to build the initial population, of N individuals, one can proceed randomly. Each chromosome of the initial population is verified by the model constraints to avoid the illegal chromosome. The procedures of generating initial population are as follows:

Step 1: Generate initial population $p(0)$ randomly by computer and determine length of chromosome coding according to the total number of emergency response team.

Step 2: Checking up whether constraints (2), (3) and (4) are satisfied. If the chromosome $p_i(0)$ of initial population $p(0)$ is illegal, then regenerate a new chromosome.

Step 3: Repeat steps 1 and 2 N times.

3.3.3 Fitness Function

The fitness of each individual h is given in accordance with the objective function in the model. If the objective function is to optimize a minimum problem, the value of the fitness function is the reverse of the objective function value; so the fitness functions can be defined as $f_h = 1/TRT$. Hence, according to the definition of f_h, the higher f_h is, the better h is, and the corresponding solution is much closer to the optimal solution.

3.3.4 Selection

Selection process is based on retaining the best individual and roulette wheel approach to select new chromosomes for a new group. We constructed the combination of retaining the best individual and roulette wheel as follows (Mitchell, 1996).

Step1: Reorder the chromosomes according to the values of fitness functions. The higher of the fitness function f_h indicates the better of the chromosomes h and the smaller of the serial number. Given the parameter $a \in (0,1)$, the evaluation function based on the orders is defined as follows.

$$eval(h_i, f_{h_i}) = a(1-a)^{i-1}, i = 1, 2, \cdots, N ,$$

Where $i = 1$ means the chromosome is the best, and $i = n$ means the worst. Reproduce the chromosome whose serial number is one into the next generation, and select other chromosomes as the following steps.

Step2: For each chromosome h_i, calculate the cumulative probability p_i.

$$p_0 = 0, p_i = \sum_{j=1}^{i} eval(h_j, f_{h_j}), i = 1, 2, \cdots, N .$$

Step3: Generate a real number $r \in (0, p_n)$ randomly.

Step4: If $p_{i-1} < r \le p_i$, then select the chromosome h_i.

Step5: Repeat the Step 3 and Step 4 with $N-1$ times, and select $N-1$ chromosomes.

3.3.5 Crossover

The crossover operations between individuals reflect a random information exchange, is done to explore new solution space and crossover operator corresponds to exchanging parts of strings between selected parents. Single point crossover has been used in GA traditionally, but this would lead to incomplete chromosomes and was not pursued. In order to avoid this limitation, the two-point crossover is used in this paper. In general, the crossover rate p_c is $0.25 \sim 0.75$ (Mitchell, 1996). The crossover operation process is illustrated as follows:

Step 1: Randomly select the crossover partner, then selected the same positions of two parent chromosomes randomly and copy it into a new offspring, and exchange the code on them with probability p_c.

Step 2: Checking up whether constraints (2), (3) and (4) are satisfied. If the new offspring is validated, this completes one offspring; otherwise, restore the parent chromosomes before crossover operation, and begin a new crossover process.

Step 3: Repeat Steps 1 and 2 $N/2$ times.

3.3.6 Mutation

The main task of the mutation operator is to maintain the diversity of the population in the successive generations and to exploit the solution space. Following crossover operation, the mutation operations of certain individuals in certain places with probability p_m are carried out according to biogenetic principles of genetic variation. In the process of variation, the corresponding bit strings of implementing variation are swapped by an integer number with two values 0 and 1. Mutation probability p_m is consistent with the biological small variation; therefore the value of Variation rate p_m is generally small, and the value of p_m is commonly $0.1 \sim 0.2$ (Mitchell, 1996). The procedures are defined as follows:

Step 1: Randomly selected the mutation chromosome, then implement genetic variation in certain places with probability p_m, and the variation genes are swapped by an integer number with two values 0 and 1.

Step 2: Check the chromosomes through constraints (2), (3) and (4). If the new offspring is illegal, restore the parent chromosomes before mutation operation, and restart a new mutation process once time until the offspring is satisfied the constraints (2), (3) and (4).

4. Numerical Example

In this section, we focus on a numerical analysis to illustrate the efficiency of the above proposed method that can be applied into practical operations of emergency response teamwork of interregional cooperation. The hypothetical emergency scenario created for the study is composed of five regions ($m = 5$), and we only consider one kind of emergency response team type in each region, and suppose the whole planning horizon of emergency response is 15 hours. If the amount of response time beyond 15 hours, the emergency response teamwork among of multiple regions cooperation is changed into normal response activities within one region.

At the first stage, let $N = 500, p_c = 0.6, p_m = 0.01$, and we iterate 50 generations according to above GA procedure (in Section 3.3), and other basic data are given in Table 1. The optimal decisions are selected all emergency response teams in region 1 and region 2, and the second emergency response team in region 3 is also chosen. The final optimal result is *Min* $TRT(t_1) = 7.5$ hours, as shown in Fig.2. It is easy to seen that the minimal total response time in the first time period is about converged at 25 generation. Due to $7.5 < 15$, so the team formation model steps into the second stage.

Table 1 Primary parameters set in the 1st time period

m (*m = 1, … 5*)	1	2	3	4	5
$a_{mqi}(t_1)$	2	1	2	3	2
r_{mqi}	1.5	2	2.5	3	3
$c_{mqi}(t_1)$	200, 300	250	100, 300	200, 200, 300	150, 250
$\gamma(t_1)$			1000		
T			15		

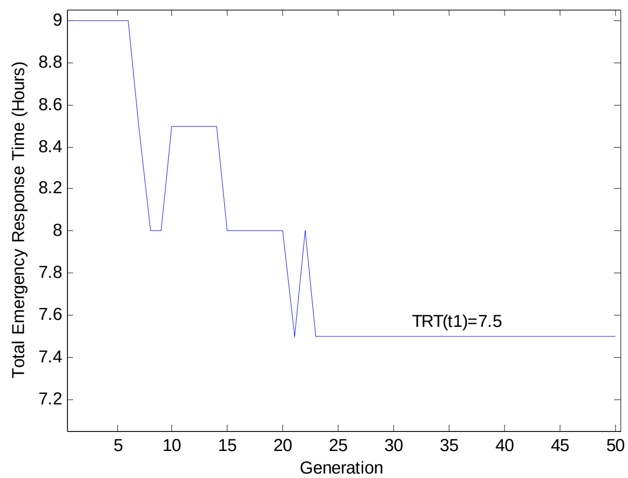

Fig.2 Optimal value of $TRT(t_1)$

At the second stage, the selected emergency response team in the first stage will return to the corresponding region, and can not work in the following stage. Hence, the basic data setting in the second stage is shown in Table 2; and we still let $N = 500, p_c = 0.6, p_m = 0.01$, and iterate 50 generations. According to the calculation of GA algorithm, the result of emergency response team formation is selected the first emergency response team in region 3, the third one in region 4 and the second one in region 5. The optimal total response time in the second stage is $Min\ \ TRT(t_2) = 8.5$ hours, as shown in Fig.3. Due to the size of the emergency response team and the minimum emergency capacity requirement is reduced in the second stage, so the optimal result is converged quickly. Moreover, the sum response time of the first and second stage is 16, and exceeds the total planning time horizon of emergency response. Hence, the emergency response teamwork of interregional operation is ended, and changed into the normal emergency response.

Table 2 Primary parameters set in the 2nd time period

m (*m* = *1*, … *5*)	1	2	3	4	5
$a_{mqi}(t_2)$	0	0	1	3	2
r_{mqi}	1.5	2	2.5	3	3
$c_{mqi}(t_2)$	0	0	100	200, 200, 300	150, 250
$\gamma(t_2)$			600		
T			15		

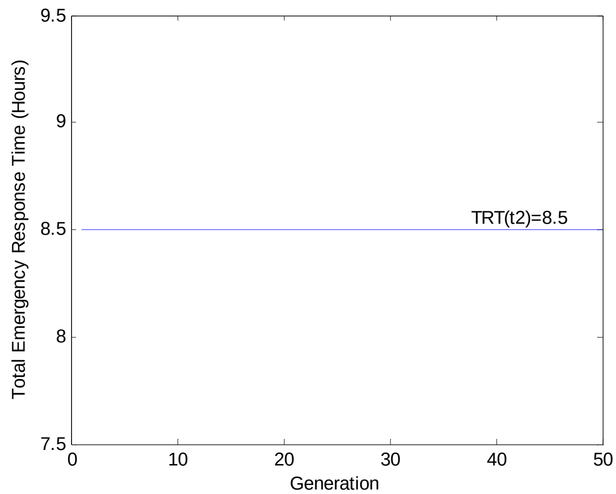

Fig.2 Optimal value of $TRT(t_2)$

5. Conclusion

In this study, an emergency response teamwork framework for the interregional cooperation is presented, whose key elements are contained information communication, .resource sharing and organization cooperation. Then a dynamic integer programming model is developed for this problem, this model seeks the total emergency response time for the team formation of interregional cooperation. Moreover, we also propose a GA-based solution methodology to solve combinatorial optimization problem contained in the proposed model. Then the applicability of the framework is demonstrated through applying it to a case study, and the results demonstrate that reasonable time. Besides, emergency response teamwork of interregional cooperation problem with more objectives of multiple disaster regions is our research direction in the future.

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